EFFICIENT AUTONOMY

Identifying Energy Efficiency Opportunities with the Introduction of Autonomous and Connected Vehicles

Masters of Science, Renewable Energy Systems
Murdoch University
2015

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Declaration

I declare that the work that I have submitted is my own work and has not been submitted for assessment before and I have given references for all sources of information that are not my own, including the words, ideas and images of others.

Acknowledgements

I wish to thank various people for their contribution to this dissertation; Jonathan Whale for guiding me through this dissertation as a supervisor; the University of Texas, in particular Peter Stone for developing the open source AIM simulator; and Lauren Wilson for her loving support through the entire process.
Abstract

Much of the scientific and policy analysis of autonomous vehicles advocates their safety and accessibility. This dissertation seeks to contribute to broadening academic discourse by examining the energy efficiency opportunities of the introduction of autonomous vehicles and vehicle communication technology. As the global market for autonomous vehicles develops, the impacts on society are beginning to be investigated including the impact on energy efficiency. This dissertation will contribute to this discourse by examining platooning and automated intersection management as techniques for improving efficiency as a result of the introduction of autonomous vehicles. In addition, this dissertation will analyse how society is likely to adapt to autonomous vehicles being introduced into the market and the how it may impact the energy efficiency of transportation networks. This examination demonstrates that there is great scope for energy efficiency as society and systems adapt to this technological change.
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Introduction

For almost as long as the automotive industry has operated, autonomous vehicles, also known as ‘self-driving cars’, have been in the minds of engineers and automotive companies alike. In 1956, General Motors hosted a car expo called ‘Motorama’ in which the autonomous car was propelled into the industries’ consciousness through a film that was produced for the expo (Radiotopia 2015). During that period, the emphasis of this technology was predominantly around safety in an attempt to address an increasing number of fatal car accidents on American roads (in excess of 30 000 per year, every year since that time) (Radiotopia 2015). Automation in cars has steadily progressed as a result of innovations by a large number of auto and technology companies as well as universities. Indeed, General Motors, Mercedes-Benz, Audi, Nissan, BMW, Renault, Tesla and Google expect to have market-ready vehicles available by 2020 that will be able to drive autonomously with little human interaction (Tampa Bay Times 2015).

Much of the scientific and policy analysis of autonomous vehicles advocates their safety and accessibility (Hars, 2015). This dissertation seeks to contribute to broadening academic discourse by examining the energy efficiency opportunities of the introduction of autonomous vehicles and vehicle communication technology. As the global market for autonomous vehicles develops, the impacts on society are beginning to be investigated including the impact on energy efficiency. This dissertation will examine the current state of technology in the market, together with the active and past research into autonomous vehicles. It will investigate the opportunities for energy efficiency as a result of the introduction of autonomous vehicles and vehicle communication technology. By examining the technology enhancements, this dissertation analyses different driving techniques and traffic systems that can be adapted in order to improve efficiency.

Prior research has found that both automation and vehicle communication when employed separately can improve energy efficiency. However, by combining the technologies and deploying them together has the potential to greatly increase energy efficiency. The precise nature of autonomous driving, coupled with vehicle communication, allows for traffic decisions to be made ahead of time. This is best demonstrated through Automated Intersection Management (AIM) which allows vehicles from all directions to safely navigate through an intersection simultaneously without the need for traffic lights. This, along with other driving techniques such as platooning (defined as the synchronised movement of two or more vehicles as a unit, travelling at the same speed with relatively small inter-vehicle spacing (Mitra and Mazumdar 2007)) and other traffic management strategies can have significant impacts on the overall energy efficiency of the transportation network. The energy efficiencies are particularly evident in urban environments. The coupling of these technologies allows for the removal of human error or latency from driving, which greatly influences both the design of transportation infrastructure and human behaviour.

This dissertation argues that the combination of information-based decision making, the precision of autonomous driving, and the changes in the way that society consumes transportation, presents great scope for increasing the energy efficiency of the transport network. In making these arguments, the dissertation will focus on platooning and intersection management that are
enhanced in the deployment of autonomous vehicles, and the resulting behavioural change. Given that such a large percentage of Australia’s total final energy consumption is based in the transportation sector (BREE, 2014), autonomous vehicles provide opportunities for the significant reduction in greenhouse gas emissions.

In presenting this argument, the dissertation is structured in the following way. The remainder of this introductory chapter outlines the research objectives and methodologies employed. It also provides background to the development of the technology, how autonomous vehicles work and the current state of the global market. Chapter One will present a literature review into platooning, with specific focus on the effects of aerodynamic drag. Chapter Two will examine vehicle communication employed through AIM, and investigate the efficiencies of a technological solution to managing intersections. Finally, Chapter Three will discuss how human behaviour is likely to adapt to automation and the potential for changes in transport systems, which will have an impact on the amount of energy the system as a whole, consumes.

Research Objectives

This dissertation has the overall objective of examining energy efficiency opportunities of the introduction of autonomous vehicles. More specifically, the dissertation has three aims. First, it will bring together different research areas to show how emerging technology will likely shape the transportation market, and, apply those methods in an energy context. Second, and following on from this analysis, the dissertation aims to demonstrate how the technology may either benefit or hinder the energy efficiency of transportation. Finally, the dissertation will examine whether the evolving technology is likely to change the way that society utilises transport services as a result of the elimination of the human driver.

The research for this dissertation uncovered numerous mechanisms to achieve energy efficiency as a result of the introduction of autonomous vehicles. However, the focus of this dissertation will be to examine efficiencies in the areas of platooning, intersection management and behavioural change. Other areas such as road space utilisation, automated parking, automated traffic routing and machine learning, are not included and are avenues for further research.

To ensure a thorough examination of the issues, the dissertation will combine a number of research methods including simulations, mathematical analysis, literature review, theoretical models and analysis. Chapters within this dissertation use different research methods based on the type of analysis conducted. Chapters examining platooning and AIM use simulations, literature review and analysis to develop arguments, whereas the final chapter examining behavioural change employs both literature review and analysis to develop conclusions.

Given that autonomous vehicles are a relatively new technology that has not matured, it is not known when or in what form they will come to market. Despite this however, it is possible to make certain assumptions regarding aspects of the final implementation in light of how the technology has developed to date. Indeed, due to the developing nature of the technology, it is difficult to quantify the amount of energy that may be saved or lost as a result of the evolving
technology. This places a limitation on the research conducted, and the dissertation can therefore only provide an estimation of the changing energy consumption. Where possible however, the dissertation identifies energy efficiencies under specific scenarios whilst making certain assumptions. These results are used to demonstrate the wider energy efficiencies potential of autonomous vehicles.

Background & Current State of the Market

In 2013 the transportation sector consumed 37.9 per cent of Australia’s total final energy, representing the largest portion of any sector (BREE, 2014). Almost all of this transportation is reliant on fossil-fuels (Droege 2008). In the context of global climate change and depleting fossil-fuel based resources, efficiencies in the transport sector should be developed in order reduce Australia’s reliance on this source of energy and its overall greenhouse gas emissions. The technological development and eventual introduction of autonomous and connected vehicles presents an opportunity not only to increase the safety and convenience of motor vehicles (Ioannou, 1993), but to also increase the efficiency of this mode of transport.

Autonomous Vehicles: Definitions and Development

‘Autonomous vehicles’ are defined as cars being driven by an on-board computer for either part or all of a journey (Folsom, 2012). The United States National Highway Traffic Safety Administration has defined different levels of automation as a method of standardising policy responses (NHTSA 2013). These include:

- No-Automation (Level 0): The driver is in complete and sole control of the primary vehicle controls – brake, steering, throttle, and motive power – at all times.
- Function-specific Automation (Level 1): Automation at this level involves one or more specific control functions.
- Combined Function Automation (Level 2): This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions.
- Limited Self-Driving Automation (Level 3): Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.
- Full Self-Driving Automation (Level 4): The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be
available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

(NHTSA 2013)

The market has already widely adopted automation classified under levels 1 and 2 (Wornes 2015). For example, features such as assisted parking and intelligent cruise control are already available in the United States and Australia (Wornes 2015). Several technology and automotive companies are developing levels of automation classified under levels 3 and 4, with Google being the most public (The Economist, 2014). These companies are directing their efforts in two ways: retrofitting automated controls (including LIDAR (light detection and ranging), GPS and other technology), and developing prototypes of custom-designed vehicles with inbuilt hardware (The Economist 2012). Both are pictured in the Figures below.

