Technologies and Processes to Reduce Carbon Intensity of Main Road Projects

A Sustainable Built Environment National Research Centre (SBEnrc) Research Report and Annotated Bibliography by Curtin University Sustainability Policy Institute

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Introduction

The coming decades will see a great deal of innovation and creativity in the way that our road networks are designed, constructed, and maintained. This will be sparked in part by the need to respond to climate change, resource shortages, shifting transport preferences, and increasing maintenance costs. There is a great deal of activity in this area and Australia has the opportunity to show the world how to prepare for and deliver the Future of Roads. The SBEnrc is committed to assisting our nation to navigate this challenging future in a way that strengthens our economy, creates jobs, and delivers strong environmental outcomes.

The 'Strategies and Solutions for the Future of Roads' project will be completed in December 2015 and is being developed in collaboration with the CRC for Low Carbon Living. Building on the previous research findings this project is being developing three modules, namely a focus on 'Technology and Processes Innovation', 'Sustainability Reporting', and 'Low Carbon Readiness'.

1. *Technology and Process Innovation*: This module is focused on three areas selected by the project steering group, namely: the potential for active traffic management methods to defer capital investment in road infrastructure, while reducing traffic congestion, trip time, and vehicle emissions; the updating of route and signal lighting to advanced lighting options; and the inclusion of renewable energy generation technologies in road and transport infrastructure, as outlined in this report.
2. *Sustainability Reporting*: This module will investigate the Infrastructure Sustainability Council of Australia sustainability performance tool (IS Tool). The research team will work with project partners to identify where the use of the 'IS Tool' has provided value to projects. The investigation will cover all sustainability criteria assessed by the 'IS Tool' as applied to actual projects.
3. *Low Carbon Readiness*: This module will present a detailed review of the low carbon related elements of 'IS Tool', and highlight how the tool can add value to low carbon tendering, including identification of specific client actions. The research team will undertake a supply chain investigation to identify the level of readiness to deliver on the low carbon criteria in the 'IS Tool', including: Energy and Carbon, Materials, Procurement, Climate Change Adaptation, and Management Systems.

As with all SBEnrc projects, this project works closely with government and industry partners to identify opportunities to generate outcomes that provide tangible value, both in economic and environmental terms.

1. Deferring Capital Investment through Managed Motorways

Active Traffic Management Methods

According to the U.S. Department of Transportation there are a number of benefits of investing in active traffic management measures, including:[1]

- Increased throughput,
- Increased capacity,
- Decrease in primary incidents,
- Decrease in secondary incidents,
- Decrease in incident severity,
- More uniform speed,
- Decreased headways,
- More uniform driver behaviour,
- Increased trip reliability,
- Delay onset of freeway breakdown,
- Reduction in traffic noise,
- Reduction in emissions, and
- Reduction in fuel consumption.

Whilst the use of individual active traffic management mechanisms can yield significant benefits, these benefits compound when a combination of measures is used as part of a coordinated freeway management system. Such systems can deliver significantly reductions in accident and congestion related externalities (including reduced noise, carbon dioxide emissions, particulate matter emissions, and fuel use). Such benefit allow the road system infrastructure to utilise a greater proportion of its potential capacity which can lead to the prolonging of the need to invest in additional road infrastructure to meet increasing demand driven by population growth.[2] Along with informing traffic management devices the data collected on vehicle flows and timings is valuable in the design of new road infrastructure to minimise design related impacts on travel time and traffic throughput. Also this data can assist efforts to achieve greater efficiency of the wider road system by decongesting other parts of the road network as motorists seek to minimise their generalised cost of travel by shifting onto a less congested, more reliable managed freeway.

This report overviews a range of methods to achieve automated motorways to deliver sustainability benefits, such as reduced congestion related greenhouse gas emissions. Managed Motorways as a concept began in the United Kingdom in the early 2000's. Since then the active management of traffic on motorways has led to the development of a number of measures, which according to VicRoads include:[3]

- Lane Use Management,
- Variable Speed Limits,

- Traveller Information, and
- Freeway Ramp Metering.

These active traffic management measures can influence road user behaviour and improve traffic flow, increase road safety, reduce fuel consumption of vehicles, reduce time spent in congestion. Due to the interconnected nature of road systems such outcomes can influence the performance of other sections of the system, such as traffic re-routing due to ramp controls, that need to be accounted for. However despite the potential improvements to freeway performance VicRoads cautions that '*not every freeway needs to have every component of managed freeways*',[4] and hence it is important to ensure that the measures implemented are suitable for the freeway and the road system as a whole.

Given that many of the measures involve providing information to the road user through electronic screens the success of managed motorways relies on effective asset management in order ensure that active traffic management measures are operated effectively. This can ensure that the measures are delivering the best level of service and that the anticipated return on investment is received.

According to VicRoads, '*In specifying assets and their installation, whole of life costs [including operational and maintenance] need to be considered in both financial and economic (road user impacts) dimensions'*.[5] Benefits to road users not only benefit the user but as an aggregate can deliver efficiency and productivity gains for the economy such as better managing congestion to reduce trip times while allowing greater traffic volume throughout. Other benefits include reductions in accidents and injuries, fuel use, and transport emissions (noise, particulate matter, carbon monoxide and greenhouse gasses).

As mentioned above motorways can be managed with various active traffic management measures to improve their performance. Such measures can be organised into a road network management framework such as the one developed by VicUrban as shown in Figure 1.

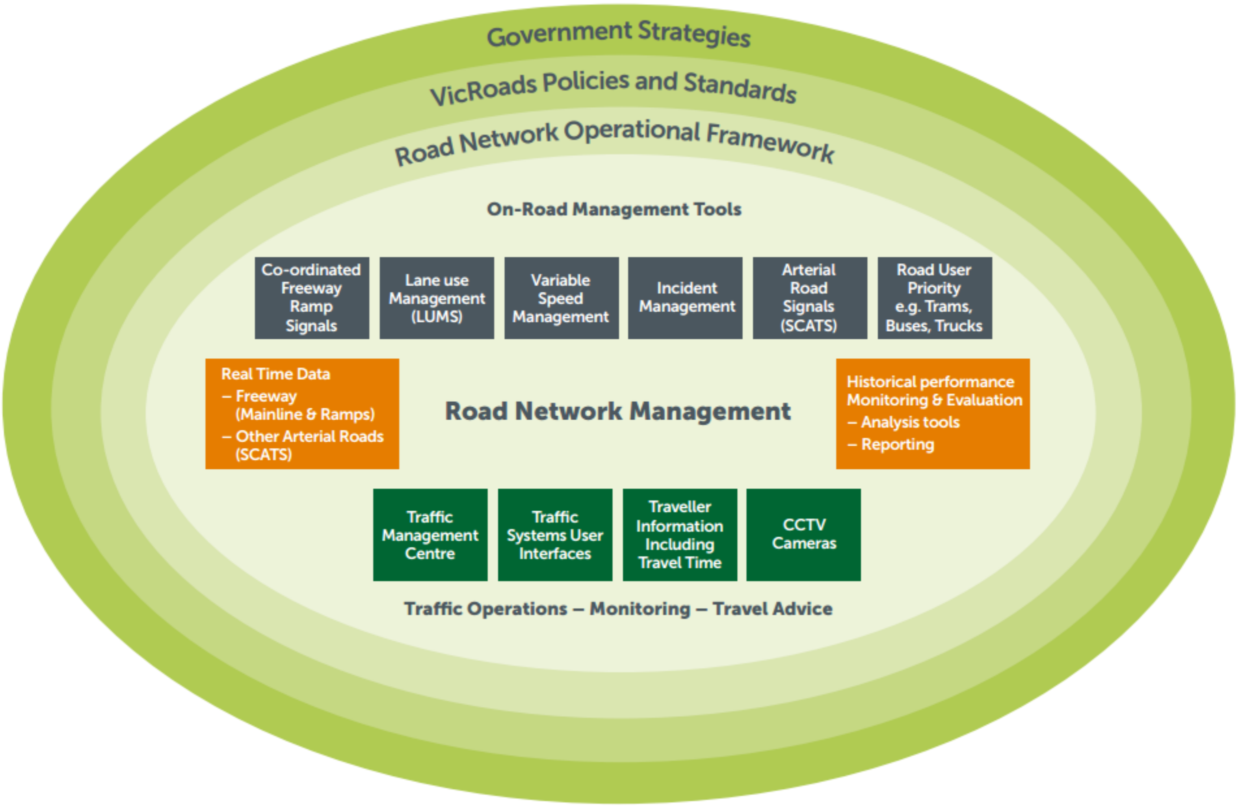

Figure 1: VicRoads Road Network Management Framework[6]

The Road Network Management Framework summarises how VicRoads uses active traffic management measures to manage traffic freeway operations. The following section will provide a brief overview of key traffic management measures and their roles in managed freeway operations, based on the experience of VicRoads.

The following provides an overview of three key types of active traffic management measures, namely:

- Detection and Monitoring Devices,
- Freeway Control Systems, and
- Driver Information Technology Systems.

Each of these measures will be briefly introduced and where possible their implementation will be illustrated to form the basis for the discussion of their implementation in Australia.

Detection and Monitoring Measures

The detection and monitoring of freeway operations is the foundation of managing freeways and informs the control measures and information provision measures along with informing performance and outcome monitoring.[7] A summary of key detection and monitoring measures are presented in Table 1 (which contains edited extracts from the VicRoads Managed Freeway Guidelines[8]) and are illustrated in Figure 2, compliments of VicRoads.

Table 1: Managed freeway detection and monitoring measures[9]

Active Traffic Management Measure	***Description***	***Illustration of the Measure***
Vehicle Detection Equipment	Vehicle detection equipment provides volumes, speed, occupancy (density) and vehicle classification on a lane by lane basis, and is the basis of freeway monitoring and control.	*See Figure 2*
Closed Circuit Television (CCTV)	Provides vision of the freeway, enabling more detailed assessment of conditions than provided by vehicle detection equipment and are also shared with key incident and emergency management.	*See Figures 2 & 3*
Incident Detection Capabilities	Direct detection of incidents (image processing systems), algorithms applied to traffic data, and help phones.	*Central Operations*
Environmental Monitoring	Monitors environmental conditions such as temperature, wind speed and water levels, and can also directly activate equipment such as pumps and warning signs.	*Central Operations*
Travel Time Tracking Equipment	Tracks vehicle movements for travel time calculations.	*Central Operations*

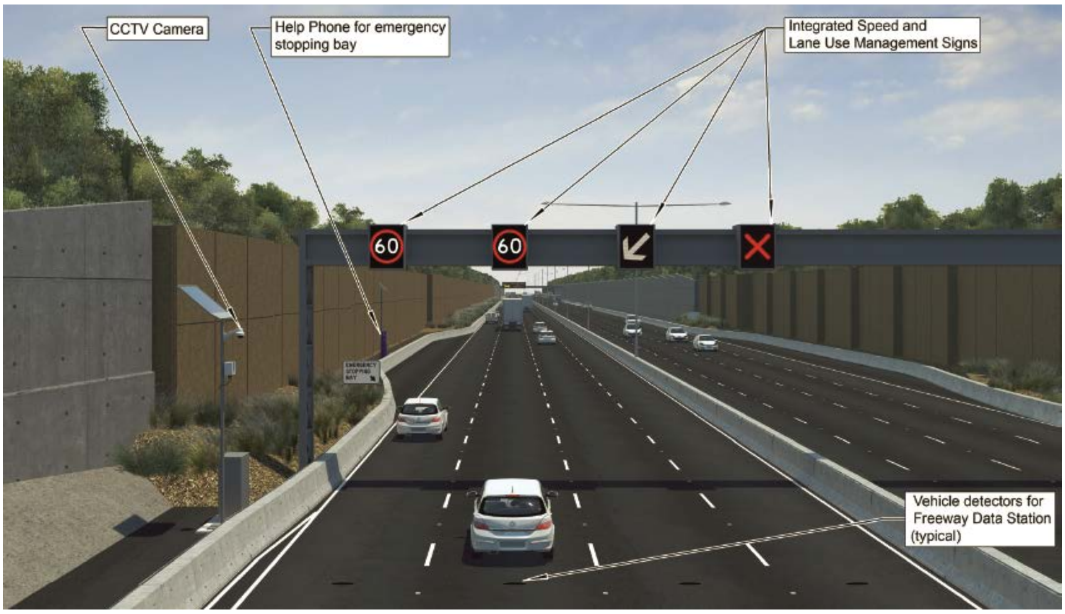

Figure 2: Integrated speed and lane use management[10]

Freeway Control Systems

Drawing on data from the detection and monitoring measures a number of freeway control systems can be used to improve freeway performance, safety, fuel efficiency, and capacity. A summary of key control systems are presented in Table 2 (which contains edited extracts from the VicRoads Managed Freeway Guidelines[11]) and are illustrated in Figure 2 and 3, compliments of VicRoads.

