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SMART STREETLIGHTS:

A FEASIBILITY STUDY

Thesis submitted by
Karl Andrew Mohring
BEng (EE)/BIT, James Cook University

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in the School of Information Technology
James Cook University

Supervisors:
Associate Professor Trina Myers
Professor Ian Atkinson

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Nature of Assistance	**Contribution**	**Names and Affiliations of Co-Contributors**
Intellectual Support	Editorial assistance	Dr. Trina Myers Professor Ian Atkinson Sam Gillespie Steven Vandervalk Dr. Mangalam Sankupellay
	Statistical support	Dr. Anne Swinbourne Sam Gillespie Caleb MacDonald
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	Access to Reid Park raceway for controlled traffic testing	Townsville City Council Mark Robinson Dylan Furnell Karin Wunsch

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List of Publications

Chapter	**Details of publication on which chapter is based**	**Nature and extent of the intellectual input of each author**
4	Sensors in heat: A pilot study for high resolution urban sensing in an integrated streetlight platform IEEE International Conference on Intelligent Sensors, Sensor Networks and Information Processing Presented in April 2015 [3]	Mohring, Myers, Atkinson, Vanderwal, and Vandervalk I developed and constructed the hardware systems used in the urban sensor trial, performed the analysis, and wrote the chapter. Dr. Trina Myers and Professor Ian Atkinson assisted in interpreting the results and editing. Professor Ian Atkinson, Dr. Jeremy Vanderwal and Steven Vandervalk assisted in designing the study.
5	*Playing in Traffic: An Investigation of Low-cost, Non-invasive Traffic Sensors for Streetlight Luminaire Deployments* Journal of Grid and Utility Computing Published in 2018 [2]	Mohring, Myers, and Atkinson I developed and constructed the hardware systems used in the traffic trials, performed the analysis, and wrote the chapter. Dr. Trina Myers and Professor Ian Atkinson assisted in designing the tests, interpreting the results and editing.
6	*A controlled trial of commodity sensors for a streetlight-mounted traffic detection system* Australasian Computer Science Week Multi-conference Presented in January 2018 [1]	Mohring, Myers, and Atkinson I performed testing with the developed hardware systems in the traffic trials, performed the analysis, and wrote the chapter. Dr. Trina Myers and Professor Ian Atkinson assisted in designing the tests, interpreting the results and editing.
7	*Financial valuation of a smart streetlight traffic detection system* Journal of Technological Forecasting and Social Change To be submitted to the journal in January 2019	Mohring, Myers, and Atkinson I designed and programmed the simulation tools used in the evaluation and wrote the chapter. Dr. Trina Myers and Professor Ian Atkinson assisted in interpreting the results and editing.

8	*Public acceptance of a smart streetlight sensor network* IEEE Conference on Smart City To be submitted to the conference in January 2019	Mohring, Myers, Atkinson, and Swinbourne I designed the survey, performed the analysis, and wrote the chapter. Dr. Trina Myers and Professor Ian Atkinson assisted in survey design and editing. Dr. Anne Swinbourne assisted in the survey design an analysis of results.

Abstract

The world's cities are growing. The effects of population growth and urbanisation mean that more people are living in cities than ever before, a trend set to continue. This urbanisation poses problems for the future. With a growing population comes more strain on local resources, increased traffic and congestion, and environmental decline, including more pollution, loss of green spaces, and the formation of urban heat islands. Thankfully, many of these stressors can be alleviated with better management and procedures, particularly in the context of road infrastructure. For example, with better traffic data, signalling can be smoothed to reduce congestion, parking can be made easier, and streetlights can be dimmed in real time to match real-world road usage. However, obtaining this information on a city-wide scale is prohibitively expensive due to the high costs of labour and materials associated with installing sensor hardware. This study investigated the viability of a streetlight-integrated sensor system to affordably obtain traffic and environmental information. This investigation was conducted in two stages: 1) the development of a hardware prototype, and 2) evaluation of an evolved prototype system.

In Stage 1 of the study, the development of the prototype sensor system was conducted over three design iterations. These iterations involved, in iteration 1, the live deployment of the prototype system in an urban setting to select and evaluate sensors for environmental monitoring, and in iterations 2 and 3, deployments on roads with live and controlled traffic to develop and test sensors for remote traffic detection. In the final iteration, which involved controlled passes of over 600 vehicle, 600 pedestrian, and 400 cyclist passes, the developed system that comprised passive-infrared motion detectors, lidar, and thermal sensors, could detect and count traffic from a streetlight-integrated configuration with 99%, 84%, and 70% accuracy, respectively. With the finalised sensor system design, Stage 1 showed that traffic and environmental sensing from a streetlight-integrated configuration was feasible and effective using on-board processing with commercially available and inexpensive components.

In Stage 2, financial and social assessments of the developed sensor system were conducted to evaluate its viability and value in a community. An evaluation tool for

simulating streetlight installations was created to measure the effects of implementing the smart streetlight system. The evaluation showed that the on-demand traffic-adaptive dimming enabled by the smart streetlight system was able to reduce the electrical and maintenance costs of lighting installations. As a result, a 'smart' LED streetlight system was shown to outperform conventional always-on streetlight configurations in terms of financial value within a period of five to 12 years, depending on the installation's local traffic characteristics. A survey regarding the public acceptance of smart streetlight systems was also conducted and assessed the factors that influenced support of its applications. In particular, the Australia-wide survey investigated applications around road traffic improvement, streetlight dimming, and walkability, and quantified participants' support through willingness-to-pay assessments to enable each application. Community support of smart road applications was generally found to be positive and welcomed, especially in areas with a high dependence on personal road transport, and from participants adversely affected by spill light in their homes.

Overall, the findings of this study indicate that our cities, and roads in particular, can and should be made smarter. The technology currently exists and is becoming more affordable to allow communities of all sizes to implement smart streetlight systems for the betterment of city services, resource management, and civilian health and wellbeing. The sooner that these technologies are embraced, the sooner they can be adapted to the specific needs of the community and environment for a more sustainable and innovative future.

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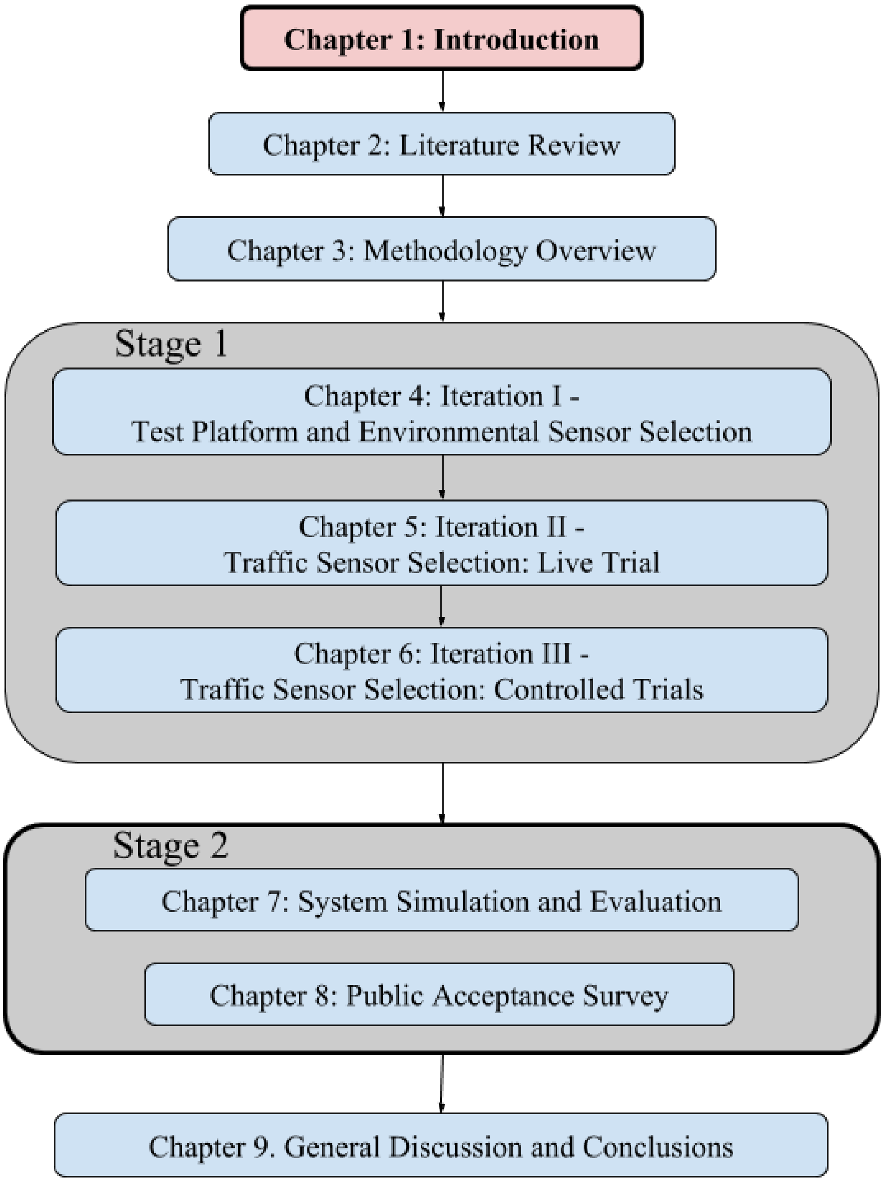
Chapter 1 - Introduction



The world’s cities are growing. As stated by the United Nations in a 2016 report, over half of the global population live in urban centres, with over 23% of people living in cities with over one million residents [4]. This proportion is only expected to climb in the future with the current trends of population growth and increased urbanisation. If nothing else, the current trends show one thing: the future of humanity is in cities [5-7].

This increase in urbanisation poses problems for the future. Local resources such as water and electrical supply are put under an increased amount of strain [8]. Atmospheric pollution increases as industrial activity expands and traffic congestion builds [9], which decreases the effectiveness of the road network [10-12]. The heightened need for housing causes urban development to push the city fringes further into rural areas. This expansion can cause a reduction of green spaces, which is associated with an increase in mental health problems, loss of social cohesion, and the formation of urban heat islands [13, 14]. The high density of living in cities can also result in a loss of quiet areas, which can cause sleep problems and lower living standards [15, 16]. In response to these difficulties, the current paradigm is a push for cities to adopt more sustainable urban practices and initiatives to maintain and improve the quality of living for its citizens [17, 18].

1.1 SMART CITIES AND THE INTERNET OF THINGS

Smart city initiatives, though debated in exact definition, are those that apply technological solutions to improve urban living and sustainability [17, 19-22]. This definition is broad, but generally these improvements seek to make better use of city resources, improve quality of living and comfort, and/or improve the social capital, cohesion, and education of citizens [17, 23-27]. For example, smart electricity grids can implement practices such as using renewable energy generation for a more sustainable network and monitoring demand to efficiently distribute power and quickly respond to any faults or changes [28, 29]. Similarly, educating citizens in energy-efficient technologies and practises, combined with real-time household metering to bring usage habits to the foreground, empowers citizens to make the right choices in cutting waste and adjusting their usage to save money. The same practices can apply to other utilities such as water [30]. Neirotti et al. classified smart city applications into six primary domains, which are listed and described in Table 1.1 [19]. The applications in each of these domains interact with cities and their citizens in different ways, but they all have one thing in common: they need data.

Table 1.1 - Classification of smart city application domains

Application Domain	Description[1]
Natural resources and energy	The development and practice of more efficient and sustainable production and use of resources like power, water, and food. This domain includes how resources are spent on public services such as transport and lighting.
Transport and mobility	Improving how people, vehicles, and goods move about the city. Sustainable use of public transport and efficient road networks are included in this category.
Buildings	This domain focuses on improving comfort, management, and quality of housing and offices.
Living	Improving how information and public services are delivered to citizens and visitors, including healthcare, safety, air quality, entertainment, etc. Management of public spaces, social and cultural welfare, and social cohesion also come under this domain.
Government	Transparent and inclusive administration of public services and decision processes.
Economy and people	Nurturing local innovation and talent through incubators, education, and opportunities. This domain also seeks to attract and retain human capital.

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[1] Descriptions of application domains are aggregated and adapted from original descriptions of sub-domains by Neirotti et al. [19].

Many smart city applications can use Internet of Things (IoT) technologies to obtain the data they require [31, 32]. Like smart cities, IoT has many definitions. In the context of this study, IoT is described as an interconnected web of heterogeneous, everyday objects that can communicate with one another and other systems by using communications technologies and often embedded computing [25, 27, 33-35]. This kind of connectivity allows objects to be monitored remotely and/or controlled to interact with their environment, and can enable other automated services, all of which have far-reaching implications for smart cities. For example, homes and offices can be equipped with sensors that monitor the interior and exterior conditions and relay that information to appliances and services such as heating, ventilation, air conditioning (HVAC) and lighting [34]. These systems can interact with other without the need for human input or intervention. External weather conditions can inform whether natural cooling can be used instead of air conditioning to save electrical costs without sacrificing human comfort [36]. Likewise, occupancy information can inform which lights should be switched on or off according to real-time needs to reduce wasted electricity, and indoor air quality monitoring can alert occupants of any health risks posed by pollutants [37, 38].

This study investigates the use of IoT concepts for smart roads. Road-centric approaches to improving city liveability and function have two distinct advantages. Firstly, roads and transport are vital to any city of any size and used by everyone within for commuting, transportation of goods, etc. Any initiatives and improvements that affect roads have the potential to positively impact a large proportion of citizens, businesses and government organisations. Similarly, roads are everywhere within cities; next to homes, businesses, industrial areas, tourist destinations, city centres, hospitals, utilities, etc. As roads involve all types of people and groups, they can also impact all kinds of geographic/demographic areas within cities. Secondly, the advantage of this road-centric approach is that there are many smart city applications around roads, covering multiple domains, that can be improved if additional information were readily available and in real time.

One of the primary areas that can be improved about roads is their traffic. Congestion and idle times can be reduced by smoothing out traffic signalling to improve flow, cut idle emissions and time at intersections, and reduce frustration and stopping frequency of road users [39-43]. Aside from mobility, the process of parking can be greatly simplified if drivers could readily know where empty parks could be found instead of the time and frustration involved in searching, especially within city centres and other crowded areas or during busy periods [44-46].

Public lighting is another area that could be made more sustainable with real-time information. The problem with the current paradigm of public lighting is that lamps on roads and footpaths are typically run on an always-on basis, which wastes light and electricity when no one is active in the lighting area. This waste is alarming, as an estimated 19% of global energy generation is used to power artificial lighting [47]. Aside from the waste that excessive light causes at night, it can also cause health and sleep disorders and negatively impact the environment and its fauna through light pollution and by obscuring the night sky [48-50]. However, despite these detriments, public lighting provides a vital service in allowing safe moment at night and deterring criminal activity and cannot simply be switched off without compromising safety [51, 52]. But with real-time information on local traffic, lighting technologies such as LED can be dimmed down in accordance with actual activity levels on roads and paths [53-58]. Not only would this decrease the financial burden that lighting places on the community, adaptively dimming public lighting could also mitigate the associated negative and environment affects without affecting road safety or user experience.

Environmental monitoring on roads can also have benefits for both short and long-term applications. In the short-term, climate information can assist in tracking the formation of urban heat islands [59] and informing citizens which areas are comfortable for outdoor activity. Like the smart home example, pollutants, greenhouse gases, and pollen could also be observed remotely to protect citizen health [27, 60-62]. Environmental factors such as flooding can also be tracked in emergency situations to assist civil defence efforts and safeguard citizens [33, 63]. In the long-term, this same information could be used by urban planners and local governments to inform which areas could be improved with interventions such as shade or the development of green spaces to promote healthy lifestyles and environments, and which areas need to curb emissions [64, 65].

1.2 TRAFFIC DETECTION

The problem with the discussed applications in traffic improvement and dimming is their reliance on real-time data, which can be prohibitively expensive to obtain. Traffic information is especially difficult to obtain at a high spatial resolution because of how the detection hardware is mounted (Figure 1.1). Traffic and vehicle detection systems can be categorised as either intrusive or non-intrusive systems [66].

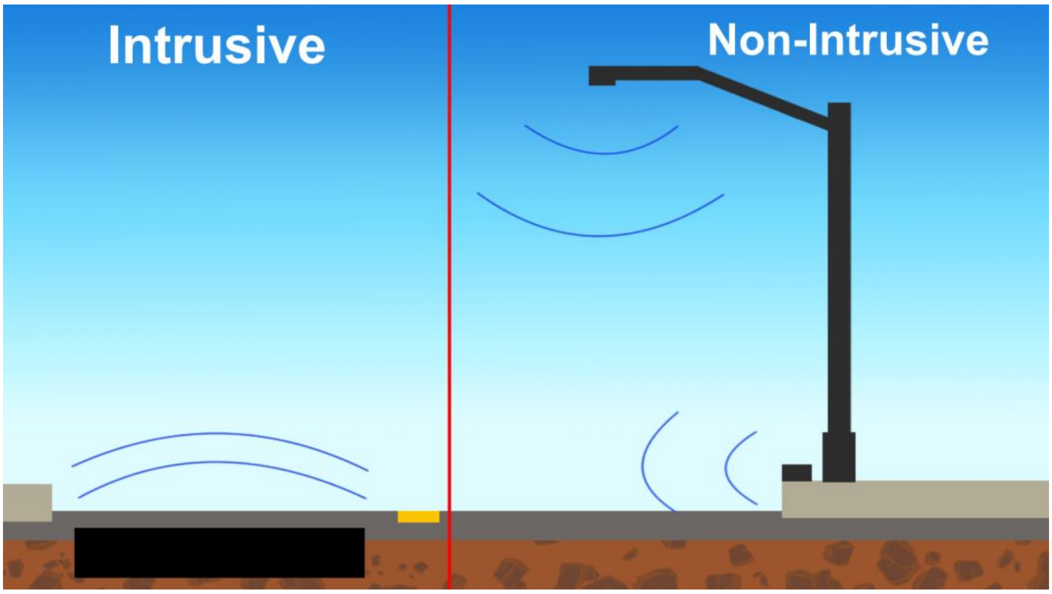


Figure 1.1 - Mounting configurations of Intrusive and Non-Intrusive Traffic Detection Systems

Intrusive refers to systems where the detection hardware is installed on the road surface or buried within the roadbed. These kinds of systems place the detector near vehicles, which makes them capable of detecting and counting vehicles with a high degree of accuracy and reliability [67, 68]. For this reason, intrusive detection systems are commonly used around the world.

However, intrusive vehicle detection systems come with high installation and maintenance costs [69]. Technologies such as the common inductive loop sensor need to be buried, which requires excavation of the road surface for installation and maintenance access, as well as the need to run cabling for power and data [70]. These necessities are labour and cost-intensive and disrupt the flow of traffic. As a result, traffic sensors are placed far apart, separated by hundreds of metres [71], or installed only in areas of interest such as highway ramps or signalled intersections [66]. This separation of detection systems poses a problem for applications such as traffic-aware road lighting, which requires multiple detection points along roads to efficiently light the road to minimise waste (See Figure 1.2 to Figure 1.5). Furthermore, intrusive detection options tend to not be able to detect pedestrian traffic, meaning they are not suited to footpaths or mixed-use roads. [71-73].

The alternative is to use a non-intrusive sensor, which can be positioned either above or beside the road, out of the way of traffic [74, 75]. However, these sensors have their own set of problems. Since non-intrusive sensors do not have the road to protect them, they are exposed to the elements, and are vulnerable to theft, tampering, and vandalism. Consequently, any hardware needs to be contained in a secure and weatherproof enclosure and mounted to a pole or other fixed structure, which can incur high costs, like that of intrusive systems [76, 77]. Finally, non-intrusive systems are located further away from the traffic they are supposed to detect, which can introduce noise, uncertainty, and errors that reduce the reliability and accuracy of the system.

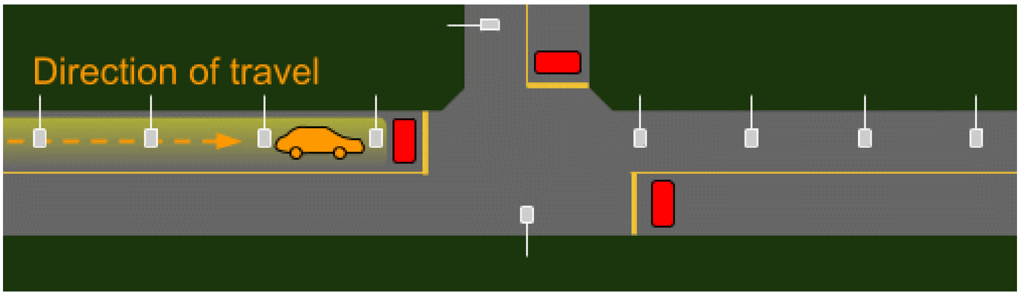


Figure 1.2 - Low-density traffic detection - The 'active' portion of the road is lit ahead of the vehicle. This would have occurred after a previous detection.

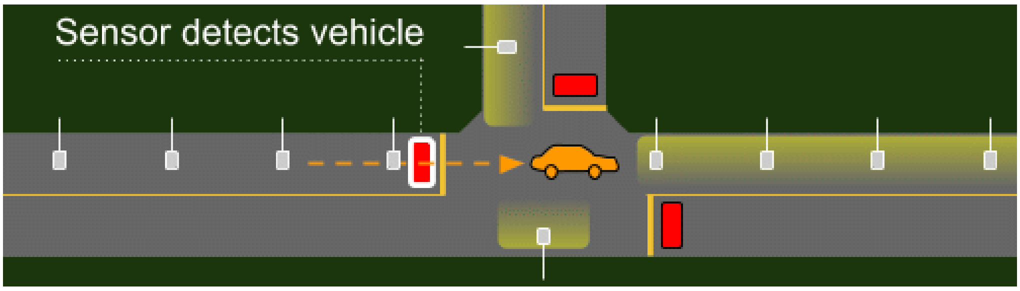


Figure 1.3 - Low-density traffic detection - The vehicle is detected by the sensor, prompting lights behind the vehicle to switch off, and lights ahead of the vehicle to switch on.

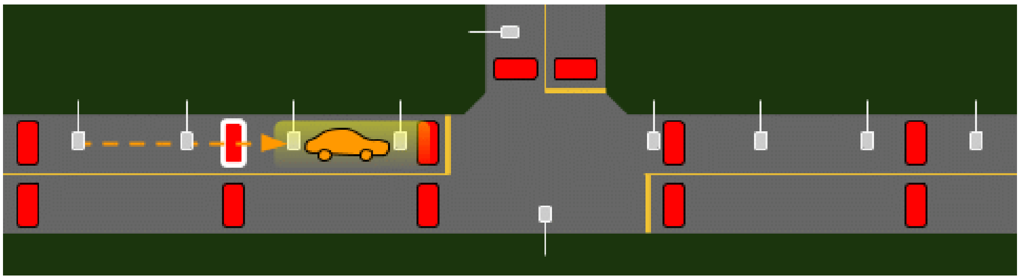


Figure 1.4 - High-density traffic detection - With more frequent sensors, vehicles can be localised to a much smaller area.

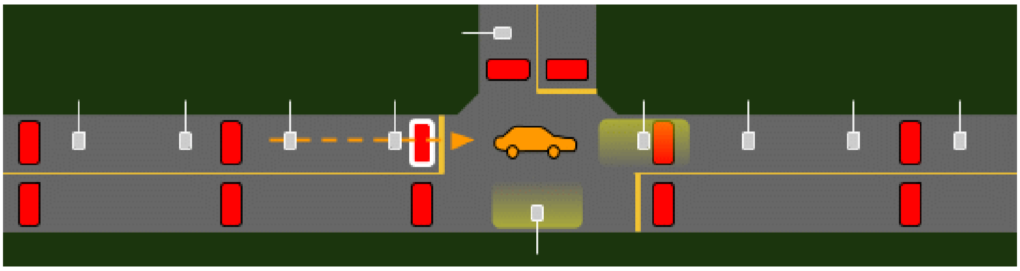


Figure 1.5 - High-density traffic detection - This localisation allows for fewer lights to be turned on without affecting road user experience or safety

1.3 STREETLIGHT-MOUNTED SYSTEMS

This study investigates integrating sensor hardware into streetlight infrastructure for cost-effective sensing and actuation for smart city applications. Streetlight-mounted sensors present a unique set of benefits and challenges for urban monitoring:

- Streetlights already have access to stable power, so no new cabling, or its requisite excavation needs to be performed [78, 79].
- Streetlight housings are designed to be weather and vandal-proof, which eliminates the need to construct a separate housing [52].
- The control equipment that interfaces with the sensor hardware to collect data can also interact with the streetlights' control system to perform dimming in response to detected events and monitor lamp health [80].
- Most importantly, many streetlight housings are designed to be modular, which facilitates rapid maintenance. This means if sensor hardware is pre-installed inside a replacement housing, then equipment can be easily deployed during routine maintenance without adding any substantial costs when compared to a typical roadside sensor installation.

The challenges with a streetlight-mounted approach include imitations in the housing and positioning. The space inside streetlight housings is limited, meaning that sensors and other hardware need to fit within a very small footprint. Secondly, due to how streetlights are positioned, sensors for traffic and environmental monitoring would need to be able to reliably function from an overhead position, located high above the road surface (up to 12 metres in some cases) [81]. These restrictions limit the types of traffic detection methods that are practical in the given scenario.

1.4 OBJECTIVES OF RESEARCH

The primary aim of this research was to investigate whether a streetlight-mounted sensor system for smart city applications is feasible with current technologies. To conduct this investigation, the following objectives were created to guide the study:

- The hardware solution must fit within the confines of a streetlight housing, roughly 200 x 100 x 60 millimetres, and weigh no more than 500 grams.
- Traffic detection had to be reliable from an overhead configuration at least 5.5 metres above the road level to coincide with preferred mounting heights in Australia in residential areas [81], and detect all traffic types (vehicle, cyclist, and pedestrian).
- The combined hardware costs should be less than AU$400, or at least break even with the expected savings of its functions (i.e.: dimming, etc.) in its given deployment conditions within a 10-year period.
- The detection system had to be made of already existing and commercially available components and sensor technologies to determine if the current state-of-the-art systems would function in the given circumstances.

1.5 SUMMARY OF CONTRIBUTIONS

The contributions made in this study include the following:

- This thesis explores the past solutions and current state-of-the-art for smart road technologies in Chapter 2. Both existing and concept solutions around smart roads and lighting are investigated for their technological and mounting approaches, and functionality within the context of smart city applications.
- An approach was devised to explore the currently available technologies to evaluate their capabilities and usefulness in a streetlight-mounted setting (Chapter 3). This approach is defined in two parts: an iterative development stage for constructing and testing a hardware prototype of traffic detection and environmental monitoring, and an evaluation stage to assess the financial and social viability of the prototype.
- The hardware and computational requirements for a streetlight-mounted sensor control system were investigated in Chapter 4. An urban sensor

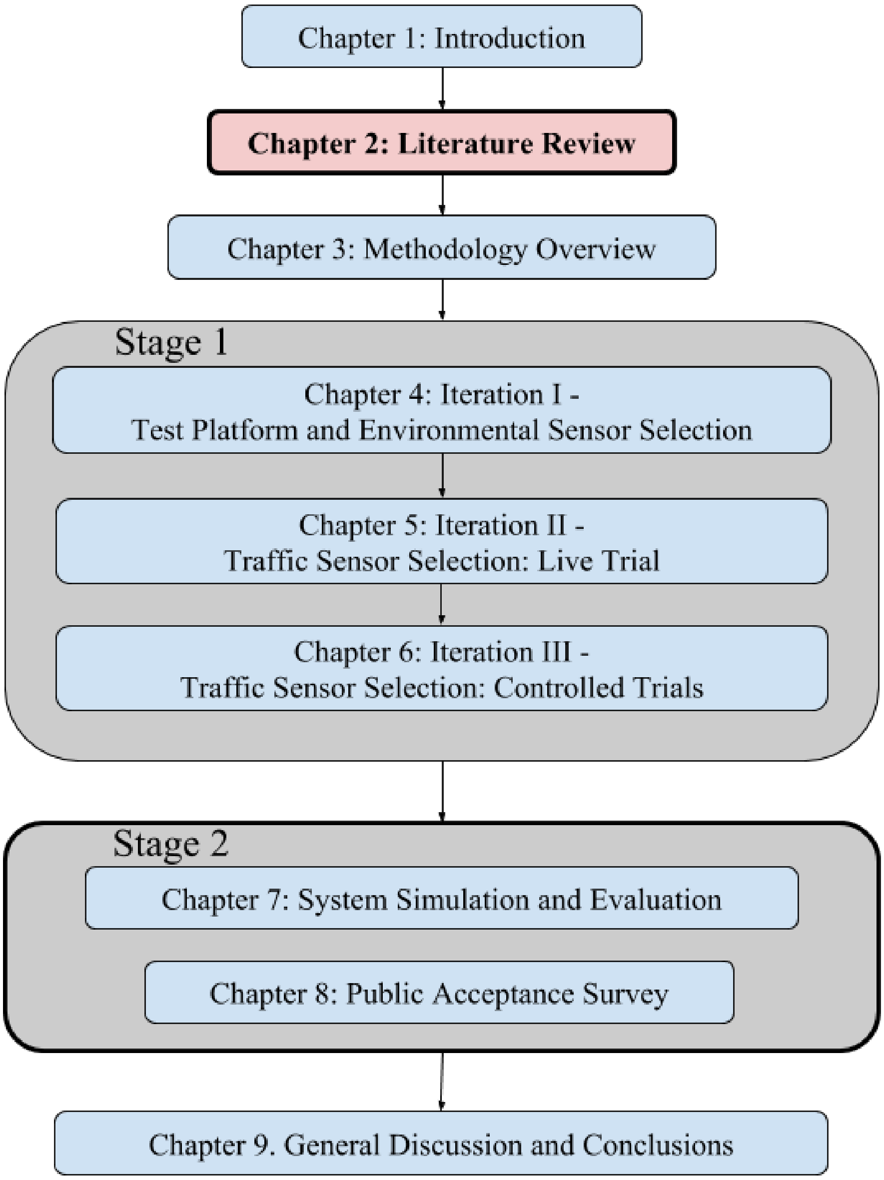
network was deployed as part of the first design iteration of the prototype sensor system to explore the capabilities and risks to long-term urban sensor projects. Results from this iteration show that microcontroller-based systems are well-suited to a streetlight-mounted environment, given their low weight and power requirements, but could be limited by their memory restrictions. Battery-based systems were found to be ill-suited to the urban environment due to the high temperatures encountered. This research was conducted in parallel with an environmental sensor project regarding human comfort within buildings. As a result, the sensor system developed in this research has a minor focus in environmental monitoring to improve human comfort in commercial and residential buildings.

- Following the urban sensor network trial deployment, the second iteration of the prototype system evaluated sensors for traffic detection. In this iteration, after conducting multiple trials involving actual traffic, binary motion detection systems were found to be effective at indicating road activity, but ineffective at counting or categorising traffic under varying traffic conditions (Chapter 5).
- In the final development iteration of the prototype sensor system, methods and technologies for improving traffic counts and categorisation were investigated. Controlled trials comprising vehicles, cyclists, and pedestrians showed that the combination of lidar, thermal, and motion detection technologies was able to detect all types of traffic and count vehicle volume with 99% accuracy (Chapter 6).
- An evaluation tool for modelling streetlight energy consumption and maintenance with traffic-aware dimming was developed in Chapter 7. The final prototype system was modelled and entered into the evaluation tool to assess its financial impact on streetlight installations compared to conventional, always-on systems. The simulated results show that an LED streetlight installation equipped with the prototype sensor system

would provide more net value than conventional options within a 10-year period in most cases.

- A survey on smart road applications was conducted to gauge public support and acceptance of the technologies involved (Chapter 8). The results of the survey show that citizens are mostly accepting and supportive of improving road infrastructure, particularly in areas where there is a high reliance on commuting or dissatisfaction with lighting comfort around the home.
- Finally, the study is concluded in Chapter 9 by evaluating the outcomes of the research in the context of its objectives and research questions, followed by the implications and possible directions of the research in the future.

Chapter 2 - Literature Review



2.1 CHAPTER OVERVIEW

The previous chapter introduced the concept of smart cities and the application domains that can be addressed with technological solutions. These domains were: natural resources and energy, transport and mobility, buildings, living, government, and economy and people. From there, the concept of smart streetlights was introduced as an approach to fulfil the data needs of these application domains in a city-wide context. This chapter explores the current state of streetlight-integrated control and sensor systems, as well as their deficiencies. Possible traffic detection solutions for streetlights are discussed regarding how they could be used for a low-cost ubiquitous sensing solution. Gaps in the research are then identified before establishing research questions to direct the study.

2.2 OVERVIEW OF SMART CITY APPLICATIONS COVERED BY SMART STREETLIGHTS

An upgrade to road lighting infrastructure with a smart sensor network has the potential to impact every smart city application domain. The most pronounced and obvious effects are in the domain of natural resources and energy. The elevated awareness of the smart streetlight network would allow lamps to be dimmed in accordance with real traffic levels to save power [57]. Internal monitoring of power usage and faults can also ensure that the lamp and driving electronics are operating properly. Power usage of lamps can be tracked to quickly identify faults and predict when the hardware is reaching its end-of-life stages to improve maintenance scheduling and avoid the costs of manual checking [82]. A networked lighting system would also allow for centralised control and management of all public lighting across a city. This network would allow lamps to be remotely controlled and dimmed based on conditions or events such as inclement weather, traffic collisions, or cultural and sporting events, etc. [83]. The impact of such a system would be that the appropriate amount of illumination is delivered by public lighting at every individual site in the lighting network at any given time, allowing for flexible control compared to the conventional, passive, and always-on installations.

The next most impactful applications are in the ‘transport and mobility’ domain. Real-time monitoring and classification of vehicles can improve road user experience and efficiency. Traffic coordination is a method of using synchronised scheduling between signalled intersections to allow groups of cars to flow through intersections on the road to decrease stopping and reduce overall trip times. The use of real-time information could improve these systems by providing the framework for integrating all intersections with this system. The ability to localise traffic to a defined area may improve the effectiveness of existing traffic coordination systems by supplying the system with better data and enabling coordination where the infrastructure did not previously exist. This localised traffic information could also supply road users with detailed information on congestion and road activity to better plan trips and predict traffic behaviour in real time. Automated classification of vehicle types such as distinguishing between cars, trucks, and buses can be used for maintenance by identifying 'heavy use' roads or other purposes such as with tolls and ticketing systems. A wider-scale network would open the possibility for more applications to improve road design and use. For example, the observation of trucks on a residential road may indicate a need to construct a bypass for improved road utilisation and mobility.

In the buildings and living domains, the environmental information that could be collected by a city-wide network of smart streetlights can improve both indoor and outdoor spaces. Much like the smart home example discussed in the last chapter, information on outdoor conditions can affect and influence buildings and offices to supply comfortable internal conditions while leveraging outdoor conditions for heating, cooling, and ventilation to save power. In the same way, knowledge of localised weather conditions and microclimates of areas such as parks or markets can inform citizens, vendors, and tourists/visitors of places favourable for outdoor activity. Areas that are identified as having high pedestrian activity could be highlighted as hotspots for tourism or even show the attendance of public events in real-time. From another approach, the presence of an integrated hardware platform in streetlights may make it easier to roll out services such as public Wi-Fi for leisure or in emergency scenarios.