Figure 1 – Retrofitted automation technology

(The Economist 2012)
As of June 2015, Google’s autonomous vehicle had driven over 1.6 million kilometres on public roads in the United States, which is the equivalent of 75 years driving of a typical adult (Google Self-Driving Car Project 2015). Despite this progress, there are some limitations that still exist. For example, Google has not yet tested the vehicle in heavy rain or snow and the car has had difficulty determining when some objects on the road are harmless (such as plastic bags), which has caused unnecessary manoeuvring (Gomes 2014). Despite these issues Google, as well as a number of other manufacturers expect to have commercially-ready models available by 2020 (Gannes 2014).

As the industry for autonomous vehicles develops, legislators are increasingly enacting changes in order to allow self-driving vehicles on public roads. In the United States, the states of Nevada, Florida, Michigan and the District of Columbia have passed laws allowing autonomous vehicles to be tested or used. Similar laws have also been enacted in the United Kingdom, France and Switzerland, allowing for vehicles to be tested on public roads or within specific regions. In Australia, trials will begin in November 2015 in Adelaide (Motoring.com.au 2015). Currently, South Australia is the only state in Australia that has amended legislation, removing the requirement for vehicles to have a human driver. Chapters One and Two give further details about the implementation of autonomous vehicles and Chapter Three examines the behaviour change that will result.

Vehicle Communication: Definitions and Development

Vehicle communication uses wireless technology to allow travelling vehicles to communicate with other nearby vehicles and a broad range of road and transport infrastructure (Chan, 2011). This
allows vehicles to plan their movements based on other vehicles that are on the road as well as any changes to traffic conditions. Vehicle communication has had limited development to date, however, it is considered to be dependent on the introduction of vehicle automation. Significantly, precursor-technologies such as Google Traffic, though not employing vehicle-vehicle communication, uses smart phones carried in the vehicle to determine traffic conditions (NCTA 2013). Chapter Two further examines how this preliminary innovation may be further adapted to vehicle communication.
Research Methodology

To ensure a thorough examination of the issues, the dissertation will combine a number of research methods including simulations, mathematical analysis, literature review, theoretical models and analysis. Chapters within this dissertation use different research methods based on the type of analysis conducted. Chapters examining platooning and AIM use simulations, literature review and analysis to develop arguments, whereas the final chapter examining behavioural change employs both literature review and analysis to develop conclusions.

Chapter One will examine platooning and how it can reduce energy consumption through the reduction of aerodynamic drag. In achieving this, the chapter will review literature surrounding the measuring of aerodynamic drag in determined the forces that impact on a vehicle whilst in motion within a platoon. From the equations derived from the literature, this chapter will also calculate the contributions to resistance on a moving vehicle and will use this data in order to determine how reductions in aerodynamic will affect vehicles under different conditions (see Worksheet A in the Appendix spreadsheet for calculations).

Chapter Two will study AIM\(^1\) as a methodology of managing intersections in order to facilitate an increase in energy efficiency. This chapter will first present an overview of how communication technologies have been used in vehicles previously, and demonstrate how this methodology increases efficiency, particularly at low to moderate levels of congestion, via reducing the amount of acceleration required on average when passing through an intersection. In demonstrating this, this dissertation will use an AIM simulator originally developed by the University of Texas in Austin, originally developed in order to demonstrate the AIM system. The simulator was modified by applying the energy consumption equations (see Equations 1 to 6) as examined in Chapter One in order to measure the amount of energy each vehicle consumed as it passed through the intersection. The results of the simulations conducted under different congestion levels and using different vehicles provide insight into how energy consumption can be reduced through AIM.

Chapter Three reviews case studies and other literature to study how societal behaviour could change as a result of the introduction of autonomous vehicles. These case studies examine a shared autonomous vehicle (SAV) model, which allows commuters to consume transport by ride sharing as part of an autonomous vehicle fleet, replacing the ownership model for private transport. This dissertation analyses how as a result of energy efficiencies could be obtained through decreased congestion, greater utilisation of transport services, as well as providing a younger fleet servicing the transportation needs of the population.

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\(^1\) For clarification, AIM is composed of three distinct components: the management process, the implementation of that process and the simulation software. ‘AIM’ refers to the management process; the ‘AIM system’ refers to the implementation of that process; and the simulation software will be referred to as the ‘AIM simulator’.
CHAPTER ONE – Platooning

Since their introduction, the safety of vehicles has been a primary concern in both their design and the rules regulating use. One of the most important road rules seeks to ensure motorists travel at a safe distance behind other vehicles, so to ensure that, in an emergency situation, the second vehicle can safely brake without colliding with the vehicle in front (Road Safety Commission 2015). An average driver’s reaction time to notice the incident and engage the brake has always been central to determining how far behind a car can travel safely (Road Safety Commission 2015). The elimination of the driver via the introduction of automation and vehicle communications in turn eliminates driver reaction times. Indeed, the introduction of this technology thereby allows a reduction in the safe travelling distance between vehicles.

The term ‘platooning’ describes the synchronised movement of two or more vehicles as a unit, travelling at the same speed with relatively small inter-vehicle spacing (Mitra and Mazumdar 2007). Platooning facilitates a reduction in the amount of aerodynamic drag incurred on the group of vehicles, and as a consequence, reduces the average total energy consumed. This Chapter reviews the literature examining the effects of platooning, changes in aerodynamic drag and the relationship in the reduction of drag and the energy consumed.

Platooning in Practice

Inter-vehicle communications facilitate the ability for vehicles to adjust their position and speed based on the information sent in the network. The ‘reaction time’ \( R_t \) for a vehicle to respond to other surrounding vehicles is approximated by determining the distance between the two, and the processing time it takes to interpret and act on the message. Given the speed of modern computing and the small distance between vehicles when travelling together in a platoon, the time for one vehicle to send a message, and be received and processed in other vehicles, would be, in a large majority of circumstances, negligible. On this basis, and for the purposes of this dissertation, \( R_t \approx 0 \), that is, reaction time is approximately instantaneous. In comparison, human drivers are estimated to have reaction times of approximately 1.5 seconds (Summala 2000).

Vehicles with the same intended route over a distance (for example on a highway) that are already nearby to each other will form into platoons in order to travel across long distances with greater efficiency. The travelling distance between each vehicle has been suggested to be implemented between 1m and 0.3 vehicle lengths without compromising safety (Ali, Garcia and Martinet 2015; Zabat et al. 1995). The final implementation however, as well as regulation may dictate changes to this figure. It is important to note that a distance range (as opposed to a fixed distance) is likely to be part of the final design of platoons in order to maintain traveller comfort as well as reduce fuel consumption from constantly adjusting to the speed of the preceding vehicle (Alam 2011). Given the amount that the safe travelling distances can be quite dramatically reduced, this will reduce the amount of aerodynamic drag on all vehicles in the platoon and consequently the fuel consumed.
Measuring Drag Reduction

From the research and simulations conducted by Zabat et al., the aerodynamic drag effects on a platoon of vehicles have been simulated in order to demonstrate their impacts on fuel consumption. Zabat et al. used a drag coefficient ratio to describe the change in drag across each vehicle and the aerodynamic savings which can be gained whilst travelling (Zabat et al. 1995). Zabat et al. used wind tunnel simulations in order to measure the amount of drag incurred on each vehicle under different scenarios. Figures 3, 4 and 5 depict the change in the coefficient of drag across 2, 3 and 4 vehicle platoon sizes. Zabat et al. notes that as the vehicle platoon increases in size, the average drag across the platoon is reduced, however the drag reduction diminishes as the number of vehicles in the platoon increases (Zabat et al. 1995).