Table 2: Managed freeway control measures[12]

Active Traffic Management Measure	*Description*	*Illustration of the Measure*
Freeway Ramp Signals (FRS)	Manages access to the freeway, to prevent capacity being exceeded (and subsequent flow breakdown), by breaking-up groups of entering vehicles to avoid overload of the merge area. This is most effective when implemented as a corridor-wide adaptive system providing full control of the freeway and allowing effective management of queues at entry ramp signals.	*See Figure 3*
Variable Speed Limits (VSL)	Assists in maximising safety in adverse conditions, such as high winds, road works and incidents. VSL can also assist in maximising capacity during heavy demand and is best achieved in conjunction with FRS.	*See Figures 3 & 4*
Lane Use Management	Allocation and management of available road space to achieve desired performance outcomes and can include dynamic use of the shoulder for exit queue storage.	*See Figure 4*

Figure 3: Example of Freeway Ramp Signalling (FRS) and Variable Speed Limits (VSL)[13]

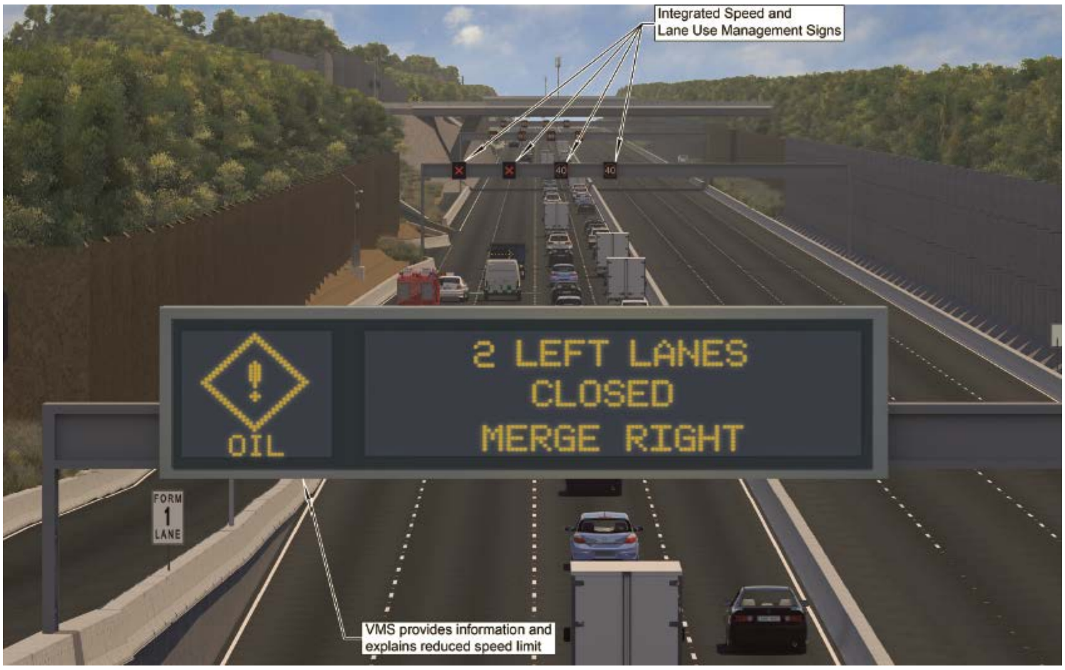

Figure 4: Example of Lane Use Management, Variable Message Signs (VMS) and Variable Speed Limits (VSL)[14]

Driver Information Technology Systems

Driver information technology (ITS) can be used to inform road users on the performance of the freeway in order to make decisions about which routes to take, which is valuable information to avoid delays in the case of accidents or road works. According to VicRoads '*An overall traveller information strategy for potential freeway users should consider: pre-trip (e.g. before leaving home or work); en-route but before entering the freeway; and en-route, after entering the freeway*'. A summary of key driver information technology systems are presented in Table 3 (which contains edited extracts from the VicRoads Managed Freeway Guidelines[15]) and are illustrated in Figure 5, compliments of VicRoads.

Table 3: Managed freeway ITS measures[16]

Active Traffic Management Measure	*Description*	*Illustration of the Measure*
Real Time Information Signs (RTIS)	Variable message signs located on arterial roads on the approach to freeway entry ramps providing travel time and other freeway condition information and enable motorists to make route choice decisions before entering the freeway.	***See Figure 5***
Variable message signs (VMS)	Allows information to be conveyed to motorists once on the freeway. This information can warn them of expected travel times, hazards or disruptions and detail action for them to take	***See Figures 5***
Website	Pre-trip information and should form part of a broader network-wide travel information strategy. This can include links to CCTV cameras to provide a visual indication of freeway conditions at selected locations	***Central Operations***
Radio	Radio messages can reach road users both before and during the trip.	***Central Operations***

Figure 5: Example of Real Time Information Signs (RTIS)[17]

Case Studies of Active Traffic Management Methods[18]

MONASH-City Link-West Gate (M1) Upgrade

In 2007 VicRoads undertook a pilot project worth $1M to investigate the use of managed motorway measures at six locations along the Monash Freeway. This pilot upgraded the existing traffic lights that were used to control flow entering the motorway to be controlled by a ramp signal algorithm. The algorism uses data on flow at the on-ramp to control signalling and the results have exceeded expected improvements to delay times and traffic throughput. According to VicRoads, '*Improved travel speed both in the AM and PM peak has resulted in a net savings of approximately 5 minutes per vehicle over the 15km section which is equivalent to 1900 veh.hrs of delay savings per day. The daily economic benefits (travel time savings and vehicle operating cost savings) were estimated to be around $94,000 per day. Consequently the payback period against a cost of the project of $1M is 11 days*'.[19]

Figure 6: Example of project freeway Ramp Metering[20]

Building on the success of the Pilot project VicRoads has developed a $1.39 billion M1 upgrade project that includes a Freeway Management System consisting of coordinated Freeway Ramp Signals at 64 sites along the 75km corridor to improve traffic operations. The project also uses a Lane Use Management System on over 19.5km of the motorway that comprises of integrated lane control, variable speed controls, and an en-route information system that can use pictograms or text messages to communicate directly with drivers in real time about traffic conditions, expected trip times, and safety reminders. The project was completed in 2010 and according to John Gaffney from VicRoads the use of active traffic management measures resulted in '*a reduction in congestion which was resulting in a 30 per cent reduction in freeway performance during peak periods, a reduction in crashes of up to 20 per cent, and an expected community benefit of $14.5 billion* [in terms of reduction in crashes and monetised travel time saving]'s.[21] This would indicate that the project has benefit cost ratio of over 10, driving a very compelling argument for its extension to other parts of the network.

The City of Edmonton's Smart Roads Projects, Canada

According to IBM in their Smarter Cities Challenge Report (2011), the City of Edmonton's mission is to be the global leader in urban traffic safety. It has adopted a longer term Vision Zero for fatalities and serious injury collisions, with shorter term strategies and targets using safe system approach. The City's Office of Traffic Safety (OTS) is renowned worldwide for its work and leadership. Its international conferences have sought greater collaboration among experts, enforcement agencies, governments and universities, to drive forward the mission of better traffic safety.

The City of Edmonton is using a range of smart road options including:

- *Intelligent Transportation Systems* (ITS): ITS use new and emerging technology to reduce congestion, save money, improve safety and reduce environmental impacts in all areas of transportation.
- *Northlands Traffic Responsive System:* The Northlands Traffic Responsive System actively monitors traffic patterns in the Northlands area 24 hours a day, 7 days a week, and automatically applies the appropriate signal timing plans to improve traffic flow.
- *Yellowhead Trail ITS Simulation Laboratory and Edmonton Showcase:* The City has completed the concept and planning phase of the Yellowhead Trail ITS project and is waiting funding for implementation. By combining the current intelligent traffic tools with the new computer system, traffic will be controlled more efficiently.

Although the aim of this strategy is primarily to improve traffic safety a knock-on effect of improving traffic flow will be improved traffic fuel consumption. However as fuel consumption is not stated as a goal or a KPI it is unlikely that feedback on the performance of these systems will include any fuel consumption benefits achieved.[22]

Automation of French Motorway - 40 Workstations on Fibre Optic Network

April 2000, Fieldbus & Industrial Networking – Adroit Technologies.[23]

- A busy French motorway system is using Adroit scada MMI software for effective traffic control and streamlined toll management
- The motorway is operated by VIA-GTI within the SCE A14 group. G. le Roux, Director of via AutoRoute, explains, "These traffic peaks demand the full operational availability of the toll equipment and require excellent accident response capabilities."

'Freedom Transit- The Sustainability Answer'

Freedom transit is a transit system that is proposed to solve traffic congestion, the growing demand for oil and global warming caused by transportation. The design is as follows: there would be an automated roadway which would be elevated (three lanes) built either beside or in the middle of existing roads and the roof would be solar panels. The outside two lanes of the raised road would be would be used for normal travel with the centre lane being reserved for switched bidirectional maintenance or emergency travel.

The site details the environmental and energy related benefits of an automated roadway as well as the governmental benefits and the citizen benefits. It details an investment plan and also provides some pictures of the theoretical road system.[24]

'Smart Highways in the Netherlands will glow-in-the-dark'

Designers in the Netherlands have created a road that lights up using photo-luminescent power which glows in the dark. The photo-luminescent powder will be used for road markings (it will gather energy from the Sun during the day, also when the road temperatures go below a certain temperature, glow-in-the-dark snowflakes will appear on the road to warn drivers. They are also looking into heated cycle tracks.

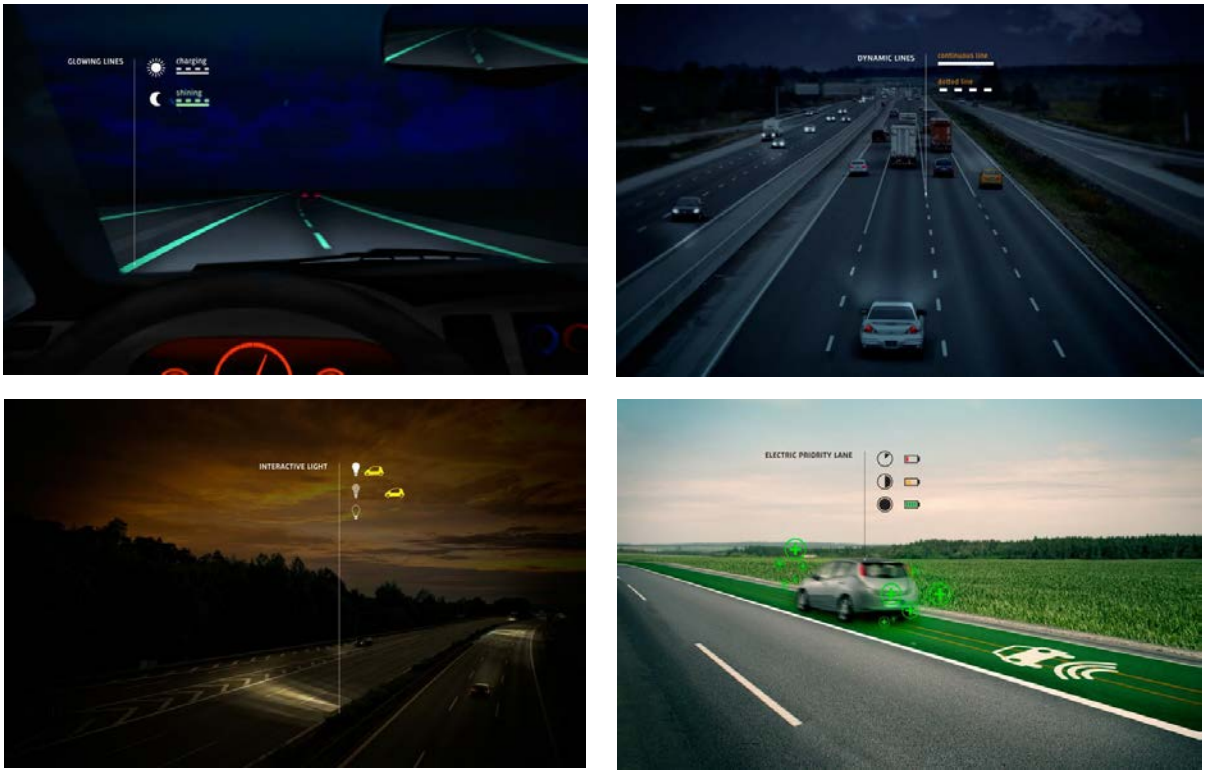

Figure 7: Computer Generated Images of Different Applications of the Glow-in-the-Dark Technology[25]