The implementation of a smart streetlight network would influence applications in the Economy and Government domains in a subtler way. For government purposes and applications, the data collected by the smart streetlight network could influence the spending of public funds in areas shown to need interventions, for example, road upgrades in areas of heavy traffic, revitalisation of parks and green spaces in underutilised areas, etc. The collected traffic and environmental data can also be shared and made open to the public to justify and promote discussions of how public funds should be used and distributed. Lastly, in the Economy and People domain, there are many potential community and business uses for the data collected by a smart streetlight network. Traffic data can be useful to advertising companies, particularly if vehicles can be classified and sorted into specific demographics. Properties can include climate information, as well as walkability, foot and vehicle traffic in their valuations to assess property values. Entertainment businesses such as restaurants and eateries may want to establish themselves in areas frequented by foot traffic during certain hours of the day. The presence of a city-wide network also presents opportunities for citizen science and community projects or use by local governments to support public utilities such as sprinkler systems and power metering for public areas. However, these application domains were not directly explored in the overall study.

2.3 STREETLIGHT CONTROL, MONITORING, AND DIMMING

Public lighting on roads and pathways is a vital component of modern society. Streetlights increase safety on the road by enabling motorists and pedestrians to identify potential hazards and move safely and comfortably along roads or paths at night [84, 85]. Public lighting also serves an aesthetic benefit, acts as a psychological deterrent against crime, and promotes perceptions of personal safety among pedestrians. For example, pedestrian safety is improved by increasing opportunities for natural surveillance, reducing potential hiding places for attackers, and by displaying areas for escape [51]. The ubiquity of public lighting is something that is expected as a constant in modern society, and the absence or failure of lights can be deemed as a miscarriage of administration or municipal responsibility [86].

However, road lighting also comes at a cost. Streetlights are a tremendous financial burden to local municipalities and other lighting operators. In Australia, the annual costs for using and maintaining public lighting installations exceed AU$250m and represent between 30 - 60% of greenhouse gas emissions from local governments [87, 88]. Aside from financial costs, public lighting is also associated with negative health and environmental effects. Light from the road can reflect upwards into the sky to cause light pollution or 'sky glow', or spill into households, causing glare and disturbing the comfort of residents [58, 89]. Studies have shown that this glare may have adverse physiological effects on humans, and can disrupt the body's circadian rhythm, is linked to sleeping disorders, and can have carcinogenic effects [90-92].

2.3.1 Light Reduction

Reducing the amount of light at night can help to lessen the costs and effects associated with public street lighting. Road lighting is often designed for the worst-case conditions of typical traffic levels in a given area [93]. For example, road lighting around a shopping centre or mall will be designed around mixed traffic with high pedestrian activity. However, the lighting prescribed for these conditions may be considered excessive late at night or during the early morning, when shops have shut and traffic levels are much lower [94]. To better conform the lighting conditions to the typical requirements of the road, some municipalities have taken to dimming road lights during inactive periods according to a fixed schedule, or in some cases, switching lights off entirely [95]. These approaches have been conducted in a variety of scenarios, scales, and locations, and typically result in an average energy reduction of 30% [96-102].

Schedule-based light reduction certainly decreases electrical consumption and wasted light, but with the risk of under-illuminating roads during periods of abnormal traffic. Normally quiet roads may be subject to abnormal traffic behaviours, such as high traffic at night during holiday periods, emergencies, or sporting events. Schedule-based light reduction during these periods may result in roads being under-illuminated and operating under potentially unsafe conditions. Lighting designs can attempt to make allowances for abnormal traffic by not dimming as much and/or reducing the amount of time that the lamps are dimmed for, but these allowances also compromise the effectiveness of the dimming scheme. Alternatively, by not accounting for abnormal traffic behaviours, the road operators must accept that the lighting supplied on the road may be inadequate and could compromise road safety. In either case, the experience of any road users during dimmed periods is diminished in terms of safe movement, aesthetics, and personal safety, especially in the case of pedestrians. Operating costs are reduced, but the purpose of public lighting is undermined in the process.

Furthermore, most existing road lighting installations cannot be easily dimmed. Most streetlights around the world are comprised of High Intensity Discharge (HID) type lamps such as High-Pressure Sodium or Mercury-Vapour, which require specialised and expensive ballasts to enable dimming [103]. Even then, the amount of dimming is limited to between 50 - 100% of the lamp's rated output and can potentially shorten the lifetime of the fitting, reduce its output efficacy, and degrade colour rendering of the lighting installation, making it difficult for road users to distinguish colours [104, 105]. Another significant problem is the slow transition times of the lamps. When HID lights are first switched on, they take up to 15 minutes to 'warm up' to their full brightness, and this same transition period applies when switching between dimming levels [103, 106]. Changes to lamp brightness need to be applied slowly and gradually to account for the transition time, severely hindering the lamp's response to controls and limiting the dimming schemes that can be implemented [53].

2.3.2 LED Lamps

Fortunately, the paradigm of public road lighting has started to shift. The HID technologies that have illuminated roads around the world for over half a century are now beginning to be replaced by solid-state technologies like Light-Emitting Diodes (LED). There are two main reasons for this change: Firstly, LED boasts a much greater longevity than existing technologies, with manufacturers claiming lifespans over 2-4 times longer than traditional lamps currently in use [54, 104, 107-111]. Consequently, lamps need to be replaced much less often, resulting in lower maintenance costs and better value for money. Secondly, LED streetlights can illuminate roads using up to 50% less energy than previous technologies due to their improved colour rendering and better uniformity, which can also reduce the amount of spilled light into homes [107, 108, 110, 112, 113]. Due to these reasons, there have been many recent streetlight mass-replacement projects in major cities around the world [114-116], and lighting authorities are recommending that any new lighting project use LED technology [117, 118].

One crucial feature of LED lamps that is often overlooked in public lighting is its dimming capabilities. LED lamps can dim across their full output range (0 - 100%) and can change between output levels nearly instantaneously and without any detriment to the lamp's lifespan. In fact, unlike HID technologies, dimming LED prolongs the lifetime of the fitting [97, 113, 119-121]. This capability means that more sophisticated and precise control over road lighting installations is possible.

2.3.3 **Networked Controllers for LED Lamps**

In addition to the shift in lamp technology, another emerging practice in road lighting is individually networked lamp controllers. Several manufacturers and research projects have developed modular control systems that can be easily installed onto new and existing LED streetlight installations to add networking for centralised and responsive control over the entire installation. Some notable examples of these 'intelligent street lighting' controllers include the LightGrid system by GE [83], the Philips CityTouch platform [80, 82], and Cisco's Kinetic platform for lighting [122, 123], though many similar systems exist [108, 124]. While each system differs in its implementation, these systems typically enable some common features:

- Remote control and individual dimming of every light in a lighting installation. This feature allows specific areas of the road to be lit manually in response to changing conditions, such as high traffic, events, or collisions.

- Individual power metering at each lighting site. A common practice for street lighting installations is to pay a flat fee for electricity, based on the rated consumption of the light fitting, and the time per year the lamp is expected to operate [125]. The possibility of dimming means that this practise may no longer apply, and each lamp needs to be separately metered, so electrical consumption can be tracked and billed accurately.

- Automatic fault detection and asset tracking. These features mean that lighting sites can self-report their location and working status to lower maintenance costs involved with manually checking for lamp faults.

2.3.4 Adaptive Road Lighting

LEDs' ability to quickly transition between output levels allows for adaptive lighting schemes. This means that the output of the lamps can be dynamically adjusted to suit real-world conditions, as opposed to static lighting paradigms such as schedule-based schemes. These real-time conditions could be in response to any type of stimuli, including weather conditions, ambient light levels, or public events. For example, Guo et al. [119] describe a system of measuring reflected light levels off the road after events such as rain or snowfall and dimming streetlights to account for the added reflectivity of the road to save power and reduce glare. Another example by Ceriotti et al. [126] shows a similar concept of dimming tunnel lighting to match ambient daytime light levels.

A developing type of dimming possible with LED is traffic-adaptive lighting, which adjusts lighting in accordance with road use. The literature describes two main types of traffic-adaptive lighting schemes for public lighting: 1) level-based, which scales the output of streetlights with traffic volume [93, 127, 128]; and 2) on-demand lighting, which creates what can be described as a "tunnel of light" that precedes and follows individual motorists or pedestrians [53, 57, 129, 130]. These two schemes have different user experiences, but both serve to cut wasted light, reduce electrical consumption, and prolong the lifespan of the lamps without compromising on road safety. However, a problem with traffic-aware dimming schemes is obtaining and distributing real-time traffic information to individual streetlight controllers.

2.3.5 Traffic-Aware Adaptive Road Lighting with Existing Detectors

Some traffic-aware adaptive lighting installations used existing sensors to gather the information that they needed to function. Pioneering examples of this concept can be seen as early as 1997 in the DYNO system tested by Kaptein et al. [131], along the M65 Motorway in Britain in 2002 [72], and the Ring III and VT7 installations in Finland in 2008 [132]. Both of these systems operated on similar level-based traffic adaptive dimming schemes and were defined by two to three lighting levels. Information from nearby traffic detection systems allowed the road usage conditions to be continually re-assessed on a regular basis (e.g. every 15 minutes) to adaptively dim the lights, which was found to reduce energy consumption by up to 40%. These level-based dimming schemes are an improvement on scheduled lighting reduction systems. However, the same disadvantages of using the road during an 'inactive' or dimmed period remain. Also, most existing traffic sensors do not detect pedestrians, so existing traffic detection can be limited in its practical applications in areas with mixed or predominantly foot traffic.

Another method of implementing traffic-adaptive road lighting with existing infrastructure is to gather traffic information directly from the road users. In three similar approaches, Gibbons et al. [93, 127, 128], Müllner and Reiner [133], and Cygan et al. [134] propose the use of GPS localisation of individual road users to enable on-demand road lighting. In these scenarios, this localisation is performed by personal devices such as smartphones in the case of pedestrians or connected vehicle technologies in the case of motorised transport, which continually transmit their location back to the road light management system. Now, with an overview of the positions of every pedestrian and vehicle on the road, individual lights can be switched on ahead of moving pedestrians and vehicles and dimmed to a minimal level at all other times. This practice provides maximum energy savings without compromising road safety or, from the perspective of the road users, changing the lighting experience at all. In addition, this approach is possibly the best in terms of cost-saving, as little to no additional infrastructure is required to support the lighting management system.

The two main drawbacks of this system come from the side of the road users. Firstly, the problem of ownership. Smartphones, vehicular networks, and GPS-enabled devices in general have become increasingly prevalent in modern society, but ownership of such devices cannot be assumed for every citizen. A public lighting system predicated on the ownership of these devices means that citizens without them, such as young children, those from low socio-economic backgrounds, or possibly visitors to the area, are then excluded the basic rights of safety. The second major problem with this approach is the possibility of device failure. GPS localisation can be easily obstructed by geography, large buildings, tunnels, etc., and especially in the case of personal devices such as smartphones, the energy required to continually obtain a GPS position and transmit the user's location could drain the device's battery. In either case, any such failure would cause the lighting system to stop functioning for some individuals, potentially rendering the road unsafe. These same problems are encountered when using crowdsourced traffic information, such as that from Google Maps, which is also not captured in real time [135].

2.3.6 Traffic-Aware Adaptive Road Lighting with Integrated Detectors

A current approach to on-demand lighting is to integrate detection systems into the lighting infrastructure. Notable examples of this practice include commercial solutions, such as CitySense by Tvilight [136, 137] and Lumewave by Echelon [138], as well as several trial implementations and concept systems [139-145], particularly those by Juntunen [129], Vitta [53], and Lecesse [146]. The common factor between these systems is the use of motion-based sensors mounted on the streetlight poles to enable on-demand dimming. By mounting detection equipment at each pole, the lighting management system can monitor activity at each lighting site to localise traffic along road sections at a far greater spatial resolution than when using pre-existing detection systems. Additionally, integrating detection systems to the lighting infrastructure means that the lighting system does not discriminate or require any specific devices of its road users to function properly. However, a shortcoming of motion detection for path lighting is that pedestrians that are entering the path must pass underneath a sensor to be detected. Before detection, lamps would be operating at their passive, low-light levels.

Motion detection, and in particular, the Passive Infrared (PIR) motion detection technologies used by these systems, has many advantages for traffic-adaptive road lighting. Firstly, PIR sensors detect motion by optically monitoring changes in infrared radiation, which is naturally emitted by all objects. This method of detection means PIR sensors can detect all types of moving traffic, and as the sensor does not rely on visible light, it can operate in low-light environments. Secondly, the sensor hardware is common, inexpensive, has a small physical size, is easy to configure, and requires minimal processing, which are all particularly useful features when deploying the technology at scale [147]. A third benefit of PIR is the ability to select a specific detection area size and shape by using lensing, or as used by Tvilight's CitySense, multiple sensor units [136]. Lens housings can be manufactured to have multiple detection zones, allowing motion detection to occur across multiple lanes of traffic and footpaths [148].

2.3.7 Problems with PIR Approach to Traffic-Aware Dimming

Integrating PIR sensors with streetlight poles is an effective approach to on-demand road lighting. The ability to detect whether a road is in use allows light reduction systems to save power without compromising on road safety, decreasing the attractiveness of the surroundings, or diminishing the crime-deterrent effects of public lighting. However, a limitation of the systems and experiments discussed is that there is very little to no publicly available information regarding the financial effectiveness of implementing these systems over conventional lighting or other dimming types. One exception of this trend is Arani [138], who provided a basic costs-benefit breakdown of dimmable fixtures. Also, detection accuracy and reliability of the motion detection systems used in these systems is largely not discussed, despite other sources stating that the detection accuracy of PIR motion sensors can vary across implementations and sensor models [147], and in changing weather conditions such as rain or fog [148].

Aside from the lack of information, the disadvantage of using PIR traffic detection for on-demand road lighting occurs with other traffic-related smart city applications. As mentioned, PIR motion detectors operate by observing moving changes in infrared radiation. This dependence on movement causes PIR detection to be unsuited to applications such as parking occupancy detection where objects are stationary. Another limitation of PIR is that the information provided by most sensors is very basic. Most PIR sensors give a binary output, which shows only whether something is currently moving in the detection area (Figure 2.1). No other information, including the size, direction, speed, or even number of moving objects can be obtained. This inability to distinguish between traffic types means the information supplied by PIR sensors is not suited for classification tasks or applications where traffic counts, or even a distinction between pedestrian and vehicle activity, is required.

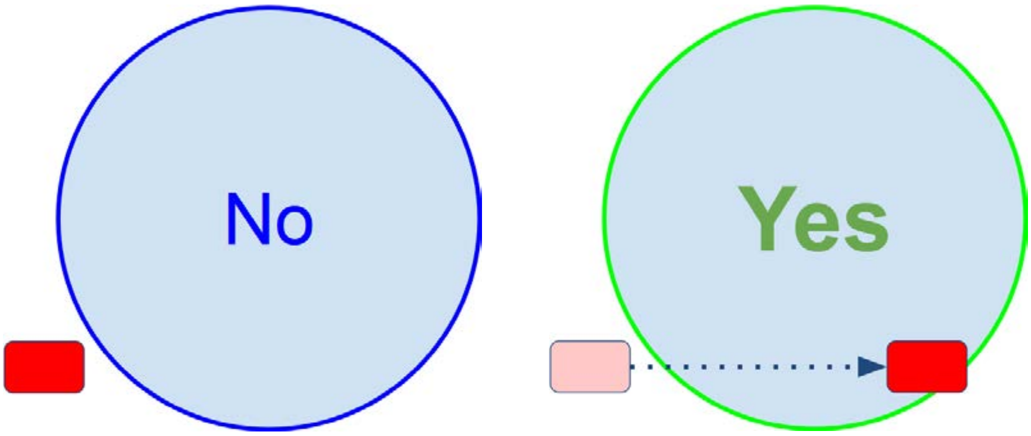


Figure 2.1 - Output conditions of binary PIR motion detection sensors, showing only basic output is available

Table 2.1 shows a summary of the effectiveness and capabilities of each of the discussed lighting reduction schemes. On-demand lighting schemes show the most potential for energy savings, but also requires the installation of new detection systems.

Table 2.1 - Summary of capabilities of lighting reduction schemes and systems

Lighting Scheme	Typical energy savings	Preserves road safety and prestige	Adapts to abnormal traffic	Network required	Individual control required	Source of traffic information
Conventional	N/A	Yes	Yes	No	No	None
Scheduled	30%	No	No	No	No	Historic
Level-based	40%	No	Yes	Basic	No	Existing sensors
On-demand (GPS)	Not available	Yes	Yes	Yes	Yes	Road users
On-demand (Integrated PIR)	40 - 92%	Yes	Yes	Yes	Yes	Integrated sensors

2.4 TRAFFIC IMPROVEMENT AND PARKING

The following sections discuss the extended applications of traffic data outside that of road and pathway lighting. These applications instead focus on the road usage itself to identify systems that could be improved for better mobility, better road experience for drivers, and a potential reduction in pollutants from road vehicles.

2.4.1 **Traffic Optimisation**

Traffic in densely-populated areas can often exceed the capabilities of the road and result in congestion. One option to address this congestion, aside from increasing the capacity of the roadways, is to use traffic light coordination. Traffic light coordination systems such as SCATS [40], SCOOTS [149], and STREAMS [150], actively synchronise the timing of traffic light intersections to allow ‘platoons’ of vehicles to pass through intersections without stopping. Optimising traffic flow in this way has multiple benefits: travel times can be decreased and/or made more predictable, idle wait times at intersections are minimised, and vehicles are required to stop less frequently, which contributes to an overall better road experience and reduced vehicle emissions.

The addition of a smart streetlight network could help to further improve traffic management in two ways. Firstly, traffic coordination systems are not enabled at all intersections, even in major cities. The network infrastructure required to run a smart streetlight installation could also be used to relay instructions between intersections and enable coordination in more areas. Secondly, streetlight-mounted traffic detection systems may be able to improve traffic coordination by supplying a complete picture of road activity across an entire city. Localising traffic along roads, and not just at intersections, would allow traffic management systems to adapt to any changing conditions such as vehicle speed and density to improve coordination in real time [151]. This practice can even be applied on an individual vehicle basis to aid traffic flow and improve road user experience, especially in off-peak periods [151-153]. A limitation of most existing traffic-aware road lighting systems is their inability to precisely localise or distinguish between pedestrian and vehicular traffic, meaning they are not able to determine which roads are being used, and in which direction.

However, if this limitation can be overcome, more advanced traffic coordination schemes can be implemented and in more areas.

2.4.2 Smart Parking

Another application of traffic information in cities is parking. Parking in urban areas can be very difficult, especially during busy periods or special events when traffic is dense and potentially chaotic. These conditions, or a low availability of parks in general, mean that motorists can spend extended periods of time searching for parks, which can both be frustrating and present a road hazard as drivers spend less time concentrating on the road. This frustration can also discourage motorists from visiting areas such as city centres, potentially causing a reduction in revenue to shops and restaurants in those areas [44]. Smart parking structures pose a solution to this frustration by actively monitoring and directing drivers to vacant parks, effectively eliminating the need to search. A streetlight mounted traffic detection system could replicate this same behaviour outside of dedicated parking structures to ease the inconvenience of roadside parking in a wide variety of situations. Unfortunately, as previously mentioned, detecting parked or stationary vehicles is an application that current, motion-based traffic-aware road lighting systems are not capable of performing.

2.4.3 Non-Intrusive Traffic Detection Technologies

Traffic detection systems need to be able to detect, count, and classify all traffic types to maximise their effectiveness in smart city applications. Table 2.2 shows the typical costs and accuracies for commonly-used, commercially-available traffic detector types. The combined hardware and installation costs were aggregated from the US Federal Highway Administration Traffic Sensor Handbook [65] and several field trials conducted using commercial traffic detectors [68-70, 153-155]. Installation costs can vary significantly, depending on the type of sensor and installation scenario. However, sensors were typically priced at several thousand dollars per installation. Detector counting accuracy information obtained from field trials shows that most detector types operate with a minimum accuracy of 90%, with accuracies exceeding 95% in typical traffic and weather conditions. This study investigated only sensor technologies that could operate from an overhead position and at an affordable cost.

Table 2.2 - Summary of traffic detector costs and capabilities

Sensor	Cost (US$) [70]	Counting Accuracy	Weather immunity	Multi-lane detection	Vehicle classification	Pedestrian detection	Computation load
Inductive loop	3300 - 17500 [73, 154]	92% - 98% [75, 155]	Yes	No	Yes	No	Low
Microwave Radar	1000 - 6500 [74]	90% - 99% [74, 156]	Resistant	No	No	No	Low
Active Infrared	2500 - 24000 [74]	90% - 95% [74]	Yes	Yes	Yes	No	Moderate
Passive Infrared	1000 - 1800	Not available	No (fog)	Yes	No	Yes	Low
Ultrasonic	900 - 2800	Not available	No (wind)	Yes	Partial	No	Low
Acoustic Array	4500 - 11800	Not available	No (cold)	Yes	Partial	No	Moderate
Video Image Processing	3300 - 38000 [73]	> 95%	No	Yes	Yes	Yes	High

2.4.3.1 Vision-Based Detection

Video image processing uses computer vision techniques to visually monitor traffic using live or recorded video. A video camera overlooking the road feeds footage of the road to a local or remote computer, which runs a detection algorithm to count and differentiate between traffic types, including cyclists, pedestrians, and both moving and parked vehicles. This technique can overlook multiple road lanes or arbitrarily-defined areas at once to provide accurate (approximately 98%) vehicle counting and localisation [74]. Aside from basic detection and classification, video image processing can also be used to extract information about individual vehicles, including speed, occupancy, and vehicle class [147].

Video-based detection methods offer a high degree of versatility but are impeded by three problem areas: the high volume of data they produce, sensitivity to external conditions, and high maintenance [157, 158]. The high bit-rate of video data means that processing traffic information using computer vision is a computationally intensive task that requires powerful and expensive hardware to perform in real time [74]. In the context of streetlight-mounted traffic detection, this would require either a video-processing platform at each lighting site, or a high-bandwidth network connection to transfer the video footage for offsite processing at a data centre. Both options can be expensive, especially at scale, which would limit the viability of such a large implementation.

A second problem with vision-based traffic detection is that its effectiveness can be hampered by changes in ambient conditions. The low-light conditions of night-time traffic may degrade detection accuracy, particularly with traffic types without headlights, such as pedestrians or cyclists [157]. Infrared cameras can circumvent this problem as they capture infrared radiation instead of visible light, but these cameras typically have a much higher cost compared to conventional cameras [159], although low-cost hardware does exist at low image resolutions [160]. Counting accuracy can drop in heavy rain, fog, or snow, where visibility is obscured, resulting in inconsistent vehicle counts and classifications. Vehicles and pedestrians can also obscure one another, depending on the vantage point of the camera [66]. Lastly, traffic cameras are particularly susceptible to dust build-up on the lens and require regular maintenance for cleaning, which would be amplified for a city-wide installation at every streetlight.

To date, there have been very few examples of integrating vision-based traffic detection into streetlight housings. One recent and notable example is the CityIQ system by Current (a subsidiary of General Electric™), that is being deployed in San Diego in 2018 [161]. According to the limited information that is available, the CityIQ system includes a pair of high definition cameras, microphones, and an environmental sensor suite [162, 163]. It uses these sensors to perform its main tasks: 1) the detection of parked vehicles, and 2) integrating with the existing ShotSpotter system to triangulate the location of gunshots. Aside from these two functions, the capabilities of the system are not clear. The camera systems and integrated computer hardware would allow for computer vision detection of vehicles and pedestrians, but there is no indication whether this is available in real time. Very little information is given about the unit costs of the system, but the savings afforded by dimming and provided by data services have given the San Diego installation an expected return on investment within 13 years.

2.4.3.2 Sonar Detection

An alternative to vision-based traffic detection is to use distance-based measures. Sonar or ultrasonic vehicle detection systems operate by measuring the time of flight of reflected sound waves to determine the presence of traffic, and to calculate distance between the detected object and the sensor [164, 165]. Both the hardware and processing costs of sonar are much lower than those of computer vision systems due to the simpler operation and data processing required. Also, as this is an active detection method based on sound, rather than visible light, detection accuracy is not affected by the low-light conditions of night.

The functions and capabilities of sonar traffic detection change depending on the mounting configuration of the sensor. In a side-fire configuration, the sensor measures distances across the road, potentially across multiple lanes. In this configuration, sensor measurements can individually detect and determine which lane a vehicle or pedestrian is in, based on their distance from the sensor.

Two case studies with side-fire sonar have reported high vehicle counting accuracy in differing deployment scenarios [166, 167]. Jo et al. [166] could detect 98% of the 522 vehicles during the study using an array of custom-made sonar devices. Kim et al. [167] were also able to successfully detect 98% of vehicle traffic over a series of tests involving over 3500 vehicles, but no sensor hardware information was disclosed in the study. Both studies concluded that inaccuracies in traffic counts were caused by vehicle occlusion, where vehicles in the foreground blocked the sonar from reaching vehicles in the background, and vehicles changing lanes, but detection accuracy was not affected by low visibility or adverse weather conditions [74]. Very basic vehicle classification is also possible in this configuration by estimating the length of vehicles by measuring how much time is taken for the vehicle to pass by the sensor, based on a typical speed.

Sonar can also be implemented in an overhead configuration, facing downwards from above the road. In this configuration, pulses reflect off the road to provide a ‘background’ distance. Vehicles underneath the sensor cause the measured distance to lessen, which indicates passing traffic or the presence of a parked vehicle [168]. From this vantage, the sensor is likely restricted to detection in a single lane but can measure the vertical profile of objects underneath. This vertical profile may allow detections to classify between large and small vehicles (i.e. buses and cars), and possibly between pedestrians and cyclists as well. Studies by Oudat et al. [169] and Fernandez-Lozano et al. [170] featured commercially-available low-cost sonar units (Maxbotix MB7066) in an overhead configuration. Both studies found the sensor was able to count vehicles with 97% accuracy, but no tests involving pedestrians were mentioned, nor were the mounting heights of the sensor platforms disclosed. As such, the suitability of sonar for traffic detection in a streetlight-mounted scenario is unclear.

2.4.3.3 Active Infrared/Lidar Detection

Active infrared or lidar uses the same time-of-flight principle used in sonar, but instead uses pulses of infrared light for detection and ranging [171]. Light-based, and especially laser-based, ranging provides a much narrower detection area compared to sonar sensors, and over a much longer range [172]. However, like all light and distance-based detection, the sensors are prone to occlusion and can fail from dirt build-up on the lens [74]. Commercial lidar-based traffic detection systems can also be mounted in overhead or side-fire configurations, but with some differences compared to sonar. In a side-fire configuration, the lidar's narrow field of view allows the sensors to count the vehicle axles across multiple lanes of traffic to precisely determine the number of passing vehicles, as well as their approximate size and speed [74]. Minge et al. [74] found a commercial lidar-based system (PEEK AxleLight) could detect traffic volume with 94.6% accuracy across three lanes of traffic. However, the system was not intended to be permanently installed and can only operate up to 48 hours at a time with the supplied battery. The system cost of approximately US$31,000 makes this sensor far too expensive for wide-scale deployment, even for an equivalent permanent system. Axle detection also requires the sensor hardware to be mounted close to the ground, which negates most of the benefits of a streetlight-mounted system.

Scanning lidar is typically used in overhead mounting configurations to compensate for the small detection area. Rather than the static detection area used by side-fire lidar or sonar, multiple distance measurements are taken in a line, across the width of the lane(s) by use of multiple sensing elements or a rotating mirror. A result of the extra hardware and complexity is an increase in processing load and cost, but the multiple-point measurements allow the shape and size of vehicles and pedestrians to be measured for classification [173, 174]. An overhead-mounted scanning lidar was tested by Fernandez-Lozano et al. as part of their traffic detector testbed, which provided a high vehicle detection accuracy (87% - 100%) across two lanes of traffic. However, the sensor used in the testbed had a high cost of US$5,200 [170, 175], which is prohibitively expensive to use at scale in the context of smart road lighting, but low-cost sensors are being actively developed and becoming increasingly available [176].

2.5 ENVIRONMENTAL MONITORING FOR BUILDINGS AND PUBLIC SPACES

Data on climate, air quality, traffic levels, etc. is valuable to the decision-making process in urban infrastructure planning and development. Factors such as temperature, humidity, and wind speed all play a key role in human comfort [177], but are often ignored in planning due to their unavailability or high cost to obtain, and lack of communication between planners and climate experts [178]. Conversely, urban development itself can have a significant effect on the surrounding microclimate [179]. Common building materials trap heat, which, when combined with the increased density of buildings and roads in cities, can cause urban heat islands to form, increasing the need for air-conditioning and the subsequent power it consumes [180-182]. As previously discussed, this information can be used in conjunction with homes and workplaces to improve the efficiency of heating, cooling, and ventilation systems, or direct efforts to mitigate the formation of urban heat islands in the first place. Microclimate conditions and thermal comfort also affect how people perceive and use outdoor spaces [177, 183-185]. Citizens that are not comfortable with the climate in an urban environment are much less likely to use or remain in the area [186]. Simple factors such as the presence of trees and greenery in the urban setting can be used to provide shade and more attractive outdoor areas, as can the use of wind and water to provide passive cooling [187].

The World Health Organisation states that insufficient physical activity, such as walking, is a leading risk factor for non-communicable diseases such as cancer and heart disease [188]. A problem faced in many cities is that the development of sprawling and disjointed, single-purpose suburbs creates neighbourhoods that are not attractive or practical places for walking [185, 189]. Thankfully, modern urban design movements such as New Urbanism place an emphasis on pedestrians and walkability, as opposed to vehicle-centric suburbs. Walkability is the extent to which an area or environment is attractive and accommodating to pedestrian activity. There is no universal measure of walkability at this time, but several influencing factors have been identified [190]. These factors include, most notably, mixed land use, which puts a useful variety of shops and amenities near residential areas to serve daily needs [191, 192], high residential density and connectivity [193], a sense of belonging and community, and visual appeal of the surrounding environment [191]. Areas that possess high walkability scores have been associated with a higher degree of physical activity and health among residents [194, 195], reduced crime, higher housing values, and a lower risk of foreclosure in periods of economic crisis [192]. The built environment has a pronounced effect on physical activity levels of a city’s occupants, but other factors need to be considered.

Urban sensing is the process of gathering data about the environment in which we live and work. Historically, there are many methods in which urban sensing has been performed, each with their advantages and disadvantages. Fixed structures such as weather stations are perhaps one of the most common approaches to climate monitoring and can be a reliable and consistent source for climate information [196, 197]. Unfortunately, these stations tend to be located sparsely throughout cities, meaning the information that the stations provide would only be useful to the limited number of nearby buildings, but less useful moving further away from the station due to changes in microclimate [196, 198]. In other words, weather stations have a high temporal resolution and can gather information on demand but tend to have a low spatial resolution due to their sparse placement in urban environments. In contrast, other techniques for climate monitoring such as remote sensing have a high spatial resolution, but a low temporal resolution. Remote sensing describes the use of aerial or satellite photography to provide a thermal snapshot of an entire city at once, which is particularly useful for the detection of urban heat islands [199], but the irregularity of measurements likewise makes this approach ill-suited for smart home and building applications.

A streetlight-mounted environmental sensor network would be able to supply climate data at a high spatial and temporal resolution. The use of a wireless sensor network is not a particularly new concept for urban environmental monitoring. Many examples exist of sensor networks for climate and pollution monitoring [200, 201], such as Harvard's CitySense network [202]. However, ubiquitous sensor deployments within an urban setting are uncommon due to the costs involved in powering and housing sensor equipment, and obtaining the permissions needed for mounting and access for maintenance [203]. As with traffic detection systems, mounting sensors within streetlight housings would resolve most of the problems involved in implementing a climate monitoring network. Also, as with traffic detection systems, the financial viability of this style of ubiquitous deployment is not widely, or at least publicly, known.

2.6 RESEARCH GAP

To summarise the three main gaps in the literature:

1. Smart road lighting installations rarely have publicly available information regarding implementation costs. The literature around the effectiveness of traffic-aware dimming schemes tends to focus only on the energy reduction aspects of the system or scheme, rather than the costs of implementation. This lack of cohesive and detailed cost-benefit analyses means that lighting operators are not able to determine if smart road lighting systems are feasible in different lighting environments, scenarios, and under all budgets.
2. Very little attention has been given to streetlight-integrated traffic detection systems in both commercial and research settings. The current state of the art for traffic-adaptive road lighting tends to focus on pre-existing sensors or the use of low-cost motion detection. Neither of these approaches provides traffic information that is detailed enough for use with smart city applications around mobility and traffic improvement. Potential candidate technologies that could supply this information do exist, such as sonar or lidar, but have yet to be tested in a streetlight-integrated implementation for inexpensive and ubiquitous traffic detection. Therefore, the counting and classification accuracy, and the cost-effectiveness, of these technologies is not currently known.
3. The financial viability of a streetlight-integrated environmental sensor network across a city-wide implementation is not known.

2.7 RESEARCH QUESTIONS

From these gaps in the research, this study will focus on the following two research questions:

RQ1: Can a streetlight-integrated traffic detection system reliably detect vehicles and pedestrians, produce accurate counts, and distinguish between traffic types for use with smart road applications?