Figure 3– Co-efficient of drag in a two vehicle platoon

![Figure 3](image3.png)

(Zabat et al. 1995)

Figure 4 – Co-efficient of drag in a three vehicle platoon

![Figure 4](image4.png)

(Zabat et al. 1995)
The change in drag from different platoon sizes highlights the energy efficiency potential from travelling closely together. As expected, the closer the vehicles travel together, the greater energy savings potential. As more vehicles are added to the platoon, each vehicle lowers the total average drag experienced by the platoon. Zabat et al. determined that the total overall platoon performance be determined by defining an average drag co-efficient ratio. The ratio is displayed in the figure below across two, three and four vehicle platoons. Figure 6 shows that at zero spacing (that is, no space between two vehicles), the average drag has been halved across a four-vehicle platoon.
Using a conservative figure of 0.3 vehicle spacing for where platooning could be implemented, Figure 6 shows that this could achieve a 45 per cent reduction in the average co-efficient of drag. As shown in the subsequent section, this reduction in the co-efficient of drag can have a large impact on the total resistance of a vehicle, particularly at high speeds.

**Relationship between Drag and Fuel Reduction**

It has been widely recognised that when a second vehicle travels in close proximity to a leading vehicle, the amount of drag incurred on the trailing vehicle is reduced, leading to an increase in energy efficiency (Zabat et al. 1995). Quantifying the resulting efficiency increase from platooning is determined by calculating the contribution of aerodynamic drag to the overall resistance to vehicular motion and any other power losses incurred in the vehicle. Based on the simulations conducted by Zabat et al., the total fuel savings can be estimated as well as the energy efficiencies gained. This dissertation assumes that energy consumption can be determined by calculating the total resistance on a driving vehicle, and the total resistance can be calculated by the following equations (Equations 1-6).

**Equation 1 – Calculation of total resistance on a driving car**

\[
\text{Total Resistance} = D + R_R + R_g + R_A
\]

- \(D\) = Aerodynamic drag
- \(R_R\) = Rolling resistance
- \(R_g\) = Gravitational / climbing resistance
- \(R_A\) = Acceleration resistance
Equation 2 – Aerodynamic drag

\[ D = C_D \frac{1}{2} pV^2 A \]

- \( C_D \): Co-efficient of drag (dimensionless)
- \( p \): Density of air (kgm\(^{-3}\))
- \( V \): Velocity assuming no relative wind (m/s)
- \( A \): Cross sectional area (m\(^2\))

Equation 3 – Rolling resistance

\[ R_R = R_o M g \]

- \( R_o \): Tyre rolling resistance (dimensionless)
- \( M \): Mass (kg)
- \( g \): Gravity (m/s\(^2\))

Equation 4 – Gravitational/climbing resistance

\[ R_g = \sin \phi M g \]

- \( \phi \): Road grade angle (degrees)
- \( M \): Mass (kg)
- \( g \): Gravity (m/s\(^2\))

Equation 5 – Acceleration resistance

\[ R_A = M (1 + E_i) a \]

- \( E_i \): Rotating masses in gearbox (dimensionless)
- \( a \): Acceleration (m/s\(^2\))

(\textit{Zabat et al. 1995})

Once the total resistance has been calculated, the total engine power required to maintain a particular velocity (V) against that resistance can be determined. Equation 6 illustrates the total amount of power required to operate under a certain set of conditions (road incline, relative wind speed etc.) against a certain set of vehicle characteristics (co-efficient of drag, vehicle mass, design shape including frontal area etc.).

Equation 6 – Engine power of a moving vehicle against resistance

\[ P = \frac{\text{Total Resistance}}{N_T} V \]

- \( P \): Power (W)
- \( V \): Velocity (m/s)
- \( N_T \): Losses in the transmission (typically around 0.9, dimensionless).

(\textit{Zabat et al. 1995})

Subsequently, energy consumption can be calculated once the engine power of a moving vehicle against resistance has been determined. From the above equations, the derived percentage of resistance of both rolling resistance and drag can be calculated. The following graph was developed using the characteristics of a 2003 Toyota Prius (as shown in Table 1), assuming no acceleration, and a level ground surface (see Worksheet A in the Appendix spreadsheet for calculations).
Table 1 – Values used to determine contribution of aerodynamic drag and rolling resistance

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of drag</td>
<td>0.26</td>
</tr>
<tr>
<td>Density of Air</td>
<td>1.2041 kg/m³</td>
</tr>
<tr>
<td>Cross sectional area</td>
<td>2.23 m²</td>
</tr>
<tr>
<td>Tire Rolling Resistance</td>
<td>0.0065</td>
</tr>
<tr>
<td>Cross sectional area</td>
<td>2.23 m²</td>
</tr>
<tr>
<td>Gravity</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>Mass</td>
<td>1325 kg</td>
</tr>
</tbody>
</table>

Figure 7 – Comparison of contribution of aerodynamic drag and rolling resistance

As expected, the amount of resistance due to drag increased as the velocity increases. This indicates that the energy efficiency as a result of platooning would have greatest effect on the highway at greater speeds.

Highways

Zabat et al. calculated the approximate reduction in fuel savings using the American Environmental Protection Agency’s driving schedule for highways. Zabat et al. performed this modelling with reference to a Chevrolet Lumina APV across a number of different vehicle spacing measurements, and the results are provided in Figure 8 below.
Figure 8 illustrates significant fuel savings when travelling in platoons for all vehicles. Even under two vehicle platoons, Figure 8 shows that under 0.3 vehicle spacing, savings of approximately 10 per cent could be achieved. Further, this highlights that four vehicle platoons could achieve a reduction in fuel consumption of over 25 per cent, where as previously discussed, the greater the size of the platoon, the greater the energy savings. Under highway conditions, these results indicate that there is significant opportunity for energy efficiency through vehicles travelling in platoons.

**Urban areas**

Reduced benefit could also be obtained at lower speeds in urban environments. Figure 7 shows that a vehicle travelling at 60km/hr experiences an almost equal amount of resistance from aerodynamic drag to rolling resistance. This speed limit is the standard speed limit in urban areas in Australia. This indicates that although the efficiency gains are not as high, there is potential to still benefit from platooning in urban environments. Zabat et al. found that platooning in urban settings will deliver fuel reduction savings between 5 and 10 per cent for 0.1 to 0.2 vehicle length spacing.
Conclusion

Importantly, there is limitation in the studies conducted by Zabat et al. In practice there will not be a uniformity of vehicles (size, shape, mass), and therefore the results will vary. Indeed, changes in the cross-sectional area and co-efficient of drag due to variety of vehicles travelling in the platoon, will greatly impact the aerodynamic drag incurred. For example, a truck trailing a smaller car is going to experience far less fuel savings due to the smaller car having a lower cross-sectional area to the succeeding truck. Whereas, a smaller car travelling behind a truck will experience greater fuel savings than the previous example due to the greater cross-sectional area and lower co-efficient of drag of the truck.

Nonetheless, the introduction of automation and vehicle communications enables vehicles to travel in platoon formation, and consequently, reduce the amount of aerodynamic drag incurred on the trailing vehicles without compromising passenger safety. Despite, the inconsistency in vehicle sizing and conditions, generally speaking, platooning vehicles will have a significant impact on fuel reduction of vehicles travelling on highways. Fuel efficiencies are also gained in urban environment but to a lesser extent. As explained in this Chapter, urban environments have lower speed limits and intersections which impact the efficacy of platoon driving. The following Chapter will examine how this road infrastructure which is more common in urban settings than highways, can be adapted in order to further enhance energy efficiencies in this setting.
CHAPTER TWO – Automation and Vehicle Communication Technology in Intersection Management

Although vehicle automation represents a significant step forward in transportation technology, the safety of driving and the convenience of transportation, it alone does not address the energy consumption of the network. Only through changes to the broader transportation network and the resulting modifications in driving practices, can significant energy efficiencies be achieved. Innovative communication systems will allow vehicles to receive messages from other vehicles and the broader transportation network. This in turn, will facilitate more efficient routes and techniques to be computed in on-board systems in the vehicle, thereby achieving great efficiency in the network and in energy consumed. Specifically, these potential efficiencies can be created through implementing techniques such as platooning (as previously discussed in Chapter 1) and intersection management.

This Chapter will examine automation and vehicle communication technologies that can be deployed in new models of intersection management. It will first provide an overview of vehicle communication technologies, and then present simulations of these adapted models of intersection management. This analysis will show that energy efficiencies can be obtained when employing automated intersection management (AIM) at low to moderate levels of congestion such as that present in urban areas.