Studio Roosegaarde, the designers behind this concept have partnered with Heijmans, a listed company that combines activities related to property development, residential building, non-residential building, technical services and infrastructure. Heijmans is active in the Netherlands, Belgium and Germany. A pilot consisting of two 500-metre road sections with Glowing Lines will be constructed on the N329 provincial highway near Oss (Province of Noord-Brabant) by mid-2014. The clients for the pilot are the municipality of Oss and the Province of Noord-Brabant, the initiators of the N329 Road of the Future. The pilot project was in part realised with the advice and financing of the Brabant Knowledge Centre for the Arts and Culture. This pilot will be expanded internationally in 2014.[26]

Adaptive Signal Control Technology

The city of Pittsburgh introduced ASCT primarily as a means to reduce vehicle wait time in the high-traffic sections of East Liberty in Pittsburgh. Over a 3 month period from June to September 2012, the system has demonstrated reductions in wait times by an average of 40%. Travel time through the area has decline d by 26% and vehicle emissions are down by 21%. The system, developed by Carnegie Mellon University (CMU) initially covered nine intersections as a pilot study. Each intersection uses cameras or in-road sensor loops to measure traffic volume and fine-tunes green light lengths in real time to best accommodate vehicle flow. It then forwards those changes to neighbouring intersections in the street grid. The pilot program cost US$150,000 and was funded by three local foundations however it is difficult to establish cost benefits when the benefits are predominantly social in nature.[27]

Annotated Bibliography on Automated Motorways

'An Overview of Automated Highway Systems (AHS) and the Social and Institutional Challenges they face'

Sanghyun Cheon

Talks about automated driving – *'limited access roadway where specially equipped vehicles are operated under completely automatic control'.* Dr Nico Kampchen, Project Manager of Highly Automated Driving at BMW Group Research and Technology, has completed almost 5000 test kilometres in a highly automated BMW 5 Saloon which can brake, accelerate and pass other vehicles on its own whilst monitoring and adapting to traffic condition.[28]

'Sensor Networks for Smart Roads'

Marcin Karpinski, Aline Senart and Vinny Cahill - Trinity College, Dublin, Ireland

This article explores the potential of a system that would provide divers with early warning of potentially dangerous situations that may arise, more specifically a system that will provide drivers with a consistent view of the road situation a few hundred meters ahead of them so they can react safely. Essentially they would like to place sensor nodes on both sides of the road a few meters apart and they will be equipped with magnetic sensors. The sensors will form an 'ad hoc radio network' which will exchange information about passing cars (location and speed), the information is then communicated to the vehicles. The article touches on the software architecture of the nodes, as well as implementation issues.[29]

'Congestion Management and Electronic Road Pricing in Singapore'

Mark Goh, National University of Singapore

This paper looks at how to reduce road congestion without the traditional response of widening roads and building more. Singapore has chosen to employ a regulated pricing system to manage traffic congestion and prioritize road usage by harnessing the technology. The article goes through a timeline regarding how Singapore has reacted in the past to road congestion. There was a recorded decrease in road congestion when the electronic road pricing was implemented in 1998. However the article also explores other congestion management systems in Singapore. For example, GLIDE with is an advanced traffic management system that helps to increase road usage efficiency, and EMAS (express monitoring and advisory system) is a system that monitors traffic conditions and provides motorists with up to date traffic information.[30]

‘Partnerships for Progress- Toward Sustainable Road Systems’

Roger Toleman and Geoff Rose, Transportation Research Record 2067

The paper begins by outlining the concept of sustainability and highlights four perspectives (negative, superficial, weak, and strong). The article focusses on an extended view of Sweden’s Vision Zero (which states that it is ethically unacceptable for people to die or be seriously injured on the road system). The extension of the Vision Zero that is more tailored to sustainability:[31]

- The transportation sector and its users will directly bear the whole of the costs imposed on society.
- The transportation sector will not generate any emissions to air that are harmful to human health or the ecosystem.
- No noise generated by the transportation sector will be harmful to human health or the ecosystem.
- No water runoff from the transportation system will be harmful to human health or the ecosystem.
- Nobody will be killed or seriously injured in the transportation system.
- The transportation sector will use only renewable energy.

‘Green information and communication technology: energy efficiency in a motorway model’

W. Feng H. Alshaer J.M.H. Elmirghani Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK 8th June 2009[32]

The focus in Green ICT (information and communication technology) is on software and hardware solutions to reduce energy consumption. Here the authors consider the design of vehicular *ad-hoc* networks (VANETs) to reduce energy consumption through improved communications. Based on a realistic transport traffic scenario on a motorway, ‘M4’ in UK, this study computes the energy consumption in a motorway *ad hoc* wireless network. *This is based on a geographical adaptive fidelity (GAF) topology management protocol, where the energy consumption has been analysed for equal-grid, adjustable-grid and genetic algorithm models.*

- Green ICT (information and communication technology) is a new focus with the goal of saving energy by optimising mobile network communications and ultimately protecting the natural climate.
- Discusses energy consumption in peak time traffic models vs. off peak time traffic models.
- Conclusions: Based on transport traffic profiles observed at different ILs on the M4 motorway in the UK, this paper introduced, analysed and evaluated three GAF models to optimise energy consumption in vehicular ad hoc networks.

'Smart Cars on Smart Roads: Problems of Control'

Pravin Varaiya, Fellow, IEEE TRANSACTIONS ON AUTOMATIC CONTROL, Volume. 38, Number 2, FEBRUARY 1993[33]

Proponents of Intelligent Vehicle / Highway System or IVHS see it as a technology which will make a major change in highway transportation. Control, communication and computing technologies will be combined into an IVHS system that can significantly increase safety and highway capacity without building new roads. This paper outlines key features of one highway automated MIS system, shows how core driver decisions are improved, proposes a basic IVHS control system architecture, and offers a design of some control subsystems. It also summarizes some experimental work.

- Highway congestion is imposing an intolerable burden on many urban residents. Because congestion occurs when the demand for travel exceeds highway capacity, a sound approach to reducing congestion will involve a mix of policies affecting demand and capacity depending on local circumstances and priorities.
- IVHS proponents claim that a proper combination of control, communication and computing technologies, placed on the highway and on the vehicle, can assist driver decisions in ways that will increase highway capacity and safety without building more roads.
- Section 2 presents a framework for describing IVHS functions and their relation to key driver decisions. Different IVHS proposals can be compared according to the degree of influence they exert on those decisions.
- Section 3 outlines a fully automated IVHS system which promises a threefold increase in capacity. Designing such a system poses a challenging problem of control.

'Traffic Density Control for Automated Highway Systems'

Cheng-Chih Chien, Youping Zhang, and Petros A. Ioannous, Automotive, Volume 33, Number 7, 1997.[34]

This paper was published in 1997, it has been included to provide a comparison to more recent works and show development. In an automated highway system (AHS), the driver's actions are replaced by those of a computer control system that is designed to optimize traffic flow. A roadway controller calculates the desired speed commands to be followed by vehicles in each section of the freeway lanes, to achieve desired traffic density distributions. The paper presents a discrete traffic flow model and a problem statement is given. It then presents details pertaining to the design and analysis of the proposed roadway controller. The paper concludes that by making use of the proposed roadway controller that instability can be counteracted and congestion can be avoided.

'The Automated Highway System'

Nita Congress, Federal Highway Administration, Public Roads Volume 58, Number 1, 1994.[35]

This is an interesting article written in 1994 regarding the implementation of an automated highway system (AHS) program. It states that in this system the car will be guided by the road rather than the driver, sensors and communication devices will link the road and the vehicle to maximize driving performance, thus reducing driver error. The article states that the technology for this AHS exists and will be readily available in 1997. It details the programs that were in progress in 1993: 15 contracts totalling 14.1 million dollars were put together to determine the issues and ricks related to AHS design, development and implementation (there is a full list of what each study was examining). The article talks about their thoughts regarding how the general population will respond to AHS and notes that driver acceptance is a key issue in the feasibility and usability of an automated highway.

'A dynamic and automatic traffic light control expert system for solving the road congestion problem'

W. Wem, Expert Systems with Applications, Volume 34, Issue 4, May 2008.[36]

Although this article focuses on intercity roads and not 'smart highways' it still focuses on reducing traffic congestion. This paper proposes a framework for a dynamic and automatic traffic light control system that will solve the problem of traffic congestion. The article explains a simulation model that adopts inter-arrival time and inter-departure time to simulate cars arriving and leaving on the roads. There are two types of traffic congestion, recurring and non-recurring, recurring congestion is when there are recurring demands that exist daily and the road use exceeds existing capacity. Non-recurring congestion is caused by temporary disruption; the main reasons for this type of congestion are traffic incidents, work zones, weather and special events. The article briefly discusses what other researchers' simulation models have concluded (potential for further research). The author then goes into detail about their simulation model. The simulation model consists of 6 sub-models each of which have 3 intersections. The simulation model did provide positive results with greater traffic efficiency in an urban area. Note the simulation model does not account for cars turning right or left.

'On the Dynamic Optimisation of Traffic Lights'

M. H. Nguyen, T. V. Ho, T. H. Nguyen, Proceedings of ASIMMOD Asian Simulation and Modeling, 2013.

This paper describes one of many systems designed to optimise traffic flow at traffic intersections. It introduces an algorithm to dynamically optimize the routing at an intersection of a transportation network. In this algorithm, the next green sign of a direction is based on the rate of traffic passing the intersection in previous times when the signal has been green.

The algorithm was tested using an agent-based platform across three strategies, with each strategy tested against three scenarios. Strategy one is based on the ratio of passengers who passed that direction during the last green signal. Strategy two uses an average result based on a number of times established with strategy one. The average green signal time is calculated and used as a fixed time during the whole simulation. Strategy three uses fixed green signal time by total ratio. The total number of passengers who passed each direction is counted during the whole simulation time. Then the green light time for each direction is estimated based on the ratio of passengers on that direction, over the total passengers of all directions. This green light time is then fixed for the direction during the whole simulation time. The scenarios tested were: low traffic; rush hour; and a dynamic hour where traffic changed from low to high and back several times over an hour.

The experiment results indicate that the proposed dynamic algorithm to control the traffic lights is generally better than some other traffic light control strategies and improves as traffic levels increase in density. From a practical perspective the implementation of this strategy would be simpler than one that requires vehicle communications because there would be no need for any type of communication device to be installed in motor vehicles.

'Dynamic Traffic Control with Fairness and Throughput Optimisation Using Vehicular Communications'

Lien-Wu Chen, P. Sharma, Yu-Chee Tseng. IEEE Journal on Selected Areas in Communications, Vol. 31, No. 9, September 2013.

This paper recognises the importance of efficient traffic management as a means of reducing fuel wastage as the primary intent. The authors propose a dynamic traffic control framework using vehicular communications and fine-grained information, such as turning intentions and lane positions of vehicles, to maximize traffic flows and provide fairness among traffic flows. With vehicular communications, the traffic controller at an intersection can collect all fine-grained information before vehicles pass the intersection. A Zigbee-based prototype of the system has been built called "Eco-sign" which includes a traffic control unit (TCU), a light unit (LU) and a vehicle unit (VU). The system communicates via a Zigbee-based wireless system. The VU includes an automatic ignition control which is activated when the vehicle speed is 0 km/hr and the remaining waiting time is larger than 30 seconds.

A proposed signal scheduling algorithm considers the flows in all lanes, allocates more durations of green signs to those flows with higher passing rates, and also gives turns to those with lower passing rates for fairness provision. Simulation results show that the proposed framework outperforms existing works by significantly increasing the number of vehicles passing an intersection while keeping average waiting time low for vehicles on nonarterial roads. The throughput maximization problem for multiple intersections in the road network is highlighted as needing further investigation but there is no discussion on commercial feasibility at this stage.

'Traffic flooding the Low Countries: How the Dutch cope with motorway congestion'

Piet H. L. Bovy, Transport Reviews: A Transnational Trans-disciplinary Journal, 2010.[37]

This paper discusses motorway congestion. It is a common characteristic of the larger conurbations all over the world. Using the example of the Randstad region in The Netherlands, the causes and conditions for the growing congestion on main roads are presented and explained. From an international comparison it appears that the Randstad region is characterized by a relatively high density and high-access quality of its motorway network, giving rise to an extremely high level of usage. The Dutch policy of coping with the consequent congestion problems at the network design level is outlined, followed by a presentation of the dynamic traffic management approaches to these problems. Special attention is given to the so-called target group policy that aims at prioritizing specific user groups such as freight traffic and trucks. Finally, attention is given to the Dutch attempts to introduce congestion pricing as a means of tackling congestion. The report talks of two dynamic measures are described from which the Dutch road authorities expect to gain a significant contribution to congestion reduction: dynamic information provision to drivers and dynamic congestion tolling: Dynamic information provision about current congestion conditions in the network leads to sensible adaptations of route and departure time choices and to significant improvements in traffic conditions.