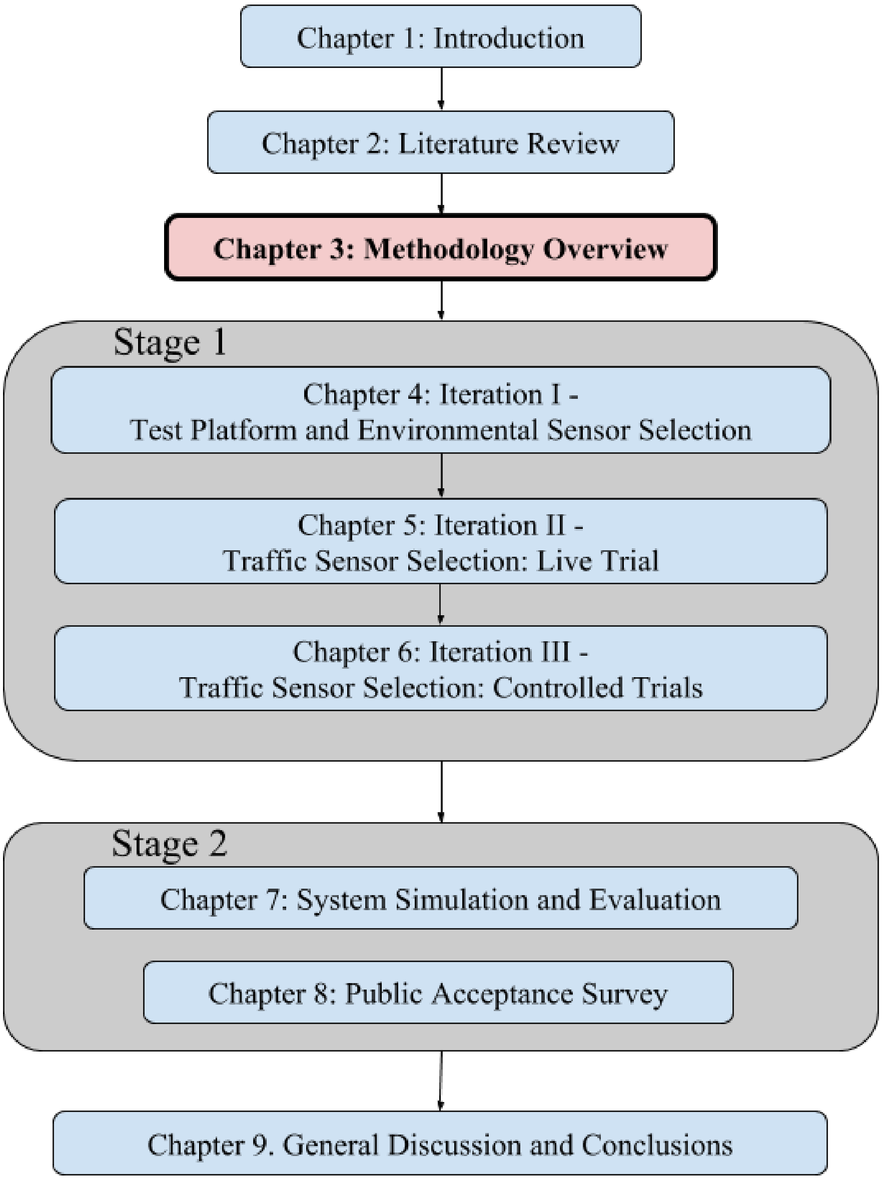
RQ2: Is a streetlight-integrated traffic detection and environmental monitoring system viable for a community?

In other words, can a cost-effective system be developed that is affordable for both metropolitan and rural communities? Would the developed system be able to function in multiple deployment scenarios such as on main roads, and in industrial and residential areas throughout a city? And, finally, would the public be accepting and supportive of the new technologies?

2.8 RESEARCH SIGNIFICANCE

A city-wide sensor network could stand to revolutionise the sustainability of the world's cities. If a cost-effective sensor solution can be found, cities can cut wasted power, greenhouse gas emissions, and light pollution through smarter lighting management. The traffic and environmental data collected by such a network could also improve human comfort and the efficiency of public services, both inside and outside the home, and pave the way for new innovations in all aspects of city living. If the hardware and mounting problems associated with a streetlight-integrated sensor installation can be overcome, then smarter cities around the globe may be possible and within reach.

Chapter 3 - Methodology Overview



3.1 CHAPTER OVERVIEW

The previous chapters introduced the concept and components required to support smart road lighting applications and the gaps in the relevant literature. Research questions were also presented to define the scope of the study. This chapter presents an overview of the methodologies for each stage of the study. Full details of the methodologies applied in each phase of testing are embedded in context within each chapter. An overall testing framework is introduced, as well as a summary and explanation of the thesis' structure and content.

3.2 EXPLANATION OF TESTING STAGES

The overall research methodology was split into two stages, one to answer each research question. Stage 1 addressed the research question of whether it was viable to use low-cost commodity sensors for traffic detection in a streetlight mounted configuration. This was accomplished by constructing a prototype sensor system and assessing its effectiveness at detecting and counting various traffic types.

Stage 2 addressed the second research question of whether a smart streetlight network would be viable for a community. In this stage, using the characteristics and applications made possible by the prototype developed in Stage 1, the financial and social viability of the system was evaluated in the context of a city-wide deployment. The following sections discuss each stage and its components in greater detail.

3.3 STAGE 1 - DEVELOPMENT OF A PROTOTYPE TRAFFIC DETECTION SYSTEM

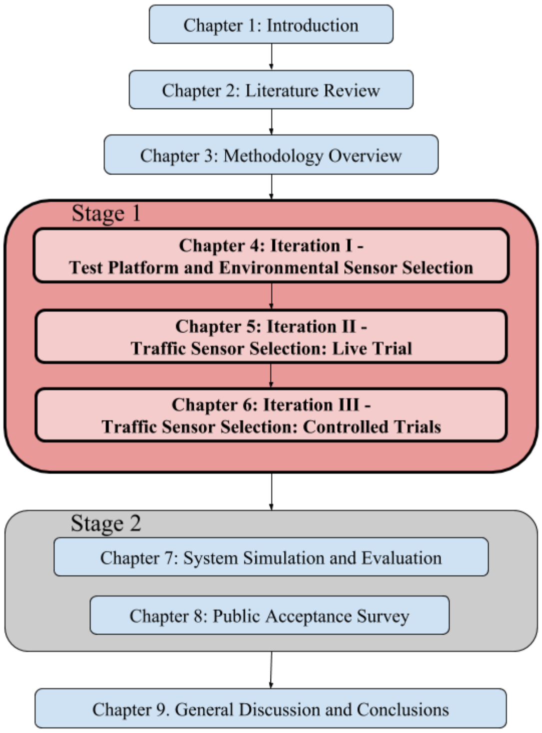


Figure 3.1 - Chapter format for Stage 1 of the study

Stage 1 was conducted to answer the first research question of whether a cost-effective streetlight mounted traffic detection system was feasible with commodity components. An artefact-oriented design approach was adopted to iteratively develop a prototype sensor system for traffic detection and environmental monitoring. This study followed Hevner et al.'s guidelines on design-science research [204], which are listed in Table 3.1, to develop the following three research artefacts:

1) A selection of sensor technologies capable of reliable traffic detection in either standalone operation or when used in conjunction with one another,
2) The detection algorithms applied to sensor data to classify traffic events, and
3) The hardware and software design of the control system to manage sensor operations, respond to traffic events, and data logging.

The development of these artefacts occurred over three distinct design iterations.

Table 3.1 - Hevner et al.'s seven design-science research guidelines

Guideline	Description
Guideline 1: Design as an Artefact	Design-science research must produce a viable artefact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artefact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact.
Guideline 6: Design as a Search Process	The search for an effective artefact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

3.3.1 Iteration I - Test Platform and Environmental Sensor Selection

The first iteration focused on selecting an appropriate hardware control system for testing and developing purposes. To accomplish this, an urban sensor network was constructed and deployed to monitor the exterior conditions of an inner-city building, in a similar environment to a streetlight-integrated installation. The purpose of this exercise was to gain further understanding of the conditions that could affect the smart streetlight network, and, to explore the hardware and software requirements of the controller that interfaced with the sensors and performed data processing. This deployment allowed for the exploration of technologies in circumstances that could not potentially endanger public safety if components behaved in an unexpected manner, as would be possible in a streetlight-mounted implementation.

In this iteration, the controller hardware was evaluated based on its ability to interact and log data from a suite of environmental sensors, particularly the amount of memory and number of additional inputs for use with traffic detection hardware. Longevity and mounting requirements of environmental sensors were also investigated during this iteration to establish which sensor models and mounting practices could be implemented for long-term operation without early failure due to damage from the elements. This exploratory investigation solidified the controller requirements for future stages and allowed for practical hardware choices in other iterations.

3.3.2 Iteration II - Traffic Sensor Selection

The second design iteration began with preliminary investigations into which sensor technologies could be added for traffic detection. Multiple short-term trials with live pedestrian and vehicle traffic were conducted from an overhead vantage point. The motion-based detection of the traffic-adaptive dimming systems was tested for its ability to detect and estimate traffic counts. Detection algorithms were also developed for other sensor technologies such as sonar, lidar, and optical flow sensors. The purpose of this stage was to determine which sensors could detect pedestrian and/or vehicular traffic and use that knowledge to differentiate between traffic types. A camera recorded video footage to quantitatively assess the counting accuracy of each sensor individually by providing a ground truth during a preliminary testing and a deployment of the prototype system on an active road, inside a streetlight housing. This evaluation determined which sensors were suitable for what purpose (e.g. vehicle counting, general activity detection, etc.), and possible ways that their performance could be improved for the next design iteration.

3.3.3 Iteration III - Traffic Sensor Selection and Improvement

The third iteration improved the sensor detection algorithms and further evaluated sensor detection and counting performance. A series of controlled traffic trials were conducted with pedestrian, cyclist, and vehicular traffic at multiple speeds, traffic densities, and directions of travel. The counting accuracy and false-positive characteristics of each sensor were quantitatively assessed, again using video footage, to determine the counting accuracy of the sensors with each traffic type. These tests assessed the reliability of each sensor's capacity to count traffic in a variety of common scenarios. Sensor performance was then compared to that of commercially available traffic detection systems to determine their suitability for active use, estimate the final costs of the developed system, and to respond to the first research question of the study.

3.4 STAGE 2 - EVALUATION OF A SMART STREETLIGHT NETWORK

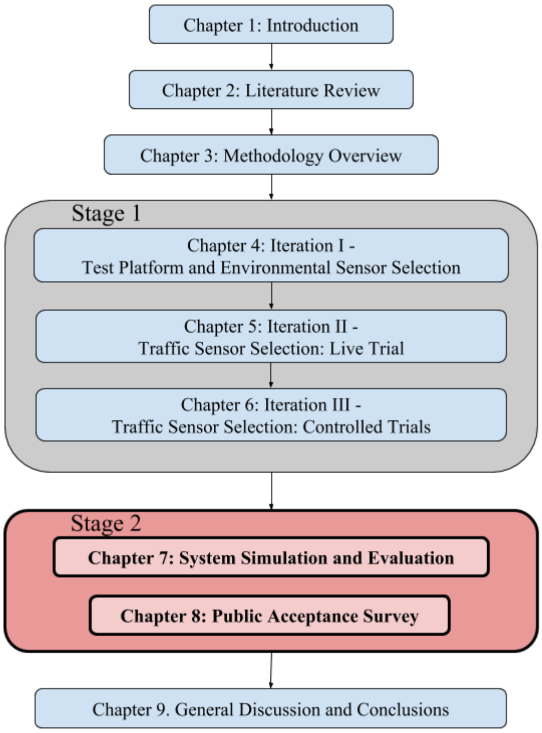


Figure 3.2 - Chapter format for Stage 2 of the study

Stage 2 focused on the second research question of whether a smart streetlight sensor network was viable for a community. This stage was split into two distinct sections: a financial analysis, and an assessment of public acceptance. Both evaluations were necessary to measure the viability of the proposed smart road lighting system, since functions such as road light dimming can be associated with social costs as well as financial implications.

3.4.1 System Simulation and Evaluation

The financial analysis comprised of a quantitative cost-benefit analysis against existing road lighting paradigms to evaluate its financial viability. In this analysis, road lighting installations were simulated with and without smart road lighting hardware to determine their lifecycle costs from hardware, installation, electricity consumption, and maintenance. Installations with smart road lighting systems had additional costs, based on the prototype traffic detection system developed in Stage 1 of the study, but at a reduced electrical consumption due to the dimming options that the hardware allowed. Dimming effectiveness was calculated using historical traffic data to estimate the amount of dimming possible without compromising road safety. The net present values of lighting installations with and without smart road lighting hardware were compared to evaluate whether the dimming functionality afforded by the system justified the additional costs.

3.4.2 Public Acceptance Survey

Social acceptance of smart lighting systems and applications was assessed using a public survey. The survey was a cross-sectional study of Australian citizens, which discussed the applications of smart road lighting that directly affect citizens, such as traffic improvement, dimming, and weather services. Participants were asked how much they would be willing to pay for the service or sacrifice from other services to quantitatively measure support. Descriptive statistical analysis of responses showed the proportion of participants that were willing to support each of the discussed services, and logistic and linear regression analyses were conducted to identify trends and possible explanations behind the participants' willingness to support these services, and to quantify the extent of that support. The identified trends and demographics associated with support could then be used to estimate the social acceptance of the technologies and services of smart lighting across the population.

3.5 TEST LOCATION

Stage 1 of this study was conducted in tropical North Queensland, Australia and used locally applicable guidelines around road lighting. These guidelines include government policies and Australian standards that govern factors such as streetlight mounting heights, weight restrictions of streetlight housings, and maintenance procedures regarding lamp replacement. Furthermore, tests involving the effectiveness and longevity of sensor hardware were restricted to tropical climate conditions, which may not apply in other countries or in temperate climates. The survey in Stage 2 of the study was advertised Australia-wide through social media pages and was not restricted to any specific location.

3.6 ETHICS

Human ethics (H7063) approval was obtained prior to the release of the survey questionnaire. Each participant was presented with an information sheet before starting the survey, and informed consent was given in the form of implied consent upon completion of the survey questionnaire. Survey completion was entirely voluntary and anonymous.

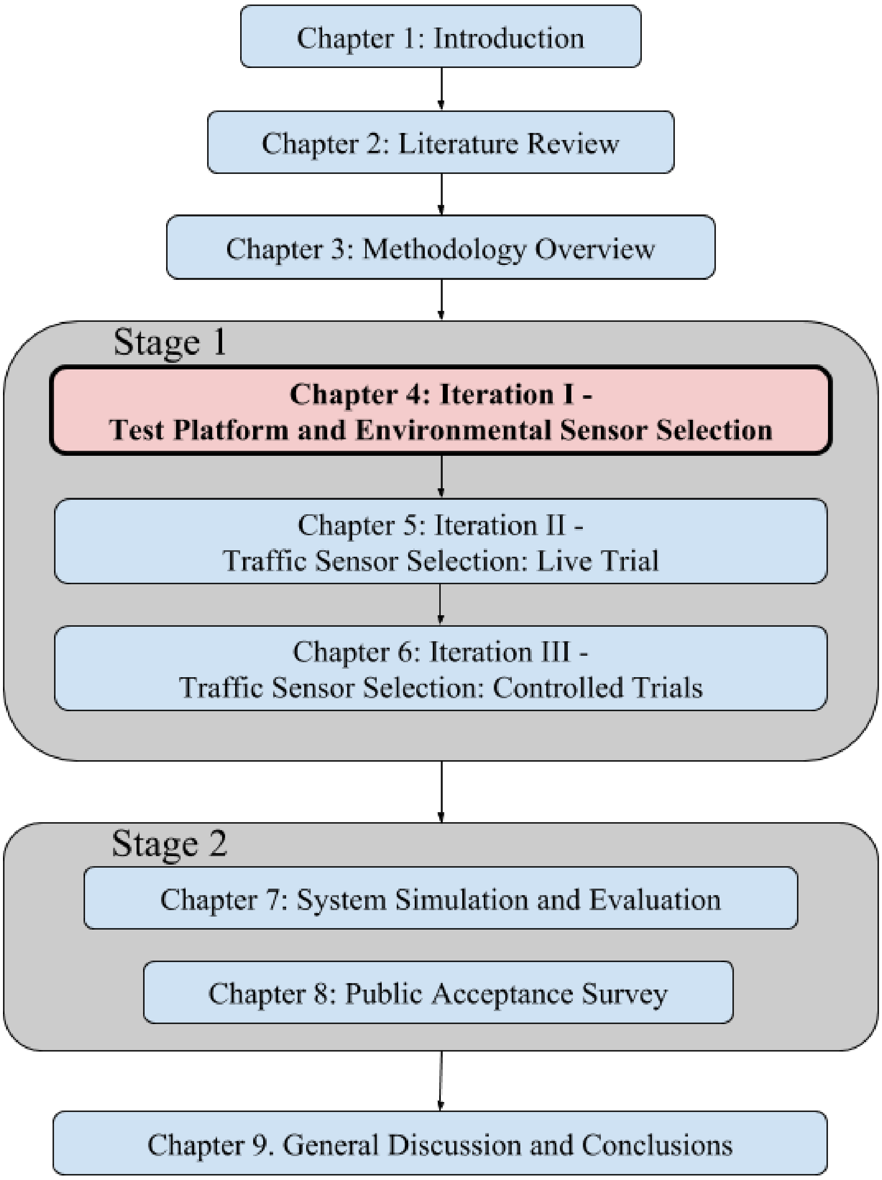
3.7 THESIS FORMAT

Chapters 4 - 6 were originally written as papers that have been reformatted and adapted into thesis chapters. These chapters may include additional information from the original publications that was not able to be in the article due to length or other reasons. However, the main findings within each chapter remain unchanged. Redundant sections have been aggregated and relocated as appropriate.

3.8 CURRENCY

All calculations involving money used Australian dollars for consistency of values between cost-benefit analysis and responses collected from survey data, which were conducted in Australia.

Chapter 4 - Test Platform and Environmental Sensor Selection



This chapter was presented at the 2015 IEEE Tenth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP 2015) as follows: ‘K. Mohring, T. Myers, I. Atkinson, J. VanDerWal, and S. Vandervalk, “Sensors in heat: A pilot study for high resolution urban sensing in an integrated streetlight platform”’ [3]. The publication discussed the wireless sensor network, its deployment, and the heat effects that were found. Additional information has been added surrounding environmental sensor selection, sensor platform requirements, and the suitability of the testing platform as it relates to other development iterations.

4.1 CHAPTER OVERVIEW

The previous chapter outlined the testing stages that this study followed to evaluate the current state of smart streetlight technologies. This chapter begins with the start of Stage 1, which oversaw the development and construction of a prototype streetlight-integrated sensor system. The first development iteration of this stage was an exploration in the hardware and mounting requirements of the prospective sensor system. An urban sensor network was constructed and deployed as an exercise to better understand the available sensors and electronics, and to investigate the potential risks and difficulties in implementing a long-term sensor system. An initial prototype design for urban environmental monitoring is presented and tested in a live deployment. Observations of the sensor nodes during development, deployment, and from collected equipment afterwards were used to identify the potential risks to the system’s longevity, and the controller and mounting requirements of the sensor platform. The chapter concludes with an overview of the possible changes and improvements that could be made to the prototype system in following iterations.

4.2 CHAPTER INTRODUCTION

The design of a sensor network of any size must consider far more than just the sensors themselves. A controller is needed to interact with all the connected systems and sensors to gather and process raw data to extract meaningful information. That information can then be used locally or transmitted via a communications network to a centralised system to be used externally. Aside from data considerations, the physical construction and hardware of the sensor network must be protected from the elements, so the system is not damaged and does not produce incorrect information. Finally, the entire system must receive power to function, either by battery or connected to the electrical grid. The failure of any of these factors can render a sensor network inoperable, and therefore, careful consideration must be taken in choosing components for the system’s intended deployment environment and conditions. To explore these conditions, this chapter outlines the development, construction, and deployment of a sensor network for inner-city environmental monitoring.

Development and deployment of the sensor network was undertaken as part of a project parallel to this study. The goal of the parallel project, named the Townsville City Council Urban Sensor Network, was to enable smart building applications for an inner-city municipal office. The premise behind the project was that sensor nodes placed on the outside walls of the building would deliver information to the building's climate control system. This information, collected from multiple points, would then be used to track changes in internal conditions as a result of external weather effects such as direct morning or afternoon sun hitting an outside wall. After establishing causal relationships, the climate control system would ideally then be able to pre-empt the effects from weather changes and adjust air-conditioning and ventilation within individual rooms or sections inside the building to keep conditions consistent and comfortable for its occupants. Like the project's urban setting, this application of climate data for smart buildings is also shared by that of smart road applications. This overlap of project goals also allowed for the exploration of different environmental sensors and supporting hardware to determine their effectiveness in both deployment conditions.

4.2.1 **Summary of Contributions**

This chapter presents the following research contributions:

- A system design and hardware selection for an urban environmental network is presented in Section 4.3. The circumstances of each sensor node's deployment location and mounting circumstances in the urban sensor trial are also outlined to give context to the recorded conditions at each node.
- Observations during development of the sensor node software revealed that the controller platform used in the trial (Seeeduino Stalker) had insufficient memory and inputs needed for a streetlight-integrated sensor system (Section 4.4).
- Results from the deployment of the urban sensor network developed in this iteration demonstrate that the high ambient temperatures encountered in tropical environments may push components beyond their safe operating conditions (Section 4.4). These high temperatures may necessitate the use of thermal insulation within streetlight housings or reflective paint.

4.3 METHODOLOGY

4.3.1 Platform Requirements and Selection

The Townsville City Council Urban Sensor Network was designed to be a temporary fixture. As such, the deployed equipment was not able to interfere with the building in any way. This condition, and the overall goals of the project, resulted in the following requirements:

1. Sensor nodes had to be completely self-contained in terms of power and weatherproofing. Unlike a streetlight-mounted installation, units installed on the building could not be connected to the power grid or be protected by any existing enclosures.

2. Likewise, access to existing wired or wireless networks was not available and thus, sensor nodes had to operate on an independent ad-hoc wireless network.

3. The sensor nodes had to be able to capture ambient temperature and humidity information and be able to determine when sunlight was hitting the external walls of the office building.

4. All electrical components and enclosure needed to be lightweight to be attached to wall surfaces using a removable adhesive.

5. Sensors and other electronics had to consist of common and inexpensive components that could be readily sourced to minimise costs.

4.3.2 Platform Description

Figure 4.1 shows an overview of the components for the sensor nodes developed in this iteration. Each node was controlled by a Seeeduino Stalker platform, based on the AtMega328P microcontroller [205]. The Stalker platform offered several features that made it favourable for quick implementation of a sensor network, including a real-time clock for independent timekeeping, microSD card socket, a socket to fit common communications hardware, including XBee modules, and a solar charging system. XBee Pro transceivers were used for wireless networking due to their low power consumption and high range capabilities in urban environments. Nodes were powered by a 0.5-Watt solar panel attached to the outside of each enclosure, which charged an internal 980 milliamp-hour lithium polymer battery.

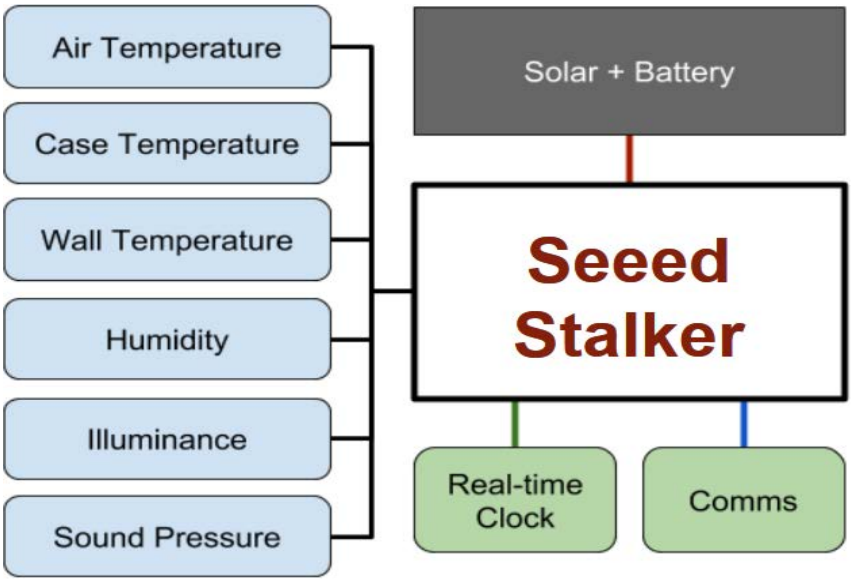


Figure 4.1 - Overview of components used in sensor nodes for building monitoring

The sensor suite in each node, summarised in Table 4.1, captured multiple environmental factors. Air temperature, humidity, and light sensors recorded basic metrics for climate monitoring, including the presence of direct sunlight. An infrared contactless thermometer and temperature probe measured the radiated heat from the surface of the walls to measure how the materials of the building absorbed and retained heat over the day and night cycles. A microphone captured a sound pressure envelope to monitor anthropogenic ambient noise levels. Finally, one sensor node was fitted with a split-core transformer sensor to monitor the power consumption of an LED streetlight being trialled in the building's car park.

Figure 4.2 shows the enclosure and mounting configuration of the sensor nodes. Most sensors, except for those measuring ambient light and case temperature, had to be mounted externally to the node's enclosure. External connections and temperature probes were sealed and made waterproof using epoxy. A conformal coating was applied to the non-contact thermometer to protect any exposed electronics from water damage. Both the microphone and relative humidity sensor were protected by the manufacturer's housings.

Table 4.1 - Summary of pilot sensor module hardware

Component Type	Component Name
Sensor platform	Seeed Stalker v2.3
Communications	XBee Pro 2.4
Air temperature	DS18B20
Case temperature	DS3231 (via Real-time clock)
Radiant surface temperature	DS18B20
Surface temperature	TMP006
Humidity	RHT03/DHT22
Illuminance	TSL2561
Sound pressure level	Freetronics MIC
External power consumption	ECS1030-L72

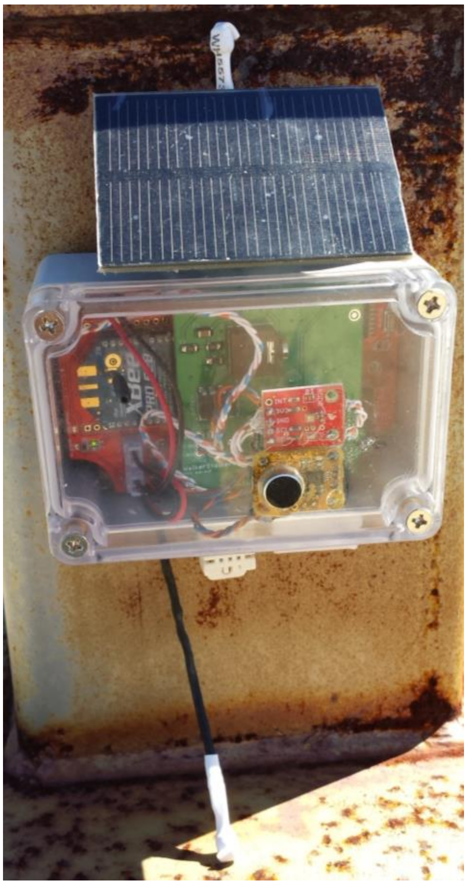


Figure 4.2 - Sensor module enclosure and mounting configuration of sensors

4.3.3 Deployment and Testing of the Urban Sensor Network

Eleven sensor nodes were installed on the exterior walls and roof of the municipal building. A Raspberry Pi with an attached XBee transceiver was installed inside the building's roof cavity and used as a centralised collection point for sensor data from each of the deployed nodes. All incoming data was processed and stored before being periodically uploaded to an online Data Asset Management platform via public internet services. Data sent to the management platform could then be viewed and analysed in a human-readable format to investigate the recorded environmental data and monitor the condition of each node.

Sensor nodes were installed in the following locations (Figure 4.3):

- Units 1, 2, and 5 - 7 were installed on walls at various heights;
- Units 9 and 11 were installed on white roofs and unit 10 on a brown roof to observe temperature differences between roof colours;
- Unit 8 was installed inside the roof cavity;
- Unit 3 was fixed to a light pole above street level; and
- Unit 4 was installed in the building's outside lobby area

Figure 4.3 - Unit location topology for the sensor node deployment

4.3.4 **Data Analysis**

Analysis of the recorded data focused primarily on the temperatures recorded and their potential bearings on a streetlight-mounted network. Case temperatures recorded by the roof-mounted units were of interest as they would receive direct sunlight for most of the day, like streetlight housings. Aside from temperature, sensor data was scrutinised to determine if the sensor hardware was still functioning as expected.

4.4 RESULTS AND DISCUSSION

Three primary aspects of the sensor network were investigated during the deployment. Firstly, the controller platform was evaluated for its capacity to control the sensors and hardware and perform the required processes to use the collected information. Secondly, the recorded temperature and humidity levels were considered to find potential risks to hardware longevity. Thirdly, the general performance of sensor node components was evaluated to identify which parts were suitable to long-term environmental sensing operations.

4.4.1 Controller Observations during Sensor Node Development

The Seeeduino Stalker platform used in this iteration was suitable for short-term urban sensing, but its usefulness was limited. The controller was able to interface with all the sensors to fulfil the information requirements of the project, but by a narrow margin. One primary limitation was the lack of available program memory on the AtMega328P microcontroller, which limited the number of software libraries that could be used, and thus, the functions that the controller was able to perform. As a result, functions such as debugging and local storage of sensor information to the on-board microSD card had to be removed from the final deployed program to fit within the capacity of the platform.

Without local data logging, the deployment had to rely solely on wireless communications to transfer data from the sensor nodes to the base station to be recorded. Any failed transmissions or loss of power resulted in the loss of sensor data. A second limitation of the controller in the context of smart streetlights was the number of inputs. The included components and functionality of the Stalker board were useful for an urban sensor network, including battery management system and microSD slot. These components may not find appropriate use for a streetlight-mounted deployment, but nevertheless, the included control systems of these components occupied many of the microcontroller's input/output ports. After the inclusion of the environmental sensors, only three ports remained to accommodate the extra sensors needed for traffic detection and any other features needed to control and monitor streetlights for dimming applications, which was likely to be insufficient.

4.4.2 Considerations for Sensor Mounting

Street lighting electronics must be protected against the weather and still be able to accurately record the surrounding environment. A major concern in tropical environments is high heat and humidity, which causes corrosion and reduces the longevity of components [206]. During the deployment, recorded humidity levels frequently exceeded 90%. A specification of the Australian standards on solid-state light controllers [207] requires the electronics to be mounted inside a waterproof enclosure, which should overcome the humidity problem. However, completely enclosing the sensors and electronics would hinder environmental monitoring such as air temperature, which needs access to open air for accurate measurements.

The temperatures recorded by the probes varied depending on their positioning. Figure 4.4 shows the recorded temperatures from three sensor units; two deployed on the building's roof, and one mounted on a pole at street level. The data shows that the temperatures recorded by probes with direct contact with the node's mounting surface were up to 10°C higher than probes mounted away from the enclosure. This difference in temperature was an expected result but had some minor implications in the context of a smart streetlight implementation in that sensors would need to be mounted on the underside of the streetlight housings, and away from any surfaces radiating heat for accurate air temperature measurements.

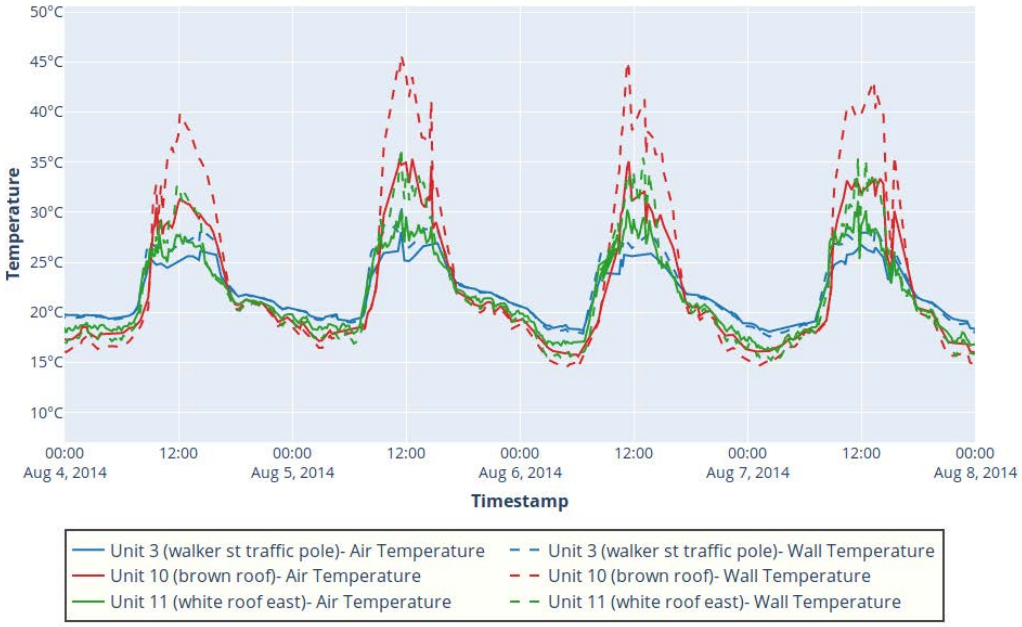


Figure 4.4 - Air temperature recorded in winter from roof-mounted and pole-mounted units

4.4.3 **Temperature Considerations**

Case temperatures inside the sensor node enclosures often exceed 50°C (Figure 4.5) to a maximum of 64.6°C recorded over the trial period (Figure 4.6). This temperature fell within the safe operating conditions for most of the electronic components in each sensor node. However, the high temperatures did pose a problem for the solar charging module used in this urban deployment. The lithium-polymer battery used with the solar charging system had a maximum safe operating temperature of 50°C [208], after which the battery's lifetime and performance were likely to degrade, and increased the risk of thermal runaway, where the battery could rupture and damage other components or the mounting structure. These risks would not be acceptable for a streetlight-mounted system.

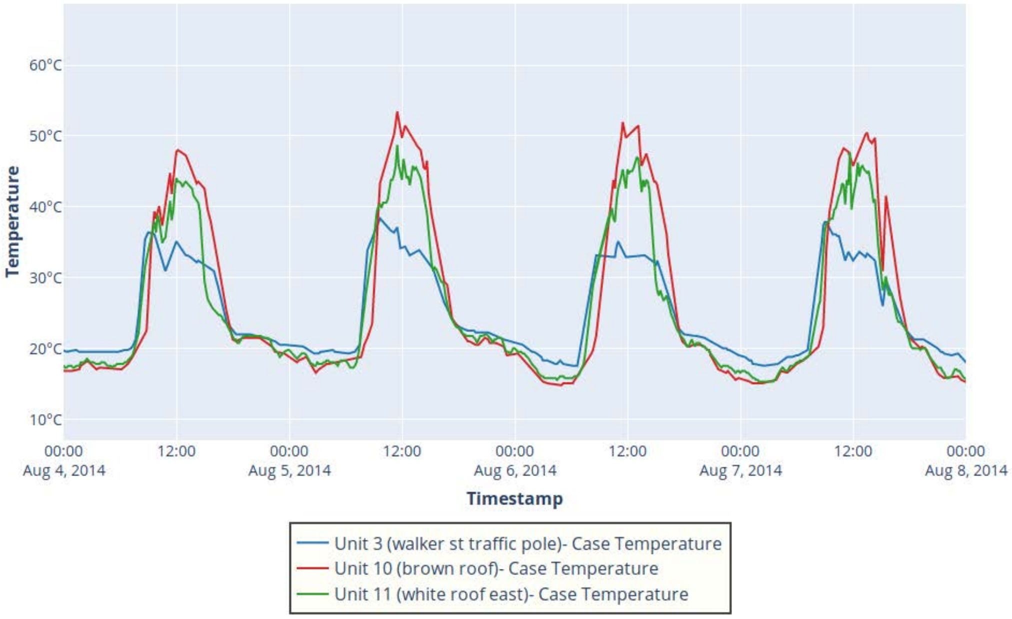


Figure 4.5 - Internal case temperature recorded during winter from roof-mounted and pole-mounted units

However, temperature conditions inside a streetlight housing would likely differ from the polymer enclosures used in this trial. Primarily, the lack of a transparent window would prevent radiation from being absorbed by the internal hardware components, and the structure and placement of streetlights would allow for greater airflow and ventilation to transfer heat away from the housing. However, the streetlight housing would still be exposed to sunlight, which may in turn trap heat inside the housing. Additionally, heat generated from the operation of the streetlight lamp may increase internal temperatures and cause a risk of damage to electronic components. Heat management techniques may be required to mitigate these risks, such as painting the tops of streetlight housings white to reflect heat during the day, and the use of insulation to protect sensor electronics from heat generated both internally and externally to the streetlight operation.