Overview of Vehicle Communication Technology

Past literature has described vehicle communication technology in two main categories. The first of these is vehicle-to-vehicle (V2V) communications, where vehicles within a given radius of each of other continually update other vehicles around them with relevant information. The second category discussed in the literature is vehicle-to-infrastructure (V2I) communications where a vehicle sends and receives communications from traffic intersections and the broader transportation network. For example, a road sign indicating the speed could also be used to send the same message digitally to the vehicle. The advantage of this model is that an autonomous vehicle does not need to visually interpret the speed sign, rather, the vehicle can simply adapt to the new command as received. As it continues to develop, the capacity for this technology to communicate with other infrastructure has also been realised. In light of its continuing evolution, a generic abbreviation is used to encompass these expanding vehicle communications: V2X (vehicle to all other sources) (Wedel, Schünemann and Radusch 2009). V2X includes information that is communicated between vehicles and a variety of different, but related systems including, but not limited to, parking lots, other connecting transportation systems such as rail, and weather stations. This dissertation will not distinguish between vehicle communication types, but will instead use this broad definition encapsulating all potential communication points.
The types of information that are broadcast vary depending on the circumstances and the intended recipients. For example, vehicles travelling along a motorway could broadcast GPS position, speed, route direction, vehicle dimensions, lane assignment, and acceleration. In this example, vehicle communications could provide all vehicles within a predetermined radius with a clear picture of a vehicle’s planned movements and to accommodate any changes when required. If a vehicle wanted to change lanes before exiting, it could broadcast that information ahead of time, allowing for other vehicles to adjust, make space and allow the vehicle to change lanes and exit. Communicating with traffic infrastructure allows automated vehicles to take intelligent instruction from the transportation network as a whole, in order to avoid hazards and select an appropriate route given the conditions at that time.

**Current Precursor Technology**

In recent years, trials have been completed of early developments in vehicle communication technologies. Completed in 2014, the Drive C2X project tested V2I technology in order to increase safety, efficiency and comfort. This was implemented through in-vehicle signage in order to alert drivers regarding key features about the transport network. These messages included information relating to oncoming traffic incidents such as road works, traffic jams, emergencies, and most significantly, green-light optimised speed advisory information (GLOSA).

In theory, vehicle communication technology can provide the driver with information to encourage more efficient driving even without any automation. For example, when approaching a traffic intersection, the vehicle could communicate with the intersection’s infrastructure in order to determine how long before the light changes and therefore recommend a speed to approach that intersection. However, a driver may or may not choose to adjust their behaviour based on this information. As part of the Drive C2X Project, GLOSA aimed to test driver behaviour as a result of reduced stop times and acceleration in urban traffic, whilst also measuring any changes in energy consumption (Drive C2X 2014). In the trial, a traffic controller would send a message to a vehicle approaching a traffic intersection indicating how long before the light changed to allow traffic to pass. On receiving this message, in-built computers would then calculate and advise the driver of a recommended speed in order to travel through the intersection with minimal initial deceleration and later acceleration.

A trial of GLOSA was conducted between 2011 and 2014 and across 200 vehicles and 1.5 million miles travelled. The trial found that drivers reacted to the information by reducing their speed “in most cases” and that, in combination with an in-vehicle speed limit indicator, fuel consumption was reduced by 2.3 per cent (Drive C2X 2014). However, it is possible that greater gains could have been achieved through full automation of the vehicle as in the model tested, the driver may have chosen to ignore the advice provided by GLOSA.

Indeed, a fully autonomous vehicle may be programmed to choose the most energy efficient method to reach the destination without compromising travel time or the safety of the vehicle. Through vehicle communications, autonomous vehicles can adjust their behaviour in order to increase energy efficiency, without significantly affecting the transportation requirements of passengers. This technology also has the ability to reroute vehicles, which may lead to energy
efficiencies, however this will not be addressed in this dissertation. The following section will examine how automation and vehicle communication technology can lead to greater energy efficiencies at intersections.

### Improving Efficiencies of Intersections

As explained earlier, vehicle communication technology has the broad potential to deliver range of energy efficiency advantages in the existing transport map. Information pertaining to actual current traffic levels, common destinations and vehicle incidents, has the capacity to produce large energy efficiencies by harnessing this information, analysing relevant inter-connected data and sending commands to automated vehicles. Logically, this will in turn help to reduce congestion and improve efficiency, and of particular relevant to this dissertation, energy efficiency.

One specific area of existing road infrastructure that may deliver the greatest efficiencies, and thereby reduce congestion, is traffic-light intersections. Currently, intersections with traffic lights are either statically operated on a timer, or through a magnetic sensor detecting when a vehicle is stopped. The magnetic sensor in the road, although providing a guide to the light controller to change in particular timeframe, only provides a small efficiency gain through a reduced amount of idling; often the driver will be required to stop before the lights, to engage the sensor below. Minimising the amount of deceleration and acceleration when passing through an intersection will lead to improved energy efficiency. Recent studies have proposed a range of mechanisms to increase efficiency at intersections, with specific attention given to levels of driver automation and V2V and V2I communications. Although it may be difficult to eliminate all speed changes near intersections due to the variability in congestion and road availability, changes in speed can be minimised using AIM.

### Overview of Automated Intersection Management

Developed by the University of Texas, the AIM system works by co-ordinating digital messages between vehicles, and allocating space within the intersection for any given point in time. More specifically, the system improves the energy efficiency of vehicles at intersections by both reducing the amount acceleration required when travelling through an intersection, and, reducing the congestion by increasing the amount of traffic that can travel through an intersection over a period of time. Space is allocated on a first-come-first-served (FCFS) basis and any subsequent requests that impinge on space that has already been claimed must be moved to a later time, thereby allowing all vehicles to remain in motion. A command with the allotted time segment is sent back to the vehicle to carry out. The AIM system assumes that only vehicles that have been granted a time segment are allowed to enter the intersection, and this ensures that all vehicles going into the intersection are co-ordinated in order to ensure safe passage of all participants. Each car must send and receive its access request at a predetermined distance from the intersection before it is allowed to enter. In low-density intersections, the AIM system can also be configured to allow a small number of vehicles to manage progression through intersections.
without traffic lights using V2V communications (VanMiddlesworth, Dresner and Stone 2008). Figure 9 shows a vehicle passing through an intersection with its time segment allocation indicated by the grid.

Figure 9 – Vehicle passing through an intersection controlled by the AIM system

(University of Texas 2012)

Simulating the AIM system to measure energy efficiency

This dissertation will simulate AIM in order to examine the impacts of automation and vehicle communication technology on intersection management on energy efficiency. These simulations will attempt to measure how much energy is consumed when travelling through an intersection under timed traffic lights and using FCFS in order to conduct a comparative study. Through measuring the energy consumed over a simulated course, this dissertation can draw conclusions on how well FCFS can operate, as an example of how automation and vehicle communication technology can reduce energy consumption.

Method and Background

The University of Texas in Austin produced an open source application that is used to perform simulations of the AIM system. This dissertation presents findings of modifications to the University’s base-source code, which simulate the energy consumption of each vehicle passing through the intersection. Additional properties including mass, co-efficient of drag, cross-sectional area, rolling tire resistance, and transmission losses were added to the vehicle specifications in the original program. For each time iteration, Equation 6 (see Chapter 1) was applied to calculate the energy consumed for each 0.02 of a second, equating to 50 events per second per vehicle. Each time iteration was then stored and captured after the simulation was
completed. Each simulation recorded the first 500 vehicles to complete the course. For the purposes of this simulation, idling energy consumed not accounted for.

Table 2 lists variable values required in Equation 6. Table 3 lists variable vehicle properties (coefficient of drag and vehicle mass) in order to complete the calculation of the vehicle’s resistance. Simulations were run to compare three vehicles with different variable properties for comparative purposes.

Table 2 – Values used to measure energy consumption in the AIM simulator

<table>
<thead>
<tr>
<th>Environment Variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>Density of Air</td>
<td>1.2041 kg/m³</td>
</tr>
<tr>
<td>Road angle</td>
<td>0 deg. (flat road)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vehicle Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire Rolling Resistance</td>
<td>0.0065</td>
</tr>
<tr>
<td>Cross sectional area</td>
<td>2.23 m²</td>
</tr>
</tbody>
</table>

Table 3 – Values Toyota Prius, Subaru Forrester and Honda Civic used to calculate resistance

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Coefficient of drag</th>
<th>Coefficient of drag</th>
<th>Coefficient of drag</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003 Toyota Prius</td>
<td>0.26</td>
<td>1998 Subaru Forrester</td>
<td>0.405</td>
</tr>
<tr>
<td>Mass</td>
<td>1325 kg</td>
<td>1996 Honda Civic</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1415 kg</td>
<td>1050 kg</td>
</tr>
</tbody>
</table>

In order to perform the simulation, a 320 metre course was configured with one intersection with three lanes going in each direction (north, south, east and west). A graphic depiction of this simulation is shown in Figure 10.