Challenges and Issues Related to Managed Motorways

Whilst there are significant benefits for the Australian road and transport authorities from the investment in the infrastructure and technology to enable active traffic management of freeways, there are also a number of challenges that need to be considered for these benefits to be achieved.

Lack of National Guidelines for Managed Motorways

Australia currently does not have a set of national guidelines for managed freeways which presents a challenge to road and transport authorities intending to incorporate the use of active traffic management measures on freeways. The lack of a national guideline has led to disparate approaches to active traffic management measures amongst the state and territory road and transport authorities. Furthermore there is a lack of international consensus on the role of contemporary traffic theory and the appropriate metrics of success for active traffic management measures. For instance the U.K. measures performance of motorways by looking at the reliability of travel times and the reduction in the impact of incidents on traffic flow. In Victoria however, the performance of motorways is measured primarily based on lane throughput, safety factors, the number of accidents, and travel times.

As part of the enhancement of the understanding of managed motorways in Australia, the 'National Smart Managed Motorways Program' has been established by the Australian Government Department of Infrastructure and Regional Development to '*deliver more efficient motorways through the application of smart infrastructure technologies to improve real-time management of major motorways*'.[38] As part of the program the government is investing in active traffic management measures in the absence of.

Lack of Central Integration of Active Traffic Management Measures

The central integration of the active traffic management measures enables a system wide approach to motorway management and allows greater effectiveness of managed motorways. A centralised system can allow:

- The provision of information to road users (such as information on conditions on the motorway and other motorway)s,
- Greater integration of traffic management devices such as ramp signalling and variable speed limits to maximise traffic throughput across the motorway system, and
- Enhance management of flow during accidents, road works and other events through lane use management.

The central integration of the active traffic management measures, and the data collected from motorways, can deliver real benefits through the use of automated algorithm driven system responses in a live traffic environment, enabling greater utilisation of the motorway capacity while reducing trip time and delays to motorists – a win-win situation.

Energy Saving Options for Route and Signal Lighting

LED Lighting Technology

LED lighting for streets and parks is no longer an innovative technology in itself. It is clear that, in terms of energy efficiency, there is nothing to prove – LED globes use 40% less electricity than conventional globes and thus produce approximately 40% less carbon emissions[39] depending on which GHG (GreenHouse Gas) Accounts factor is used, which vary from State to State and country to country. Innovations appear to be focussing more on lighting controls and energy sources instead.

The research will consider key performance criteria (such as AADT levels, crash rates, pedestrian security, etc.) to assess suitable lighting levels and investigate the potential for lighting controls to reduce usage at appropriate times (i.e. when the road is not in use) to reduce electricity costs and associated greenhouse gas emissions.

There are approximately 2.28 million street lighting lamps in service in Australia, with around 33% on main roads and 67% on local roads. The annual energy cost of public lighting in Australia exceeds $125 million (and more than $250m including maintenance). Street lighting is the single largest source of greenhouse gas emissions from local government, typically accounting for 30 to 60 per cent of their greenhouse gas emissions.[40]

- Major road lighting makes up only 27% of the 2.28 million streetlights installed nationally but represents 60% of the energy consumption.
- The major lighting types are mercury vapour (12% of major road lighting national numbers – down from 25% in 2002/3) and high pressure sodium (86% of national numbers – up from 75% in 2002/3).
- Of the recommendations for major road lighting replacing high wattage Mercury Vapour lights is the easiest way to reduce emissions although this only covers 15% of major road lighting and is declining (down from 25% in 2003).

Case Studies of LED Lighting Upgrades

Street lighting is currently going through what could potentially be a dramatic transformation. Pilot projects are appearing in many cities across the USA and the world (e.g. New York, Los Angeles, Seattle, Buenos Aires, Sydney) and unsurprisingly, through significant savings in energy and maintenance costs, many of these pilots will be rolled out further in their home cities.

The largest City project is in New York City, announced by Mayor Bloomberg in October 2013[41]. The city plans to replace all 250,000 High Pressure Sodium (HPS) streetlights with Light Emitting Diode (LED) fixtures over a three year period. This project may be significant however an already completed fixture replacement project is in operation in Los Angeles where over 140,000 fixtures were replaced by LEDs.

Globally it is expected that shipments of LED streetlights will rise from less than 3 million in 2012 to 17 million in 2020[42]. Other advantages offered by LED's include better dimming control and easier integration of control nodes. This in turn has the potential to drive up the adoption of smart street lighting which can improve efficiencies through how we control the illumination of our cities.

Los Angeles LED Street Replacement Program

The key outcome for this project is that it has, thus far, provided savings significantly in excess of what was predicted by the City of Los Angeles Bureau of Street Lighting.

In 2008 energy consumption from street lighting was in the order of 190 million kWh/year at a cost of $16 million/ year based on energy prices at that time. The total cost of installation over the four years it took to complete was $US57 million of which $40 million had to be financed. The loan will be repaid in seven years with repayments being made entirely from savings in energy costs and maintenance costs. After repayment the City will benefit directly from savings in the order of $10 million/year.[43] In summary, the benefits to the City are: a reduction in energy consumption of 60% equating to a saving of $7.5 million/year; a maintenance saving due to longer life lamps to a value of $2.5 million; and a reduction in carbon emissions of 40,500 tons/year.

Over the period the project was rolled out there has been a number of improvements in LED technology which has contributed to the benefits shown in Table 2.

Table 4: Yearly comparison of LED Fixtures

	2009	2010	2011	2012
Average Price (US$)	$432	$298	$285	$245
Efficacy (Lm/W)	42	61	72	81
Lifespan (hours)	80,000	111,000	150,000	150,000
Warranty (years)	5	6	6	7

In terms of financial feasibility for similar projects going forward the price and lifespan are clearly important so a 43.3% reduction in cost per lamp and an increased lifespan of 87.5% provide compelling evidence of the viability of LED street lamps, even for those smaller local governments who don't necessarily have the spending power for projects with high upfront capital costs.

The City engaged in a public outreach program to raise awareness of the program, providing information to the general public to offer assurances of the costs and benefits that the program would deliver. Feedback received was mostly positive according to the Bureau of Street Lighting however it was noted that the cooler the colour temperature of the lamps, the greater the number of complaints over glare were received.

Another key benefit is the reduction of light pollution because LED's can be better directed, preventing unintended light leakage, as demonstrated in Figure 13

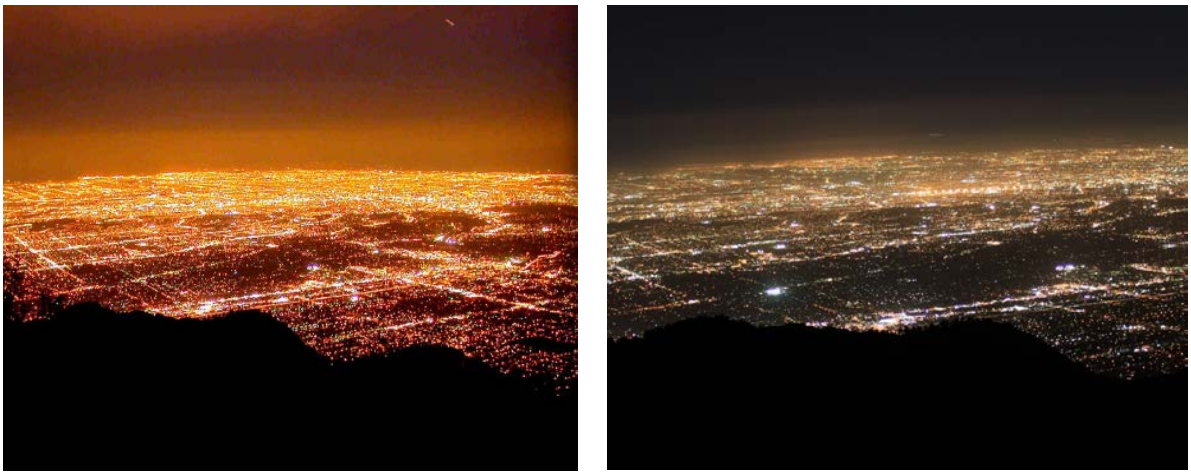

Figure 7: Los Angeles Basin View from Mount Wilson Before and After the Retrofit

A range of other operational and social benefits have been highlighted by the Bureau of Street Lighting, including;

- Smaller lamps making them easy to transport and install
- Reduced packaging which amounts to a 50% reduction in warehousing space requirements
- Improved uniformity ratio ("carpeted Effect") and visibility
- Compatible with remote monitoring systems

- Instant off-on operation while having the option to be dimmed
- The availability of a house-side shield (to prevent glare)

In addition a reduction in crime statistics of 10.5% between the hours of 7pm and 7am has been recorded from 2009 to 2011. The incident types examined were vehicle theft, burglary-robbery-theft and vandalism and there may be a correlation between the installation of the LED's and the reduction in crime because of the perceived improvement in lighting levels, clarity and reduction in

City of Sydney LED Lighting Project[44]

The City of Sydney has installed 2,600 LED street and park lights across the city's LGA, and is planning to replace a further 6,500 over the next three years. The City has saved almost $300,000 since the introduction of the lamps in March 2012, and has seen a reduction in their energy bills of 25%.

The City has 22,000 public street lights installed however approximately 13,500 are maintained by Ausgrid (formerly Energy Australia) therefore the City has a limited scope in terms of possible savings when compared with city's such as Los Angeles where the full responsibility of ownership, operations and maintenance fall under the control of a single party – the Bureau of Street Lighting.

A public survey revealed that over 90% of participants though the LED lighting was appealing and 75% thought that they improved visibility.

Energy Efficient Public Lighting in Australia

A number of Australian examples of Energy Efficient public lighting projects are listed in Table 3. Some LGA's have opted for T5 fluorescent lamps which offer savings in capital outlay however the gap in cost is closing rapidly as LED prices fall, as demonstrated in Table 2.

Table 4: Some Australian Local Governing Bodies Moving to LED Street Lighting

		Date	Type	Qty	Cap. Cost	Annual Savings
Logan City Council[45]	QLD	2014	LED/CFL	222	undisclosed	$16,500
City of Whittlesea[46]	VIC	2014-15	T5	6,900	$2.6 million	$387,000
Yarra Ranges[47]	VIC	2014	T5	7,000	$1.85 million	$400,000
Lighting the Regions Project*	VIC	2013-16	LED	23,000	$5.1 million	$2 million
City of Sydney	NSW	2012-15	LED	6,500	undisclosed	$300,000

* The Lighting the Regions project is a joint effort between Mount Alexander, Central Goldfields, Hepburn, Pyrenees, Loddon, Swan Hill, Gannawarra, Greater Bendigo, Buloke, Ararat, Northern Grampians, Hindmarsh, Horsham, Yarriambiack, West Wimmera and Mildura Councils and the Central Victoria Greenhouse Alliance and Wimmera Mallee Sustainability Alliance.

Another reason that LED's may not been chosen is that LED's are not yet included in the Australian Standards. This does not preclude the use of LED's by governing bodies should they choose to not to follow the standards. However, there is a challenge of split incentives where ownership and operation of street lighting doesn't fall under the control of the local government. In many instances across Australia, street lighting is controlled by the local network provider and the local government pays for the electricity. In some situations the network provider will follow the standards and thus, not allow the use of LED's at present, particularly when there are alternative high efficiency lamps that meet the standards.

The LED market is primarily in Europe and the US where standards for street lighting tend to be much higher than those in Australia. This means that the outputs of units that are available tend to exceed the Australian standard by, in some cases, up to seven times[48]. Manufacturers are starting to produce lower power units in line with the Australian market but it is not known how long it will take for the market to mature. The fact that the market has already made the move to LED's in some places would suggest that there is a driver for industry to move relatively quickly.

The Federal Government's Community Energy Efficiency Program has been utilised for a considerable number of lighting projects across Australia[49]. The program was open to local governing bodies to part fund energy efficiency programs in council or community owned buildings or sites that ranged from lighting. This program was closed in February 2013.

Philips Green Road lighting solutions, 2010

Royal Philips is a diversified technology company, focused on healthcare, consumer lifestyle and lighting. In terms of lighting, the company specialises in energy efficient lighting solutions and new lighting applications. Philips street lighting division currently has four primary systems: an LED system; a high efficiency High Pressure Sodium (HPS) system; a system called StepDim; and a system called SON-T PIA Eco.

Figure 8: An Example of Before and After Installation of LED's (left) compared with yellow sodium (HPS) lamps (right)

Their 'EssentialLine' product is an LED product that offers similar energy savings as other LED products, in the region of 45% compared with a standard HPS lamp. Low maintenance and long life attributes are present as with typical LED installations. Figure 14 shows an example from Holland on the A44 between Burgerveen and Kaagbrug, of a section of highway where Sodium Lamps have been replaced with LED's.