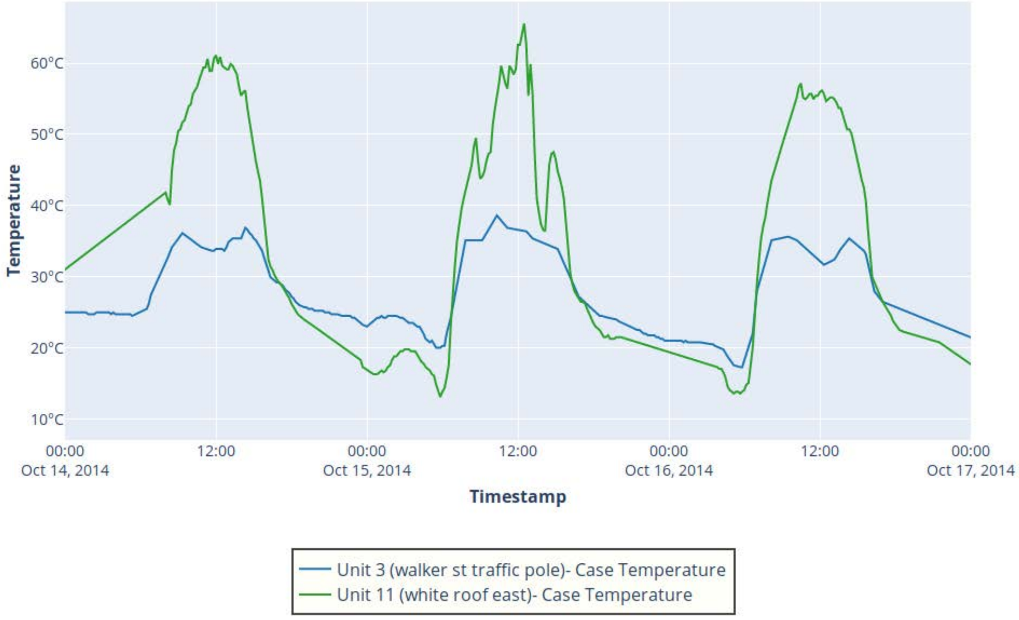


Figure 4.6 - Internal case temperature recorded during summer from roof-mounted and pole-mounted units

4.4.4 Environmental Sensor Performance and Considerations

Most of the tested sensors appeared to work well during the deployment period and reported no problems. These effective sensors were: the temperature probes used for air and surface temperature measurement; the microphone module for noise measurement, and the illuminance sensor. The remaining three sensors (humidity, radiant wall temperature, and current monitor) were subject to mounting or configuration problems that caused them to fail in the deployment environment or cause them to be unsuitable for an urban or streetlight-mounted deployment (shown in Figure 4.7).

The non-contact infrared thermometer, for the most part, functioned as intended and could successfully measure the heat radiating off the sensor node's mounting surface. However, a major problem of the sensor was how it was mounted. The acrylic window of the sensor node enclosure was opaque to infrared radiation, so unlike the illuminance sensor, the non-contact thermometer had to be mounted externally, which exposed it to the elements. Despite the applied conformal coating, corrosion was visible on some modules within two weeks of deployment.

Regardless of mounting, the TMP006 non-contact thermometer was not suitable for a streetlight installation due to its wide measurement angle (120°). For the building-mounted network, the sensor was only intended to measure the temperature of the sensor node’s mounting surface at a distance less than a metre away. However, for a streetlight mounted system, a non-contact sensor to measure the road temperature would need to get an accurate reading from a surface over a much larger distance (over six metres), necessitating a much narrower field of view. Overall, the lack of a sensor enclosure, combined with the wide measurement angle make the TMP006 ill-suited to a streetlight-mounted sensor network for road temperature monitoring.

The humidity sensors used in the sensor deployment were also mounted externally to the sensor node’s enclosure, which may have degraded sensor reliability. During the deployment, three of the 11 humidity sensors recorded levels that deviated from the typical humidity curve recorded by other sensors and their own historical data. Instead the sensors, separately and starting at different dates, reported long

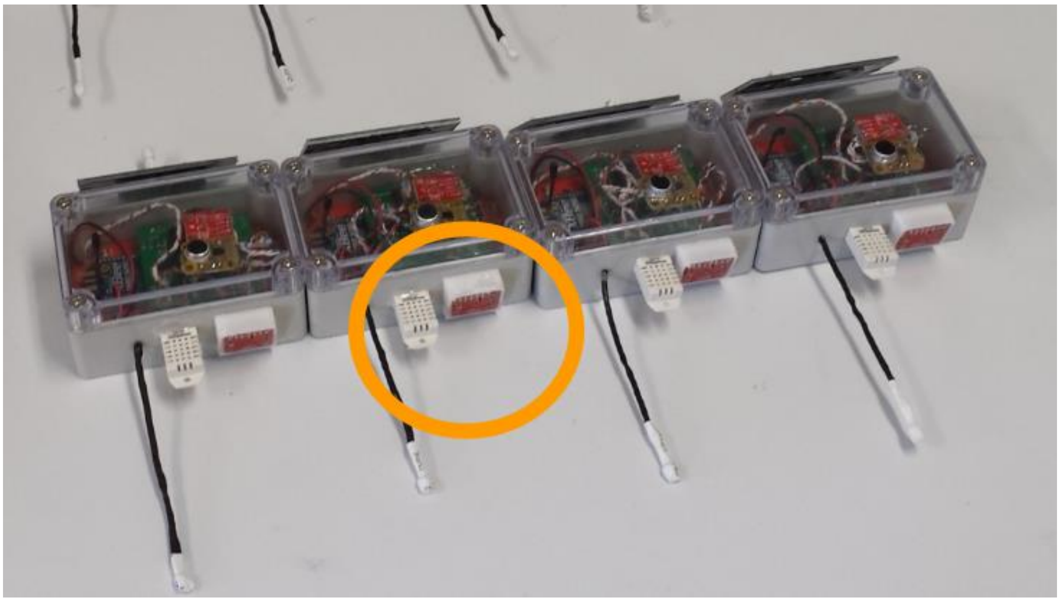


Figure 4.7 - Underside of the deployed sensor nodes, showing the mounting configuration of the humidity and non-contact temperature sensors

periods of 100% humidity at night, followed by 0% humidity during the day. This behaviour somewhat followed the observed humidity curve from other sensors, but the accuracy had completely degraded to the point that measurements were no longer useful. All remaining sensor nodes continued to report reasonable humidity values for the region during the sensor deployment. No specific weather events were observed prior to the sensors failing, but failure was attributed to general outdoor exposure as corrosion was visible on the retrieved sensor nodes three to six months after deployment (individual nodes were retrieved after failure). Like the non-contact thermometer, a more enclosed sensor would be preferable in the future to improve sensor longevity in a streetlight-mounted deployment.

Lastly, the current monitor was unable to detect the low current used by the LED light in the parking area. The monitoring circuit used with the sensor was a generic configuration originally intended for loads ranging from zero to ten amperes. Because of this range, the relatively minuscule current that would be drawn by the LED light (in the range of 300 milliamps) could not be detected by the controller's analogue-to-digital converter. As such, no comments could be made as to the effectiveness of the power monitoring solution aside from that the measurement circuit should be specifically tuned for target load for accurate measurements.

4.5 CONCLUDING REMARKS

This chapter presented a preliminary trial to study the requirements and considerations of a streetlight-mounted sensor network. A wireless sensor network was deployed on an inner-city municipal building to emulate the conditions of a streetlight-mounted system, and trialled multiple sensors for environmental monitoring. Observations made during the sensor node's development and after their deployment identified the following improvements and considerations that must be made during development of the sensor selection and hardware design:

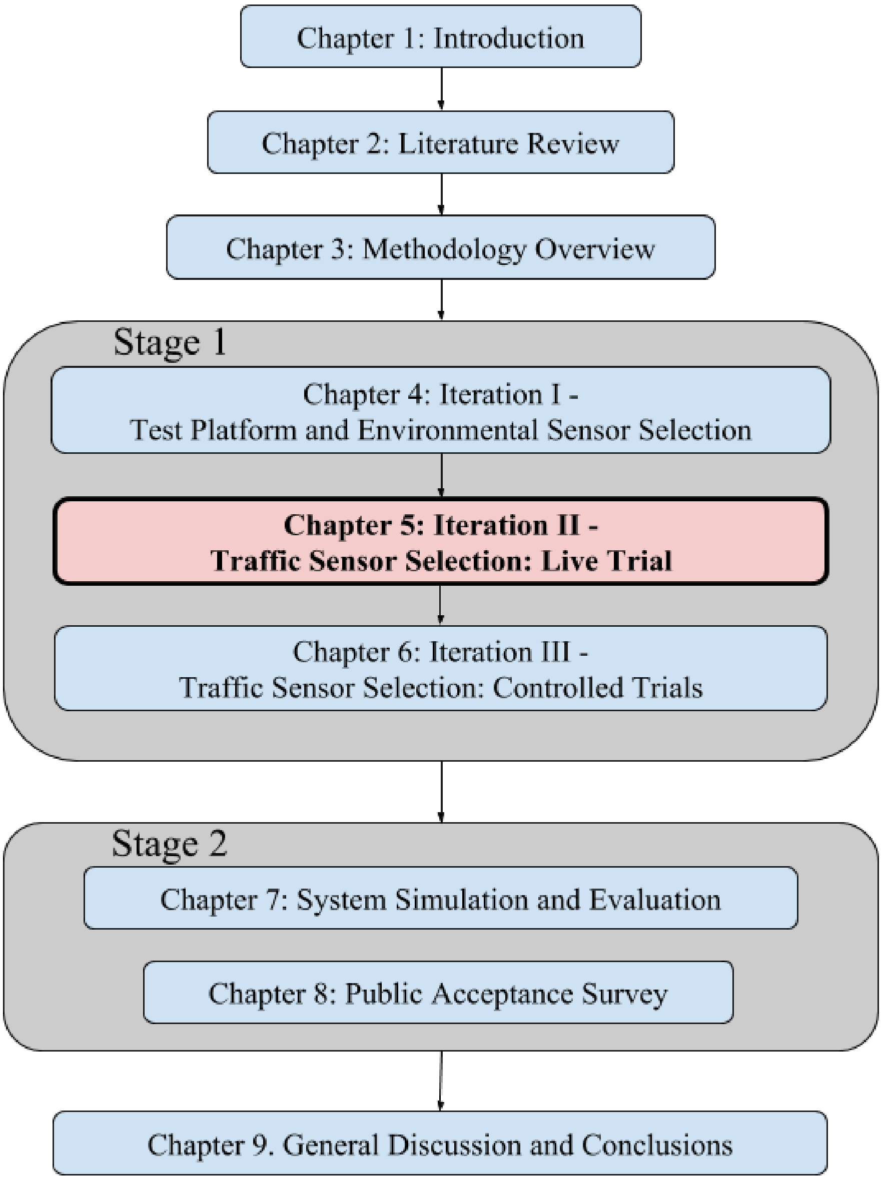
1. A more capable controller platform than the Seeeduino Stalker used in the trial deployment is required for smart streetlight applications. A greater memory capacity for program files is required to allow for the expanded functionality of traffic detection operations, and to re-enable functions such as logging and debugging that had to be

removed for this trial. A greater number of input and output ports is also a likely requirement, depending on which technologies are employed for traffic detection and interfacing with lighting control systems.

2. The high internal temperatures recorded from the sensor node enclosures may pose a risk to electronic components in tropical areas. More volatile or temperature-sensitive components such as the lithium-polymer battery used in the trial should be removed from the system design wherever possible to lower the risk of damage or reduction of hardware longevity in a long-term deployment. Other interventions such as insulation or other heat mitigation practices may be necessary for a streetlight-mounted hardware configuration for use in tropical environments.
3. Sensors that required mounting completely externally to the sensor node enclosure should be replaced with waterproof equivalents wherever possible. For example, sensors such as the non-contact thermometer can be replaced by variants with completely enclosed sensing elements. While not particularly suited to the trial deployment discussed in this chapter, these variants would better serve the long-term deployment of a streetlight-mounted sensor network.

At the end of this initial deployment iteration, a prototype sensor node design for urban environmental sensing was established. The knowledge gained over this trial deployment provided insights into how this prototype design should be modified and improved for a streetlight-mounted configuration and guided the hardware selection and operating procedures of the prototype's development.

Chapter 5 - Iteration II - Traffic Sensor Selection: Live Trial



The major findings from this chapter were published in the Journal of Grid and Utility Computing as follows: ‘K. Mohring, T. Myers, and I. Atkinson “Playing in Traffic: An Investigation of Low-cost, Non-invasive Traffic Sensors for Street Light Luminaire Deployments”’ [2]. Most of the information pertaining to the preliminary sensor selection and testing were omitted from the publication due to length restrictions. Similarly, results and discussions of the tested environmental sensor performance was also omitted from the published article. This information has been incorporated back into the chapter as presented.

5.1 CHAPTER OVERVIEW

Findings from the first development iteration explored the requirements needed to build a stable platform for urban sensing. This chapter presents the second development iteration of the prototype streetlight-integrated sensor system, which builds on these findings by investigating which traffic sensor technologies can be included in the design. Low-cost commodity sensors were investigated for their effectiveness at traffic detection in two phases. The first testing phase was a preliminary test to determine whether each sensor type was able to detect pedestrians and/or vehicles at the minimum mounting height of a streetlight-integrated implementation.

The second phase of testing installed these sensors into a streetlight housing to test their detection performance in a live and long-term traffic trial. Sensor information collected during this deployment was also analysed to determine what further changes and considerations had to be made to the prototype. The chapter concludes by reviewing the performance of each of the tested sensor types and remarking on their current applications and how performance might be improved.

5.2 CHAPTER INTRODUCTION

Realtime traffic information is a vital part of smart road infrastructure and can be categorised into three types: presence, volume, and class. Presence indicates if the road or footpath is actively occupied, which is useful for adaptive road lighting and other applications that need to respond rapidly to individual events. For the example of adaptive road lighting, presence information informs which road sections need to be illuminated within the lighting installation to provide safe movement for vehicles and pedestrians. Networked presence detection systems, such as those discussed in Chapter 2, can share this presence information between neighbouring lights to pre-empt traffic movements, and on a larger scale, localise and track moving groups of traffic.

Traffic volume and classification by comparison are a measure of road activity over time, and by which group of road users. Rather than being used in applications that require quick reaction, this kind of information is more useful in the longer term. Traffic counts can identify platoons of cars for traffic-light improvement techniques, and to identify busy road sections in real time for navigation purposes. Road authorities can also incorporate historic traffic volume and classification to maintain and improve roads to cater to the needs of each road's primary users or develop policies for more efficient and safer road travel.

This chapter presents the second development iteration of the prototype sensor system for streetlight-integrated traffic and environmental sensing. The focus of this iteration was to investigate which commercially available, low-cost sensors could be suitable for traffic presence detection from the vantage point of a streetlight housing, as well as its traffic counting capabilities. This chapter also investigated hardware and design changes to remedy the concerns and problems encountered with the prototype's hardware design during the previous iteration.

5.2.1 Summary of Contributions

This chapter presents the following contributions:

- Preliminary testing of commodity sensors was conducted to select traffic sensors appropriate for installation within a streetlight housing. The tests demonstrated that passive infrared (PIR) and sonar sensors could be useful, but some models of PIR responded poorly to the outdoor environment. Testing also showed that optical flow sensors were not able to detect traffic using the manufacturer's inbuilt detection system but showed that basic greyscale imagery was possible with the microcontroller platform used in the trial (Section 5.3).

- An in-situ trial of three inexpensive, non-invasive sensors for traffic detection was conducted in a streetlight-mounted configuration using live traffic on a campus road. The sensor platform included passive infrared (PIR), sonar, and lidar devices. Recorded video footage was used to ground truth the sensor data to determine each sensor's traffic detection and counting accuracies (Section 5.4).

- A streetlight-mounted testbed and mounting solution was developed to investigate the performance of the chosen traffic sensor in an actual road environment. The HC-SR501 PIR motion detector was shown to be the most accurate sensor of the three types tested, with an overall counting accuracy of 73%. Video analysis shows that the sensor could detect the presence of both pedestrian and vehicular traffic with 92% reliability, although it significantly undercounted vehicles (Section 5.5).

5.3 PRELIMINARY TRIAL

The first testing phase of this iteration was to determine which sensor technologies could detect pedestrians and vehicles at streetlight height. This section provides an overview of the findings of the multiple preliminary tests conducted in iteration II and focuses mostly on the final preliminary testing phase.

5.3.1 Sensor Selection

Three types of small, lightweight, and low-cost sensors were tested in the preliminary trials. Table 5.1 shows the specific models of each of these sensors, five in total, and whether they were included within the final preliminary trial. Each sensor, and its reasons for being included or omitted from the final preliminary trial, is discussed in the following sections.

Table 5.1 - Sensor types and models included in preliminary traffic detection testing

Type	Model	Included in final preliminary testing?
PIR	DFRobotics AM412	No. Too sensitive for outdoor conditions
PIR	HC-SR501	Yes
Sonar	Maxbotix MB1320	No. Interference problems
Sonar	Maxbotix MB1240	Yes
Optical Flow	ADNS3080	Yes

The HC-SR501 PIR sensor was selected for detection of both pedestrians and vehicles in the preliminary trials. This sensor was chosen over the AM412 model mostly due to its wide seven-metre radius detection area and adjustable sensitivity options. Earlier trials showed that the high and fixed sensitivity of the AM412 caused the sensor to almost continuously record movements in outdoor environments due to wind, etc. The adjustable sensitivity of the HC-SR501 sensor was able to be configured to ignore small movements and only register the large movements from vehicles or pedestrians. Another feature of the HC-SR501 was an adjustable hold-off time, which sets the minimum amount of time between sensor recordings to avoid recording multiple movements for the same traffic event.

For the sonar sensor, a Maxbotix MB1240 (XL-MaxSonar-EZ4) was used to detect traffic directly under the sensor using distance-based measurements. The MB1240 was selected for its narrow detection area after it was found that the wider area model (MB1320) was reflecting its signals off the mounting surface, causing incorrect distance measurements. Signals from sonar devices leave the emitter in a cone pattern. The narrow detection of the selected sensor allowed it to be mounted a reasonable distance away from the mounting surface without causing interference from reflected signals.

The ADNS3080 optical flow sensor was included in the trial to visually detect moving traffic. Optical flow sensors use a low-resolution camera to measure uniform movements across their entire field of view, and are the key technology in the optical computer mouse, but have also been used to determine the ground speed of unmanned aerial vehicles by tracking terrain changes beneath the vehicle [209]. The ADNS3080 used in the trial was equipped with an on-chip detection algorithm to perform basic visual processing tasks to determine the direction of movement of observed objects.

5.3.2 Testing Location and Setup

Traffic tests were conducted on a pedestrian overpass that was overlooking a low-traffic road and footpath. The pedestrian overpass was located at a height of approximately 5.5 metres above the road’s surface and had a hand railing, which allowed sensor hardware to be securely attached and mounted over the roadway to observe both pedestrian and vehicular traffic below.

Figure 5.1 shows the physical mounting configuration of the sensors tested over the preliminary testing phase. All sensor hardware was fitted to an outreach pole, approximately 0.5 metres in length, which was clamped to the railing of the pedestrian overpass and held in position using a stay line. All sensors were attached securely to the pole, facing downwards to receive an unobstructed view of the road (Figure 5.2). The sonar, which was sensitive to interference from nearby objects and surfaces, was positioned at the end of the pole to allow for maximum clearance from the mounting surface.

The sensor controller (ITEAD WBoard Pro [210]) was directly connected to an external computer system to receive power and data transfer for logging. A video camera was also mounted on the outreach pole to record traffic events for the duration of the test. Timestamps from recorded sensor events were correlated with those from actual traffic events provided by the video footage. The final sensor test was conducted over a short timeframe (< 1 hour) to determine which sensors were able to detect traffic.

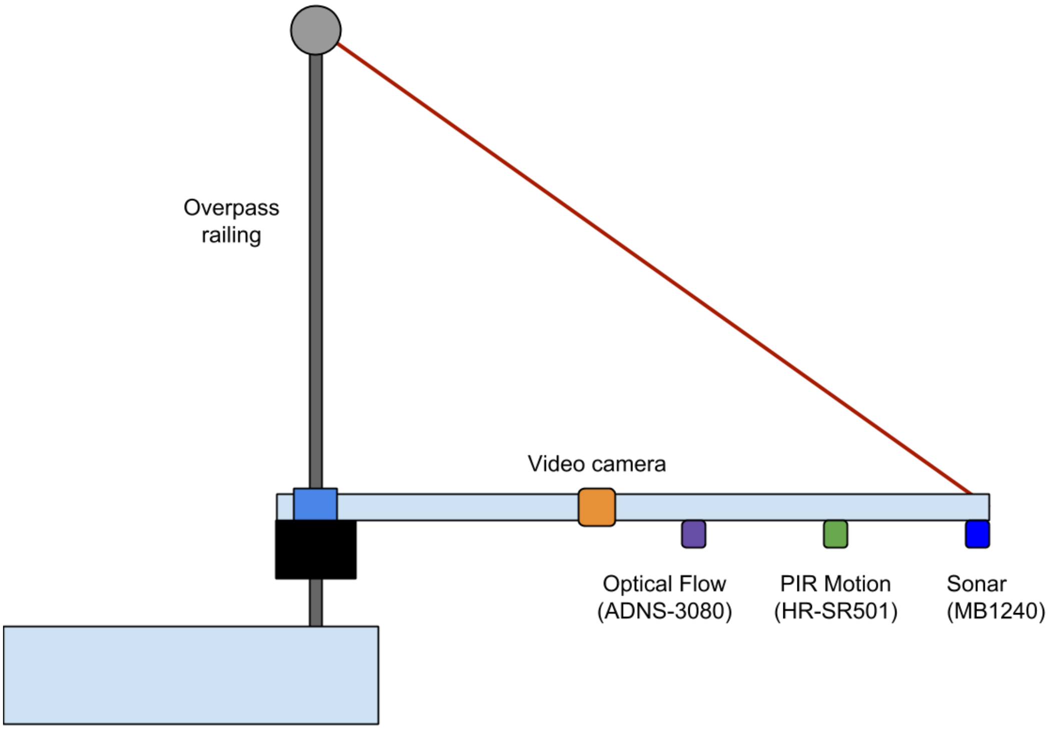


Figure 5.1 - Physical arrangement of traffic sensors for preliminary testing

Figure 5.2 - Sensor vantage point over the road and footpath during preliminary testing

5.3.3 Preliminary Results and Analysis

The final preliminary test involved 50 combined traffic events. Of these events, there were five vehicle passes, five cyclists, and 47 pedestrians (either alone or in groups). Table 5.2 shows a summary of the number of traffic events recorded by each sensor. The following sections discuss the implications of this data.

Table 5.2 - Traffic events recorded per sensor in preliminary test

Sensor Type	Number of traffic events detected
Actual (Video footage)	50
Sonar (MB1240)	3
PIR motion sensor (HC SR-501)	109
Optical flow sensor (ADNS 3080)	0

5.3.3.1 Preliminary PIR Outcome

A cool-down time between motion events was set to two seconds in software. One observed consequence of the low hold-off time was several multiple sensor detections for traffic events, where targets took longer than the cool-down time to cross the sensor's field of view. Overall, 109 traffic events were captured by the PIR sensor, covering all types of traffic (the sensor is unable to distinguish between traffic types). Despite the much larger number of detections, the traffic count and timing from the PIR sensor appeared to correlate with the traffic events captured by the video footage (Figure 5.3).

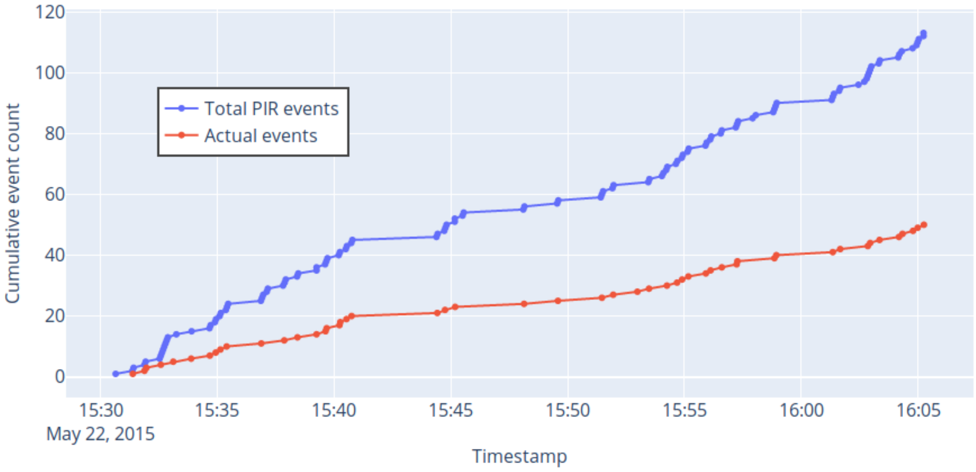


Figure 5.3 - Comparison between traffic events recorded by the PIR sensor and actual traffic events, showing similar trigger timing

Figure 5.4 - Comparison between PIR-recorded traffic events, actual traffic events, and total traffic counts over final preliminary trial

To demonstrate the cause of over-counting, all duplicate detections were removed from the data. Duplicate events were filtered from the PIR traffic count by only counting ‘rising edges’ from the sensor, meaning that only ‘new’ events were considered. Comparison of ’new’ detection events and video events showed a very high correlation between count timelines, as well as a very close total count (54 for PIR vs. 50 for video), as shown in Figure 5.4.

5.3.3.2 Preliminary Sonar Outcome

The sonar did not appear to detect pedestrians travelling beneath the sensor platform. In fact, over the trial period, the sonar detected only three events. Time correlation with the video footage showed that these recorded events coincided with vehicles passing underneath the sensor. Table 5.3 shows a summary of the vehicle events from the trial. All vehicles detected by the sensor were travelling directly underneath the sensor enough so that their roofs were visible in the video footage. The other two vehicles in the trial that were missed by the sensor were further away from the testing area and likely fell outside of the sonar’s relatively narrow detection area.

From the overhead position, the sonar was likely not able to detect pedestrians due to their low cross-sectional area when viewed from above. In other words, the sonar signals reflected from the heads of pedestrians were not strong enough to be received by the sensor, or perhaps the footpath was outside the sonar’s detection area. Regardless, the sonar demonstrated that it was only able to detect vehicles during the test.

Table 5.3 - Summary of vehicle events during preliminary traffic detection test

Vehicle Event	Detected by Sonar	Notes
1	No	Vehicle appeared at the edge of the video frame. Roof not visible in video
2	Yes	Electric buggy. High & flat roof clearly visible in video
3	Yes	Sedan. Reasonably close to the curb. Roof visible in video
4	No	Vehicle far away from the curb. Roof not visible in video
5	Yes	Vehicle very close to the curb. Roof clearly visible in video

5.3.3.3 Preliminary Optical Flow Outcome

The optical flow sensor did not record any events during the final preliminary trial, or in the previous trials where it was included. The on-chip detection algorithm was able to detect movements over relatively small distances of less than one metre but was not able to produce any measurable results when applied to road traffic at greater heights.

5.3.4 Outcomes of Preliminary Testing

Comparison of the video footage and the sonar traffic counts indicated that the sensor could detect vehicles, but not pedestrians. The PIR sensor detected all traffic, regardless of type, meaning the combination of sensors could be used with sensor data fusion to classify traffic as pedestrian or vehicle, depending on which sensors recorded an event.

The PIR motion sensor used in the preliminary trial could produce a much more accurate traffic count when ignoring run-on events. The two-second hold-off period was too short for pedestrian events and caused the sensor to fire multiple times during the same traffic event, leading to inflated traffic counts. Ideally, the cool-down time should be equal to the amount of time it takes for traffic to travel across the sensor's detection area to avoid over-counting. For pedestrian traffic, this was roughly six seconds in this instance.

5.4 STREETLIGHT-MOUNTED LIVE TRIAL

The second phase of the iteration was to test the chosen traffic sensors on a larger scale. Before this phase, the sensors had only been tested with limited traffic volumes and only over short periods of time, typically on the scale of hours. This phase involved a trial installation of the prototype traffic and environmental sensor platform inside a streetlight housing to evaluate its real-world performance.

5.4.1 Testing Location and Setup

The location of the test bed streetlight was on a moderately busy road, situated next to a raised pedestrian crossing (Figure 5.5). The presence of the pedestrian crossing allowed the traffic sensors to be evaluated for foot traffic as well as road traffic. Sensors were fixed to custom 3D-printed mounting plates that were installed

Figure 5.5 - Location of streetlight-mounted test bed showing detection area, pedestrian walkways, and raised crossing

inside the active streetlight housing (Figure 5.6). All traffic and environmental sensors pointed down to the road surface, approximately 7.7 metres below. The microcontroller and attached sensors were powered throughout the day using the lamp's power supply with all external components sealed inside to protect the internal electronics from weather conditions.

A secondary effect of the pedestrian crossing was that it acted as a speed bump, causing vehicles to pass through the detection area at a relatively low speed, which also gave more time for detection to occur. The test environment for the sensors was in the tropics where the sensor platform was active over the summer months. Elevated temperatures and humidity were recorded over the sensor platform's deployment, with

Figure 5.6 - Mounting configuration of testbed sensors. (Left) Traffic sensors are located on the rightmost plate and environmental sensors are located on the leftmost plate. (Right) The mounting plates aimed the sensors at the roadway below.

infrequent episodes of extreme rainfall. These conditions formed a hostile and difficult environment for sensor deployment.

5.4.2 Hardware Selection

The hardware installed inside the streetlight housing was built on the previous work established in iteration I (Chapter 4). Aside from the addition of sensors for traffic detection, the following changes were made to the platform's design (Figure 5.7):

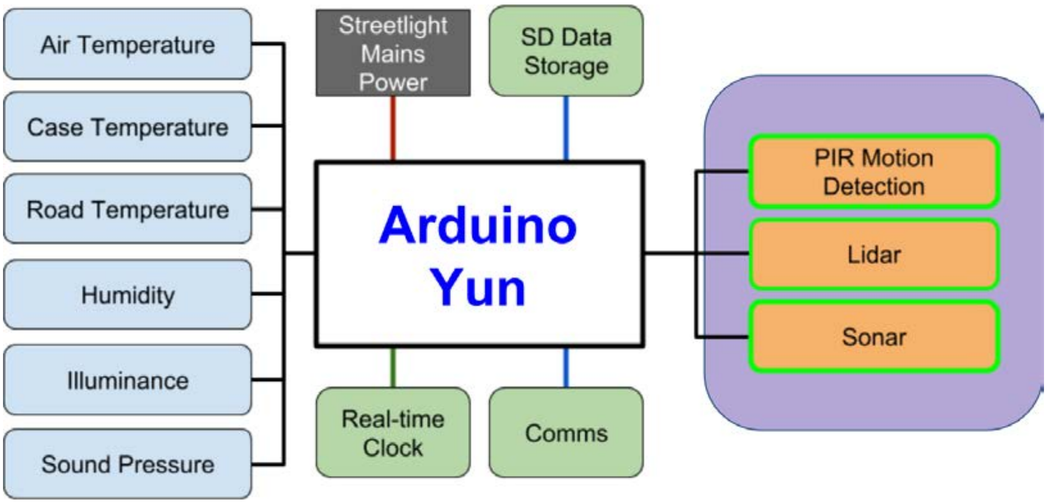


Figure 5.7 - Overview of prototype sensor platform in development iteration II showing addition of traffic sensors

1) The controller platform was changed from the Seeeduino Stalker to an Arduino Yun. The Arduino Yun used two processors: an ATmega32u4 microcontroller that ran a controller script, and an Atheros AR9331 processor that ran a modified Linux distribution of OpenWRT. The combination of the two processors allowed the low-powered and resource-scarce microcontroller to directly interface with the sensors, while being able to offload tasks such as data processing and logging to the more powerful processor. This ability to perform independent logging was a primary reason for using the Arduino Yun in this deployment, following earlier trials where logging had to be disabled due to the memory constraints of the microcontroller-based sensor platforms [3]. The platform also enabled Wi-Fi network capabilities.

2) The humidity sensor and non-contact thermometer from the previous iteration were replaced with completely enclosed components. In the case of the humidity sensor, the sensing element was supplied as a bare part from the manufacturer. A custom screen for the sensor was designed and constructed for the prototype out of 3D printed components to better protect the sensor from rain ingress. The non-contact thermometer was replaced with a longer-range sensor that could detect the road temperature from the streetlight mounting and featured a completely enclosed design.
3) The prototype was powered by connection to the electrical grid, rather than solar charging.
4) Three off-the-shelf sensors were included in the testbed to detect traffic: PIR, sonar, and lidar (Table 5.4).

The HC-SR501 PIR sensor performed well in preliminary testing and could detect all traffic types in a 360° detection area around the sensor platform with a counting accuracy of 92%. The sensor was polled every 200 milliseconds to determine if a detection had occurred. The hold-off time of the sensor was set to five seconds to reduce the duplicate counting of pedestrians as encountered in the preliminary trial.

Table 5.4 - Sensor hardware included in streetlight-mounted traffic test

Sensor Type	Sensor Name
PIR motion detector	HC-SR501
Lidar	PulsedLight LidarLite
Sonar	MaxBotix MB1240
Air temperature	TMP36
Road temperature	Melexis MLX90614-ACF
Relative humidity	Honeywell HIH-4030
Ambient illuminance	DFRobotics BH1750FVI
Ambient sound pressure	Freetronics MIC
Current draw	ECS1030-L72

Sonar vehicle detection was performed by the Maxbotix MB1240. This sonar model was selected for its narrow detection area to avoid interference from the streetlight pole or housing, and featured a relatively high range of 7.5 metres [211], the approximate height of the streetlight. The sonar was intended to detect vehicles only, following preliminary testing that showed that the sonar could detect vehicular traffic directly underneath a sensor platform mounted at five metres, but was not able to detect pedestrians from the overhead configuration. The LidarLite was added to the sensor platform as an auxiliary unit to the sonar, in case of a failure due to the sonar's operation beyond its rated range. The lidar offered improved performance over the sonar, featuring a longer maximum range of 40 metres and a very narrow field of view (approximately 3°), but at a higher unit cost.

Both the sonar and lidar used a 'vertical tripwire' system to detect traffic. With the sensors facing downwards, objects passing underneath the sensor caused the distance measured by the sensors to lessen compared to the baseline value of the road. Each sudden drop in the measured distance indicated that a traffic event was in progress, which would continue until the measured distance returned to the baseline. This mechanism ensured that long or slow-moving vehicles did not trigger multiple detections and enabled individual detection of vehicles travelling closely together. A 70-centimetre threshold was added to filter out small variations caused by small animals on the road and any noise in the sensor measurements.

Environmental sensors, while not the focus of the test bed, were included to determine if the traffic sensors were affected by changing weather conditions. Five environmental sensors recorded temperatures of the streetlight housing, air, and road surface, as well as the relative humidity, light levels, and ambient noise levels (Table 5.4). A clamp-style current sensor measured the total power consumption of the lamp and control equipment.