Figure 10 – Depiction of vehicle course using the AIM simulator
Simulations were conducted under two scenarios: a FCFS intersection and a timed traffic light intersection. Under both scenarios, the simulator was run using different vehicle types, rates of congestion, and speed limits in order to compare the results. Table 4 lists the properties used in each scenario.

Table 4 – Parameters used in the AIM simulator in FCFS and traffic light scenarios

<table>
<thead>
<tr>
<th>FCFS Specific Parameters</th>
<th>Traffic Light Specific Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping distance before intersection 1m</td>
<td>Green light duration 30 seconds</td>
</tr>
<tr>
<td></td>
<td>Yellow light duration 5 seconds</td>
</tr>
</tbody>
</table>

The simulator was first run using a set of parameters to form a base case scenario. This included a set speed limit of 60 km/hour; a congestion rate of 500 vehicles per hour per lane; and used a Toyota Prius as the vehicle. Once established, the program was run against results from the first simulation using speed limits of 60km/hour and 80km/hour in each subsequent simulation to examine the effect of changing speed limits. These speed limits reflect a large portion of speed limits where traffic lights are currently in operation in urban environments in Australia.

Similarly, the congestion rates specified in Table 5 were used in all comparative simulations. The values used in these simulations were drawn from theoretical capacity rates of major urban road arteries in Sydney, which have congestion rates of between 1000 and 1300 vehicles per lane per hour (Roads and Maritime Service 2015).

Table 5 – Congestion rates used in the AIM simulations

<table>
<thead>
<tr>
<th>Congestion Value (vehicles/lane/hour or V/L/H)</th>
<th>Equates to one vehicle per lane every</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>18 seconds</td>
</tr>
<tr>
<td>500</td>
<td>7.2 seconds</td>
</tr>
<tr>
<td>1000</td>
<td>3.6 seconds</td>
</tr>
<tr>
<td>1500</td>
<td>2.4 seconds</td>
</tr>
<tr>
<td>2000</td>
<td>1.8 seconds</td>
</tr>
</tbody>
</table>

Limitations of the Simulation

The simulation is limited in predicting the wider energy efficiency potential, as the simulation conducted was over a single intersection in isolation of other traffic infrastructure. In order to simulate energy savings over a complete transportation network, a local network covering the size of a small town or city would need to be built into the simulator. The simulator is also limited by not including sensor-activated traffic lights. In practice, traffic lights are often timed differently depending on the time of day and the how traffic flows through the intersection in order to maximise flow. As previously discussed, idling has not been incorporated into the simulation. Idling will impact the fuel consumed in petroleum-fuelled cars however this will not be as apparent for electric vehicles as the engines do not turn over when the vehicle is idle (Sciarretta and Guzzella 2007). Similarly, regenerative breaking was not considered as part of this simulation.
As this method is a simulation, it is difficult to determine how different the driving patterns are of real drivers as opposed to simulated drivers. For example, the simulation does not take into account slowing the vehicle down without breaking – that is, allowing the car to come to a stop using road resistance. Driver behaviour is also difficult to simulate as drivers can accelerate or decelerate at different rates than what was simulated, which may have an impact on the overall outcome.

Results and Analysis

The results from the simulation broadly found that the FCFS intersection management strategy yielded a lower average energy consumption across the simulation: where the lower the rate of congestion, the greater the energy efficiency. As congestion rates approached approximately 1300 vehicles per lane per hour, traffic-jam-like scenarios were observed causing the FCFS model to consume a greater amount average energy. In addition to this, the average time that it took for a vehicle to pass through the intersection was also reduced. Although only a simulation, the FCFS model showed great potential energy savings for urban traffic management.

This section of the dissertation presents the results from the simulations described above. First, the base case results are presented, and then the results are compared using each of the variable properties (congestion levels, speed limits, and vehicle types).

Base Case Results

Running the simulation with a moderate traffic level (500 vehicles per lane per hour) showed that, on average, the energy consumed using the FCFS intersection was 60.8 per cent of that used by vehicles under the timed traffic light model. This result was determined based on an average of all three of vehicles (Toyota Prius, Subaru Forrester and Honda Civic).

Under the timed traffic light model, 91 (out 500) cars passed through the course without accelerating or decelerating compared to 96 under the FCFS model. However, the average time spent accelerating under the FCFS model was 2.27 seconds, with an average acceleration of 7.93 meters per second (m/s), compared to 7.25 seconds and an average acceleration of 25.35 m/s under timed traffic lights. This equates to just over three times the amount of average acceleration required to pass through the intersection using timed traffic lights.

These results indicate that although that most vehicles are changing speed in order to pass through the intersection safely, the amount at which vehicles slow down and speed up is significantly different. It is this amount of acceleration time and rate which has led to a substantial difference in the average energy consumed. Under low to moderate traffic conditions, these results show a substantial reduction in average energy consumed as a result of a corresponding reduction in the amount of acceleration required to pass through the intersection.

The energy reduction is also shown by the average speed across all vehicles to complete the two models. Figure 11 shows that all vehicles completed the FCFS model in substantially less time from when the vehicle first entered the intersection, indicating a greater average speed through the intersection. Under a FCFS intersection, Figure 11 shows that 90 per cent of vehicles
complete the model between 15 and 25 seconds after entering, also demonstrating that time savings can be made as part of this intersection management strategy.

The remaining 10 per cent of vehicles complete the FCFS model between 25 and 40 seconds from first entering the intersection. This slower rate is expected to be a result of vehicles that turn across the intersection (turning right under a left-side of the road rules, or left under a right-side of the road rules) requiring longer wait times in order to enter the intersection. Despite this, all vehicles completed the FCFS model in significantly less time when compared to the traffic light controlled intersection. Under the timed traffic lights, vehicles complete the model under a more uniformly spread completion pattern. As shown in Figure 11, 99 per cent of vehicles complete the model in 100 seconds.

**Figure 11 – Vehicle Completion Time over FCFS and Timed Traffic Lights**

(See Worksheet B in the Appendix spreadsheet for data)

The FCFS model maintained a higher average speed or velocity over time as a result of reduced deceleration and acceleration (Figure 12). Figure 12 also shows a substantial difference in the average velocity maintained in the different models. A greater average velocity indicates a reduced amount of deceleration and acceleration and therefore requires less energy to be consumed through a set distance. As shown in Figure 12, the FCFS model has a greater or equal average velocity after a given start time from entering the model in comparison to the timed traffic light model throughout the simulation.
Although not used as part of the energy consumption calculation, of note is the average time that each vehicle spent idling through the course. Under a FCFS model at 500 vehicles per lane per hour, the average time spent idling was just over half a second (0.58 seconds), compared to an average of 21.34 seconds under the timed traffic light model. This shows that the FCFS model also presents an energy saving potential due to a decrease in the amount of idling at an intersection, particularly for petroleum fueled vehicles.

Comparing Congestion Levels

Under lower levels of levels of congestion, namely 200 vehicles per lane per hour, the average energy saving across the FCFS course was greater than that at higher congestion levels. An average energy consumed was just over half (51.4 per cent average) that of the traffic light course. As anticipated, this result is primarily due to the amount of acceleration required under timed traffic lights, where a large portion of vehicles are required to significantly slow down or come to a complete stop. As discussed above, the amount of acceleration required was significantly smaller and therefore requiring less energy to complete the course on average.