The system includes dimming options which allows the light intensity to be reduced from 100% during rush hour to 20% during the hours following it. This reduction can potentially yield a saving of 180,000 kWh annually. The dimming system can increase safety for road users, for example when it's raining or if there's been an accident, the light intensity is adapted accordingly.

A second option is an energy efficient HPS Integrated system comprising of highly efficient light sources, low power loss electrical ballasts and fixtures with high reflector efficiency. Philips claim an energy saving of up to 44%. The design of the reflector increases projection and distribution which allows lamp standards to be spaced further apart by 15% It is unclear whether the 44% overall energy savings accounts for the additional spacing of the lamp standards – an important consideration if the system is being considered for a retrofit project.

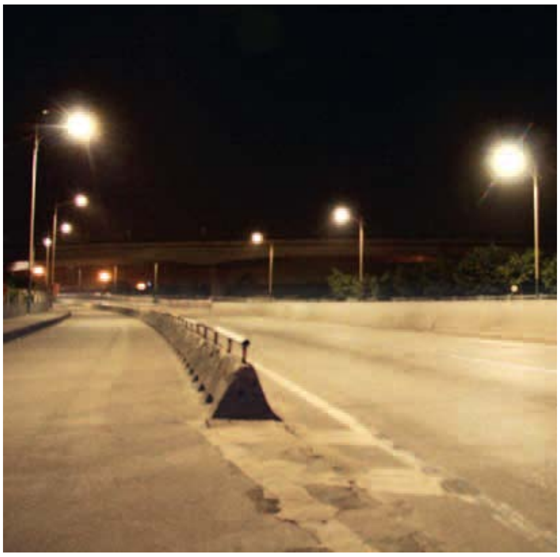

Figure 8: Example showing 250W Sodium Lamps (inset) and the Replacement 140W High Efficiency HPS Lamps

The example shown in Figure 15 is from Guangzhou City, China and compares yellow sodium lamps in the inset photograph compared with a high efficiency integrated sodium lighting system (CosmoPolis) installed with electronic ballasts. Philips claim a 44% energy saving as well as delivering illumination averaging 19 Lux. This translates to a 22% increase in the illumination of the road surface and uniformity rates. The colour spectrum has also increased from 25 to above 70, resulting in urban nightscapes that are potentially safer and more comfortable.

'StepDim' is basically a replacement ballast that allows a range of lighting luminance levels to be set based on their time of operation. Figure 16 is an example from China where, during the peak period the lighting levels are set at 100% (250W), then steps down to 150W after

11pm. Fuzzy logic circuits integrated into timer control enable gradual adjustments of the system in order to avoid the risks associated with sudden changes in road conditions due to abrupt lighting adjustments.

Philips claim that the StepDim ballast and timer controls have no impact on the reliability or the life of the lamps they are fitted to.

The system works with LED lamps as shown in Figure 14, as well as with HPS lamps.

Off-peak periods: Starting from 11pm street lights with step dimmers operate at 150W.

Peak periods: Starting from 6pm street lights with step dimmers operate at 250W.

Figure 9: Suzhou Province, Wuxi City, China – The StepDim system in operation with HPS Lamps

The SON-T PIA Eco is another high efficiency HPS lamp designed for retro-fit projects, thus they can fit into existing fixtures. Deploying this lamp as a stand-alone strategy has the potential to reduce energy consumption by 18%.[50]

LED Traffic Signals Upgrade

Main Roads WA has a rolling program, upgrading traffic signal lanterns with LED lamps, which started in 2012. Thus far 670 traffic signal controlled intersections have been upgraded to LED lamps with a further 50 planned for 2014. This project is set to enhance Main Roads WA in its long term mitigation measures – reducing risk and exposure to increases in energy costs. The overall cost savings from operation and maintenance is projected to be in the order of 71%. In addition, key environmental benefits will include a saving of 320 tonnes of GHG emissions annually and a reduction of materials sent to landfill due to the longer life of the lamps.

Annotated Bibliography on LED lighting

'Towards More Sustainable Street Lighting'

Mawer G., King B. and Bridger G for the Institute of Public Works Engineering Australasia (IPWEA), Practice Note 11, July 2014.

The aim of this Practice Note is to:

- provide independent, authoritative and impartial information, laying out the emerging street lighting options for councils;
- help accelerate the widespread adoption of more energy efficient street lighting to reduce costs to local councils, improve service levels and improve environmental outcomes; and
- highlight the potential safety, security, amenity, energy, environmental and financial benefits of improved lighting, as well as to outline the current position and the key impediments that need to be overcome in order to secure these potential benefits.

'Smart Street Lighting'

This report analyses the global market opportunity for lamp upgrades and networked lighting controls across five categories of public outdoor lighting: highways, roads, parking lots, city parks, and sports stadiums. The report provides a comprehensive assessment of the demand drivers, obstacles, policy factors, and technology issues associated with the growing market for street lighting controls. Key industry players are profiled in depth and worldwide revenue and capacity forecasts, segmented by lamp type and region, extend through 2020.[51]

'Energy Efficient Street Lighting'

Energy efficiency is at the heart of the EU's transition to a resource-efficient economy and the realisation of its 2020 strategy for smart, sustainable and inclusive growth. This includes three complementary energy and climate headline targets by 2020: to lower greenhouse gas emissions by 20% relative to 1990, to generate 20% of primary energy from renewable sources and to achieve 20% primary energy savings relative to the 2007 projections for 2020. One key area for investment in energy efficiency is street lighting, where there are not only major opportunities to significantly reduce electricity consumption, but also additional benefits associated with phasing out environmentally harmful technologies, reducing maintenance costs and achieving much better overall control of the street lighting environment. The potential for energy efficient improvements to street lighting in Europe is substantial, given that there are about 56 million street lights in Europe, of which around 18 million run a 1930s standard. With advances in available technology it is now possible to realise energy savings on the scale of 30-50%.[52]

'Demonstration Assessment of LED Street Lighting, Kansas City, Missouri'

Prepared by Pacific Northwest National Laboratory for the Solid-State Lighting Program, Building Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, June 2013.[53]

"This report documents a study of nine different light-emitting diode (LED) street lighting products installed in February 2011 as replacements for incumbent high-pressure sodium (HPS) luminaires in the city of Kansas City, Missouri… The street lighting applications investigated span four different incumbent wattage categories, including 100 W, 150 W, 250 W, and 400 W. Initial measurements and comparisons included power, illuminance, and luminance (with luminance restricted to only four of the nine locations); sample illuminance readings have continued at each of the nine locations at roughly 1,000-hour operating intervals since then."

'Demonstration Assessment of LED Street Lighting, Oakland, California'

Final Report prepared in support of the U.S. DOE Solid-State Lighting Technology Demonstration Gateway Program and PG&E Emerging Technologies Program.[54]

"This report summarizes the third phase of an LED street lighting assessment project conducted to study the applicability of LED luminaires in a street lighting application. In Phase I of the project, pre- and post installation measurements were taken to assess impacts from the installation of the LED luminaires in a parking lot owned by the City of Oakland. With no significant concerns identified, the project progressed to Phase II, in which fifteen 78-watt LED luminaries replaced a like number of 121-watt high-pressure sodium (HPS) luminaires (nominal 100-watt) on Sextus and Tunisroads between Empire Rd and Coral Rd in a residential area of Oakland."

'Demonstration Assessment of LED Roadway Lighting, Philadelphia, Pennsylvania'

Prepared by Pacific Northwest National Laboratory for the Solid-State Lighting Program, Building Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, September 2012.[55]

"For this demonstration assessment, 10 different groups of LED luminaires were installed at three sites in Philadelphia, PA. Each of the three sites represented a different set of conditions, most importantly with regard to the incumbent HPS luminaires, which were nominally 100 W, 150 W, and 250 W. The performance of each product was evaluated based on manufacturer data, illuminance calculations, field measurements of illuminance, and the subjective impressions of both regular and expert observers. Most, but not all, of the LED luminaires had a higher rated luminous efficacy compared to the HPS product they were replacing. Some provided more lumens than their HPS counterpart, whereas others emitted fewer, and they drew between 10% and 40% less power. All of the LED luminaires had improved color rendering and a higher CCT."

'Economic Analysis of Solar-Powered LED Roadway Lighting'

M.S. Wu, H.H. Huang, B.J. Huang, C.W. Tang and C.W. Cheng, Renewable Energy; an International Journal, January 13, 2009.[56]

This article revolves around a study that investigates the design of solar powered LED roadway lighting. The study looks at the design of a solar-powered LED roadway that is

10km of highway with 2 lanes, installation costs are estimated with poles being 30m apart. The study established that using LED lighting over the conventional mercury lights would reduce about 75% of energy consumption and cost 22 million USD to install LED and 26 million USD for solar powered whereas mercury lights cost 18 million USD. However, the payback time for the excess investment of LED is 2.2 years and 3.3 years for LED using solar power.

'Energy Saving of Large-Scale High-Intensity-Discharge Lamp Lighting Networks Using a Central Reactive Power Control System'

Wei Yan, S.Y.R. Hui, Henry Shu-Hung Chung, IEEE Transactions on Industrial Electronics, August 2009.[57]

Abstract: This paper summarizes the test results on several large-scale lighting systems based on a range of high-intensity-discharge (HID) lamps. The study focuses on the energy-saving, energy-efficiency, and dimming characteristics of magnetic-ballast-driven HID lamp systems that are suitable for public lighting networks. This paper reports the dimming characteristics of large lighting networks based on HPS lamps. The dimming function is provided by a low-loss central energy-saving system that provides a sinusoidal output voltage with controllable magnitude. It is found that the six types of HPS lamps under test can work smoothly without flickering under dimming conditions.

'Street Light Control: Innovative Light Control'

OSRAM Street Light Control (SLC) is an innovative light management system for outdoor lighting. It provides demand-oriented control and monitoring for both individual luminaires and up to thousands of light points. SLC thus facilitates a reduction in energy consumption, CO2-emission and light pollution. The central element is the SLC software, which allows you to keep the entire street lighting under control. For optimized maintenance planning for your lighting and thus improving safety on the roads. Report talks about: Energy efficiency and cost savings, Safety with light - Powerline technology (Powerline technology is used to extend existing mains power networks into data transfer networks – without the need for additional wiring - the ideal technology for lighting installations that can be extended simply and cost-effectively to produce communication networks).[58]

Dynamic Road Lighting

Case Studies of Dynamic Dimming

Dynamic Dimming: The Future of Motorway Lighting, Lancashire County

Andy Collins, Tom Thurrell, Robert Pink and Dr. Jim Feather, the Lighting Journal, October 2002.[59]

Lancashire County Council's leading role in lighting innovation and energy management was recognised in November 1999, when it became the first Highway Authority to achieve Energy Efficiency Accreditation Status

– The system chosen for this project was Royce Thompson's Elgadi electronic control gear, complete with power line modem, and the Horus street lighting control system. Elgadi incorporates a high frequency electronic ballast for high pressure sodium lamps from 50W to 250W
– The M65 Project: The opportunity to put dynamic dimming into practice - which proposed the concept of optimising motorway lighting efficiency by means of dimmable lighting controlled by traffic flow.
– There are three lighting levels based on traffic flow: full brightness and two dimming stages according to the average number of vehicles passing over a half-hour period.

Annotated Bibliography on Dynamic Road Lighting

'Intelligent dynamic road lighting and perceived personal safety of pedestrians'

Thijs H.J van Osch, December 8, 2010.[60]

"A second motive for reducing abundant road lighting is sustainable energy usage. The total energy consumption of public lighting in the Netherlands is currently estimated to be 600.000 to 700.000 MWh a year, of which about 500.000 MWh is used for the lighting of infrastructure such as roads, bicycle trials and footpaths (SenterNovem, 2009). Reducing energy consumption and light pollution by road lighting can be realized using intelligent dynamic road lighting systems with LED technology."

- In a meta-analysis of thirteen studies on the relation between street lighting and crime rates Welsch and Farrington (2008) showed that improved street lighting significantly reduces crime. Furthermore, these results showed that improved street lighting increases perceived personal safety of pedestrians (Blobaum & Hunecke, 2005) (Loewen et al., 1993).
- "An Intelligent dynamic road lighting system is able to distribute light only when and where it is most needed thereby reducing light pollution and energy waste. During periods with very few of no traffic activities the road lighting can be reduced to a bare minimum. Such a road lighting system should be highly intelligent to detect pedestrians, define their exact position and the direction he or she is moving in."

- Methods: “A three condition (light distributions: dark spot, spotlight, control condition) within subject experiment was conducted with perceived personal safety as the dependent variable. The interactive road lighting test bed “de Zaale” on the campus of the Eindhoven University of Technology will was used to address the research question.”