5.4.3 **Data Collection and Analysis**

The Arduino Yun's storage was used to collect and store sensor information for all sensors and platform operations. Data was routinely, but manually, collected from the testbed platform by downloading the log files over the Yun's wireless network, as physical access to the storage media was not possible.

A video camera was used to ground-truth the traffic detection capabilities of the sensors. Limited availability of the camera equipment restricted the number of verifiable traffic tests to only three times over the deployment of the prototype system. A traffic detection algorithm was used to calculate traffic counts from the video data

[212]. Manual spot checks of the footage at different parts of the day were used to ensure the validity of the detection algorithm.

5.5 ITERATION RESULTS AND DISCUSSION

During the ground-truth tests of the sensor prototype, the video camera recorded a total of 3,477 traffic events over an 8.5-hour testing period. This period occurred during daylight hours as the traffic camera was ineffective at night. The automated counting process provided an accurate basis of comparison for the recorded sensor data but could not determine the direction of travel of vehicles or classify between traffic types. Manual classification was performed for the first 2.5 hours of video footage to verify the algorithm's counting accuracy and to obtain a more detailed breakdown of traffic during this time (Table 5.5).

Table 5.5 - Breakdown of traffic event types from 2.5 hours of footage recorded at test-bed site

Traffic Category	Number of events
Incoming vehicles	843
Outgoing vehicles	279
Pedestrians	137
Cyclists	34

5.5.1 PIR Outcome

The PIR sensor recorded a total of 3,569 events throughout the day and aligned with the predicted traffic timing and types. Most traffic events occur during daylight hours (Figure 5.8), which was expected as the test bed lies on a main entrance to a university campus with similar business hours. Traffic peaks were clearly visible as they typically occurred 5-15 minutes before the hour changed. These peaks are most notable at 7:50 AM, 8:50 AM, and 1:45 PM, which had the highest peak of the day. Troughs in traffic activity are also consistent, occurring halfway through the hour. Both peaks and troughs in traffic correspond to the university timetable and are likely a result of students arriving and leaving classes. Traffic event data from the PIR sensor showed the expected traffic behaviour, which indicated that the sensor is successfully recording traffic. However, counting accuracy cannot be evaluated by the sensor data alone.

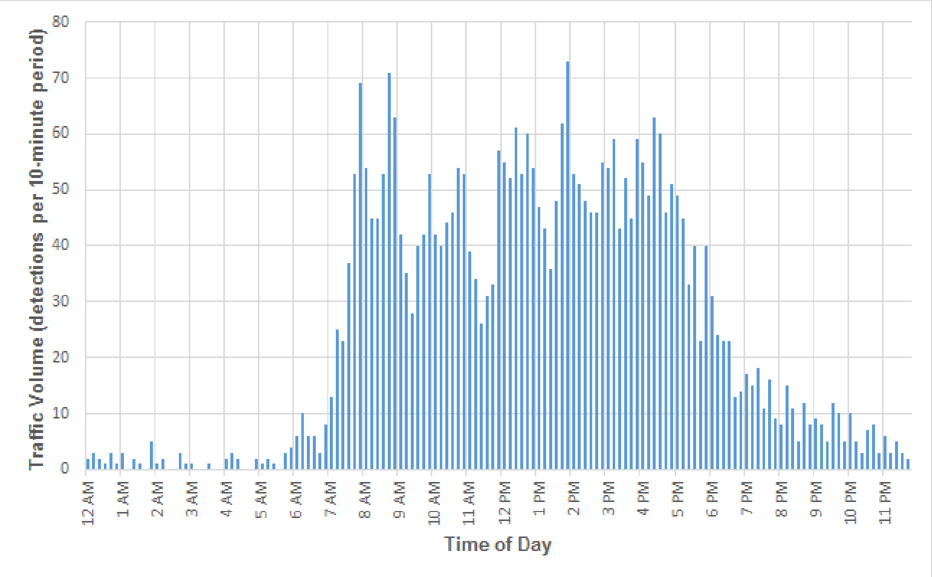


Figure 5.8 - Frequency of traffic events detected by streetlight-mounted HC-SR501 PIR motion sensor over full day. Traffic volume is calculated in 10-minute intervals.

The PIR sensor undercounted traffic when the video footage was used to ground truth the data. The PIR data was compared to the 3,477 events counted by the video processing algorithm and there was a deficit of 936 as the PIR only captured 2,541 events in the recorded period. This result gave the PIR sensor an overall average accuracy of 73%.

A comparison between video and PIR sensor detections shows that undercounting was most prevalent when the traffic volume was high (Figure 5.9). This effect is particularly noticeable during the morning peak between 8:50 AM and 9:00 AM, where only 52% of the 122 traffic events were detected. The recorded footage during this time shows relatively steady 'streams' of cars typically less than two seconds apart. The raised crossing at the detection site created a bottleneck of traffic as vehicles slowed down before the speed bump (to 20 - 30 kilometres per hour) or stopped entirely for crossing pedestrians. Thus, 'queues' of closely-packed vehicles began to form behind the crossing. Undercounting by the PIR sensor during traffic peaks imples that the sensor cannot 'keep up' with the traffic volume.

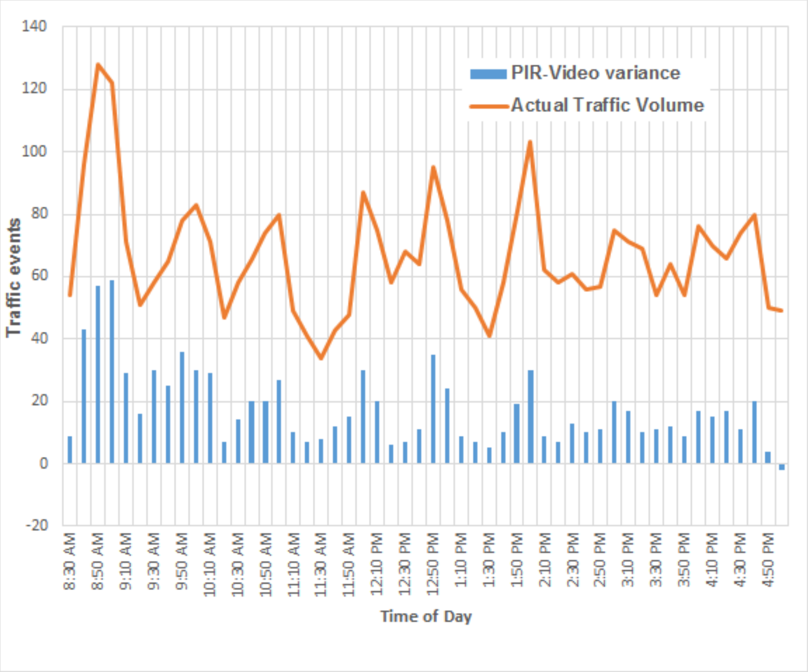


Figure 5.9 - Traffic count variance between video data and PIR sensor detections showing variance increasing with higher traffic volumes

The PIR sensor initially over-counted pedestrians in preliminary testing as the pedestrians would take up to six seconds to cross the sensor's detection area. Pedestrians would trigger a detection when they first entered the zone and would trigger a second detection if they lingered in the area for more than two seconds. This behaviour is due to a hold-off time too short for the observed traffic type. However, a long hold-off time (e.g. ten seconds) may cause the sensor to ignore and miss fast-moving traffic, such as cyclists and vehicles (see Figure 5.10). In the case of this deployment scenario, the sensor's hold-off setting of five seconds proved too high for dense traffic, where the sensor could miss one or two passing vehicles following each detection event. This mechanism explains why periods of dense traffic have a lower counting accuracy than of sparse traffic, where vehicles are less frequent and have more space between one another. This figure is significantly lower than the typical minimum of 90% counting accuracy produced by the commercially available traffic detection systems shown in Table 2.2.

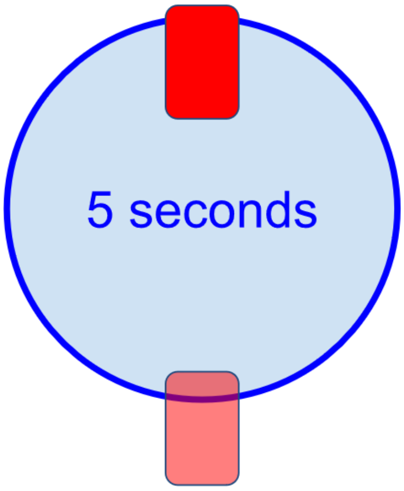
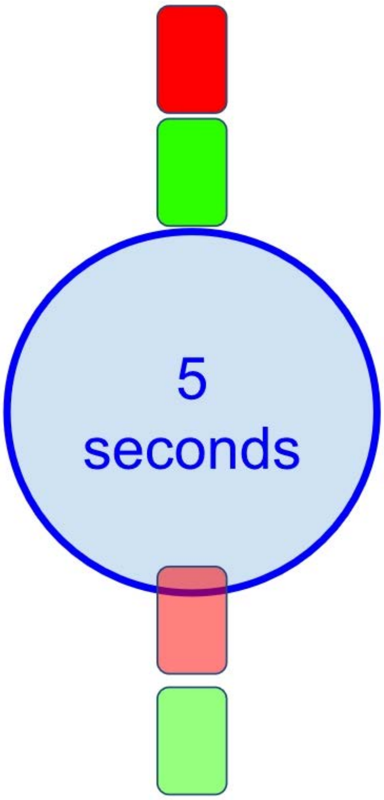
	
Traffic is too slow, causing additional detections before leaving the detection zone	Traffic is too fast for the hold-off time and can allow multiple vehicles to pass through the detection zone as a single event

Figure 5.10 - Potential problems with traffic counting of PIR sensors caused by an incorrectly-configured hold-off time

A simulation subjected the video data to the same hold-off conditions as the PIR sensor by ignoring video detections for a minimum of five seconds after an initial event. With both the video and PIR sensor data subject to the same limitations, hold-off could be removed as a factor attributing to PIR undercounting. The video data with the simulated hold-off counted 709 traffic events (down from the actual 915). Event times appeared to correlate with PIR detection events and resulted in similar detection counts (PIR recorded 751 events in this period), as shown in Figure 5.11. The hold-off added to the video detection algorithm caused the counting variance between video and PIR events to drop (Figure 5.12), resulting in an adjusted detection accuracy of 92%.

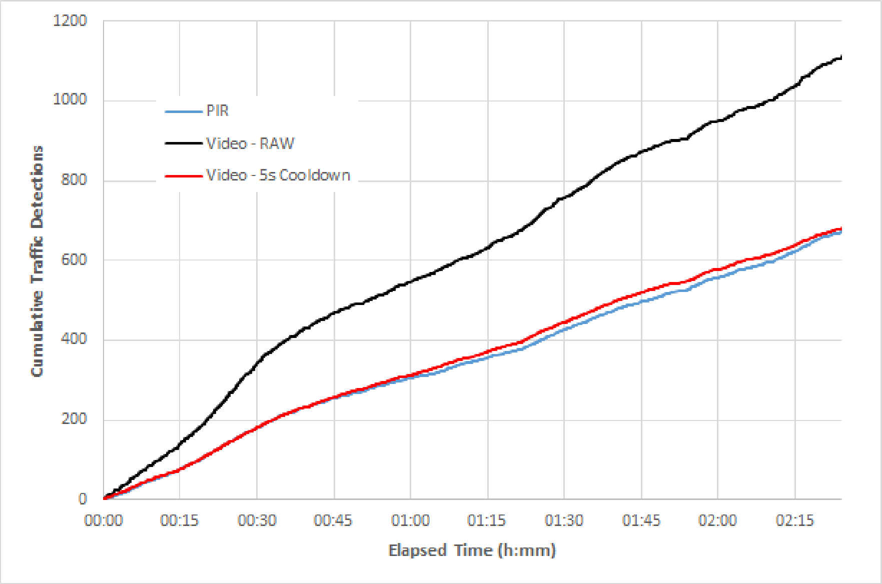


Figure 5.11 - Comparison of cumulative traffic detection count between streetlight-mounted PIR sensor and manual video analysis, showing similarities between PIR detection behaviour and video with an added hold-off effect

Traffic counts from the adjusted video data were typically lower than from the PIR sensor, possibly due to the lower detection area of the video camera compared to the PIR sensors, which gives vehicles a smaller window of time for detection. Incidentally, the hold-off time of two seconds used in the preliminary trial would have been ideal for vehicle-only roads as it corresponds with many countries' laws and best practices regarding minimum safe following distances between vehicles (commonly known as the "2-second rule") [213]. Discounting the possibility of tailgating, a two-second hold-off should be appropriate to capture all passing vehicles over a single lane but will result in duplicate detection on roads with mixed pedestrian traffic. Aside from adjusting to a more appropriate hold-off time, the platform's counting accuracy could potentially be improved by installing additional PIR sensors with different detection areas. Narrow-lens PIR sensors can perform 'spot' detections over a small area. The small detection area allows the sensor to use a low hold-off time without risk of duplicate detections.

Economically, the PIR sensor may be well suited for use with adaptive road lighting if the counting accuracy could be improved. The low hardware cost (as low as AU$4 from some vendors) of the PIR sensor used in this trial would allow for a widespread deployment in streetlights without significantly increasing the cost of the overall lighting infrastructure. The small physical footprint and simple operating mechanics make the sensor compatible with almost any sensor platform.

5.5.2 Sonar Outcome

The sonar over-counted traffic compared to the video data. The sensor reported a total of 15,036 detections between 8:30 AM and 5:00 PM where the video showed 3,477 events. This count results in a ratio of 3.32:1 false sonar detections per actual traffic event recorded by the camera, assuming the sonar could detect all traffic types across both lanes of the road. However, the sonar detecting all traffic is unlikely as preliminary testing showed the sensor was not capable of detecting pedestrians or vehicles that were not directly beneath the sensor platform.

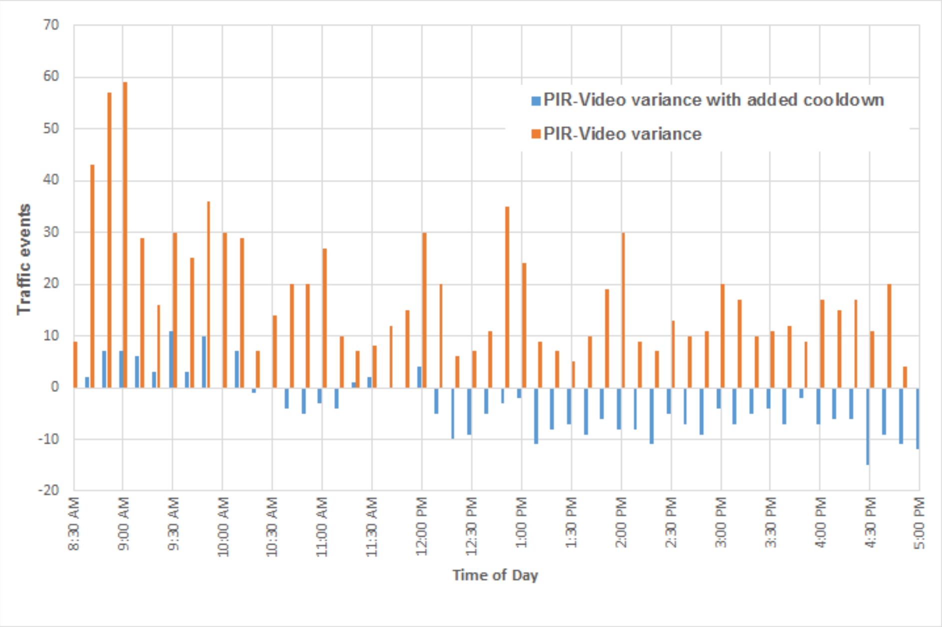


Figure 5.12 - Comparison between Video-PIR variance with and without a 'hold-off' effect added to the captured video data

Sonar activity shows elevated traffic during daylight hours, like the PIR sensor, but the recorded peak times do not correlate with the video data. If the sonar were only reporting duplicate entries for actual traffic events, the shape of the sonar data would be like the video data. However, the lack of correlation indicates the sonar was not correctly detecting traffic. Sonar events over the entire day result in a total of 32,538 detections (shown in Figure 5.13). Two anomalous periods of high activity were observed between 2:00AM and 6:00AM and between 11:30PM and 11:59 PM on the day of the video-recorded trial. Data from the other traffic sensors do not reflect any elevated traffic levels during these two periods (Figure 5.14). High humidity was recorded during the night in both cases but did not have any clear link to the sonar behaviour. Sonar data from subsequent days shows similar anomalies occurring during the night, but time, duration, and number of occurrences are inconsistent. Real time monitoring of the sonar's distance measurements shows erratic sensor reads. Measurements typically stayed at the baseline value of approximately 7.4 metres but would occasionally jump to values as low as three to four metres when no traffic was present on the road, causing false detections. This behaviour may be a result of the sensor operating beyond its operational range, or may indicate a problem with the quality of the sonar's supplied power within the deployment, as the sensor's range is sensitive to voltage changes [211]. However, this avenue of investigation was not pursued.

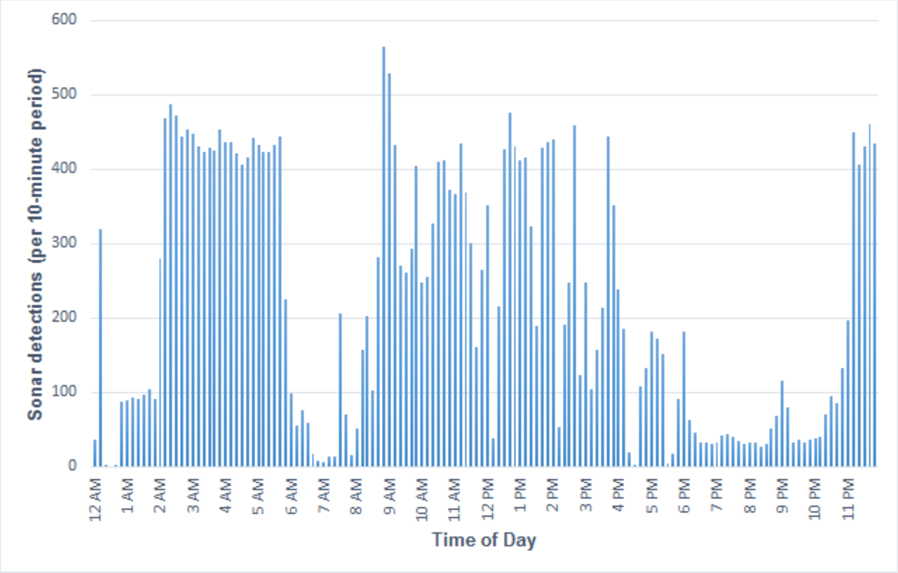


Figure 5.13 - Frequency of traffic detections recorded by streetlight-mounted sonar for a single day

Preliminary tests showed that sonar could detect vehicle-only traffic in individual lanes at the lower mounting height of five metres. Sonar measurements may also be used to keep track of the road level and indicate any anomalies such as parked cars or water over the road at a moderate price point of AU$70. However, in this deployment, the sonar was not able to reliably detect the road level or count traffic consistently due to its erratic measurements.

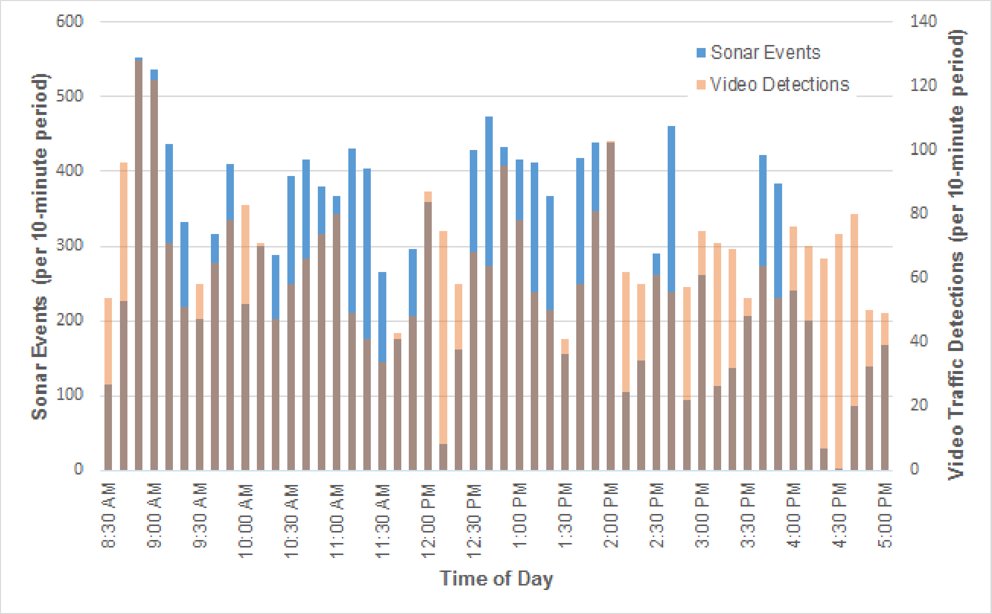


Figure 5.14 - Sonar detections compared to video data showing no correlation between peaks and troughs

5.5.3 **Lidar Outcome**

The lidar used in this trial undercounted traffic, with only 24 detections compared to the 3,477 readings of the video capture during the 8.5-hour period. A visual check of footage at each detection time showed that 13 of these events coincided with a cyclist in the detection area (Table 5.6). Three events were recorded in error, including one duplicate count and two sensor misreads that show a distance of zero centimetres.

Table 5.6 - Log of lidar events showing traffic underneath the sensor at the time of detection

Time	Reported Lidar Distance (centimetres)	Vehicle description (from video)
08:48:38	700	Motorbike
09:02:20	611	Cyclist
09:06:55	648	Cyclist
09:21:03	681	Cyclist
09:23:19	701	Cyclist
09:23:20	613	Duplicate event
09:23:35	0	No event
09:24:04	652	Cyclist
09:26:31	0	No event
09:41:07	672	Cyclist
10:08:52	633	Pedestrian
12:16:35	688	Garbage truck
12:16:37	515	Large truck
12:24:20	659	Cyclist
13:01:35	594	Utility
13:27:39	653	Cyclist
13:54:19	682	Cyclist
14:48:45	693	Utility
15:57:34	652	Cyclist
16:47:35	617	Cyclist
17:08:31	670	Pedestrian
17:12:00	614	Pedestrian
17:21:04	649	Cyclist
17:38:41	674	Cyclist

The remaining events coincided with large vehicles or pedestrians in the detection area, travelling close to the lane marking. The limited detection radius of the lidar was the cause of the disparity between the video and lidar traffic counts. The detection area of the lidar is narrow and measures only 40 centimetres across when mounted at the streetlight's height (Figure 5.15). Video analysis between 9:00 AM and 11:00 AM showed that only six out of an actual 21 cyclist events were captured by the lidar. Observations of 'missing' entries show that cyclists riding outside the lane were not detected, whereas cyclists travelling directly on the lane marking were recorded by the sensor. This detection behaviour, and the small number of vehicle detections, implied the lidar was functioning correctly, but the detection area was located on the lane marking instead of its intended position in the middle of the incoming lane.

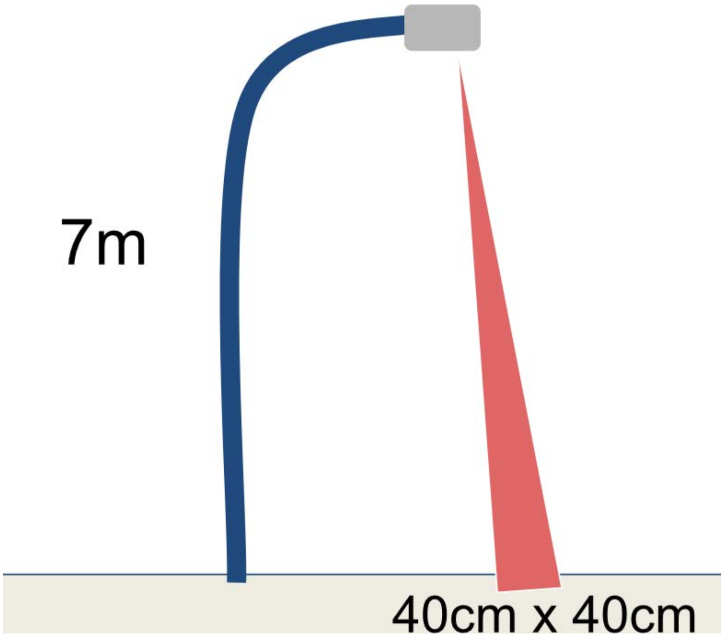


Figure 5.15 - Representation of lidar detection area from streetlight-mounted vantage point

The management of the lidar's limited detection may not be feasible at a large-scale deployment such as in each streetlight. The mounting bracket for the lidar positioned the sensor to point straight down and relied on the streetlight housing's tilt to position the detection area over the road. However, the mounting position and angle of the housing were not enough in this case and the detection area fell short of the road. A simple solution is to use a mounting bracket with an adjustable angle to precisely position the lidar's detection area to cover the centre of the lane. However, when scaling this solution up to a wide-scale deployment, the differences in pole positioning, outreach, tilt angle, and general differences in streetlight housing construction mean that the mounting angle may need to be calculated on a case-by-case basis.

The LidarLite's long range and narrow field of view would allow lane-specific traffic detection at any mounting height. However, the sensor's high price-point of AU$125 combined with the more involved configuration processes and general lack of availability (sensor is not available for purchase at time of writing) make this sensor less practical than other sensor options.

5.5.4 Sensor Reliability

An important consideration of using inexpensive sensors for traffic detection is reliability. In the harsh deployment environment, the sensor platform operated unattended and unmaintained for a five-month period before a computing malfunction rendered the platform unable to record sensor data, but sensors continued to operate for a further two months before the hardware was retrieved. The PIR sensor also appeared to malfunction and recorded a traffic count that was 80% lower than its typical daily count. Heavy rain in the week leading up to the malfunction would suggest that water or high humidity inside the streetlight housing caused the sensor platform and/or individual sensors to fail. This failure would indicate that the sealants or 3D-printed mounting plates that were used to hold the sensors were ineffective at keeping water out of the housing.

None of the sensors used in this trial were rated for harsh urban environments. The control platform and communications system can be sealed to further protect the electronics from the elements, but other sensors that physically interact with the outside world, such as sonar, cannot be completely sealed without affecting their function. These are the sensors that are vulnerable to rain, dust, and humidity, which could lead to increased maintenance, sensor malfunction, or failure.

Individual sensor failure is not as much of a problem as it initially appears. Traffic sensors along the same road section will likely observe the same or similar traffic volumes and times. In a ubiquitous sensor platform deployment, the high density of sensors means that traffic data can be sourced from nearby nodes over the wireless network in the event of a detected sensor failure. This method of using remote traffic data bypasses the need to immediately replace sensors. However, since the sensor platform is no longer able to detect traffic independently, the streetlight would need to be kept active for longer periods to compensate for variations in traffic between lighting zones.

Sensor drift presents a more insidious problem than sensor failure. Sensor failure is typically recognised by a drastic change in the sensor's output or non-responsiveness, whereas inaccuracies caused by drift are more difficult to detect. A solution to this issue is ongoing verification of the data. Since the proposed system operates using a wireless sensor network, all sensor data can be collated and verified by a centralised system with a broad overview of the entire deployment. Sensors that deviate from local 'normal' values or pre-set thresholds can be blacklisted to indicate that data from the sensor can no longer be trusted, and data should be sourced from another platform instead, pending further investigation or maintenance.

Temperatures inside the streetlight housing reached a maximum of 53.9°C over the course of the deployment. This temperature was recorded in the peak of summer at midday. While still high enough to warrant concern around the use of lithium batteries, this temperature was well within the safe operating conditions of the electronics used in the prototype. Temperatures inside the housing at night did not rise above 40°C, indicating that the operation of the streetlight did not significantly affect the internal temperature.

5.5.5 Sensor Platform Cost

Sensor hardware cost (Table 5.7) was significantly lower than that of the commercially available traffic detectors (Table 2.2) by a factor of at least 10 in almost all cases. The most successful sensor (HC SR-501), combined with the cost of the Arduino Yun platform and supporting electronics resulted in a total cost of approximately AU$100. Installation costs in this case, however, were not comparable, as the test platform was only installed temporarily. However, modification and retrofit of the platform inside the streetlight housing was performed on-site in less than 30 minutes and used approximately AU$3 of raw materials. Regardless of the low cost, the PIR sensor's average counting accuracy of 73% did not reach the same minimum performance expected of commercial traffic detectors, resulting in low-quality and therefore less valuable data.

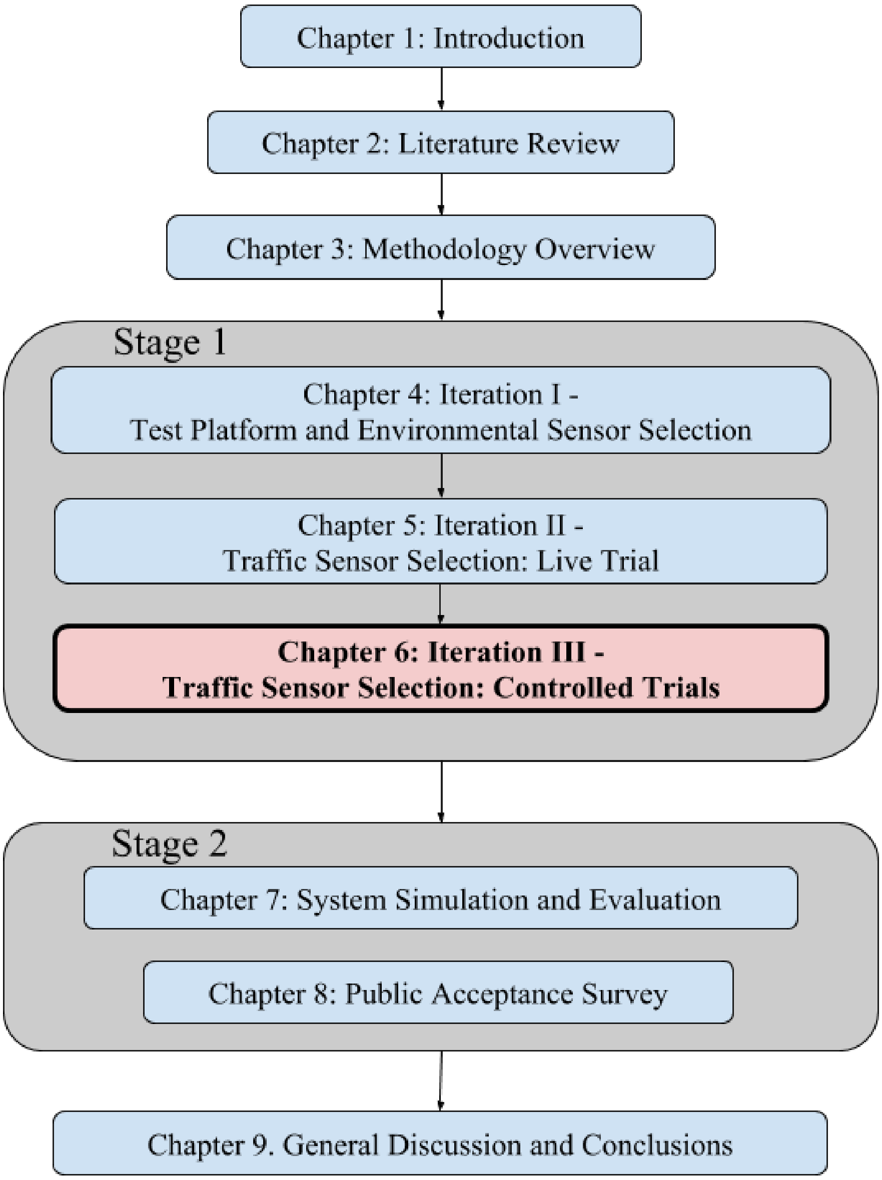
Table 5.7 - Summary of sensor performance in streetlight-mounted testbed

Sensor	Hardware Cost (AU$)	Counting accuracy	Advantages	Disadvantages
PIR Motion Sensor (HC-SR501)	4 - 10	73%	Detects vehicle and pedestrian traffic; Low relative cost; Minimal processing and sampling requirements	Cooldown must be tuned to traffic speed to prevent over-counting/under-counting
Lidar (LidarLite v1)	125 - 170	inconclusive	Narrow detection area; Can also monitor road height and flood levels; Low processing and sampling requirements	Must be precisely mounted to focus detection area on the road; High relative cost
Sonar (MB1240)	80	inconclusive	Can detect vehicles in a reasonably narrow area; Low processing and sampling requirements	Moderate relative cost Maximum range restricts deployments to low street lights and underpasses

5.6 CONCLUDING REMARKS

Of the three low-cost sensors used in the trial, the HC-SR501 motion detector was the most suitable for ubiquitous deployment for traffic detection. The relatively low counting accuracy (73%) of the sensor signifies that the platform is currently unable to accurately monitor traffic volume, especially during periods of dense traffic. However, the sensor correctly reported the road as active for 92% of traffic events during the recorded period, indicating that the sensor may have utility in adaptive road and footpath lighting, which considers traffic presence rather than volume. Detection accuracy could be further improved in a ubiquitous deployment using data aggregation. Sensor platforms deployed in the same area would be able to notify neighbouring platforms of any missed or miscounted traffic events to enable data verification across the entire network. With these considerations in mind, a streetlight-integrated traffic detection system based on PIR technology would be cost-effective if the sensor accuracy could be improved.

Chapter 6 - Iteration III -Traffic Sensor Selection - Controlled Trials



This chapter was presented at the 2018 Australasian Computer Science Week Multiconference as follows: ‘K. Mohring, T. Myers, I. Atkinson “A controlled trial of commodity sensors for a streetlight-mounted traffic detection system”’ [1]. The publication discussed the experimental setup, testing, and results of the prototype traffic detection system. Additional information from the two follow-up trials conducted after the publication have been added to show further development of the prototype and address problems found in testing.

6.1 CHAPTER OVERVIEW

The previous chapter presented development iteration II of the prototype streetlight-integrated sensor system, which investigated sensors that could be suitable for traffic detection. This chapter continues by focusing on improvements to the traffic detection platform to improve the reliability and counting accuracy of the system. The new sensor hardware configuration is presented, as well as the controlled traffic test environment that was used to evaluate the performance of the sensors under a variety of different traffic behaviours. The chapter concludes by discussing the strengths and weaknesses of each sensor type and finalising the design of the hardware prototype for Stage 1 of the study.

6.2 CHAPTER INTRODUCTION

Preliminary and live sensor deployments were conducted to investigate the traffic detection performance of streetlight-integrated passive infrared (PIR), sonar, and lidar sensors. Live testing of the traffic detection system showed that the mounting configuration and variability of traffic conditions severely limited the performance of the sensors to the point that the tested sensors were not capable of counting or classifying traffic to the standards required for many smart city applications. This iteration focused on resolving these configuration issues and the improvement of the detection and counting algorithms for each of the sensors, including a thermographic detection system that was added to the prototype. The effects of traffic variability on sensor effectiveness are also explored through a series of controlled traffic trials involving vehicles, pedestrians, and cyclists, at varying speeds, directions, and densities.