When comparing the results across each levels of congestion, the results showed that the amount of energy consumed through an automatically managed intersection slowly increased as the congestion increased, even surpassing the energy consumed for timed traffic lights between a congestion of 1500 to 2000 vehicles per lane per hour. These figures are an average of all vehicle types simulated.
Figure 13 – Comparison of average energy consumption in congestion

As shown through Figure 13, the average amount of energy consumed under FCFS gradually increased until it reached and surpassed the traffic lights average at approximately 1500 vehicles per lane per hour. The gradual increase as traffic congestion under FCFS was observed and was due to the way in which traffic responds to high levels of congestion. Under heavy traffic, if there are no available spots for vehicles to enter into an intersection, all cars stop at the entry point to the intersection and await the time in which they can enter. If this occurs, many vehicles can sit behind the vehicles entering the intersection in a queue. Because vehicles enter into the intersection one by one, the vehicles behind creep forward one at a time in a similar way that traffic moves under a traffic jam. This creeping forward, means that instead of stopping for a period of time then moving forward through the intersection all at once as under traffic lights, that each vehicle accelerates for a very short period for each creep. Added up together, these forward creeps consume more energy overall than the acceleration required to complete the course under a timed traffic light. This is confirmed through the results by examining the average positive acceleration across each congestion level. As shown in Figure 14, the average total positive acceleration follows a similar pattern to the average energy consumed for both courses.

(See Worksheet D in the Appendix spreadsheet for data. See Worksheet I in the Appendix spreadsheet for the data for each individual vehicle configuration)
Average velocities across different congestions under a timed traffic light course is very similar in pattern. Under the FCFS intersection however, the average velocity over time is vastly different. The average velocities are largely lower due to the amount of congestion and the time spent waiting in a queue to enter the intersection as previously discussed. As a consequence, the time spent in the intersection is actually longer when compared to a traffic light model and has a lower average speed across the entire course.
Figure 15 – Comparison of average velocity over time in congestion

![Graph showing average velocity over time](image)

*See Worksheet F in the Appendix spreadsheet for data*

Although not an energy consumer under this simulation, the amount of time spent idling will impact the overall fuel consumed under real conditions, particularly for petroleum fuelled vehicles. The amount of time spent stationary (idling) under a FCFS intersection is minimal at very low congestion rates. Under the timed traffic lights however, the amount of time spent idling is fairly constant, and only slightly increases as the congestion increases. At high congestion rates, despite the increased fuel consumption that occurs under an FCFS intersection, the amount of time spent idling is still lower. This is due to the traffic constantly slowly entering the intersection and causing the car to creep forward a vehicle length in order to move towards the intersection as discussed above.
When examining the different rates of congestion, the amount of energy saved as an average is significant at congestion rates comparable to Sydney’s major road arteries (13.3 per cent reduction in energy usage at theoretical capacity congestion rates of 1000 vehicles per lane per hour) and greater savings at lower rates of congestion. This in combination with the potential time savings via this mechanism, make FCFS a potential large energy reduction mechanism across an urban centre.

**Comparing Speed Limits**

Simulations were run across different speed limits, using a constant figure of 500 vehicles per lane per hour, to determine if this would also have had implications for energy consumption. As shown in Figure 17, the speed limits shown had a linear relationship between the energy consumed under both traffic lights and FCFS. For the purposes of this dissertation, the energy consumption saving potential does not appear to be significantly affected by adjusting the speed limit of the course.
Figure 17 – Comparison of average energy consumption under different speed limits

(See Worksheet H in the Appendix spreadsheet for data)

Comparing Vehicles

Comparing the different vehicles, the fluctuation between ratios of energy consumption between was minor ranging from a minimum 59.6 per cent (Toyota Prius) to a maximum 62.6 per cent (Honda Civic). This represents a significant energy saving across all three vehicle types despite idling not factoring into the energy consumption formula.

The simulation was re-run with a number of different vehicle configurations in order to contrast the results at 60km/hr and a congestion rate 500 vehicles per lane per hour (see Table 2 and Table 3 for the input parameters used). The vehicles mass and co-efficient of drag were adjusted in order to simulate different vehicle travelling through the course and their relative average energy consumption.
Figures 18, 19 and 20 – Comparison of average energy consumption for different vehicle configurations

Due to its low mass and relatively streamlined coefficient of drag, the Honda Civic consumes considerably less energy on average compared with the other two vehicles. As expected, the Subaru Forrester consumes the greatest of the three vehicles due to its mass and poor drag properties. Despite this, both the Forrester and the Prius show similar ratios and energy savings for each level of congestion. The Civic, however, has a lower congestion level at which the amount of average energy consumed becomes greater for FCFS than that of traffic lights.

**Conclusion: Using AIM to Maximise Efficiency**

Under AIM, urban traffic systems can utilise different approaches in order to maximise efficiency of the transportation sector. The FCFS implementation of AIM has shown that in low and medium levels of congestion, an average energy saving can be achieved when compared to timed traffic lights. A key advantage of the AIM system infrastructure, as a technological implementation, is...
that the system can be adapted to best meet the needs of the transportation network. The system developed by the University of Texas has the primary function of safely allowing vehicles to pass through an intersection safely and unhindered. As such, it can adapt its implementation under certain environmental or traffic conditions in order to maximise efficiency. For example, the AIM system could be programmed to implement a FCFS intersection mode during times of lower congestion, and switch to a timed traffic light style implementation after a certain traffic threshold is reached where it is known to save energy. This flexibility also allows for improvements to, or new implementations of the system, in order to meet different outcomes without additional burden of upgrading infrastructure as needs arise. As previously discussed, this outcome has been developed in order to work through V2V communications without the need for an installed intersection controller. The AIM methodology has demonstrated the ability to assist energy reduction through reducing congestion and idling at traffic light intersections. This is a prime example of automation and vehicle communications used together in order to make transport systems more energy efficient. The following Chapter discusses how these technologies may influence consumer behaviour and presents a model of shared transport which adapts to these behavioural changes.
CHAPTER THREE – Vehicle Automation, Behavioural Change and Efficiency

Complete vehicle automation (no human involvement), allows the public to consume transportation in fundamentally different ways. This decoupling – human decision making from driving – frees up transportation systems to provide travel services without the cost burden of a driver. Convenience and cost have been the two major contributors to increasing private ownership of vehicles – a model that is dominant through a large part of western society (Dargay, 2001). Privately owned vehicles are typically utilised less than 10 per cent of the time, and consequently spend the majority of time parked (Rac Foundation, 2012). The introduction of autonomous vehicles enables vehicles to be utilised when they otherwise would be parked, as the vehicle no longer needs a driver to provide transport. An increased potential utilisation rate, as well the removal of a driver to provide transport services, reduces the cost of private vehicle ownership. As a result, it has been theorised that private ownership will gradually diminish and be supplemented by a ‘shared autonomous vehicle’ (SAV) model (Rigole, 2014). A SAV model describes vehicles that are shared in a subscriber-network, and allow consumers to maintain convenience while reducing cost burden of private transportation hire, such as taxis. In the presentation of the SAV model, this dissertation examines four case studies which examine the effects on consumers when the private vehicle ownership is removed replaced by a shared system. The studies demonstrate that this model presents energy efficiency opportunities through reduced congestion, a significantly younger fleet, and a transportation system that more is adaptive to demand. This model produces greater energy efficiencies in areas with high population densities thereby capturing a large portion of the transportation sector (Rigole, 2014).

This chapter reviews case studies that have simulated the SAV model and examines how this model could lead to energy efficiencies. As a result of the introduction to the SAV model, this dissertation explores how a greater utilisation transport services can be enacted, congestion could be reduced and a younger fleet could drive efficiencies when compared to our current model.

The SAV Model

Historically, private car ownership has been propelled by reasons of convenience, cost and availability of on-demand transportation when required (Dargay, 2001). Due to the nature of these requirements, in the majority of cases public transport and taxi services are less convenient and less cost effective meet these demands. As a result, vehicles are more frequently owned privately, yet are utilised far less frequently in comparison to those other modes of transport when considering the ratio of hours parked to driving. Estimates have shown that privately-owned vehicles can be parked between 90 to 95 per cent of their life span (Rac Foundation, 2012). The cost of this utilisation rate is placed on the car owner in the form of taxation
(registration), environmental wear and tear on the vehicle, as well as the lower potential efficiency through using an older car (efficiency gains through improved technology). In Australia for example, the average age of a privately-owned vehicle is 10 years (Australian Bureau of Statistics, 2014), indicating a potential energy efficiency could be gained from updating Australia’s national vehicle fleet.