‘Dynamic public lighting’

Ministry of Transport Public Works and Water Management December 21, 1998.[61]

“Considering the feasibility of dynamically switching the lighting on motorways. This would provide under all traffic and weather conditions adequate illumination levels without illuminating the road unnecessarily brightly.”

- “Normal level of illumination (100%), a reduced (20%) and an increased (200%).
- Cost-benefit analysis: the costs of future DYNO projects (and accordingly the payback period) will turn out more favourably than for this pilot project but by how much cannot be stated precisely.

Informing Project Implementation and Policy Development

Annotated Bibliography on Efficient Lighting Implementation

'Barriers to Energy Efficient Street Lighting'

Mark Coughlin, Equipment Energy Efficiency Committee, July 2011.[62]

PwC has been asked by the South Australian Department for Transport, Energy and Infrastructure to provide advice on regulatory barriers to improved energy efficiency of street lights. We have also been asked to provide advice on possible mechanisms to overcome any barriers that are identified. Chapter 2 – Background and scope: The purpose of this chapter is to provide some relevant background to the issues that are the focus of this report. It describes the scope of work we have been asked to undertake, some discussion of why it is relevant to improve the energy efficiency of street lights, and how street lights are currently regulated in Australia. Chapter 4 Assessment of Regulatory Barriers to Energy Efficient Street Lighting Decision Making.

'Intelligent Road and Street Lighting in Europe (E-Street)'

Mr Bjorn Sandtveit[63]

E-street partners will increase knowledge and awareness of intelligent street lighting and accelerate the use of these technologies in Europe. *E-street Initiative Work Package 4.1 Development of legislation, recommendations and standards:* This report gives state of the art, describes institutions in the field of lighting instructions. Considerations are given for development of legislation, standards and recommendations taking into account energy saving, environmental aspects and traffic safety.

'A Municipal Guide for Converting to LED Street Lighting'

Note: May be useful in looking at how with effectively implementing LED's in street lighting.

Abstract: Driven by the promise of significant energy and maintenance savings provided by Light Emitting Diode (LED) technology, many cities are struggling with effectively implementing LED's in their street lighting. There still remains much confusion and misinformation pertaining to this technology. Furthermore much of the available literature is written in highly scientific jargon targeting an academic audience. – This document is intended as a practical, user friendly, step-by-step guide for individuals responsible for municipal street lighting who may lack a formal lighting background. Thus, the use of lighting jargon in this guide has been minimized.[64]

'Guide for energy efficient street lighting installations'

IEE – Intelligent Energy Europe, Norconsult, E-Street Project, 2007.[65]

Huge saving potentials utilizing new technology: Out-dated installations increase energy costs and new technology represents a large cost cutting potential in the rehabilitation of outdoor lighting installations. With new installations there is great saving potential when employing new enriching adaptive lighting techniques which are possible with today's high technology. Adaptive road lighting: Road lighting is present to increase the safety of traffic and to enhance the sense of security for individuals. The basis for all roads lighting engineering has been to maintain safety by being able to observe objects on and beside the road. Important factors are the roads geometrical design, complexity, traffic volume and speed. One also has to consider wet surfaces, the presence of pedestrian crossings, parked vehicles, schools etc.

'Model Specification for LED Roadway Luminaires'

The US Department of Energy Municipal Solid-State Street Lighting Consortium's Model Specification for LED Roadway Luminaires enables cities, utilities, and other local agencies to assemble effective bid documents for LED street lighting products.[66]

'Policies for Energy-efficient Lighting'

Paul Waide and Satoshi Tanishima – International Energy Agency (IEA) 2006.[67]

- Chapter 5 discusses policies to improve lighting-component efficiency in Australia and New Zealand, OECD Europe, Japan, Korea, North America, China and other non-OECD countries
- 'Traffic signals and exit signs using incandescent lamps can no longer be justified given the far higher efficiency LED alternatives that exist. There is a strong argument in favour of countries following Canada's lead and adopting MEPS that preclude the use of incandescent lamps in new products.'
- 'In order to speed local authority transition over to higher-efficacy public lighting it may be appropriate to consider imposing MEPS for street lighting as a system'

Additional Topics Related to Roadway Lighting

Annotated Bibliography on Additional Roadway Topics

'Road lighting for safety– a forward-looking, safe system-based review'

W.J. Frith and M.J. Jackett, 2009.[68]

Abstract: Road lighting for traffic is primarily a safety measure. The literature generally ascribes some level of crash reduction to improved road lighting but papers seldom specify whether lighting existed before the change, or its level where it did exist. One is left to assume that, at least after the change, the lighting satisfied the standards of the appropriate road controlling authority. These standards vary considerably worldwide and are based on practitioner consensus. This is because few data have been available to link safety to the actual standard of lighting. "The road safety literature contains many references to road lighting. These generally ascribe some level of crash reduction to improving road lighting. A good example is Austroads 2009 (2), where a 30% reduction in crashes is quoted related to improved route lighting. This is a figure quoted widely by practitioners."

'Effects of road lighting: an analysis based on Dutch accident statistics 1987-2006'

Wanvik, P O, 2009, Effects of road lighting: An analysis based on Dutch accident statistics 1987– 2006, Accident Analysis and Prevention (41) 123–128.[69]

Abstract: This study estimates the safety effect of road lighting on accidents in darkness on Dutch roads, using data from an interactive database containing 763,000 injury accidents and 3.3 million property damage accidents covering the period 1987-2006. Two estimators of effect are used, and the results are combined by applying techniques of meta-analysis. Injury accidents are reduced by 50%. This effect is larger than the effects found in most of the earlier studies. The effect on fatal accidents is slightly larger than the effect on injury accidents.

'Light Pollution - Environmental Effects of Roadway Lighting'

Carl Shaflik, Technical Paper prepared for: CIVL 582 - Transportation Engineering Impacts - Dr. G. Brown, P.Eng. University of British Columbia Department of Civil Engineering.[70]

Abstract: Environmental impacts resulting from transportation infrastructures have been the subject of research for many years. One environmental aspect of transportation facilities largely ignored is that of light pollution. In many areas light pollution has become an important aspect of both planning and design. Neighbourhoods are becoming more sensitive to the stray light that is being directed towards their property and windows. Astronomers and observatories are becoming more concerned with the increase in the sky glow around urban areas. It has been estimated by some researchers that up to 50% of all light pollution may be the result of roadway lighting. This firmly puts light pollution in the hands of traffic engineers and it will become their responsibility to find adequate and economic solutions. We will see that by employing some simple solutions, using today's technology, the effects of light

pollution can be brought under control. All that is required, and this may be the most difficult part, is the political will to act.

- Discusses Urban Sky Glow – the result of stray light being scattered into the atmosphere and brightening the natural sky background level.
- Conclusions: all roadway lighting systems should be required to use efficient, full-cut off luminaires to control the light output. All lighting designers must be encouraged to undertake their designs using the latest design principles and design programs available.

'Effects of Artificial Lighting on Wildlife'

Tiffany Saleh - Road RIPorter Issue: Summer Solstice 2007, Volume 12 #2.[71]

Note: May be of possible interest. Dimming highway lighting in low traffic times and using cut-off luminaires to control light output would have a positive impact on surrounding wildlife.

- "Ecological light pollution" affects wildlife at the individual, community, and ecosystem level through "direct glare, chronically increased illumination, and temporary, unexpected fluctuations in lighting"
- Exposure to artificial light can create problems for species adapted to using light- or the absence of light- to aid in orientation.
- Lighting produced and compounded by human structures can result in high mortality rates of wildlife living around them.
- Many species of wildlife operate specific internal cycles or rhythms that help them determine when to initiate foraging, migratory or reproductive behaviour. The addition of artificial light to the night-time environment disrupts the precision of these cycles, thus modifying behaviour.

Generating Renewable Energy in Road Infrastructure

This section will focus on technologies potentially appropriate to various road infrastructure types such as tidal and wave power associated with bridges, solar and wind power associated with road easements and structures, thermal power associated with pavements, etc.

Solar Power

Solar energy has the potential to provide a range of applications which is expanding rapidly due to the increasing efficiency of technologies that collect and consume energy. An example of this is the increasing efficiency of solar collectors (photo-voltaics) and the improvements in efficiency of LED lighting, reducing energy demand.

The Solar Highway Program[72]

In 2008, a Solar Highway was installed by the Oregon Department of Transport (ODOT), adjacent to a highway right-of-way. The 104kW system was initiated as a proof-of-concept project which provides power for the interchange illumination at its location while contributing to reducing the agency's carbon footprint through the ownership of Renewable Energy Certificates (REC's). This is achieved by feeding electricity into the Grid during the day and consuming electricity from the grid at night when the illumination is required.

Figure 9: Oregon Solar Highway Project[73]

The commercial feasibility of the project relied on a public-private partnership between ODOT and Portland General Electric (PGE), Oregon's largest electricity utility. In simple terms, under the partnership conditions ODOT was responsible for finding a "shovel ready" site suitable for the construction of the PV Array. Importantly from a financing perspective, a power purchase agreement (PPA) committed ODOT into purchasing electricity from PGE for a 25 year period. In return PGE, through a subsidiary, took responsibility for financing, ownership, design, operation and maintaining the asset.

Advantages for ODOT include not having to find the capital for the project or to be involved in managing a generator – a task that wouldn't normally form part of a DoT's core business. Also, having a predictable, long term picture of energy expenditure is advantageous in forward planning and at rates which can often better those on offer from competing utility companies. PGE have the benefit of having a ready-made long term customer locked in providing an income stream that will assist in gaining finance for the asset as well as capitalising on the tax benefits and incentives available.

ODOT has three future projects planned: firstly, expanding the existing project described above; a 1.75MW PV system at the Baldock safety rest area on Interstate 5; and a 3MW system at a maintenance and storage facility in the City of West Linn.

Photovoltaic Noise Barriers[74]

Traffic noise is recognised by the World Health Organisation (WHO) as environmental pollution which can have negative health impacts on those living close to busy roads and highways. In response the European Parliament introduced a directive to assess and manage environmental noise (END) but has been a challenging area for which to find funding for those areas recognised as being in need of noise abatement controls.

Figure 10: A photovoltaic noise barrier runs alongside the A22 autostrada at Brennero in Italy

To this end, an interesting partnership has evolved which explores the use of solar PV panels as a means of providing noise abatement by designing them into the 'fabric' of the noise barriers.

This has the potential to be a game changer with an otherwise inert asset becoming capable of saving energy and/or generating revenue. It is possible to use a similar funding model to that described in A.1.1 above, utilising the benefits that come with public-private partnerships and PPA's. The alternative for standard noise barriers would be to attempt funding through unpopular charges such as fuel taxes, road tolls, vehicle registration, etc.

There is little information available that provides cost-benefit analyses (including for those that have already been implemented) which is likely due to the unique nature of this kind of project, which is subject to a large number of variables from project to project.

Solar Roadways

Solar Roadways is a company that is working to create a prototype for the first ever solar road panel. The road would house solar cells to collect energy and the 'paint' on the roads would be LEDs. Each road panel would consist of three basic layers: a road surface layer (translucent, weather proof and high strength that provides traction), an electronics layer (contains a microprocessor board, controls lighting, communications etc.) and a base plate layer (distributes the power collected by the electronics layer, weatherproof).[75]

Figure 11: Photomontage of a Solar Roadway in Use

Additional features that can be incorporated into the design include heating elements to melt snow and ice in winter, active signage that would for example' flash a "SLOW DOWN" message on the approach to a pedestrian crossing activated by pressure plates when stood on by pedestrians adjacent to a crossing point. Other concepts include the ability to recharge electric vehicles as they pass over the surface of the road, detection of wildlife or obstacles on the road and thus, warning drivers in advance. There appears to be no peer-reviewed articles that discuss this particular technology however the ongoing development of the system is progressing with the developers having moved on to a Phase II prototype as part of a Small Business Innovation Research (SBIR) contract with the Federal Highway Administration. It consists of a 12-foot by 36-foot solar parking lot which is fully functional, with solar cells, LED's, heating elements, and a textured glass surface. Tests performed on the glass so far include: load testing; traction testing and impact resistance testing and the glass has exceeded all expectations according to the developers.

It is envisaged that the first commercial offerings of this technology would be for use in parking lots and driveways where there is a clear beneficiary (the owner of the property on which it is installed) for the energy produced by the system. For the system to be rolled out to cover public roads and highways it is less clear who the beneficiaries will be. Statistics provided by the developer tell us that should solar roads be rolled out across the 48 contiguous States in the US they could potentially generate enough electricity to meet the country's needs – possible because of the changing time zones allowing States that are in darkness to be supplied with electricity by those that remain in daylight.