6.2.1 Summary of Contributions

This chapter presents the following contributions to the research:

- Three infrared-based sensor technologies were evaluated for their vehicle detection and counting accuracy in a series of tests involving over 600 vehicle events, 400 cyclist events, and 600 pedestrian events. All traffic events were tested under different speeds, ranging from 10 to

100 kilometres per hour, and proximities between one and eight seconds in the case of motor vehicles (Section 6.4).

- Traffic detection algorithms for the sensor platform's three passive infrared motion detectors, thermographic sensor, and a lidar are presented in Section 6.2. These algorithms included a vertical tripwire system for lidar, and a thermal tracking algorithm that was able to detect and monitor moving vehicles.
- The results of multiple trials from heights at least 5.5 metres above the road surface were used to evaluate the performance of each sensor type. The three PIR sensors were shown to be reliable for detecting the presence of traffic at any given speed, but not able to accurately count pedestrians or vehicles in dense traffic scenarios. Lidar and the thermographic detection system were each able to count vehicles with up to 99% accuracy, following improvements to the detection algorithms over follow-up trials (Sections 6.6 and 6.7).
- Overall, the trials demonstrated that none of the tested sensors were able to independently count all traffic types accurately in every given scenario. PIR sensors were unable to count but were useful in presence detection and error checking of other sensors. Lidar was able to accurately count vehicles, but only if they travelled directly in the centre of the lane. Finally, the thermographic sensor was able to detect vehicles, pedestrians, and cyclists across the lane, but the detection accuracy was hampered by cold weather (Sections 6.8 and 6.9).

6.3 HARDWARE CONFIGURATION

The prototype system used in this iteration was mostly the same as that used in iteration II, but with three key differences (Figure 6.1): Firstly, the sonar used in the previous iteration was removed from the prototype's design due to its failure to detect pedestrians or vehicles in the live traffic trial (Chapter 5). Secondly, a thermographic array sensor was added to the prototype to attempt to combine infrared detection and basic image processing techniques, which are discussed in Section 6.3.2. Thirdly, two

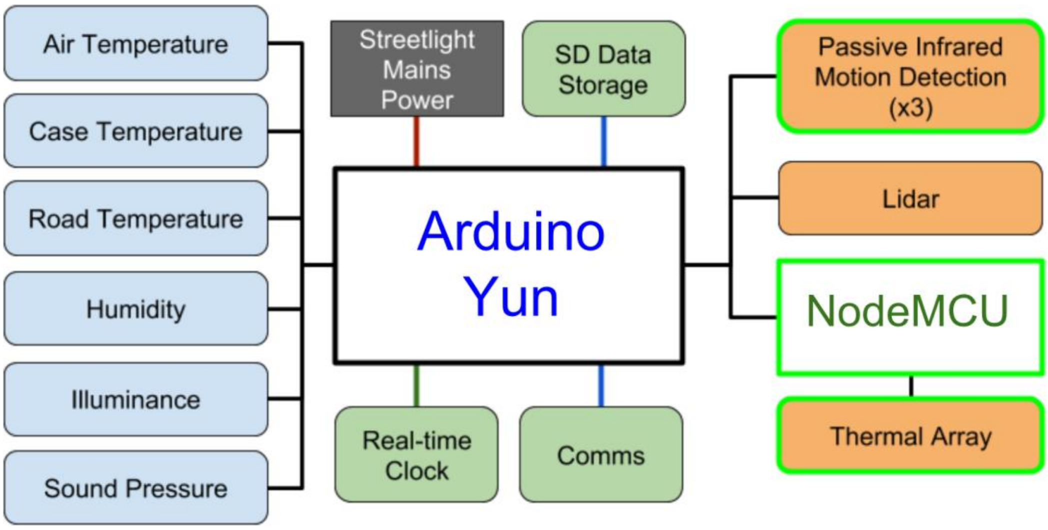


Figure 6.1 - Overview of the prototype sensor system in iteration III

Table 6.1 - List of sensor types and systems comprising the traffic detection platform

Sensor Type	Model	Cost (AU$)
Narrow PIR	Panasonic AMN33111 Spot Motion Sensor	35
Wide PIR (left)	HC-SR501 Motion Sensor	7
Wide PIR (right)	HC-SR501 Motion Sensor	7
IR Array	Melexis MLX90621 Infrared Array	62
Lidar	PulsedLight Inc., LidarLite v1	125
Data logging	Arduino Yun	104
Thermographic Processing	NodeMCU	10

additional PIR sensors were included as part of the traffic detection suite for a total of three PIR motion detection sensors. A summary of the traffic sensors and systems used in the prototype (excluding environmental sensors) is shown in Table 6.1.

6.3.1 Passive Infrared Detection

Passive infrared motion detectors, or PIR detectors, monitor changes in heat to perceive objects passing in front of the sensor. As shown in the previous development iteration, these sensors do not typically distinguish between individual objects moving in their detection area and are mostly used for basic presence detection and localization rather than counting [214-217].

PIR sensors typically vary from each other in three ways: the size and shape of the detection area, the sensitivity of the sensor, and the length of hold-off time between detections. The size and shape of the detection area can be altered to suit the deployment environment by selecting the appropriate lens type. Wide-angle lenses are common on PIR sensors and capture movement in all directions over a large radius, but narrow, directional, and/or shaped lenses also exist. Sensitivity is the minimum amount of movement that occurs before the sensor triggers a detection and is typically arbitrary and cannot be changed from the manufacturer's settings. Lastly, the hold-off time dictates the minimum delay between sensor detections.

PIR motion sensors are typically binary devices, meaning they transmit a signal while motion occurs, then stop when no further movement is detected. A hold-off time adds a delay between repeat detections to improve the counting accuracy of the sensor based on the object's speed. Slow-moving objects moving through a wide detection zone need a long hold-off to avoid duplicate detections, but an excessive hold-off time can result in missed detections.

Two passive infrared (PIR) motion sensor models were used in this test: two wide-angle HC-SR501 sensors, and the Panasonic AMN33111 'spot' detector. The wide-angle sensors detected movement over a full radius of seven metres [218], which typically spans two road lanes and a roadside footpath. The large detection area makes

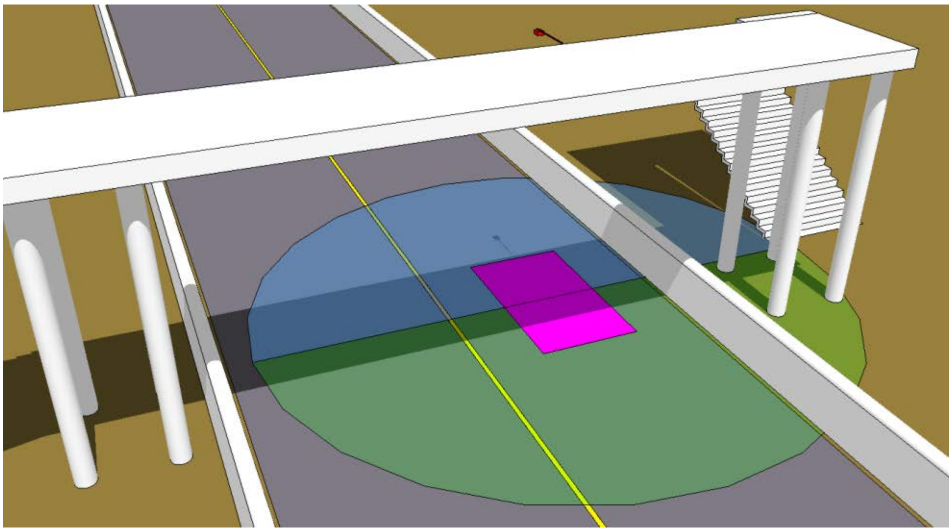


Figure 6.2 - Model of the testing location, which shows the approximate detection zones for each of the PIR motion sensors (Left-Wide as blue, Right-Wide as green, and Narrow as purple).

the sensor more suitable for pedestrian and cyclist detection, so the hold-off time was set to five seconds to match the movement speed of a pedestrian. The two wide-angle sensors were separated by an opaque divider to each halve their detection areas (see Figure 6.2) so that the travel direction of pedestrians and vehicles could be determined as they passed the sensors.

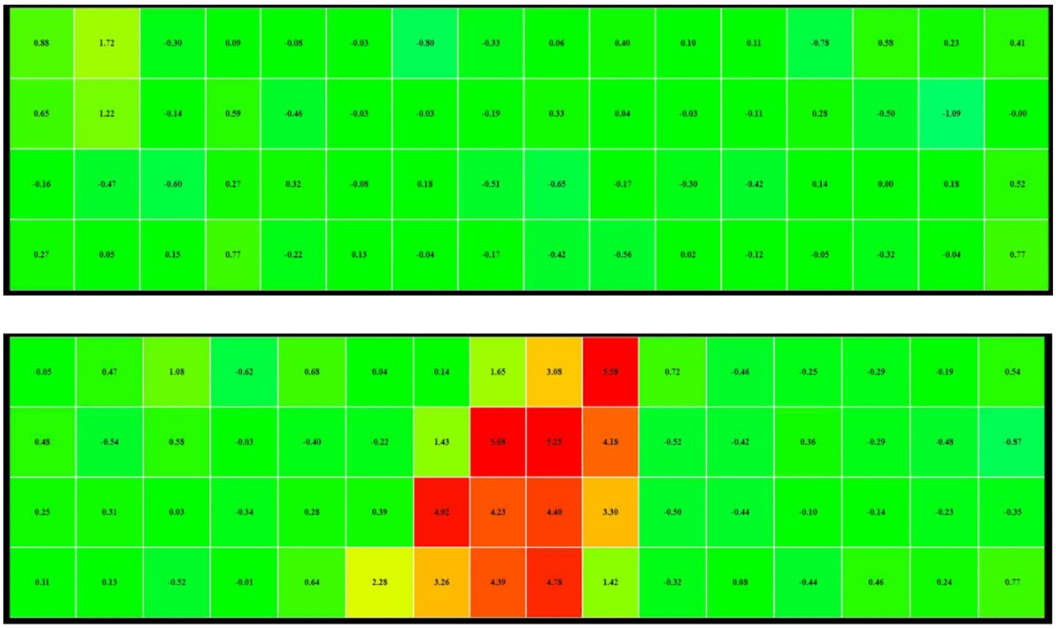
The narrow AMN33111 spot sensor monitored a smaller area, which measured an approximately six by four-metre rectangle on the ground (Figure 6.2) [219]. This detection area covered a single road lane, and the hold-off time was set to two seconds to match the minimum following distance allowed between vehicles. This short hold-off time allowed the sensor to reset between vehicles and the smaller detection zone made duplicate detections unlikely as a vehicle could easily clear the zone before the two-second delay.

6.3.2 **Thermographic Vehicle Detection**

Thermographic cameras use an array of passive infrared receivers to capture a thermal image. Like the PIR sensor, moving objects can be detected by observing changes in heat moving in the detection area, but the higher number of sensing elements allows for much more sophisticated detection. The size, shape, and speed of the object can be observed in the image to potentially identify objects and categorize them into different traffic types. The advantage of this approach to detection over motion-based methods is that multiple objects can be tracked individually, and targets that stop in the detection are not ‘forgotten’ as they are with motion detectors.

A barrier to widespread thermal detection with road traffic is the prohibitive cost of thermographic cameras. Thermographic cameras are extremely expensive relative to ordinary video cameras and are export restricted in some countries. Thermal image processing is also subject to the same high computational and data bandwidth requirements as video, which requires data to be transferred externally for processing, incurring additional costs [74]. However, low-resolution infrared arrays can perform the same basic role as a thermographic camera but can be obtained for a fraction of the cost. Infrared array sensors such as the Panasonic GridEye and the Melexis MLX90621 contain a 64-pixel sensor and can be readily obtained for under AU$60. The low resolution of the infrared array reduces the effective range and utility of the thermal imagery compared to thermographic cameras, but the processing requirements are greatly reduced such that image processing techniques such as edge detection and optical flow can be performed by a low-power microcontroller.

The infrared array sensor chosen for this test was the Melexis MLX90621. A four by one-metre image of a single road lane was captured by the sensor at a rate of 16 frames per second, which was passed to a custom thermal tracking algorithm [220]. The thermal tracking algorithm detected objects moving through the frame by comparing object temperatures against a 12-second average background. Pixels that deviated from the background by a significant amount (i.e. four times the pixel's rolling average variance) were marked as 'active' to indicate the presence of an object (Figure 6.3). Clusters of adjacent active pixels in a frame were tracked between multiple frames by matching the size, shape, and predicted position of the clusters in new frames. The travel direction of tracked clusters was determined by summing its movements after the cluster left the frame. This technique allowed traffic to be captured in both directions and could support multiple tracked objects at once.



0.88	1.72	-0.30	0.09	-0.08	-0.03	-0.80	-0.33	0.06	0.40	0.10	0.11	-0.78	0.58	0.23	0.41
0.65	1.22	-0.14	0.59	-0.46	-0.03	-0.03	-0.19	0.33	0.04	-0.03	-0.11	0.28	-0.50	-1.09	-0.00
-0.16	-0.47	-0.60	0.27	0.32	-0.08	0.18	-0.51	-0.65	-0.17	-0.30	-0.42	0.14	0.00	0.18	0.52
0.27	0.05	0.15	0.77	-0.22	0.13	-0.04	-0.17	-0.42	-0.56	0.02	-0.12	-0.05	-0.32	-0.04	0.77

-0.05	0.47	1.08	-0.62	0.68	0.04	0.14	1.65	3.08	5.58	0.72	-0.46	-0.25	-0.29	-0.19	0.54
0.48	-0.54	0.58	-0.03	-0.40	-0.22	1.43	5.08	5.25	4.18	-0.52	-0.42	0.36	-0.29	-0.48	-0.87
0.25	0.31	0.03	-0.34	0.28	0.39	4.92	4.23	4.40	3.30	-0.50	-0.44	-0.10	-0.14	-0.23	-0.35
0.11	0.13	-0.52	-0.01	0.64	2.28	3.26	4.39	4.78	1.42	-0.32	0.08	-0.44	0.46	0.24	0.77

Figure 6.3 - Observations from thermographic array sensor showing a typical thermal background (Top), and the presence of an object in the sensor's field of view (Bottom).

Tyndall et al. [221] used a similar technique for indoor occupancy detection using static frames. However, no movement tracking was performed. Presently, no projects have involved the use of an infrared array sensor to detect and count road traffic.

6.3.3 Lidar

Lidar is an active infrared technology that measures the time of flight of infrared pulses to calculate the distance between the sensor and distant objects. The LidarLite by PulsedLight Inc. was included in the test platform for its ability to operate at distances of up to 40 metres [172]. The lidar had a much smaller detection zone than all other sensors included in the trial, measuring a circle 0.3 metres in diameter from the platform's six-metre mounting height (Figure 6.4).

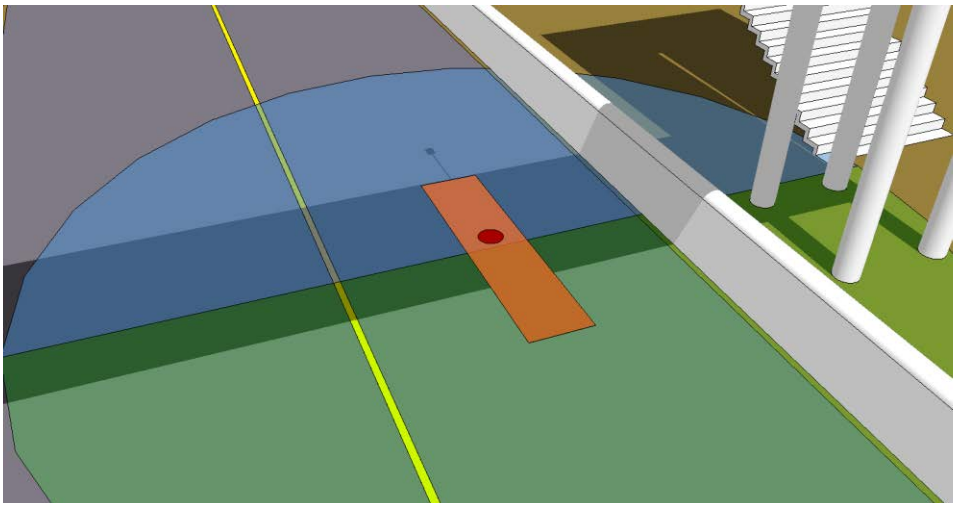


Figure 6.4 - Model showing the approximate detection zones of the lidar (red) and infrared array (orange) sensors. Wide PIR sensor detection zones kept to show scale.

In its overhead mounting position, the lidar operated as a vertical tripwire. That is, the lidar measured the distance between the sensor and the road surface below at a frequency of ten times per second. Any objects passing beneath the sensor would 'break' the tripwire and cause the measured distance to lessen. If this measured distance lessened by a minimum threshold of 0.5 metres, i.e. when the hood of a car passed underneath the sensor, a traffic event was started. This action blocked any duplicate events from being recorded until the measured distance returned to its previous base value once the vehicle had passed and the event was declared over.

6.4 EXPERIMENTAL SETUP

6.4.1 Sensor Platform

The sensors and a video camera were fixed to a one metre outreach pole and secured to a pedestrian overpass, six metres above the road surface (Figure 6.5). Two hardware systems managed data collection and control for the sensor platform: a NodeMCU, and an Arduino Yun. The NodeMCU platform, based off the ESP8266 microcontroller, performed dedicated, on-chip image processing for the MLX90621 infrared sensor array. All other sensor interactions were handled by the Arduino Yun's on-board microcontroller (ATmega32u4), while its main processor (Atheros 9331) was responsible for logging sensor events. Event times and sensor information were logged at the start of each PIR or lidar event. The thermal tracking algorithm recorded when events ended, once objects left the sensor's frame.

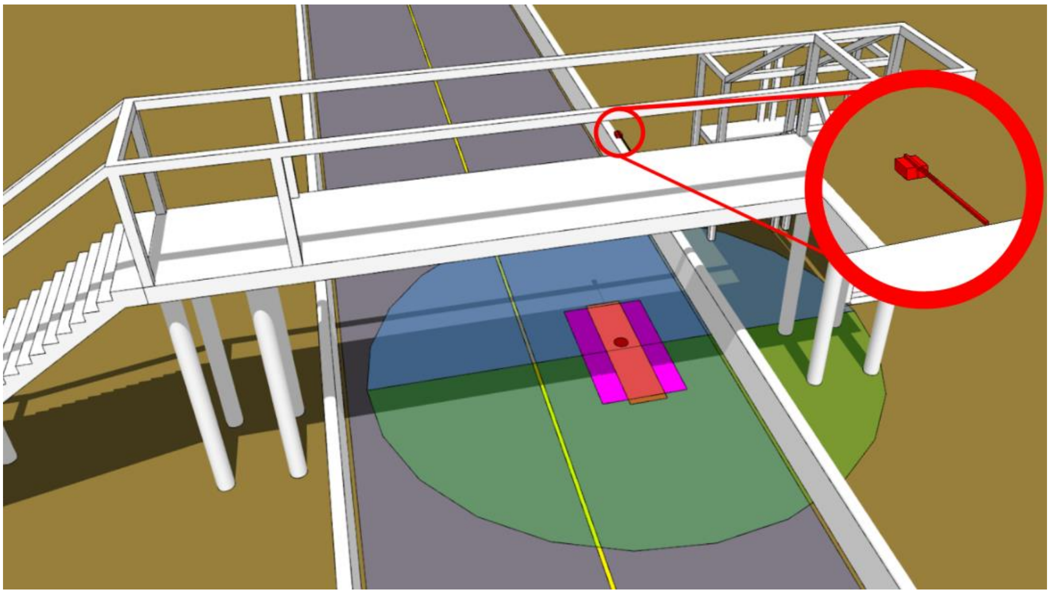


Figure 6.5 - Position of the prototype sensor platform during controlled traffic tests

6.4.2 Test Procedures

Vehicle tests occurred in two stages: controlled speed tests, and vehicle proximity tests. The speed tests aimed to establish a maximum speed at which the sensors could detect single vehicles whereas the proximity tests evaluated the sensor's ability to count vehicles in dense traffic.

Speed tests were conducted with a pair of vehicles and started with an initial speed of 20 kilometres per hour. In increments of ten kilometres per hour, drivers performed passes along the track in both directions, directly underneath the sensor and in the lane adjacent (see Table 6.3 for full testing schedule) up to a maximum of 60 kilometres per hour. Limited high-speed passes were also conducted in a single direction and directly under the sensor at speeds up to 100 kilometres an hour to further test the sensors' capabilities. A minimum gap of five seconds between vehicles was maintained to allow the PIR sensors to 'reset' between detections.

Vehicle proximity tests involved four-vehicle passes directly beneath the sensor at low speeds (see Table 6.4 for full testing schedule). Passes were conducted at three different speeds: 20 kilometres per hour, 30 kilometres per hour, and a final five kilometres per hour pass with five vehicles to simulate traffic jam conditions.

Note: Tests involving cyclists and pedestrians were also conducted during this iteration. These results are omitted from this chapter, aside from the performance of the finalised sensor system with other traffic types in the second follow-up test (Section 6.7).

6.5 PERFORMANCE ANALYSIS

Video and sensor event times were correlated to find the true-positive and false-positive rates of each sensor. The true-positive rate denotes the detection accuracy of the sensor and the probability that a vehicle was detected during a pass. A high detection accuracy is important for presence detection, and useful for adaptive road lighting, but it does not give any indication of the sensor's ability to accurately count traffic volume on its own. The false-positive rate is the proportion of events recorded in error by the sensor to the total number of recorded events and can be used to measure the trustworthiness of a sensor. For example, a sensor that recorded 200 traffic events in the presence of 100 passing vehicles would have a true-positive rate of 100% if the traffic correlated with the detection times. However, the resulting false-positive rate of 50% shows that the sensor is not very credible and can only be trusted for half of its recorded events.

No official guidelines in Australia could be found for the minimum required detection accuracy of a traffic detection system. However, the minimum true-positive detection accuracy goal for this study was 91%, to match the minimum expected detection rate of inductive loop sensors [155].

6.6 RESULTS AND ANALYSIS

6.6.1 Speed Tests

Table 6.3 shows the true-positive detections from each sensor over the speed tests as well as the rate overall, and Table 6.2 shows the same for false positives. Lidar and infrared array sensors detected traffic in a single lane only, so tests conducted in the adjacent lane were omitted from their calculations. Events recorded by the infrared array sensor were only considered if they were tracked for a minimum of two frames.

The AMN33111 PIR sensor produced the highest true-positive detection accuracy of the platform's sensors for the speed tests (98%), but also had the highest proportion of false positives (17%). False-positive detections were more prevalent at lower vehicle speeds where the vehicles take longer to clear the sensor's detection area. These false positives also occurred at times immediately surrounding a vehicle, which would indicate that the sensor was recording duplicate events. An unexpected result from the sensor, however, was that tests conducted in the lane adjacent to the sensor platform appeared to trigger the sensor, despite the vehicles travelling well outside the sensor's expected detection area. Interestingly, the sensor could detect almost all vehicles travelling in the adjacent lane, and with typically lower false positives compared to tests conducted in the closest lane, notably at the 30 kilometres per hour and 40 kilometres per hour tests (Table 6.2).

Table 6.3 - Number of true-positive vehicle detections per sensor for each speed test

Vehicle Speed (km/h)	Video (actual)	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Infrared Array
20	20	20	19	19	19	20
20 (adjacent lane)	20	20	18	19	-	-
30	20	20	17	16	15	20
30 (adjacent lane)	20	19	15	16	-	-
40	40	40	34	34	27	36
40 (adjacent lane)	18	17	17	17	-	-
50	20	19	19	18	13	20
60	18	18	17	17	14	11
70	7	7	6	6	6	7
85	4	4	4	4	2	2
100	4	4	4	4	3	4
Overall	191	98%	89%	89%	74%*	92%*

* True-positive rate calculated in direct lane only

Table 6.2 - Number of false-positive vehicle detections per sensor for each speed test

Vehicle Speed (km/h)	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Infrared Array
20	11	0	0	5	8
20 (adjacent lane)	11	0	0	-	-
30	9	0	0	1	1
30 (adjacent lane)	0	0	0	-	
40	5	0	0	0	6
40 (adjacent lane)	0	0	0	-	-
50	2	0	0	0	3
60	0	0	0	0	1
70	0	0	0	0	0
85	0	0	0	0	0
100	0	0	0	0	0
Overall	17%	0%	0%	6%	14%

The other two PIR sensors (HC-SR501) both produced moderately high true-positive rates of 89%. Neither sensor produced false positives, but both consistently undercounted traffic across all tested speeds and over both lanes. All events ‘missed’ by the wide-angle PIR sensors occurred shortly after successfully detected events, despite the test vehicles maintaining a minimum five-second gap. The true-positive rate of the sensor did not appear to change with vehicle speed.

The MLX90621 infrared array with the thermographic tracking algorithm produced the second highest detection accuracy for the speed tests (92%). Like the narrow PIR sensor, the high detection accuracy of the thermographic tracking was accompanied by a relatively high number of false positives that were more prevalent at lower speeds (14%). The true-positive detection rates for each vehicle speed was consistently high, except for the test at 60 kilometres per hour. A high number of untracked events were recorded during this test, indicating that vehicles could be detected by the sensor but were not tracked across frames. This behaviour suggests that the process used by the tracking algorithm to identify objects across multiple frames may be too strict for traffic travelling at higher speeds, causing the tracking to fail and resulting in ‘split’ duplicate events.

Untracked thermal events were also recorded at the same time as tracked events in other tests. These untracked events were typically observed before and after tracked events. This phenomenon may be due to the shape and size of objects, as seen by the sensor, changing as they entered or left the frame, resulting in the object not being recognised across frames. This theory further suggests that detection accuracy would increase, and false-positive rates would decrease if the tracking algorithm was more lenient, especially at the beginning and end of tracking objects through the detection area.

Lidar was the least accurate sensor over the speed tests, with an overall accuracy of 76% (Table 6.3). Missed events occur across the entire speed range with no apparent correlation between them. According to the video footage, vehicles in the missed events are travelling directly underneath the sensor platform and should have occupied the lidar’s detection area entirely. False positives occurred at speeds of 30 kilometres per hour and lower, and only appeared after a successful vehicle detection, indicating duplicate events. The target distance measured by the lidar during these duplicate events indicated that an object at least four meters tall was beneath the sensor. As no such object was present during testing, the sensor was presumed to have incorrectly measured during these events, possibly due to reflection of the lidar's measurement light pulses off the vehicle's windshield.

6.6.2 **Vehicle Proximity Tests**

Table 6.4 shows the true-positive detection rates for each of the sensors over the proximity tests, and Table 6.5 shows the false positives. The AMN33111 vehicle detection accuracy appeared to decrease by over 10% during the vehicle proximity tests (Table 6.4). For the first test, where vehicles travelled at 20 kilometres per hour with a two-second gap, all vehicles were detected, and some duplicate events were recorded, typically at the end of the four-car pass. Misses began to occur as the vehicle speed increased to 30 kilometres per hour. The first vehicle in the pass was consistently detected, but vehicles toward the end of the pass appeared to be missed and no duplicate events were recorded. The number of missed events increased as the time gap between vehicles was lessened to one second.

These misses were possibly a result of the sensor's two-second hold-off time. As vehicles increased in speed and lowered their following distance, the total time that movement was occurring underneath the sensor decreased. Video footage shows that vehicle runs conducted at 30 kilometres per hour with a one-second gap take approximately five seconds to complete. In these runs, the sensor would record the first vehicle, trigger again halfway through the pass, then again as the last vehicle cleared the detection area, resulting in undercounting. The opposite problem occurred in the traffic jam test, where vehicles were travelling much slower and lingered in the detection area for prolonged periods of time, over 20 seconds each pass. During this time, the AMN33111 sensor appeared to continuously fire after every hold-off time elapsed, resulting in over-counting by almost double the number of actual vehicle events.

Both HC-SR501 PIR sensors had a much lower detection accuracy compared to the previous test and produced the worst detection accuracy overall. Like the AMN33111, the wide-lens PIR sensors could detect the first vehicle in each pass, then missed most of the following vehicles. At vehicle speeds of 20 kilometres per hour, both sensors recorded two events per pass, which resulted in true-positive rates of only 50%. This trend worsened as vehicle speed increased and the time gap between vehicles decreased, as vehicles stayed in the detection area for progressively less time. For example, 6 out of the total 19 passes resulted in only the first vehicle being recorded by the sensor in the 30 kilometres per hour tests. During traffic jam conditions, all vehicles were detected during the 40-second pass. If the test were repeated at a slower speed, both sensors were expected to over-count.

The infrared array gave the highest true-positive rate at 93% for the vehicle proximity tests (Table 6.4). Both true-positive and false-positive rates were slightly improved compared to the speed tests but remained largely the same. Missed events during the proximity tests were not detected by either tracked or untracked events from the thermographic tracking algorithm. Video review of the missed events shows the vehicles travelling closer to the lane's edge than normal, but still well within the lane boundary. These misses may represent a limitation of the sensor's narrow lensing, which makes the sensor unable to detect vehicles that are not travelling in the centre of the lane. An infrared array with a larger field of view may be more suitable for the tested mounting height.

Lidar accuracy also dropped to just 66% accuracy during the proximity tests, much lower than during speed tests (Table 6.4). Except for the traffic jam test, the sensor did not produce any false positives, but missed a substantial proportion of vehicles. The pattern of these missed events did not appear to correlate with any particular vehicle, travel direction, speed, or time gap between vehicles. Most passes resulted in at least one vehicle being detected by the sensor, with only a single exception. The lidar appeared mostly accurate during the traffic jam conditions and detected every vehicle. The false-positive detections during the traffic jam test all appeared to be duplicate events. Each positive vehicle detection was accompanied by a second, duplicate detection, except for the last vehicle in the pass, which was followed by multiple duplicate events. As during the speed tests, the sensor may have incorrectly measured the distance beneath the sensor if the transmitted pulse was reflected off the vehicle's windshield and resulted in duplicate events being recorded.

Table 6.4 - Number of true-positive vehicle detections per sensor for each vehicle following test

Vehicle Speed (km/h)	Vehicle Following Distance(s)	Video Baseline	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Infrared Array
20	**2**	32	32	16	16	17	28
30	**2**	40	37	17	18	28	40
30	**1**	40	30	15	15	26	36
< 5	**1**	10	10	10	8	10	9
	Overall	122	89%	46%	47%	66%	93%

Table 6.5 - Number of false-positive vehicle detections per sensor for each vehicle following test

Vehicle Speed (km/h)	Vehicle Following Distance(s)	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Infrared Array
20	**2**	7	0	0	0	2
30	**2**	0	0	0	0	5
30	**1**	1	0	1	1	4
< 5	**1**	11	1	0	6	6
	Overall	16%	2%	2%	8%	13%

6.7 FOLLOW-UP TRIALS

Two follow-up trials were conducted to test improvements made to the sensor platform. These improvements focused on the quality of recorded data and the success rate of the thermal tracking algorithm. The previous test logged events that were pre-processed by the microcontroller. This method cut down on the amount of data sent and stored but made analysis difficult as events could not be easily identified as true or false positives. Sensor logging was changed to record both start and end events from all sensors with additional information if available, such as average vehicle height in the case of lidar, or average object temperature in the case of the thermographic sensors. The inclusion of milliseconds in event times also made event timestamps more precise.

The infrared array and thermal tracking algorithm received several changes. Firstly, a second MLX90621 IR array with a 60-degree lens was added to the system for direct comparison to the existing 40-degree lens variant. Each system ran from a separate ESP8266 microcontroller and transmitted its data directly to an external computer to avoid congesting the Yun's communications. A major concern identified in the previous tests was that objects at the edges of the IR array's detection area were not being identified in subsequent frames due to rapid changes in position, size, and shape from the sensor's perspective. Inter-frame tracking was reworked to reduce tracking penalties and improve identification of objects close to the edges of the sensor's detection area, so tracked objects were not prematurely discarded. Finally, the frame rate of both infrared arrays was doubled to process 32 frames per second. The increase allowed vehicles to be tracked for a higher number of frames to improve the granularity of tracking, particularly at high speeds.

Test conditions were kept as close as possible to the previous speed and proximity tests except for the following changes:

- The mounting height of the sensor platform was fixed at 5.5 metres above a single-lane road, down from the original 6.0 metres.
- Road access was unrestricted during testing and allowed non-test vehicles to pass through.

- Vehicle speed was restricted to a maximum of 40 kilometres per hour.
- Weather conditions were overcast and much colder during the follow-up tests with an average temperature of 21°C compared to the 35°C reached during the previous testing sessions.
- Hold-off time was removed for the AMN33111 PIR sensor, which allowed the sensor to fire in response to movement as fast as the hardware could allow, which was typically every 300 milliseconds.
- Lidar polling frequency increased from 10 Hertz to 20 Hertz

6.7.1 Follow-up Trial 1 Results and Analysis

Three tests were conducted with the new sensor configuration using a pair of vehicles, travelling in both road directions (see Table 6.6): firstly, a speed test at 40 kilometres per hour with a minimum gap of eight seconds between vehicles; secondly, a proximity test at 30 kilometres per hour with a gap of three seconds; and finally, a proximity test at 30 kilometres per hour and two seconds between vehicles.

True-positive and false-positive rates for the AMN33111 PIR ‘spot’ sensor both decreased during the follow-up trial, to 77% and 10% respectively (Table 6.6 and Table 6.7). The lack of a hold-off time caused the sensor to over-count traffic events with the total reaching over double the actual number of vehicle events. Event entries were post-processed to combine duplicate events based on their starting times, like a hold-off time. However, applying the delay to existing data allowed for the optimal hold-off to be found for the specific traffic type to minimise duplicates. The best compromise between true and false positive detections occurred when events were combined within a 1200 millisecond window. The filtered data showed strange results. True-positive detection accuracy was highest during the third test, which had the shortest gap between vehicles. This result is the opposite of what was observed during the speed and proximity tests, where detection accuracy decreased as the gap between vehicles was lessened. Most concerning was the low detection accuracy over the first test, where traffic was sparse, which was very uncharacteristic for motion-based detection.

Table 6.8 presents a breakdown of successful detections by each sensor type during the follow-up speed test and shows that detection rates were much higher with one specific vehicle over the test, labelled ‘vehicle A’. Vehicle A had been operating almost constantly for the entire test duration, including an initial 20-minute sensor calibration phase, while vehicle B joined partway through the speed test. Vehicle B and non-test vehicles may have been missed by the sensor because they had not been running for long enough for their engine heat to be detected against the cold background of the road. This trend continued through to the first proximity test, where vehicle B was detected on only 4 out of a possible 22 passes. The narrow PIR sensor was only able to detect vehicle B with regularity during the final proximity test, after the vehicle had been running for at least 30 minutes.