The SAV transport model helps to address the convenience, cost and efficiency problems faced with current transportation systems (Rigole, 2014). A SAV model works through a fleet of vehicles operating through the road network of a metropolitan area. When a consumer requires transportation between two places, they can summon a vehicle through a device (such as a smartphone application), either at the time when transport is required, or scheduled ahead of time. The system will then calculate which vehicle to assign to the customer, and send a vehicle that is either already enroute or idle. The assignment will be based on the vehicles current location, the customer’s location and destination, as well as the current vehicles intended route. The system will make this assignment automatically without any human intervention, and will factor in the efficiency of travel for both the customers in terms of time and energy required for the vehicle. This is illustrated in Figure 21 and 22.

Figure 21 – A potential trip itinerary using a SAV model
Figures 21 and 22 demonstrate examples in which a shared autonomous system can determine routes based off the current demands of consumers. Figure 21 illustrates a scenario where passengers are travelling to and from similar geographic areas (as depicted by the coloured circles labelled A and B) at a similar point in time. Figure 22 demonstrates a more complex shared-transport network, where all passengers are located in the same geographic location (circle A), but passengers 1 and 2 want to go to destination B, and passenger 3 wants to go to destination D. This requires the system to make a decision based on the relative travel times and each final destination for each passenger. The trip times of Itinerary A→D→B will be compared with A→B→D, coupled with the travel expectations of each of the passengers in order to make a decision about which route to take. After the route has been completed, the SAV system will either assign a vehicle to go to an alternate location to start another itinerary, or move to a location where it can be idle, awaiting further instructions.

The SAV model provides a service that is point-to-point and on demand (maintaining the convenience of the private car), cost efficient (similar to the public transport sector), as well as being more energy efficient by transporting more consumers across similar journeys (Rigole, 2014). Collectively, these factors increase the incentive to adopt this model over the current status quo of private car ownership. Four case studies have been examined in order to compare how SAV models can be implemented in different cities and how that affects the energy consumption of the transportation within those networks.

Case Studies

The shared autonomous model has been simulated in four jurisdictions to date; namely in Singapore (Spieser et al., 2014), Austin (Fagnant, Kockelman and Bansal, 2015), Ann-Arbour (The Earth Institute, 2013) and Stockholm (Rigole, 2014). Each study indicates that using this model will dramatically reduce the vehicle fleet required to transport the inhabitants and therefore reducing
the amount of congestion experienced in each context (Rigole, 2014). The sizing of the fleet, demonstrated through the simulations in each of the studies is based on a number of different parameters. These parameters are primarily driven based on customer expectation in terms customer wait times (i.e. vehicle availability) being below a certain threshold (Rigole, 2014), and all trips being within a certain ‘geo-fence’ (Fagnant, Kockelman and Bansal, 2015). This geo-fence allows all trips to be contained within a certain area. Although this will not satisfy all consumers transportation needs, it will be able to meet a majority. The Austin simulation approximated that 84% of consumer trips that began in the geo-fenced area, also finished within the same area (Fagnant, Kockelman and Bansal, 2015). In the case of the Stockholm simulation, factors such as the ratio of the trip duration to the unoccupied duration is also considered (Rigole, 2014).

The degree to which fleet sizes, congestion and consequently environmental impacts vary in the results of the simulation is dependent on a number of factors relating to the city such as land area, population density, currently level of transportation infrastructure (both public and private), and usage requirements (Fagnant, Kockelman and Bansal, 2015) in addition to the parameters discussed above. Although not discussed directly, a reduction in greenhouse gas emissions through these studies is assumed to be equivalent to a fuel reduction as result of the measures proposed.

In order to facilitate the system to increase the transportation efficiency, vehicles must be able to drop off multiple passengers within a single trip. Extra passengers being picked up and dropped off from different locations will increase the trip duration as well as adding extra distance to the trip based on each destination. As discussed in Rigole, different results can be drawn by altering the maximum allowable trip duration ratio as part of each individual trip. User’s expectations of what is an acceptable level will vary widely. As with current transportation models (i.e. private car vs public transportation), user preferences dictate the choice based on cost, timeliness and convenience factors (Dargay, 2001). The advantage with the shared autonomous vehicle model is that given its flexibility, it allows for some of these factors to be modified with cost in order to meet the varying demands of clientele (for example a consumer could choose to pay more for a service with lower wait times, and reduced duration for a greater cost). The results are summarised in Table 6.
Each model uses different data-sources to collate their results, however in all cases, a shared autonomous vehicle model greatly reduces the fleet size of the vehicles required in order to ‘mobilize’ the population base. The Singapore model does not consider ride-sharing as a part of its mode.

Of the studies, only two reference direct environmental impacts or efficiency improvements as a result of their work. The Austin model presented an approximate 14% reduction in energy use (Fagnant, Kockelman and Bansal, 2015), and 11% in the Stockholm model (Rigole, 2014). Beyond these studies, Fagnant & Kockelman presented an alternative study using US travel statistics to simulate the environmental impacts of SAV’s. This equated to an approximated a 5.6%, using a non-ride sharing model and 12% reduction in energy use using a ride sharing model (Fagnant and Kockelman, 2014). The reasons provided for this reduction was predominantly due to a reduction in cold starts, and replacement on the high energy consuming SUV with a smaller more efficient sedan, in addition to the reduction in required parking infrastructure (Fagnant and Kockelman, 2014). The Austin model applied the same model as Fagnant & Kockelman in determining their environmental and energy use impacts (Fagnant, Kockelman and Bansal, 2015). These factor in the increased distance required to travel in between carrying passengers, decreasing the systems overall efficiency.

All studies conclude that a shared autonomous vehicle model will reduce the size of the fleet required to service the population. The studies that incorporate ride sharing suggest that this will also lead to a decrease in congestion, particularly during peak periods (Rigole, 2014). The balance between congestion and energy efficiency is complex. However, congestion in some areas have caused serious problems due to a lack of infrastructure and the volume of cars entering a particular area. This was particularly true of London, which introduced a congestion charge in response to persistent congestion problems in 1998, when it was found that London drivers were stationary 30% of the time during peak periods (Leape, 2006). Recent surveys by the RACQ in Queensland, found that fuel consumption increased by approximately 30% when travelling in congested conditions compared to daytime traffic (RACQ, 2008). Further to this, travel duration
increased by 85% inbound and 38% outbound compared to daytime traffic conditions (RACQ, 2008). The Stockholm case study approximated a 22% reduction in congestion due compared to the baseline (Rigole, 2014). Unfortunately, these numbers are not comparable due to the wide variety of variables when calculating fuel efficiency as a function of number of cars on the road at any given point in time. However, they do show that the shared autonomous vehicle model will reduce congestion and therefore provide energy efficiencies if adopted.

Despite having efficiency gains, the shared autonomous model also contains efficiency losses due to increased distance travelled whilst empty (Rigole, 2014). As described in the various case studies, an autonomous vehicle system is required to travel to its next intended pickup point whilst empty. At the end of each day this could be to a depot during periods of low demand. The amount of empty travel required in order to service the population is dependent on a number of factors such as fleet size, and service area of the system. The Stockholm study estimated an approximate 19% of additional travel would be required as part of its service model (Rigole, 2014). Despite this, the system still reported an approximate efficiency dividend of 11% as a result of the systems implementation (Rigole, 2014). This feature is necessary in order to fulfil the requirements of the transportation system, and shows an area where energy is required to be accounted for in the design of the overall system.

The Singapore, Austin, Ann-Arbour and Stockholm SAV studies however, do not go into the de-congestion benefits of an adaptive transportation model, as they only compare private motor cars of a similar size, and therefore do not encapsulate the potential of efficiency as a result of reduced congestion.

Demand Adaptive Travel

Current public transportation and private car ownership models are not responsive to demand. Public transport systems are generally timetabled months in advance for commuters to plan trips accordingly ahead of time. However, this leads to buses or trains running according to the timetable regardless of the demand imposed on the system, causing congestion during peak periods, and near empty vehicles during the middle of the night. Similarly, with private car ownership, during peak periods, congestion causing delays and inefficiencies often occurs in metropolitan areas.