One of the original objectives was to develop a roadway that could pay for itself over time however no payback period has been provided. The target cost is $10,000 USD/panel and the target lifespan for each panel is 20 years. A simple payback calculation revealed a payback period of 22 years however this doesn't account for increases in energy prices or savings in energy infrastructure costs that would be implicit with the roll-out of the system. With the strong Australian Dollar and the cost of electricity in Australia double that in the USA the payback period could be significantly less however a more detailed analysis that would need to factor in average daily solar radiation in Australia compared with the USA is required.

In terms of timeframe to market, this project would appear to be a horizon 2 or possibly horizon 3 technical innovation[76] until further funding is secured for this technology.

Renewable Energy Carbon Offset Project

Main Roads WA have instigated a project to assess solar PV, wind and geothermal energy opportunities in terms of how best they can contribute to their Carbon Reduction Plan. Based on a 300-400kW PV system, a 20% whole of life offset would have a capital cost of approximately $1 million. The findings of the study did not recommend pursuing the project because of the uncertainty around the price of PV with it dropping dramatically in recent years, making it difficult to estimate project costs.

Annotated Bibliography on Solar Power and Roads

'Economic feasibility of solar-powered LED roadway lighting'

M.S. Wu, H.H. Huang, B.J. Huang, C.W. Tang and C.W. Cheng, Renewable Energy; an International Journal, January 13, 2009.[77]

This article revolves around a study that investigates the design of solar powered LED roadway lighting. The study looks at the design of a solar-powered LED roadway that is 10km of highway with 2 lanes, installation costs are estimated with poles being 30m apart. The study established that using LED lighting over the conventional mercury lights would reduce about 75% of energy consumption and cost 22 million USD to install LED and 26 million USD for solar powered whereas mercury lights cost 18 million USD. However, the payback time for the excess investment of LED is 2.2 years, and 3.3 years for LED using solar power.

'A high efficiency autonomous street lighting system based on solar energy and LEDs'

M.A.D. Costa, Power Electronics Conference, October 1, 2009.[78]

This work presents an autonomous street lighting system based on solar energy as primary source, batteries as secondary source, and lighting emitting diodes (LEDs) as lighting source. This system is being presented as an alternative for remote localities, like roads and crossroads. Besides, it presents high efficiency, because all power stages are implemented in DC current. The design of LEDs fixture, in order to replace a 70 W high pressure sodium (HPS) lamp, is performed. This design takes into account the human eye response in scotopic conditions. LEDs driver and battery charger experimental results are presented. The battery charger presents three control modes: maximum power point tracker (MPPT) mode; constant current mode; and constant voltage mode. The control mode depends on the battery state (charged/discharged), and solar irradiance level.

Wind Power in Road Easements and Structures

Using land adjacent to road infrastructure to install traditional wind turbines has been done for some time. An alternative concept has appeared in many forms in the last ten years which takes the concept further by attempting to utilise the wind or turbulence generated by vehicles to drive generators mounted in medians or overhead highways.

Wind Power in Road Easements and Structures

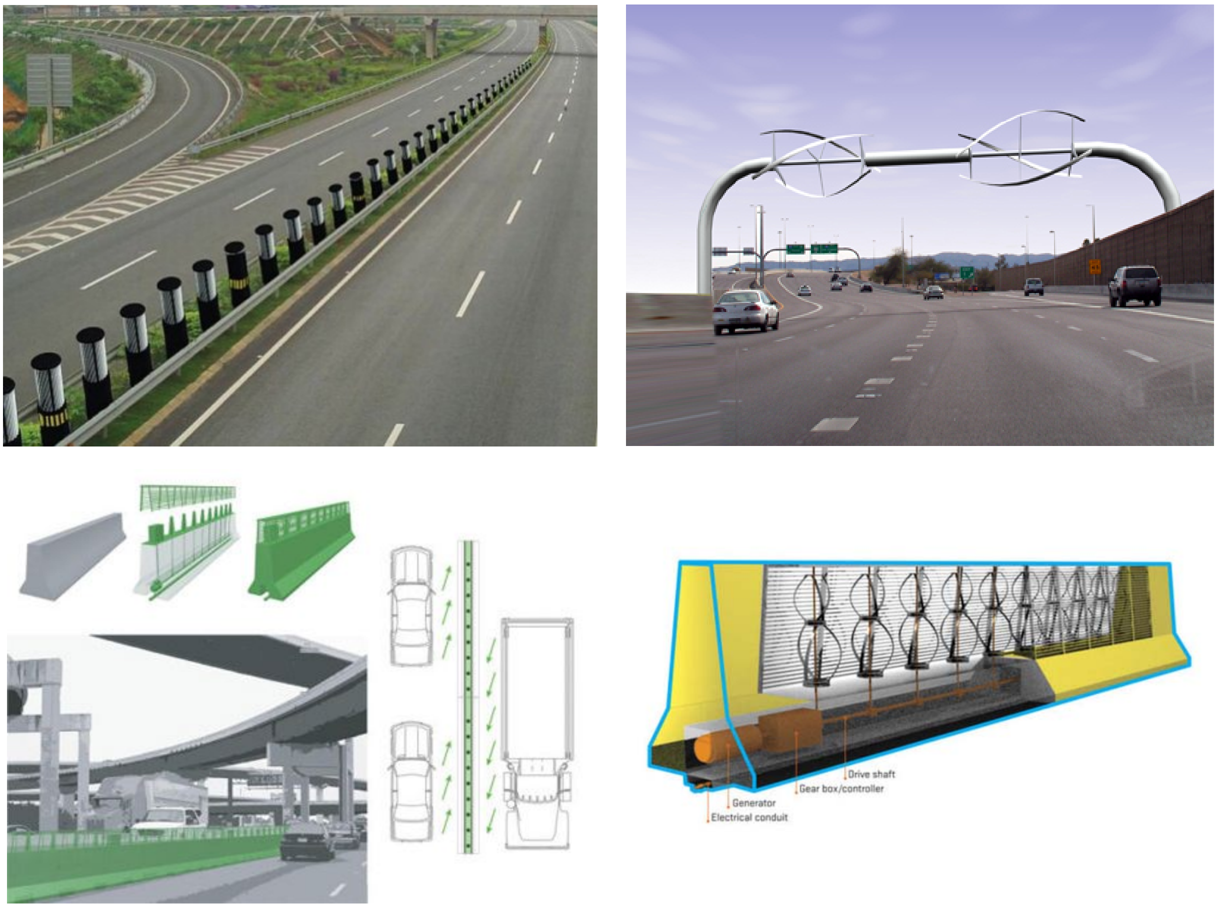

Figure 12: Examples of Wind Generation Systems that Use Air Movement from Passing Traffic to Produce Energy[79]

There are numerous examples of these projects which have been the subject of conceptual design presentations, patent applications and design competitions as shown in Figure 5 however there is a paucity of academic research or publications in this area.

Solar/Wind Stand-Alone Hybrids

There have been a number of examples of businesses venturing into the market of stand-alone lighting or signage poles that utilise a wind turbine, PV or a combination. This type of system charges a battery which then powers a street lamp or illuminates signage through the night. The stand-alone nature of these products allows them to be easily deployed, they require no trenching and have no connectivity issues.


Figure 13: Examples of Hybrid Lamp Standards[80]

Although specialised in nature, these products are available now.

Annotated Bibliography on Wind Power and Roads

‘Feasibility Study of Micro-Wind Turbines for Powering Wireless Sensors on a Cable-Stayed Bridge’

Jong-Woong Park, Hyung-Jo Jung, Hongki Jo and Billie F. Spencer Jr., Energies, 6 September, 2012.[81]

This study examines the applicability of small-size wind-power generators for operating a wireless sensor under the actual wind conditions at the bridge site. The article follows an extensive research project and includes power consumption per wireless sensor, measures wind speed, and performance tests and goes into detail regarding the turbine make-up. The study focused on the second Jindu Bridge in Korea, looking at the feasibility of installation and power consumption. The study concluded that the horizontal-axis wind turbines with 6 blades had the highest level of performance. With regards to the Jindu Bridge it was determined that the wireless sensor with the proposed micro-wind turbine can successfully perform with a wind flow of 4m/s or higher for 2.7h a day.

Harnessing Energy from Vehicle Movement

Piezoelectric Generators

This concept is derived from the Piezoelectric effect, which describes how mechanical energy can be converted into electrical energy by straining a piezoelectric material. Piezoelectric effect was discovered by J and P Curie in 1880. They found that strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field. There is significant research on the principles behind the effect and but little on the practical applications. Innowattech, a privately owned Israeli research company have done some field testing of their product, the Innowattech Piezoelectric Generator (IPEG), which can be deployed in a number of trafficked areas as shown in Figure 7, which supports the findings of their lab-based testing.

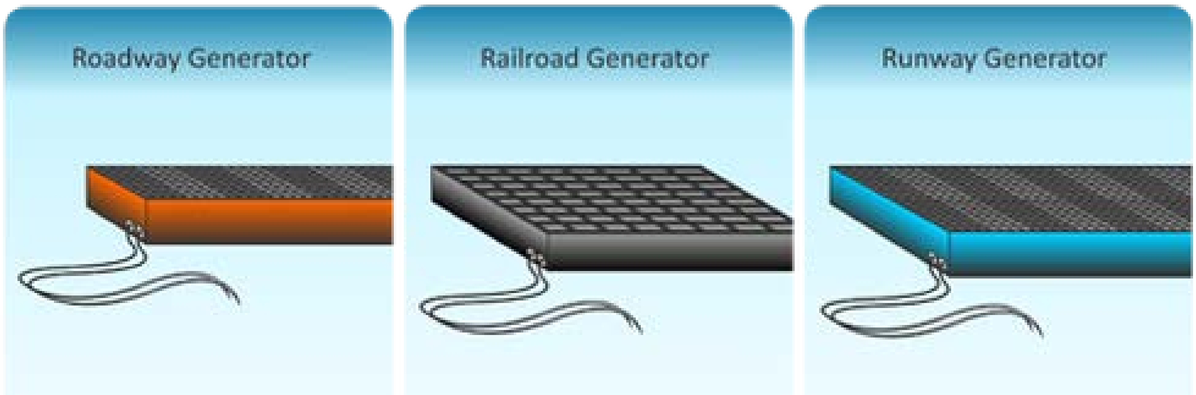

Figure 14: Deployment of Piezoelectric Generators need not be restricted to highways

"The Israeli company has developed a system using energy harvesting piezoelectric crystals to sequester the mechanical energy generated on highways, the runway and the railway."[82]

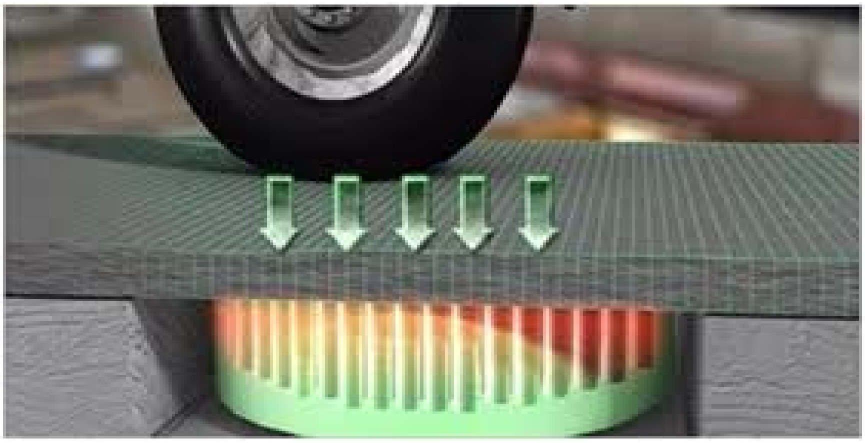

Figure 15: 3D Image of IPEG Embedded into a Highway

According to Innowattech "*IPEG is a piezoelectric device that can be embedded in sidewalks, roads, railway beds and airport tarmacs to capture the energy created from traffic. Unlike other renewable energy sources, piezoelectric technology integrates with existing infrastructure, requiring no additional real estate*".[83]

Independent data is scarce for this technology and there is little from Innowattech that explains in any detail the financial feasibility of the technology although the technical feasibility has not been questioned in the available literature.

A study from Stanford University[84] provides a review of the technology and attempts to create a business case if deployed in California. It suggests that the payback period would not be less than 12 years based purely on the cost of the primary material the device is made from. The same paper also explores the impact that larger vehicles would have, and suggests a marked improvement in performance in the order of 400% is achieved if only 18-wheeler heavy vehicles with a high fuel consumption (5mpg) travel on the highway. However this assumes that all of the vibrational energy from the road is captured by piezoelectric devices. The study refutes claims from Innowattech that a 1km stretch of highway with devices installed in both directions could generate 400kW – enough to power 162 Western-US homes, suggesting that the number of homes that could be powered was closer to fifteen.