One of the two HC-SR501 PIR motion detectors malfunctioned during the trial and recorded near-constant events, which caused a high false-positive rate of 45%. A loose connection is suspected of causing the malfunction. Detection behaviour from the functional HC-SR501 sensor was like that of the AMN33111; and was only able to regularly detect vehicle A during the follow-up speed test (Table 6.8). This trend continued for the follow-up proximity tests as well. The HC-SR501 sensor performed poorly in the proximity tests during the previous trial because the hold-off time was causing the sensor to under-count traffic. However, the cause of the missed events during the follow-up proximity tests is not clear and may have been the same excessive hold-off time for road traffic, or sensor’s apparent inability to distinguish vehicles from the road in cold weather. In either case, the HC-SR501 sensors produced the lowest true-positive detection rate of all the sensors tested, with an overall rate of just 54%.

Table 6.6 - Number of true-positive vehicle detections per sensor for follow-up trial

Vehicle Speed (km/h)	Vehicle Following Distance(s)	Video	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Thermographic (40° lens)	Thermographic (60° lens)
40	**-**	43	32	27	39	43	32	41
30	**3**	44	27	23	36	44	43	44
30	**2**	48	45	23	29	47	48	48
	Overall	135	77%	54%	77%	99%	85%	99%

Table 6.7 - Number of false-positive vehicle detections per sensor for follow-up trial

Vehicle Speed (km/h)	Vehicle Following Distance(s)	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Thermographic (40° lens)	Thermographic (60° lens)
40	**-**	4	0	37	0	0	0
30	**3**	3	0	16	0	0	0
30	**2**	4	0	32	0	0	0
	Overall	10%	0%	45%	0%	0%	0%

Table 6.8 - Per vehicle breakdown of true-positive detections over follow-up 40 kilometres per hour speed test

Vehicle ID	Actual passes	AMN33111 Narrow PIR	HCSR501 Wide PIR	MLX90621 (40° lens)
Vehicle A	26	25	26	26
Vehicle B	13	4	1	5
Non-Test Vehicles	4	1	0	1

Both infrared array sensors recorded over 1000 complete events over the duration of the test. Inspection of the sensor's event timestamps showed that up to four events regularly started within the same second of a vehicle passing underneath the sensor. This behaviour implies that the thermographic algorithm is identifying multiple separate objects instead of a single moving mass, causing duplicate events. Many of these events ended after a single frame, meaning that they were not able to be tracked. Almost all duplicate events were filtered from the two sensor's datasets separately, based on their tracked characteristics. In the case of the 60-degree sensor variant, events that were tracked for fewer than two frames were discarded, and remaining events were combined if the start time of the event was within a second of an initial detection. The best results for the 40-degree variant were obtained when the events were combined using the same rule, but the minimum number of tracked frames was lowered to one to account for the narrower detection area.

The filtered data shows that the 60-degree infrared array sensor consistently outperformed the 40-degree variant for true-positive (Table 6.6) and false-positive (Table 6.7) detection rates. Of the 135 vehicle passes, the 60-degree MLX90621 successfully detected 133 events (99% accuracy) with no false positives after applying the filter. The 40-degree variant performed comparably well in the vehicle proximity tests, albeit with some false positives, but detected only 70% of vehicle passes in the speed test compared to the 95% detection accuracy of the 60-degree array. Like the PIR sensors, the 40-degree thermal array could detect vehicle A during the follow-up speed test but appeared to miss most passes by vehicle B and other, non-test, vehicles (Table 6.8).

The two vehicles not detected by the 60-degree infrared array were also missed by the 40-degree variant. Both instances corresponded to non-test vehicles underneath the sensor platform, which were observed as parked for at least an hour. The short amount of time that both vehicles were running suggests that the 'hot spot' on the hood of the vehicles could not be detected against the ambient thermal background. A comparable situation occurred during the sensor calibration phase prior to testing, where vehicle A could not be reliably tracked until it had been running for five to ten minutes.

The lidar produced a 99% true-positive detection rate with no duplicate events after filtering. As for the infrared arrays and PIR motion detections, duplicate events were removed by combining events that started within one second of an initial event. Of the 135 vehicle passes, only a single event was missed by the sensors during the last proximity test, for an unknown reason. The sensor accuracy achieved in this test is far higher than in the previous testing session (from 76% overall in the previous testing session; Table 6.3, Table 6.4). Road conditions and polling rate may explain this increase. Firstly, the road used in the follow-up test was much narrower than during the previous trial, possibly resulting in more consistent vehicle passes directly underneath the sensor platform. Secondly, the polling rate of the sensor was increased from ten measurements per second to 20, which would have given the sensor more opportunities to detect vehicles travelling at speed.

6.7.2 Follow-up Trial 2 Results and Analysis

The second follow-up trial was conducted with a slightly more lenient algorithm for thermographic detection. Detected objects that were close together were combined to reduce the number of duplicate events from vehicles that had multiple 'hot spots'. A second change is that the algorithm would 'wait' a few frames before declaring that a traffic event was over, avoiding scenarios where tracking would end prematurely if an object failed to be detected for a single frame in the middle of a traffic event. The hold-off time for the narrow PIR sensor was also extended to 2.5 seconds to reduce false-positive detections. Aside from testing these minor changes, the second follow-up trial also tested the detection system with pedestrians and cyclists.

The testing conditions were kept the same as the previous follow-up trial, although conducted in warmer weather. Speeds and following distances were maintained from the previous testing schedule. Similarly, tests with pedestrians and cyclists were conducted with ten, five, and two second gaps between passes, all at a constant speed within the tests. Overall, the tests comprised 145 vehicle passes, 178 pedestrian passes, and 137 cyclist passes.

Results from the second follow-up trial were like those of the previous trial (Table 6.9 and Table 6.10). True positives and false positives from the lidar and thermographic sensors stayed mostly the same. The three PIR sensors all showed improvements to their detection with very little to no changes to their detection algorithms, suggesting variability from other sources such as weather.

An interesting observation from the second follow-up test was the sensors' performance with non-vehicular traffic. Table 6.11and Table 6.12 show the summary of true and false-positive detection rates with the different traffic types. The narrow PIR sensor had a consistently high detection rate, but also a high false-positive rate with pedestrians, which comes with the low hold-off period. The performance of all other sensors was reduced with pedestrians, and more so with cyclists, compared to vehicle detection trials. Lidar was especially poor at detecting other traffic types. The sensor that performed the best across all traffic types was the 60-degree thermographic sensor, which maintained a low false-positive ratio, while still being able to detect pedestrians and cyclists with 84% and 70% accuracy, respectively.

Table 6.9 - Percentage of true-positive vehicle detections per sensor for second follow-up trial

Vehicle Speed (km/h)	Vehicle Following Distance (s)	Video	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Thermographic (40° lens)	Thermographic (60° lens)
40	**10**	**46**	43	45	45	46	46	46
30	**4**	**51**	51	40	39	50	51	50
30	**2**	**48**	48	31	25	46	46	48
	Overall	**145**	98%	80 %	75%	98%	99%	99%

Table 6.10 - Percentage of false-positive vehicle detections per sensor for second follow-up trial

Vehicle Speed (km/h)	Vehicle Following Distance (s)	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Thermographic (40° lens)	Thermographic (60° lens)
40	**10**	1	11	12	0	0	0
30	**4**	6	13	7	1	0	0
30	**2**	8	12	5	0	9	3
	Overall	9%	20%	14%	1%	6%	2%

Table 6.11 - Summary of true-positive counting accuracy per sensor for second follow-up trial

Traffic	Actual	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Thermographic (40° lens)	Thermographic (60° lens)
Vehicle	**145**	98%	80 %	75%	98%	99%	99%
Pedestrian	**178**	94%	75%	76%	6%	41%	84%
Cyclist	**137**	88%	40%	42%	15%	0%	70%

Table 6.12 - Summary of false-positive counting accuracy per sensor for second follow-up trial

Traffic	Narrow PIR	Wide PIR Left	Wide PIR Right	Lidar	Thermographic (40° lens)	Thermographic (60° lens)
Vehicle	9%	20%	14%	14%	6%	2%
Pedestrian	33%	8%	1%	0%	10%	4%
Cyclist	1%	0%	0%	0%	0%	0%

6.8 DISCUSSION

Overall, the PIR motion sensors produced the least consistent detection and counting accuracies of the three technologies tested. All PIR sensors could accurately count sparsely spaced traffic at all tested speeds, but only the AMN33111 sensor could count densely packed traffic once its hold-off time was removed and vehicles had been running for longer than half an hour in the cold conditions. Wintry weather appeared to affect both the infrared array sensors and PIR motion detectors, which both use forms of passive thermal detection. A similar effect was observed in an excellent study conducted by Iwasaki et al. [222], which used a forward-facing high-resolution thermographic camera to count vehicles over multiple lanes of traffic. The study involved using image processing techniques to count the number of windshields in poor visibility conditions, such as snow and fog. Iwasaki et al. observed that the detection accuracy of their system decreased in winter as the temperature of the vehicle's windshields blended in with the ambient conditions, so engine and tyre heat from beneath the vehicle was used to supplement detections. These findings further imply that the effectiveness of the infrared array sensors would be greater in warm climates, or for vehicles that have been running long enough for their engine heat to show against the ambient conditions (Figure 6.6).

Another study by Oudat et al. [169] trialled six passive infrared thermometers in a linear array to detect traffic from an overhead position. The trial showed that when combined with a sonar sensor at its five-metre mounting height, the detection accuracy of the system was 99% over 184 vehicle passes, which is comparable to the results in Table 6.6. The study does not mention the standalone accuracy of the thermal detection, or any variations in the system due to temperature effects.

Two studies involving commercial lidar vehicle detectors show a similar detection accuracy to the LidarLite, but at a much higher cost. The first study used a scanning lidar in an overhead configuration to detect vehicles with 100% accuracy in the lane directly beneath the sensor [170]. The high sensor cost of US$5,000, however, makes the sensor impractical for widespread traffic detection. The same can be said for the two sensors used in a study conducted by Minge et al., which both detected traffic from a roadside position with over 96% accuracy, but both cost over US$20,000 [74].

6.9 CONCLUSIONS

This chapter explored the use of inexpensive and off-the-shelf sensors for non-invasive traffic detection for a streetlight-mounted platform. It did so in a series of controlled trials involving a total of 600 vehicle passes under different speed and

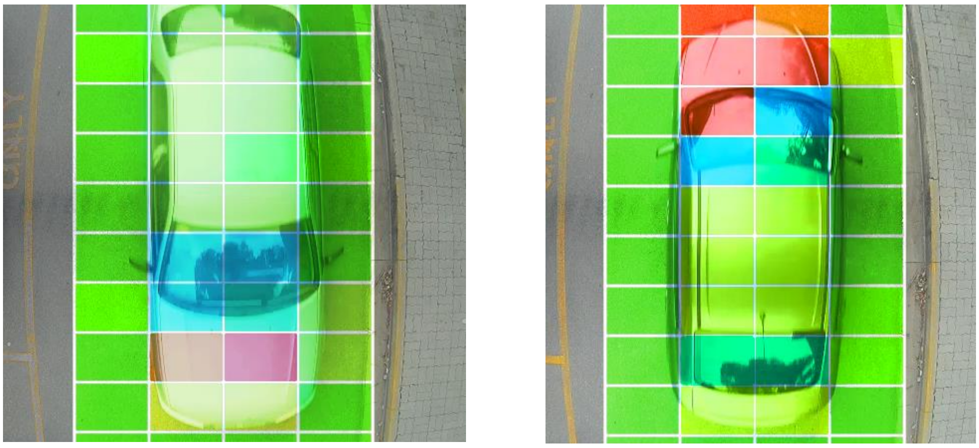

Not detected
Successful detection

Figure 6.6 - Representation of thermal contrast for traffic detection

proximity conditions. These trials showed that of the three tested technologies, lidar and thermographic detection using an infrared array sensor met the goal of a 91% true-positive detection rate and were suitable for non-invasive vehicle counting applications.

Every tested sensor presented individual merits and drawbacks, indicating that multiple sensors should be chosen in a streetlight-mounted traffic detection system. The LidarLite, aside from its high detection accuracy of 99%, was not affected by ambient temperature, and could be useful for detecting water over the road in flood conditions to improve public safety on the road. The narrow lensing of the lidar, however, means that vehicles in the lane below may not be detected if they are too close to the edges of the lane (Figure 6.7). The low cost and high accuracy of the infrared array sensor make the thermographic detection valuable as a backup, supplementary, or even alternative technology to the lidar, but like all passive infrared detection, may not function in all weather conditions if vehicles do not thermally 'stand out' against the road. Finally, while the included PIR motion sensors were not suitable for traffic counting, they are beneficial at detecting both pedestrian and vehicle traffic over a large area for lighting purposes and verification for other sensors. For these reasons, the recommendation of this chapter and Stage 1 is to combine all of the tested sensor technologies for inexpensive and non-invasive streetlight-integrated traffic detection.

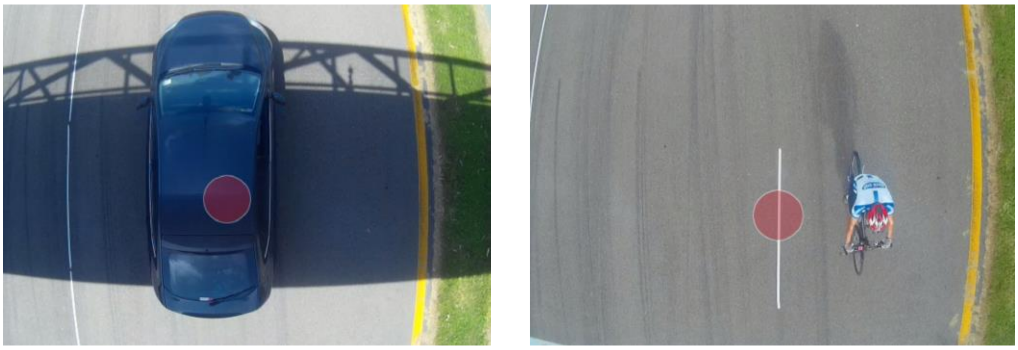

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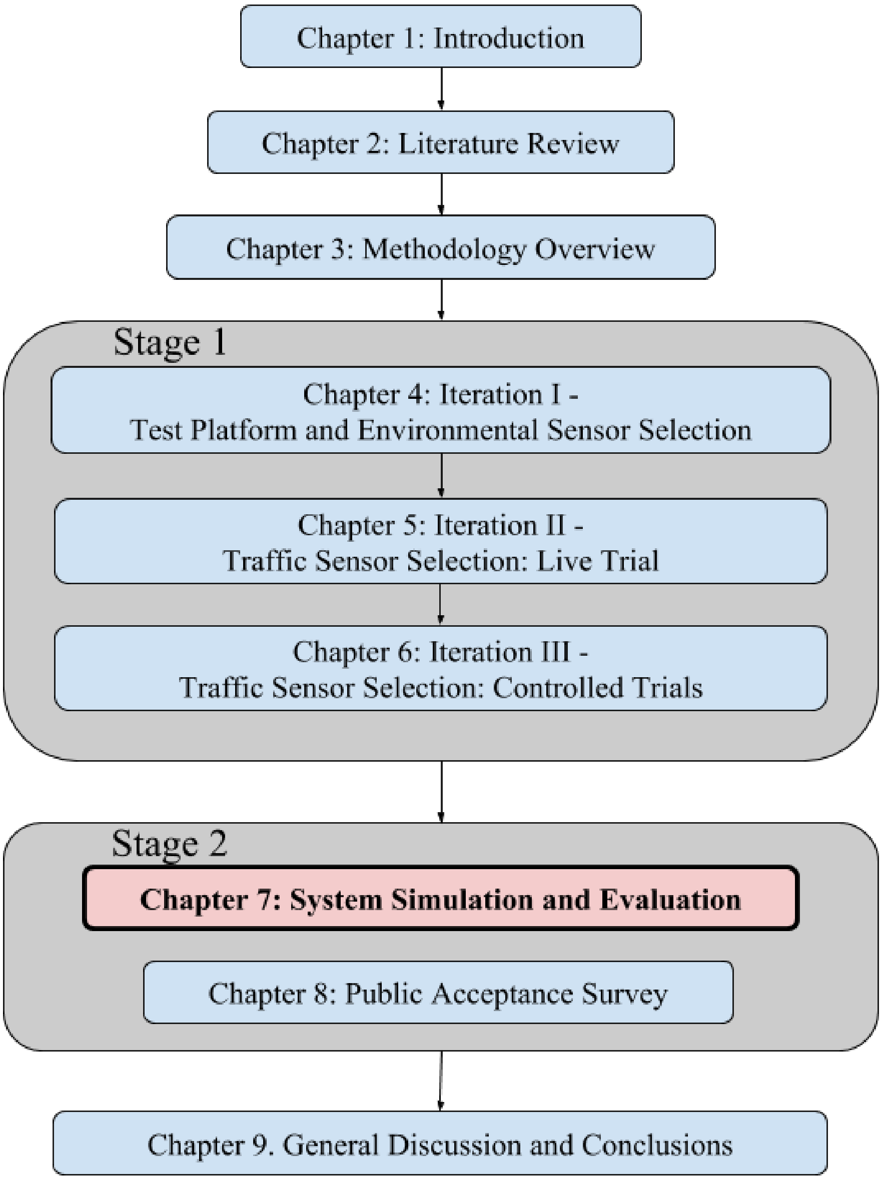
Figure 6.7 - Representation of lidar detection zone showing likely cause of undetected traffic events

Chapter 7 - System Simulation and Evaluation



This chapter will be submitted to the Journal of Technological Forecasting and Social Change as follows: 'K. Mohring, T. Myers, I. Atkinson "Financial valuation of a smart streetlight traffic detection system"'

7.1 CHAPTER OVERVIEW

The previous chapter marked the end of Stage 1 of the study. At its conclusion, a hardware prototype was presented that was capable of detecting, counting, and classifying traffic for smart city applications. Stage 2 of the study evaluates the viability of the evolved sensor prototype. This chapter presents a simulated method for evaluating the costs and benefits of a smart streetlight installation. The simulation's design and concepts are presented, followed by a case study of lighting installations involving three Australian cities. This chapter concludes with recommendations on which streetlight installations would benefit the most from the developed sensor system.

7.2 INTRODUCTION

This chapter marks the beginning of Stage 2 of the research, which focuses on evaluating the viability of smart streetlights. Stage 1 investigated the state-of-the-art commodity sensors that could feasibly be installed inside streetlight housings for ubiquitous city-wide sensing at a low cost. At the end of Stage 1, a prototype sensing system was developed that could detect, count, and potentially classify traffic on roads and footpaths from a streetlight-integrated configuration, and monitoring the surrounding environmental conditions to service a wide variety of smart city applications. Now that a viable hardware solution was established, the hardware costs could be measured against the utility of the information that the system could provide.

This chapter begins the evaluation of smart streetlights by investigating the reductions that traffic-aware dimming could have on the electrical and maintenance costs of new and existing public lighting installations. At present, there have been no studies that investigate whether the benefits of implementing traffic-aware dimming are worth the cost. This chapter aims to resolve this gap in the literature by making the following contributions:

- A method for quickly estimating the effectiveness of traffic-aware dimming on a city-wide scale is developed and demonstrated in Section 7.4. This estimation is accomplished by using historical traffic information to calculate the minimum and maximum bounds of how much dimming is possible with typical traffic behaviour without affecting road safety.

- A more accurate approach to lighting installation comparisons, as compared to other publicly available tools, is presented in Section 7.4. This approach uses an object-oriented model to individually track each asset in a lighting installation such as lighting sites, equipment, and any additional control hardware in terms of electrical costs and maintenance. By tracking lamp usage independently, electricity consumption and maintenance costs could be estimated over an entire city, despite the different traffic characteristics of its individual roads.
- Using the developed model, the simulation demonstrated that an LED lighting installation equipped with a traffic-aware dimming system was more cost-effective than a conventional, always-on configuration (Section 7.6), especially in areas of low population.
- The study concludes by demonstrating that electrical and maintenance costs were the primary drivers for whether the developed smart streetlight control system was feasible for implementation (Section 7.9).

7.3 BACKGROUND

Multiple tools for planning and comparison between lighting technologies have been developed in response to the shift in technology. Perhaps the most notable and publicly available resource for informing replacement projects is the ‘Retrofit Financial Analysis Tool’, which was released by the U.S. Department of Energy in 2015 [223]. The spreadsheet-based tool focuses on the replacement of existing lamps with new fittings and provides a year-by-year breakdown of the costs and the differences in value between the two lighting scenarios due to maintenance and electrical consumption. The evaluation is highly configurable and allows multiple lamp types and replacements to occur in the same installation, and even allows for basic passive dimming options to be configured. However, dimming is modelled very simplistically, as a flat reduction in effective lamp ‘on time’ per year across all lamps. The problem with this blanket approach is that the effectiveness of traffic-aware adaptive lighting varies with traffic level, which in turn, varies between different road sections at different parts of the day. To accurately model traffic-aware dimming schemes across a city, individual road sections would need to be added to the analysis as a separate installation after estimating the dimming effectiveness for each road, which would be a very time-consuming and labour-intensive process.

Other street lighting comparisons are similarly incapable at modelling the effects of dimming public lighting. The ‘SEAD Street Lighting Tool’ [224] and the life-cycle cost analyses conducted by Tähkämö et al. and Schmidt [225-227] perform similar analyses to that of the Retrofit Financial Analysis Tool. However, they improve their comparisons by taking lamp characteristics such as luminous efficacy and uniformity into account to estimate differences in lamp spacing and their associated costs. Unfortunately, the usefulness of these comparisons is still limited in terms of scale, as lighting requirements change on a per-road basis. This means that as with the Retrofit Tool, each road would need to be added separately to the system for an accurate comparison over an entire city. These approaches also do not take dimming into account in any way [225, 226, 228, 229].

Studies that do model the dimming effectiveness of traffic-aware schemes are not performed in a scalable manner. This limitation is due to the methods used to gauge dimming efficiency. Traffic-aware dimming schemes, such as those created and used by Juntunen et al. [129, 230] have been tested using live trials with either controlled or natural traffic. These small-scale test scenarios are useful in that they can provide an indicative dimming performance for the given or a similar lighting installation but attempting to apply these findings across an entire city would require trials to be conducted at every road and traffic archetype to accurately model the difference in electrical consumption.

Other studies have elected to evaluate traffic-aware dimming by conducting traffic simulations. These studies, such as Lau et al.’s TALiSMaN system [57, 130] and the scheme presented by Knobloch and Braunschweig [231], emulate the driving behaviour of individual vehicles in real time. These simulations allow any given traffic scenario and lighting configuration to be tested in a much more scalable manner than live trials. However, attempting to assess dimming effectiveness over the scale of a city is still an impractically complex and time-consuming process, especially considering the resources needed to simulate traffic over the timescale of multiple decades needed for lifecycle analysis. Both the live trials and simulations conducted to test dimming effectiveness also rarely, if ever, consider the costs of implementation.

To date, no studies have considered or modelled the effect that traffic-aware dimming could have on the lifecycle costs of a road lighting installation. Due to the shortcomings of existing streetlight installation comparison tools, the aim of this research is twofold:

1) To develop a method of quickly evaluating the effectiveness of traffic aware dimming schemes on city-wide scale, and;

2) To accurately compare the financial viability of traffic-aware dimming against existing, conventional installations.

7.4 SIMULATION METHODOLOGY

An evaluation model was developed to simulate the effects of dimming on a lighting installation's electrical, hardware, and maintenance costs. An object-oriented programmatic approach was taken to modelling lighting sites and other assets in each installation as separate and individual entities. This approach allowed the dimming profile of each light to be unique in response to traffic levels. The extra hardware responsible for control and dimming could be added to each site to better estimate costs, and the effects of dimming on lamp lifespan could be precisely calculated. A simplified approach to estimating dimming effectiveness was taken by using historical traffic data to calculate the minimum and maximum bounds of how long each lamp needed to be active per year (discussed further in Section 7.4.3). This method meant that the dimming profiles for each lighting site were able to be quickly calculated across every road within a city.

Figure 7.1 shows an overview of the evaluation process, which can be summarised into five steps: in Step 1, the geographical position and area of the lighting installation are defined to inform the sunrise and sunset times, which in turn advise how long the lamps are normally active per year. All road and traffic information relevant to the defined area is collected to identify typical traffic behaviours and to estimate the number of lighting sites in the area, given the total road length.

Step 2 of the simulation deals with defining the rules, hardware, and services used in the lighting installations to be tested. These rules include things such as the spacing of lighting sites, which dimming schemes to use, and the definition of maintenance cycles. The hardware options define which lamps to use, as well as any additional hardware such as sensors or control systems. Electrical supply costs and maintenance services are also defined in this step. Multiple installations can be defined in this step for comparison purposes.

Step 3 of the simulation handles the programmatic generation of the lighting sites according to the defined installation parameters. Dimming efficiency is calculated at this stage and individually assigned to each lighting site on a per-road basis.

In Step 4, each configured installation is ‘run’ for a valuation period (typically a 20-year period). Electrical and maintenance costs are calculated annually. Lamps and other hardware are individually checked each year to establish how many sites need to be serviced, and the hardware costs of any replacements that need to occur.

Finally, in Step 5, net present value analysis is performed to compare installations and their configurations. Cumulative net present value is used to calculate at which point in time installations become more financially beneficial than others. Annual cash flows also provide a breakdown of costs for each configuration to show its strengths and weaknesses. The following sections gives a more detailed discussion of the input variables and mechanisms involved in the simulation.

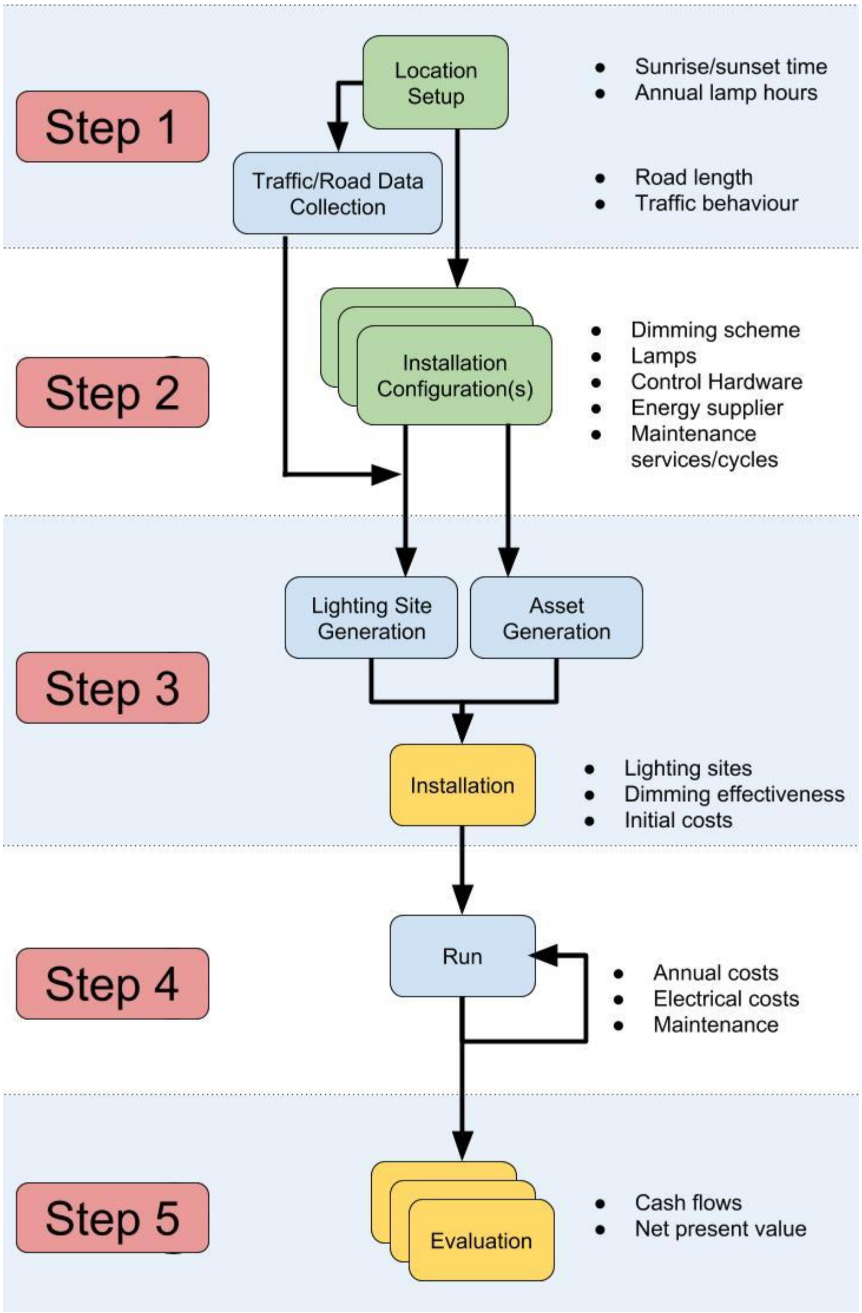


Figure 7.1 - Evaluation process flowchart showing variables defined or calculated at each step

7.4.1 Traffic Data and Roads

The traffic dataset used in this study was obtained from Queensland's Department of Transport and Main Roads [232]. This dataset gave historical traffic information for every road operated by the Queensland State Government for each hour and day of the week, averaged over the year. Roads are broken up into sections where traffic sensors were available, and in each direction of travel. For the purposes of this study, the dataset was flattened to obtain the average volume of traffic per hour over the year to give an index of typical traffic behaviour for that road section at different points in the day.

7.4.2 **Installation Configuration**

Each lighting installation is configured in terms of its lighting sites, electricity supplier, services, and supporting hardware (Figure 7.2). Lighting sites are modelled as a collection of equipment including a lamp and any other electronics or systems that would be physically located in the same housing in this simulation. In physical terms, the lighting sites represent the streetlight's pole or mounting structures and do not consume electricity and are not expected to fail for the purposes of the simulation. The main purpose of representing lighting sites is to aggregate maintenance, so multiple items per site can be replaced or serviced during the same maintenance callout.

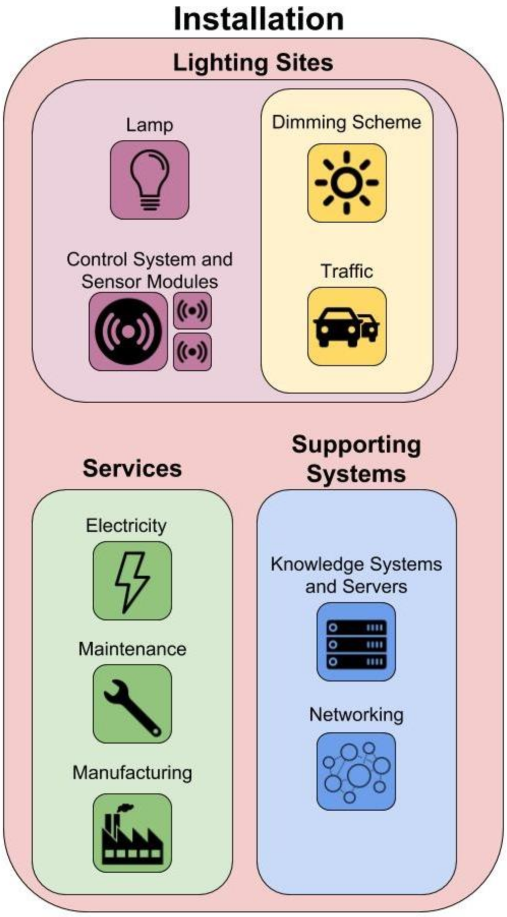


Figure 7.2 - Overview of installation configuration

Lighting sites are generated along each road (as defined in Step 1) according to the lamp spacing defined in an installation’s options.

7.4.3 **Dimming Scheme**

Aside from aggregation of assets and their costs, the function of the lighting site class is to govern the dimming output of its lamp. Simple traffic-aware dimming schemes (Figure 7.3) can be defined using four factors: the ‘active’ output level of the lamp (typically 100%), the dimmed ‘inactive’ output level, and the amount of time before and after a traffic event that the light will remain active for. For example, a scheme can light up the road ten seconds ahead of a car and stay on for five seconds after the car leaves for a minimum lighting time of 15 seconds per traffic event. Any following vehicles will reset the delay time and the lamp will stay active for a longer duration.

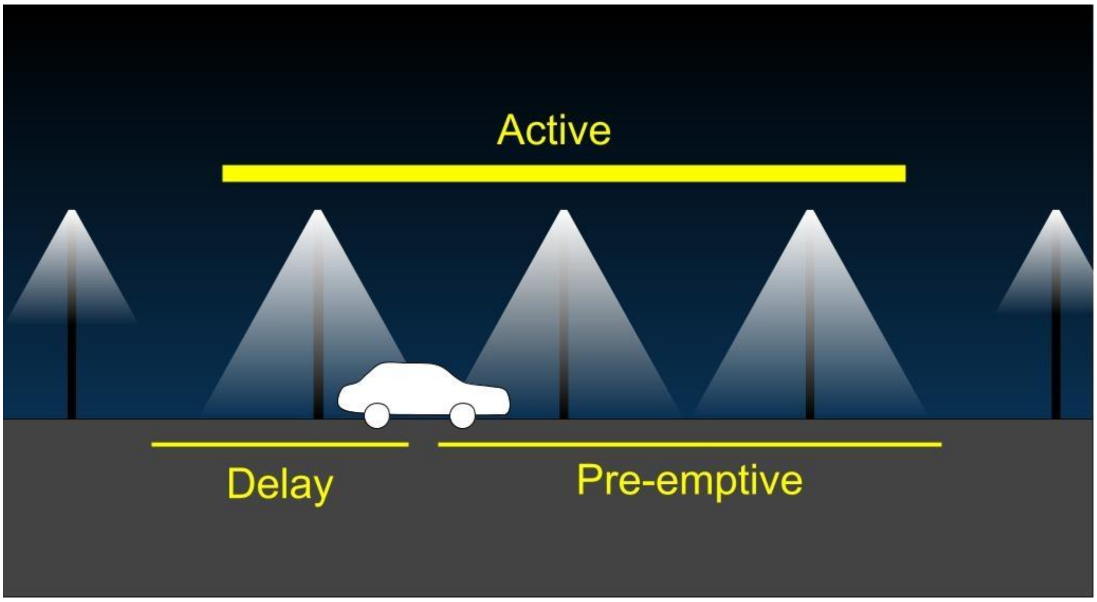


Figure 7.3 - On-demand traffic-aware dimming

The dimming efficiency of a traffic-aware scheme can be calculated on a given road within a given period using these four variables, but only if the distance between individual vehicles is known. However, the limited traffic information in the dataset used by this study only provides a typical traffic volume over an hour with no indication as to how vehicles are spaced, especially given that the data is averaged per hour over a year. Instead of finding the actual dimming efficiency from individual traffic events, the simulation works off the most and least optimistic dimming scenarios (illustrated in Figure 7.4).

The least-optimistic dimming scenario occurs when vehicles are spaced evenly within the given period. Provided enough time between vehicles, this would mean that the lighting site would go through the entire lighting cycle of becoming active ahead of a car, then waiting for the full delay period after the car passed before returning to its inactive, dimmed state. In contrast, the most-optimistic dimming scenario would occur when all vehicles within the hour consecutively pass the lighting site with a minimum following distance, especially if the road has multiple lanes. This means that the lighting site would only have one lighting cycle with a single long active period, between singular pre-emptive and delay stages.