By extrapolating the SAV model, knowing in advance what the likely demand of the system will be, even by a few hours, can allow the transport system to adapt to the demand. For example, knowing in advance approximately how many passengers will travel between two places, allows the network to send the most appropriate vehicle to accommodate that need. This change could dictate that sending a 12 seater vehicle as opposed to a 5 seater vehicle. By sending the most efficient vehicle for the need allows for the transportation system to make energy efficiency savings by reducing the amount of fuel needed to transport the same amount of passengers. Further, by applying this logic the amount of congestion on the roads will also be reduced and consequently reduce efficiency losses due to congestion based delays.
Further Efficiency Implications

When examining a private ownership model of transportation, consumers often choose a vehicle in order to account for all desired requirements over time (Dargay, 2001), leading to a decrease in transportation efficiency. Over the past several years, the popularity of larger cars such as SUVs has increased despite their lower fuel efficiency (Dowling, 2015). This is largely due to a consumer’s desire to fulfil all tasks with one vehicle, regardless of the frequency of the task. For example, families may from time to time require a vehicle with enough power to tow a trailer for short periods. This allows the consumer to have the convenience of being able to perform occasional functions at any period of time. However, in order to meet this convenience, the efficiency of the transportation for commuting (a more common task) is compromised (EPA, 2008). A shared autonomous vehicle model, due to its nature, allows consumers to summon different vehicles on demand in order to meet any requirement. If the vehicle that is selected is fit for purpose, efficiency can be optimised by the system. Taking transport away from an ownership model allows energy efficiencies to be achieved through vehicle selection that is fit for purpose as much as possible as part of a shared autonomous model.

Due to an increase in the amount of distance travelled by each vehicle in a given calendar year, energy efficiencies through technological advancements are likely to come to market sooner. Regulation exists in many countries standardising the energy efficiency requirements of vehicles, and these demands are increasing over time as technology advances (Ó Gallachóir et al., 2009). Policy instruments, such as increasing car ownership costs as the cars age, are designed to encourage efficiencies coming to market (Fullerton and Gan, 2005). Through automation, and a reduction in fleet sizes as shown by the case studies examining SAV models in Singapore, Austin, Ann-Arbour and Stockholm, dictates that the amount of distance travelled by each vehicle will dramatically increase. Rigole assumes that the average lifecycle should be comparable to taxis as they are operated in a similar fashion (Rigole, 2014). Taxis in this instance have an approximate mileage of 65,000km per year and an average lifespan of 5 years (Rigole, 2014). This is in contrast to the private vehicle which the Environmental Protection Agency estimates has an average usage of approximately 15,000 miles per year (24,140 km) (EPA, 2008). In Sweden the average distance travelled per year is approximately 12,000km (Rigole, 2014). Rather than having an aging fleet of vehicles on the road, a shared autonomous vehicle model has the potential to offer a more up-to-date (and therefore more efficient) fleet of vehicles, with a shorter replacement time, servicing the transportation market. Further, a move away from individual private ownership to corporate ownership increases the incentive of increasing energy efficiencies through economies of scale. If transport companies under a SAV model can continue to provide efficiencies, it will also increase the ability of those providers to compete and to remain competitive. Although the factors of efficiency are difficult to quantify, this service model has potential to bring efficiencies through technological advancements to market sooner, as well as a profitability incentive to drive change.

The shared autonomous model provides energy efficiency opportunities by reducing the number of vehicles required to travel between two locations, while still providing a convenient mode of transportation for consumers. In turn, this also results in a reduction in road congestion, leading
to less greenhouse gas emissions. The SAV model outlined above provides reasoning for why behavioural change is likely to occur and as a result of this change, describes disruption of the private car ownership norm that has been prevalent in western society until this point. Although it is difficult to predict when autonomous vehicles will be adopted, a change to the transportation industry is highly likely resulting in a further increase in energy efficiency through younger fleets, adaptive transportation, and reduced congestion.
Conclusion

The amount of energy that the transportation currently consumes is vast, as a result presents great opportunities for energy efficiencies in order to reduce greenhouse gas emissions. The introduction of autonomous vehicles in the near future presents opportunities in order to facilitate these efficiencies. This dissertation has examined some of these opportunities through implementing platooning during highway driving, investigating alternative intersection management strategies and analysing how society could consume transport services differently as a result of autonomous vehicles. All of these mechanisms provide potentials for greater energy efficiency to varying degrees on an individual trip as well as to the whole transportation network.

Firstly, in Chapter One, this dissertation examined how platooning could reduce energy consumption through a reduction in aerodynamic drag. As a result, using highway conditions fuel reductions of approximately 25 per cent could be achieved with four or more vehicle platoons at a spacing 0.3 vehicle lengths (Zabat et al. 1995). The research showed that although that the benefit obtained via platooning in urban environments was less than in highway driving, it was nonetheless significant (Zabat et al. 1995). Although driver-controlled platooning has already been demonstrated in a number of scenarios, it has been considered unsafe to do so on public roads in light of human reaction times to unexpected events. However, automation and vehicle communication technologies eliminate the driver and the safety-mandated distance between vehicles due to human reaction time. With quicker reaction times, these technologies may safely allow vehicles to drive in platoons, therefore delivering the efficiency benefits from this driving strategy.

Secondly, this dissertation showed that through AIM simulations, emerging vehicle communication technologies enable more efficient management of traffic at intersections. Results of a simulated intersection that utilised a FCFS model showed that, on average, energy consumption was reduced when compared to timed traffic light intersections. Only at high congestion rates (approximately 1300 vehicles per lane per hour), did FCFS consume more energy in comparison to timed traffic light intersections. Further, as a result of increasing the average velocity of vehicles travelling through the intersection, the amount of traffic flowing through the traffic network also increased, which consequently would lead to a reduction in congestion. When coupled with the benefits of an average reduction in energy consumption across the individual intersection, AIM shows that there is potential for improved energy efficiency. However, to quantify these reductions would be speculation as a key limitation of the simulations was its small sample size of an overall trip taken. In order to provide greater insight into the energy efficiency potential of this technology, a more detailed simulation would need to be conducted with a larger course (representing a small town or city). The simulations conducted in this dissertation nonetheless provide a valuable starting point in recognising the energy efficiency benefits of AIM as part of the introduction of autonomous vehicles in timed-traffic lights settings that are widespread across urban environments throughout the world.
Thirdly, the dissertation argued that how society interacts with transportation systems as a result of the introduction of autonomous vehicles could greatly impact the efficiency of the overall transport network. Analysing existing research, this dissertation compared different studies that simulated SAV models of transportation as a replacement for the current, and dominant, private-ownership model. Two of the four studies predicted a reduction in energy consumption, while the others did not specify a reduction directly (Spieser et al. 2014; Fagnant, Kockelman and Bansal 2015; The Earth Institute 2013; Rigole 2014). All studies however showed that SAV may lead to a reduction in the number of vehicles required to service the population (Spieser et al. 2014; Fagnant, Kockelman and Bansal 2015; The Earth Institute 2013; Rigole 2014). The SAV model may also deliver a number of additional efficiency benefits such as the transport system adapting to demand, a younger fleet of vehicles on the road as well as a greater utilisation of available seats during peak periods. All of these factors have the potential to increase energy efficiency of transportation systems, particularly in urban environments.

The dissertation met the research objectives of bringing together previous research and apply them to the introduction of autonomous vehicles. This was demonstrated through Chapter One, applying research into the effects of aerodynamic drag and how it will increase energy efficiency as autonomous vehicles become able to travel closer together through whilst maintaining safe driving. This was also demonstrated through the simulations conducted into adopting an AIM system in managing intersections in order to improve efficiency in Chapter Two. Chapter Three analysed how the evolving technology would impact societies consumption of transport, meeting its research objectives. Although each chapter addressed the objectives set, the ability to quantify energy efficiency reductions was limited due to simulation constraints and limited detail into the final implementation of the technology.

The research conducted for this dissertation highlighted three key areas where energy efficiencies could be achieved as a result of the introduction of autonomous vehicles and vehicle communication. In order to conduct more detailed analysis on the efficiency opportunities presented, further research would be required to look into areas such as road space utilisation, automated parking, and automated traffic routing. Further, a more comprehensive simulation model would be required in order to provide more accurate energy efficiency implications as a result of implementing AIM.

Given the nature of technology and how society responds to it, it is impossible to quantify the total energy efficiency implications of autonomous vehicles and vehicle communication technology. However, it can be said that automation provides great scope for efficiencies to be made using a variety of different techniques. Transportation sectors across the western world consume significant amounts of energy, as well as being a large source of pollution. Automation and vehicle communication technologies presents opportunities to improve efficiency and ultimately the environmental impact of these systems.
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Appendices

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