Annotated Bibliography on Energy from Vehicle Movement

'Application of Piezoelectric Materials in Smart Roads and MEMS, PMPG Power Generation with Transverse Mode Thin Film PZT'

Abbasi, International Journal of Electrical and Computer Engineering (IJECE), Vol. 3, No. 6, December 2013

In this paper, the author has presented and reviewed a method to produce pollution free electricity by some techniques like Piezoelectric effect in pyroelectric crystal and power generation by thin film MEMS, PZT, PMPG and using them in piezoelectric roads. as congestion on roads is becoming inevitable with the fancy of masses towards personal transportation systems for their growing mobility. Accordingly, it is an object of the present invention to provide a method of electrical power generation that does not negatively impact the environment.

'Conceptual Design of Harvesting Energy System for Road Application'

Dr Kok Boon Ching, 2013, Universiti Tun Hussein Onn Malaysia.[85]

Abstract: Energy harvesting becomes more and more important in our life. It refers to the practice of acquiring energy from the environment which would be otherwise wasted and converting it into usable electric energy. For this, every kind of energy can be exploited such as solar, wind or strain and kinetic energy. The idea is to propose a conceptual design that will carry out a suitable energy harvesting conversion to be applied for road application. However, harvesting energy using piezoelectric generators has been chosen for this project. The project is conducting a simulation analysis using a piezoelectric generator based on a model by S Roundy et al. The data applied from a 15 mm x 3.2 mm x 0.14 mm single layer piezoelectric bending element which produce 950 μW with a 1.727e6 Nm-2 of input stress. The simulation is done using MATLAB-Simulink-SimPowerSystems.

Thermal Power

Water Pipe Heat Exchangers in Pavements

“Dutch building company Ooms uses a series of connected water pipes embedded in the asphalt to harvest the heat from streets. Figure 9 shows a highway near Rotterdam, Netherlands, where water cables are laid underneath a sheet of asphalt.”

Figure 16: Water Cables Laid Under a Sheet of Asphalt

“The technology works like a geothermal heat pump, but instead of being installed in the Earth's soil, the water pipes are rooted in or underneath the asphalt. The hot water is later pumped into an underground aquifer where heat exchangers extract the energy from the circulating water before it returns to the surface. The aquifer stores the heat. During colder days, it is pumped into a building or back in the asphalt to prevent the road from icing up. (Source: Ooms Avenhorn Holding)”[86]

Annotated Bibliography on Thermal Power and Roads

‘Researchers Aim to Harvest Solar Energy from Pavement to Melt Ice, Power Street Lights’

Science Daily, November 10, 2010.[87]

A Science Daily news article about a team of engineering researchers from the University of Rhode Island who are examining methods of harvesting solar energy to melt ice, power streetlights, illuminate signs, heat buildings and many other purposes. The team has come up with 4 approaches to pursue; 1) wrap flexible photovoltaic cells around the barriers dividing highways to provide energy to power streetlights and illuminate road signs (embedded in between the barrier and the adjacent rumble strip), 2) embed water filled pipes beneath the asphalt and allow the sun to warm the water, the heated water could then be piped to nearby buildings to melt accumulated ice on the surface and reduce the use for road salt, (water can also be piped to nearby buildings for heating or hot water needs) (prototypes underway), 3) using thermo-electric effect to generate usable electricity and 4) completely replacing asphalt roadways with large, durable electronic blocks containing photovoltaic cells, LED lights and sensors.

'High-Performance Single and Polycrystal-Based Pyroelectric Smart Materials for energy harvesting from Pavements'

Sudip Bhattacharjee, Ashok K. Batra, Sima Meseret and Jacob Cain, Transportation Research Record: Journal of the Transportation Research Board, 2011.[88]

The goal of this study was to determine the possibility of capturing thermal energy from natural heating pavement and storing that energy and using it as an alternative power source for other devices. The study wanted to determine whether currently available pyroelectric materials can be used as smart materials for the purpose of harvesting thermal energy from pavements. The article goes through the materials used and the test method. The conclusions were as follows:

1. Both single-crystal– and polycrystal-based materials and cement composites with carbon nanofibers are viable materials, which can be used for energy conversion from pavement structures.
2. Triglycine selenate crystals show very good pyroelectric behaviour, which makes it an excellent candidate for an energy harvester.
3. Cement–carbon nanocomposites can be fabricated by using a normal mixing and compaction method, making it an attractive candidate for an energy harvester.
4. The dielectric constant of cement composite increases as the carbon nanofibre content increases.
5. The pyroelectric coefficients of the composite also increase as carbon fibre content increases. Higher content of carbon fibre in the cement nanocomposites is beneficial for pyroelectric energy conversion devices.
6. The simulation result with real-time pavement temperature data indicates that the methodology is a sound one that should be explored further with real-time pavement experimentation.
7. The laboratory demonstration of a piezoelectric-material-based energy-harvesting device indicates that piezoelectric materials are good candidates for energy-harvesting purposes, and can be used to make sensors to convert mechanical vibration from traffic into electric charges

'Simulation of Energy Harvesting from Roads via Pyroelectricity'

Ashok K. Batra, Sudip Bhattacharjee, Ashwith Kumar Chilvery, Mohan D. *Aggarwal*, Matthew E. Edwards, and Amar Bhalla, Journal of Photonics for Energy, Volume 1, Issue 1, October 31, 2011.[89]

This paper focuses on thermal-electric energy converters based on pyroelectric effect for energy harvesting and examines its possible use in ultralow power devices and sensor modules. The article provides details about all the pyroelectric materials used for designing a single domain 'micro-electric harvester' for energy harvesting from pavements. The study concludes that TGSe (triglycine selenate) is an attractive candidate for energy harvesting from pavements due to its higher pyroelectric coefficient near ambient temperatures. The article acknowledges that due to temperature, traffic, location and time the amount of electric energy that can be generated varies.

'Thermoelectric Generators using Solar Thermal Energy in Heated Road Pavement'

Thermoelectrics, 2006. ICT '06. 25th International Conference on: 6-10 Aug. 2006, Hasebe, M. Kamikawa, Y.; Meiarashi, S.[90]

Abstract: The temperature of road pavement rises up to 70C˚ in summer due to the effect of the solar radiation. The authors have developed a pavement-cooling system using thermoelectric generator. Heat in the pavement is collected as heated water in a heat collection tube installed in the pavement. River water near the road is used as a coolant. Electric power is produced by temperature difference between the hot and cool water at the thermoelectric generator. With the conversion from heat to electricity and heat flux from hot to cold water; the temperature of the surface of the pavement is reduced

'Using cool pavements as a mitigation strategy to fight urban heat island—a review of the actual developments'

Santamouris, M. (2013). Renewable and Sustainable Energy Reviews, 26, 224-240.[91]

Abstract: Heat island phenomenon raises the temperature of cities, increases the energy demand for cooling and deteriorates comfort conditions in the urban environment. To counter balance the impact of the phenomenon, important mitigation techniques have been proposed and developed. Pavements present a very high fraction of the urban areas and contribute highly to the development of heat island in cities. The use of cool pavements presenting substantially lower surface temperature and reduced sensible heat flux to the atmosphere, appears to be one of the most important proposed mitigation solutions. This paper investigates and describes the actual state of the art on the field of cool pavements. The main thermal and optical parameters defining the thermal performance of pavements are analysed. Almost all of the developed technologies, where data and results are available, are considered while emphasis is given on the presentation of reflective and permeable/ water retentive pavements. The main technological achievements on both fields are reviewed while existing applications are described and performance data are given when available. The existing results clearly show that the mitigation and cooling potential of cool pavements is very significant and can highly contribute to decrease temperature on the urban environment.

'Reducing Urban Heat Islands: Compendium of Strategies – Cool Pavements'

E. Wong, eds. K. Hogan, J Rosenberg, Neelam R. Patel and A Denny, EPA Office of Atmospheric Programs, Climate Protection Partnership Division, 2005.

Tidal Power and Bridges

Tidal power is a lesser established form of renewable energy than those described above normally associated with two types of systems, both of which can be designed into structures such as bridges which have the potential to be assets owned by Transport Authorities.

The two main generating methods are: tidal stream generators; and tidal barrages. Tidal stream generators use the kinetic energy from passing water to drive a turbine in a similar fashion to wind turbines. The tidal barrage model uses potential energy through strategically placed specialised dams which allow the tide to flow into a lagoon or upstream then, as the tide turns the potential energy captured through the difference in height either side of the dam, is converted to kinetic energy as it drops through a turbine.

The nature of the environment that tidal energy projects have to be located contributes to the high capital costs associated with them however, they are long term projects with a projected life of 60 – 120 years[92].

Annapolis Tidal Station[93]

The only tidal barrage power plant in North America, located in Nova Scotia began operation in 1984. The power plant has a capacity of 20 megawatts and a daily output of roughly 80-100 megawatt hours, depending on the tides.

Figure 17: Annapolis Tidal Station

The development of this project was assisted by the Federal government's promise to fund the renewable energy project at the same time the provincial department of transport was required to replace an aging steel truss bridge, hence providing an efficient means of financing the project. The project has had some environmental issues with increased local erosion of the river banks both upstream and downstream. The dam has also been known to trap wildlife including two separate cases of humpback whales being trapped upstream of the dam.

La Rance Barrage, France[94]

La Rance Barrage is the world's first tidal power station, located on the estuary of the Rance River is Brittany, France. The power station opened on the 26th November 1966 and is the largest tidal power station in the world in terms of installed capacity. It is generated by 24 turbines and has a peaking rate of 240 megawatts with an annual output of approximately 600GWh. This installation has also caused some detrimental environmental impacts including erosion and the loss of local fish species from the area, however other species have moved into the area and it is claimed by the operator that the eco-system is in balance.

Figure 18: La Rance Barrage Power Station, France

The construction method of building two dams either side of the site, pumping it out to provide a safe and dry construction site was expensive with the project costing around F620 million, and taking around 20 years to pay for itself. The operators now claim that the running costs are 1.8cents/kWh - cheaper than nuclear power (2.5 cents/kWh), which makes up a significant proportion of France's energy production.

Annotated Bibliography on Tidal Power and Roads

'A Sleeper Awakes: Tidal Current Power'

Roger H. Charlier, Renewable and Sustainable Energy Reviews, Volume 7, Issue 6, 27 April 2003.[95]

This paper discusses tidal currents as a form of energy; it explains tidal currents in detail as well as specific sites that have major potential for producing energy via tidal currents. The paper also provides some historical information about the technology involved in harnessing tidal currents; it also provides some examples around the world of current developments replated to this field.

'Tidal Current Power Generation Making Use of a Pier'

Yusaku Kyozuka and Kyoichiro Ogawa, 2006.[96]

This article revolves around the concept of making use of a bridge pier for tidal power generation. There are several advantages in making use of a bridge pier for tidal power generation. Firstly by incorporating a bridge pier and a tidal power unit the initial cost of infrastructure that would be needed for just the power unit can be reduced, secondly current velocity increases near a pier and thirdly the pier is convenient for maintenance of the hydraulic turbine and the power unit. The article provides information about Ikituski Bridge and an outline for how they would incorporate a tidal power system on the already constructed bridge. The outline also includes a timeline and estimations of outcome of the tidal power station as well as model experiments.

'Technology Survey for Renewable Energy Integrated to Bridge Construction'

Espen Borgir Christophersen, Ramboll, Norwegian Public Roads Administration reports, April 2012.[97]

This articles objective was to investigate the possibilities for using bridge construction to increase the potential for renewable energy production with a focus on the fjord crossings in Ferry free E39 project (Norway). The bridge crossing for Ferry free E39 is estimated to be 3.7km with a water depth of 1250 meters. The article is very specific to Norway with the potential for solar radiation and its lack of intensity there as well as the low wave potential. However it does provide a more universal example of where additional weight (of renewable energy infrastructure) can be added to the bridge without concern for structural safety for 3 different types of bridges. The article is most helpful for its research regarding the structural feasibility of adding renewable energy infrastructure to a bridge, with specific focus on wind turbines, wave and tidal power technology, solar heaters and solar cells; it also discusses technology development.

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[2] J Gaffney, Vic Roads (2014, pers. comm., 05 December)

[3] VicRoads (2013) *Managed Freeways Handbook for lane use management, variable speed limits and traveller information,* VicRoads, Pg 2.

[4] VicRoads (2013) *Managed Freeways Guidelines*, VicRoads, Page 4.

[5] VicRoads (2013) *Managed Freeways Guidelines*, VicRoads, Page 4.

[6] VicRoads (2013) *Managed Freeways: Freeway Ramp Signal Handbook*, VicRoads, Page 13, Figure 1.2.

[7] VicRoads (2013) *Managed Freeways Guidelines*, VicRoads.

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[9] VicRoads (2013) *Managed Freeways Guidelines*, VicRoads.

[10] VicRoads (2013) *Managed Freeways Guidelines*, VicRoads.

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