In lighting installations where dimming is enabled, the minimum and maximum dimming efficiency is estimated per road over the year, based on the historical traffic information. These two bounds serve as the edge cases of how much dimming is theoretically possible with the current configuration, with the actual dimming efficiency falling somewhere between, depending on traffic fluctuations. No point within these bounds was chosen to represent a 'likely' value for dimming efficiency.

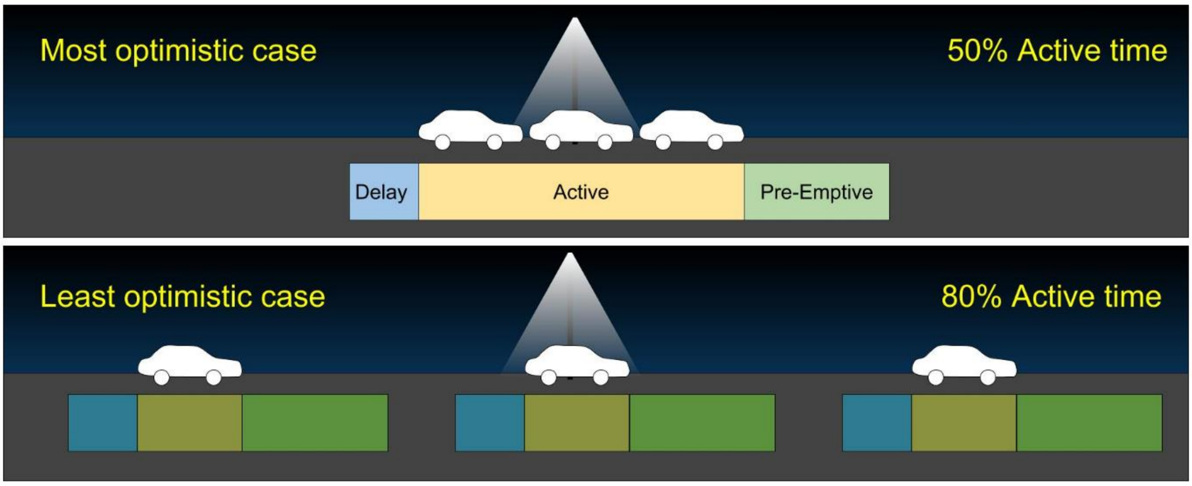


Figure 7.4 - Traffic scenarios showing the most and least optimistic dimming cases

7.4.4 Lighting Site Hardware

The hardware contained at lighting sites, namely the lamp and control electronics, are modelled as separate assets. This means that each item is associated with its own separate fixed costs, electrical consumption, uptime, and failure characteristics. For electrical assets, this failure probability is calculated as a function of usage, rather than age. Failure rates are modelled using a random annual failure rate, combined with a Weibull distribution (example in Figure 7.5) to generate a function of failure probability (Equation 1). This method of determining failure rates on an individual-component basis is necessary, particularly with LED lamps, due to manufacturing difference, and variations in deployment conditions. Dimming effects also mean that the annual effective lamp output will vary between lamps on different roads. Individual monitoring of components means that failure of non-essential systems can be handled during routine maintenance as opposed to a costly and immediate callout.

Equation 1 - Failure probability of electrical assets

$$P_{failure} = 1 - p_{random} - e^{-\left(\frac{t}{mtbf}\right)^{k}}$$

$P_{random} = 0$
$mtbf = 60{,}000$
$k = 15$

Where:

p_{random} = the probability of a random failure per year
t = effective uptime of the asset in hours
$mtbf$ = mean time before failure in hours
k = shape factor

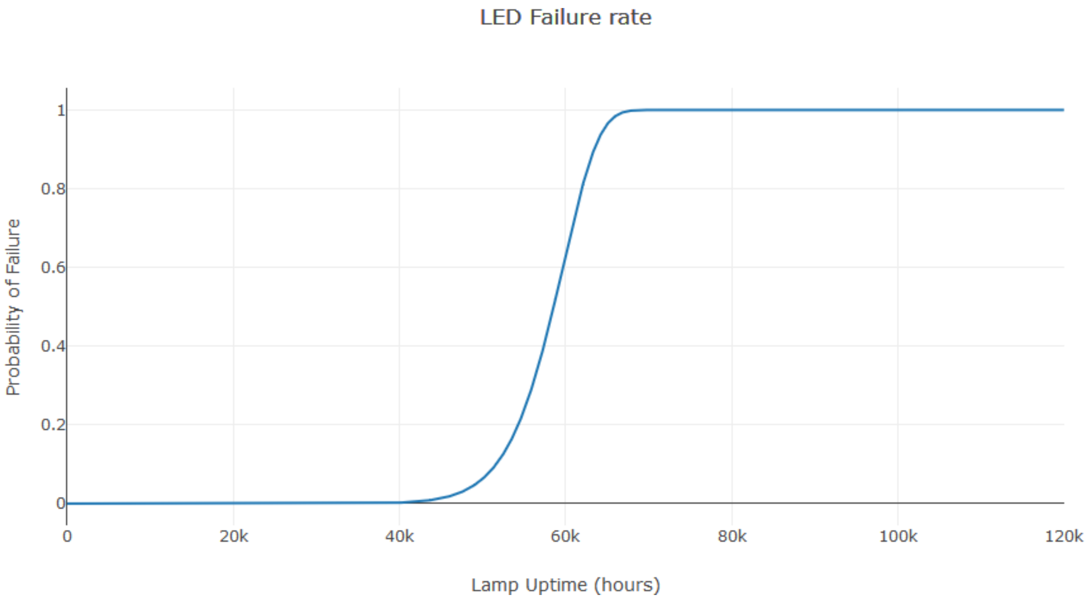


Figure 7.5 - Example of a failure probability curve showing increased likelihood of failure over an asset's lifetime

7.4.5 Sensors and Control Electronics

Lamp control hardware can be added to each site to interface with the lamp manufacturer's drivers or ballasts. This control hardware is modelled as a base platform that is physically located at the lighting site and can interface with the manufacturer's control system to perform basic tasks such as lamp control, dimming, tracking of power consumption, and lamp health monitoring. A wired or wireless communications module can be added to the base platform to provide centralised lamp control and monitoring, including the automated reporting of failed lamps or components. Lighting sites can also communicate between themselves to notify one another of traffic or control events, and to aggregate data across sites. The site's base platform can also expand its functions using one or more sensor modules, which are defined in this study as collections of sensor hardware geared toward a specific function, such as traffic detection. Any extra hardware added to the lighting site, along with its unit price, also add to the site's operational costs, including electricity costs and maintenance costs if a critical component (e.g. the communication module) fails. The additional control hardware can also be modelled with an additional manufacturing cost for constructing the circuit boards and assembly, as well as a fitting cost to modify existing lamp housings to fit the added components.

7.4.6 Services

Lighting installations require maintenance services to maintain sites and perform replacements in case of hardware failures. Maintenance services in this simulation are modelled as either spot maintenance or bulk lamp replacement, the latter being conducted as part of a preventive maintenance scheme. Both types of maintenance service can be implemented within the same installation for different purposes and scenarios. Spot maintenance is conducted when a lamp or component fails unexpectedly and requires immediate repair or replacement to maintain compliance with road lighting standards. On the other hand, bulk lamp replacements are conducted according to a fixed preventive maintenance schedule (e.g. every four years), or when the number of lamp failures per year exceeds a minimum threshold (e.g. five percent of all lamps within the installation) [233]. Other services can be added to the installation for other tasks such as disposal of hardware, manufacturing, etc.

In all cases, labour services are modelled using a time-based wage, a fixed fee, or a combination of both. For example, a manufacturing service for lamp control hardware would be associated with a per-hour wage, as well as a fixed per-unit cost for materials. Alternatively, maintenance services can be associated with a wage for tradespeople involved in the servicing, as well as a fixed cost for equipment hire that can be calculated on a daily or weekly basis.

7.4.7 **Other Assets**

Other assets may be needed to support a lighting installation, particularly if sophisticated control systems are used. Installations with long-range networks for remote control and data may require radio base stations, computer systems, and servers for storage purposes. The simulation allows all other assets, electrical or otherwise, to be added to the installation and included in its operational costs.

7.5 CASE STUDY

Following the evaluation process outlined in Section 7.4, a simulated model was implemented and tested by modelling the lighting installations of three Australian cities. These cities, Brisbane, Townsville, and Gladstone, were chosen to represent a large, medium, and small city, respectively. Due to limitations in the data, only information from state-controlled roads was available. This limitation means that lighting installations were reconstructed from a limited number of high-traffic main roads only, while sub-arterial and residential roads were omitted from the simulation.

The characteristics of each city as they pertain to the simulation are listed in Table 7.1. All three cities have similar sunrise and sunset times, meaning that streetlights will be operating at similar times across the sites. The only major change between the locations is the population, number of main roads, and the local traffic levels. The number of lighting sites is estimated using a fixed 50-metre spacing across all roads. A currently implemented public lighting tariff was used to calculate electrical costs and daily supply charges for each lighting site at a rate of approximately AU$0.34 per kilowatt hour [125].

Table 7.1 - Location information used for case study[1]

	Large	Moderate	Small
City name	Brisbane	Townsville	Gladstone
Population[2]	2,408,223	195,346	62,932
Average sunrise time	5:44 AM	6:09 AM	5:54 AM
Average sunset time	5:48 PM	6:15 PM	6:00PM
Average daylight hours	12:04	12:06	12:06
Number of main road sections	332	62	28
Total main road length (km)	784	115	64
Average vehicles (per hour, per road)	876	400	259
Average lanes per main road per direction (assumed)	2	2	1
Number of lighting sites (calculated)	15,834	2,324	1,292

Maintenance across all lighting installations was assessed on a quarterly basis using the services outlined in Table 7.2. Bulk replacements were conducted when at least five percent of lamps failed within a year. Non-critical components that failed within each lighting site were only replaced if other, critical components also required servicing during the same period or later.

Table 7.2 - Lamp maintenance service costs used for case study lighting installations

	Wages (AU$)	Rate	Fee (AU$)	Fee period
Spot maintenance[3]	230	1 unit/hour	395	per day
Bulk replacement[4]	560	1 unit/hour	1495	per week

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[1] All sunrise, sunset, and daylight hours information from timeanddate.com [234]

[2] Population information provided by the Australian Bureau of Statistics [235]

[3] Prices based on the callout fee of two electricians and a traffic controller, plus car and elevated work platform hire

[4] Prices based on the callout fee of four electricians and two traffic controllers, plus car and elevated work platform hire

7.5.1 Case Study Configurations

Each testing site was modelled with three configurations: using conventional high-pressure sodium (HPS) lamps, conventional LED lamps, and LED lamps equipped with the traffic-aware dimming system developed in previous stages of this project [1-3], henceforth referred to as ‘smart LED’. The lamp technologies and their characteristics used in each configuration are shown in Table 7.3, and the variables used for the dimming scheme in the smart LED configurations is shown in Table 7.4.

Table 7.3 - Lamp configurations for case study lighting installations

	HPS	LED	Smart LED
Lamp	Sylvania Roadster S250	Cree XSP 136W	Cree XSP 136W
Rated Power (W)	273	139	139
Rated lifetime (hours)	24,000[1]	60,000[2]	60,000
Dimming Scheme	None	None	Traffic-aware

Table 7.4 - Dimming scheme parameters for smart LED configuration

Parameter	Option
Active output ratio	100% of rated output
Inactive output ratio	20% of rated output
Pre-emptive turn on time	10 seconds
Active holdoff delay	5 seconds

Table 7.5 shows the additional hardware installed within lighting sites in the smart LED configurations. The base platform, in this case, was modelled with the costs and power consumption of containing power monitoring equipment, a dimming interface, basic motion detection sensors, and a LoRaWAN wireless communications module to enable centralised control and data collection. Wireless base stations, external to the lighting sites, were included in the configuration for every 250 sites to represent a responsive network design [237, 238]. Each LoRaWAN base station was modelled with a 40-Watt power consumption, and cost AU$1,375, based on pricing and information from retailers [239].

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[1] Lifespan of HPS lamps based off multiple claims [103, 107]

[2] Lifespan of LED based off the claims of multiple manufacturers [107, 109, 110, 236]

The traffic sensor module that was included in 50% of lighting sites represented an advanced non-invasive traffic detection system to supplement the motion detectors on the base platform. The hardware costs and power consumption shown in Table 7.5 are indicative of a sensor system able to accurately count and classify vehicles and pedestrians from the lamp housing. Aside from traffic detection, an environmental module for climate tracking, and a networking module to monitor wireless activity, were also modelled and added to a proportion of the lighting sites.

Table 7.5 - Sensor module distribution for smart LED lighting installations

Sensor Package	Proportion of lighting sites	Power consumption (W)	Unit cost (AU$)
Base platform (incl. communication)	100%	1.53	241.85
Traffic	50%	1.74	186.06
Environmental	50%	0.013	6.18
Networking	10%	0.10	32.13

Finally, Table 7.6 shows the additional services required by the smart LED installations to manufacture and install the base platform hardware in the lighting site housings. The base platform manufacturing costs were estimates, based on commercially available 'pick and place' manufacturing pricing, and the estimated fitting costs were based on the average callout fees of a licensed electrician within Australia, plus the cost of materials required.

Table 7.6 - Additional services used by smart LED lighting installations

	Wages ($)	Rate	Fee ($)	Fee period
Base platform manufacture	N/A	N/A	40	per unit
Fitting to site housing	85	2 units/hour	50	per unit

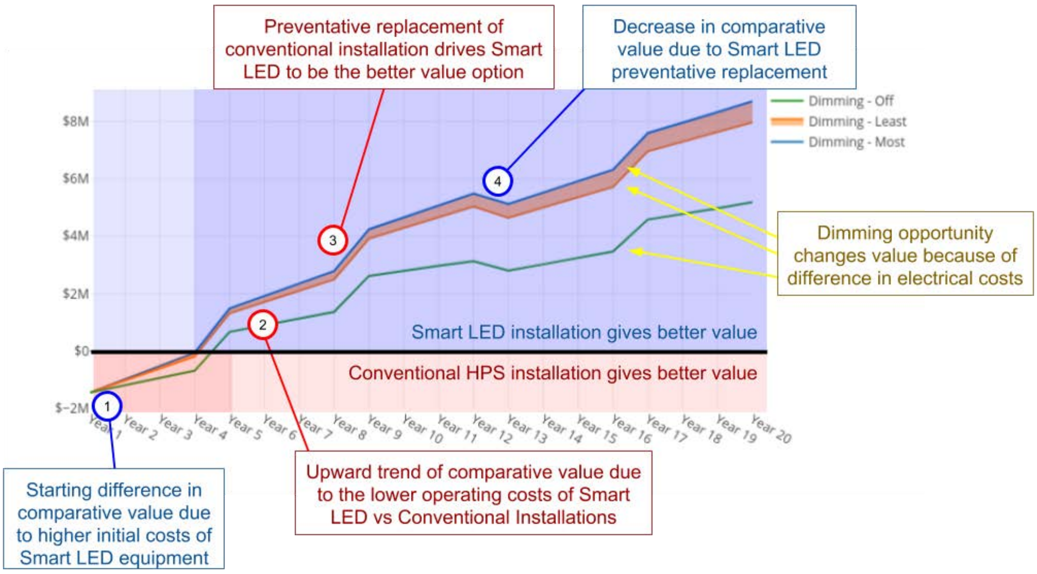
7.6 RESULTS AND ANALYSIS

Each of the configurations outlined in Section 7.5 was simulated for a test period of 20 years. Annual cash flows from this test period were used to calculate the net present value of each installation, and in the case of the smart LED configuration, with dimming disabled, and with the most and least-optimistic dimming scenarios. The cumulative net present value of each smart LED installation was then compared to that of its equivalent conventional installations to establish at which point in time one option was more financially beneficial than the other.

Figure 7.6 shows a graphical example and explanation of a comparison scenario between a smart LED and conventional road lighting installation. The figure shows four main characteristics that are common throughout most of the net present value comparisons:

1) Firstly, the smart LED installation starts with a significantly lower comparative value than the conventional alternatives due to the higher associated cost of the additional hardware.
2) Secondly, the overall trend of the comparison shows that the smart LED option increases in comparative value over time due to lower operational costs than conventional installations, especially when dimming is enabled.
3) Thirdly, the comparative value of smart LED sharply increases at regular intervals due to the bulk replacement of lamps in conventional installations for preventive maintenance.
4) Finally, the comparative value of the smart LED installation also decreases due to preventive maintenance, albeit at less frequent intervals.

The green line represents the comparative value of the smart LED system when dimming is disabled entirely, and the data collected by the sensor system has no direct impact to streetlight operation. Next, the orange band represents the comparative value of the smart LED system with traffic-aware dimming enabled, accounting for variability in traffic spacing over the duration of the simulated period. The top-most area of the band represents the most-optimistic traffic scenario, where the bottom of the band represents the least optimistic traffic scenario (see Figure 7.4). Both of these limits are theoretical cases with the actual value being somewhere in between, depending on the varying traffic conditions.



Preventative replacement of conventional installation drives Smart LED to be the better value option

Decrease in comparative value due to Smart LED preventative replacement

Dimming opportunity changes value because of difference in electrical costs

Starting difference in comparative value due to higher initial costs of Smart LED equipment

Upward trend of comparative value due to the lower operating costs of Smart LED vs Conventional Installations

Figure 7.6 - Explanation of events in comparative net present value plots

7.6.1 Comparison between smart LED and conventional HPS installations

With the chosen configuration, the smart LED option consistently provided more value than conventional high-pressure sodium (HPS) lamps (Figure 7.7 - Figure 7.9). In all the tested scenarios, the point at which smart LED became more valuable was within a period of six years, despite bearing an initial cost three times higher than conventional HPS. This result is due to multiple factors. With the given preventive maintenance rules that reflect real-world policy, HPS lamps are regularly replaced after five years of use, which would drastically increase the hardware and maintenance costs at those intervals. Even without the regular bulk replacements, the value of the smart LED option was still projected to overtake that of conventional HPS within the same period due to the reduced operational costs. With dimming enabled, the annual electrical costs for smart LED installations was reduced by 64 - 87% compared to HPS, depending on location and dimming scenario. Even in the scenarios where dimming was disabled entirely, the electrical costs of the lamps and additional control gear in the smart LED installations were approximately half those of the conventional option. This result is also despite the hardware and maintenance costs associated with replacing faulty control equipment.

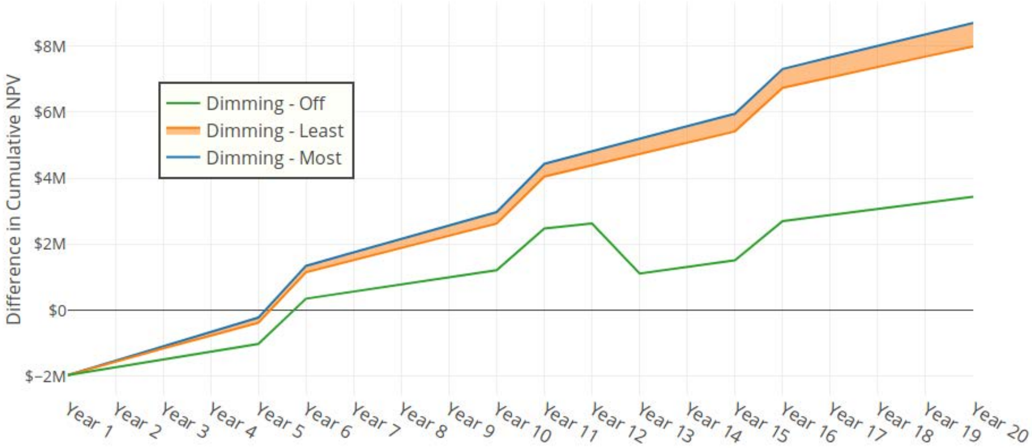


Figure 7.7 - Comparative NPV between smart LED and conventional HPS installations in Gladstone

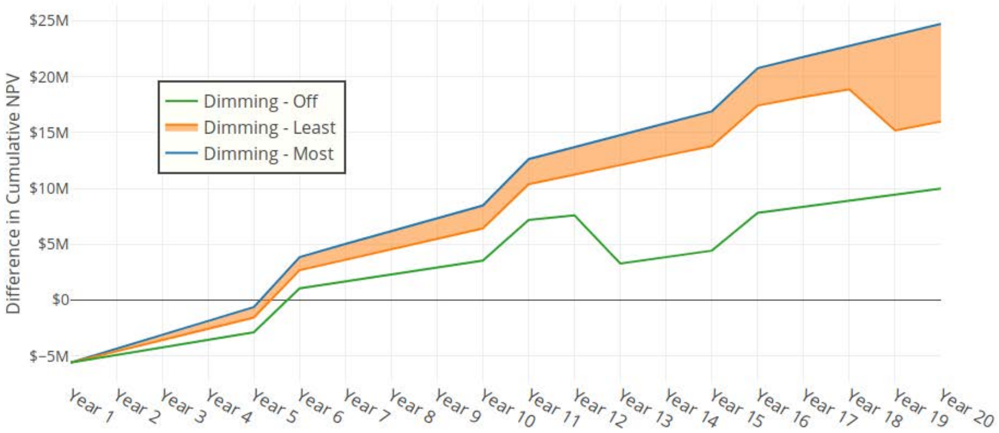


Figure 7.8 - Comparative NPV between smart LED and conventional HPS installations in Townsville

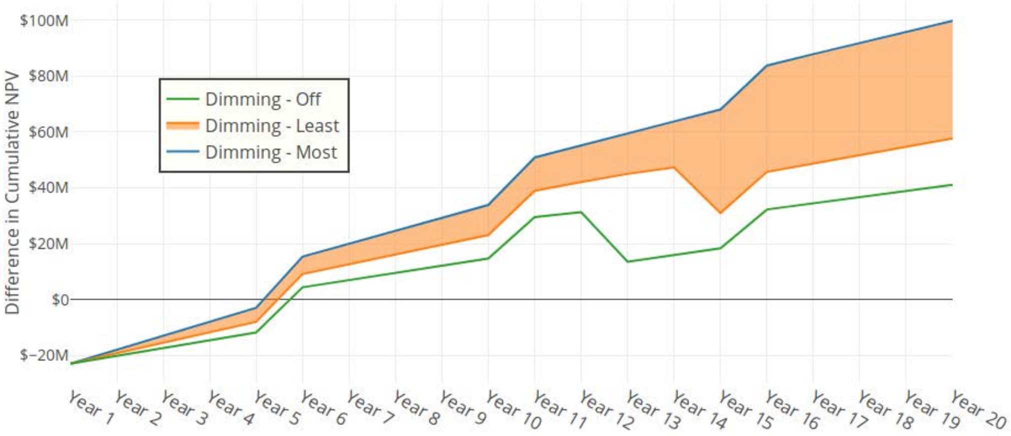


Figure 7.9 - Comparative NPV between smart LED and conventional HPS installations in Brisbane

7.6.2 Comparison between smart LED and conventional LED installations

The comparative values between conventional and smart LED installations were quite close compared with that of conventional HPS. In these cases, the only difference between the compared installations was the inclusion of the sensor hardware and the dimming that they enabled. This means that to be more valuable, the sensor modules in the smart LED scenarios had to provide enough benefit to outweigh their costs. Figure 7.10 to Figure 7.12 show the cumulative difference in net present value for the small, moderate, and large test locations, respectively. In all comparisons, the smart LED configuration provided the most value, but with much more varied results compared to the HPS comparisons.

In the most-optimistic dimming scenarios, the smart LED option became the more valuable option within a five to six-year period when compared to conventional LED. In these scenarios, dimming reduced the overall electrical consumption of the installation by 68% in the large installation, and up to 73% in the small installation (Table 7.7). A result of this decreased lamp usage was that the lifetime of the lamps was extended to the point that no bulk replacements were conducted within the 20-year evaluation period.

Table 7.7 - Differences in electrical costs between conventional LED and smart LED installations with most-optimistic dimming

	Annual Electrical Costs - Conventional (AU$)	**Annual Electrical Costs - Smart (AU$)**	**Difference**
Small installation	272,690	72,299	-73%
Moderate installation	488,878	138,464	-72%
Large installation	3,335,790	1,067,180	-68%

Results were much more varied in the least-optimistic dimming scenarios. The time taken for the smart LED installation to become the most valuable option varied from six to twelve years, depending on the size and traffic density of the test area. In these scenarios, the amount of dimming possible was much more sensitive to traffic density, resulting in far more varied differences in electrical costs between conventional and dimmed configurations (Table 7.8). Even with the least amount of dimming possible given the historical traffic levels, the dimming scheme resulted in reductions between 29% and 57%, which represents a significant amount of electrical consumption. Unlike the most-optimistic dimming scenario, the moderate and large smart LED installations required bulk replacements within the evaluation period, albeit at a heavily reduced frequency.

Table 7.8 - Differences in electrical costs between conventional LED and smart LED installations with least-optimistic dimming

	Annual Electrical Costs - Conventional (AU$)	Annual Electrical Costs - Smart (AU$)	Difference
Small installation	272,690	117,838	-57%
Moderate installation	488,878	296,519	-39%
Large installation	3,335,790	2,383,137	-29%

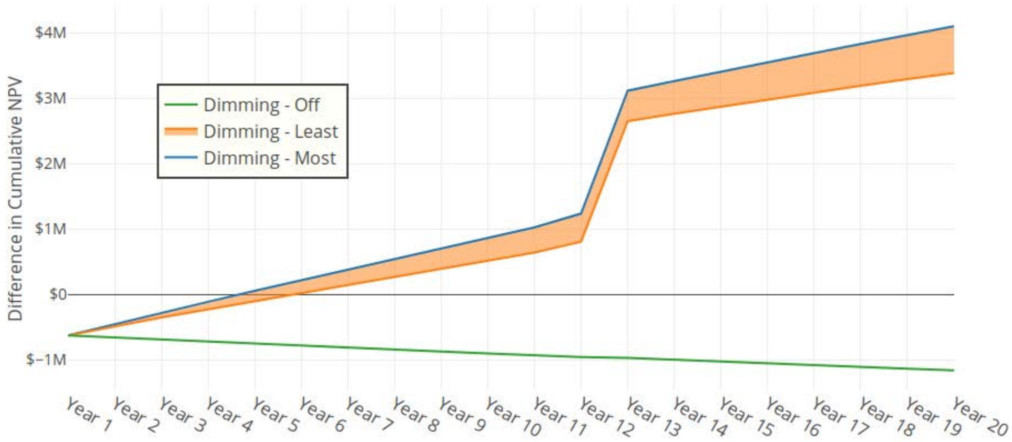


Figure 7.10 - Comparative NPV between smart LED and conventional LED installations in Gladstone

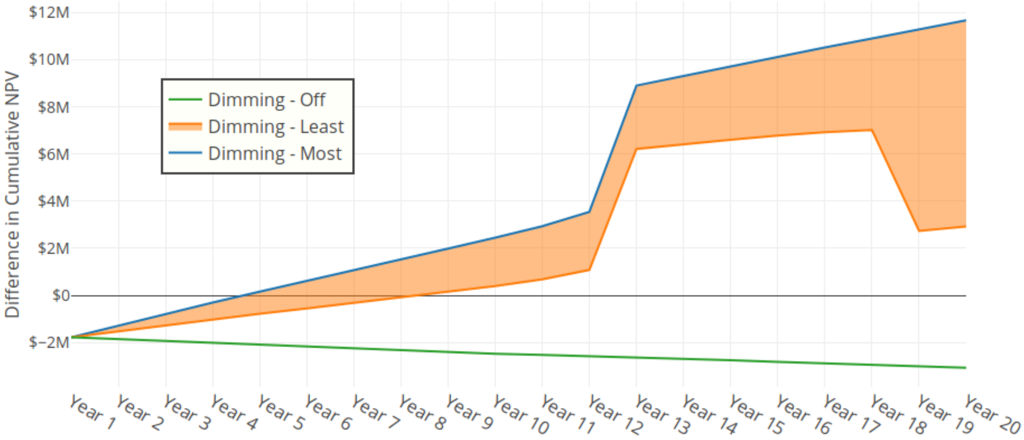


Figure 7.11 - Comparative NPV between smart LED and conventional LED installations in Townsville

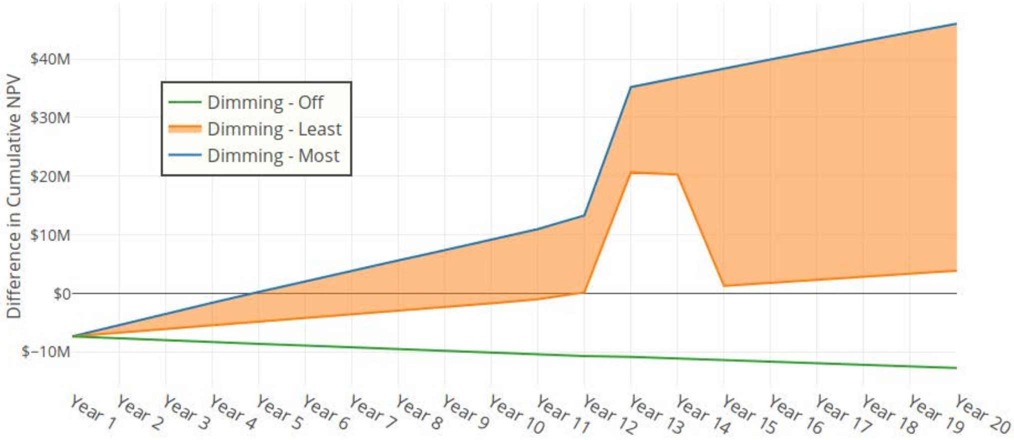


Figure 7.12 - Comparative NPV between smart LED and conventional LED installations in Brisbane

7.7 DISCUSSION

The main findings from the case study show that smart LED installations were the most cost-effective solution in all locations. When compared to conventional HPS installations, the lower operational costs consistently meant that the smart LED option would provide more value within a six-year period. In a real-world context with the same configuration, a change in lamp technology, with the addition of dimming, could result in savings in the scale of hundreds of millions of dollars in a 20-year period for a large lighting installation.

Compared to conventional LED installations, the smart LED option was still the most valuable overall, but there were differences in dimming effectiveness between the test locations, which affected the comparative net present value. The effectiveness of the tested traffic-aware dimming schemes decreased as the population of the test city increased. This result was expected, as larger cities tend to have more traffic, including during the night. As traffic-aware schemes cater to individual vehicles, a greater number of vehicles on the road means that lamps needed to stay active for longer when compared to a quiet road.

As for dimming scenario, a sensible method for comparing lighting installations would be to assume the least-optimistic effectiveness. The reason for this assumption is that night traffic tends to be sparser and more random than daytime traffic (likely due to regular business hours falling outside this time), which describes the behaviour in the least-optimistic scenario more closely than the most-optimistic scenario. To test this assumption, the calculated dimming efficiency was compared to that found by Lau et al.'s TALiSMaN dimming system. Using the same scheme on a relatively high-traffic road (>6000 vehicles per day) the electrical reduction of the scheme was calculated to be 72 - 93% over conventional road lighting. In the same circumstances, the TALiSMaN simulation claimed a reduction of approximately 75%, which falls within this range. This result confirms the assumption made during analysis that real-world dimming efficiency would be closer to the least-optimistic dimming scenario.

7.8 LIMITATIONS OF STUDY

7.8.1 Traffic Data

The main limitations of this study come from its reliance on the main roads traffic dataset used in this study. Firstly, the available traffic information only encompasses state-operated main roads. These main roads typically have a much higher traffic volume than sub-arterial roads, especially in residential areas. As traffic-aware dimming schemes are more effective in areas of low traffic, the electrical consumption of the lamps in the smart LED scenario is expected to be lower when considering all non-main roads in the test locations. As such, the amount of dimming opportunity modelled, as well as its potential energy reduction that is presented, are likely understated when compared to the rest of the city. If the traffic information from these residential roads were more complete, and individual traffic information from these were made available, a more accurate dimming scenario across an entire city could be added to the model for a more realistic result.

Secondly, the traffic data used in this study had limited temporal resolution. Traffic counts were normalised hourly, then weekly from the year's recorded traffic, resulting in a large degree of uncertainty regarding traffic behaviour. If traffic data were available in shorter intervals (e.g. in 10-minute intervals), estimates of dimming opportunity could be greatly improved. Ideally, time series data of every traffic event on the road would enable the precise calculation of power consumption due to dimming and remove the need to calculate the most and least-optimistic dimming bounds.

Thirdly, the traffic data used in the model does not change over time. Because of population growth, city traffic is expected to increase over the lifecycle of the lighting installation. Any increases in traffic would decrease the power saving effectiveness of traffic-aware dimming schemes. While not currently a feature of the simulation model, multiple years of historical traffic data could be used to estimate night traffic projections. The result of this inclusion would provide more precise dimming estimations.

Fourthly, the simulation does not take road features into consideration. Changes in the road, such as intersections and exits, may require always-on lighting to indicate possible hazards to motorists [240]. This is especially important of road entryways in a scenario with traffic-aware dimming. Vehicles entering the road should have the road lit in front of them. Always-on lighting at entrances gives a chance for vehicles to be detected and for the lighting system to become active and light the road further without initially compromising road safety.

7.8.2 **Lamps**

As with traffic information, improving the quality of lamp data in the simulation could improve its accuracy. To comply with lighting standards, an installation needs to meet minimum lighting requirements regarding metrics such as illuminance and uniformity [241]. This means that if the lamps' characteristics are too different from one another, replacing a site's lamp with a different model or technology could cause the installation to fail to meet its minimum lighting requirements. Instead, the case study currently assumes that the two tested lamps are drop-in replacements for each other as to avoid the problem of having to move existing lighting sites or install the poles or mounts for additional sites.

The accuracy of the simulation could be improved by including photometric analysis of different lamps. If the lighting requirements of each road in either new or existing installations were available, then photometric analysis could be added to the simulation to test compliance on a per-road basis. This test could inform whether a drop-in replacement between two lamp types were possible, or otherwise calculate the minimum acceptable distance between lighting sites required to meet the local lighting standards. The installation of any additional lighting sites could be incorporated into the model to give a much more realistic estimate of costs for existing installations.

The way that bulk lamp replacements are handled is another factor that may influence the accuracy of the simulation results. In the case study, bulk lamp replacement was set to occur once a minimum of five percent of lamps failed within a year, to reflect the Department of Transport and Main Roads guidelines. However, when traffic-aware dimming is introduced, this replacement scheme no longer fits the usage style of the lamps. With the current bulk replacement scheme, all lamps, regardless of their actual usage, will be replaced when the top five percent of 'busiest' lighting sites fail. This practice can lead to lamps being replaced prematurely if they are in low traffic areas, because of the varying rates in how lamps age due to the differences in night traffic across road sections. In these cases, preventive maintenance is counterproductive as it results in underutilisation of the hardware.

A benefit of the smart LED installation is that the added control hardware at each lighting site is capable of tracking its lamp's usage. With this tracking in mind, a suggested alternative to bulk lamp replacement is to perform regular maintenance cycles (i.e. annually) and only replace lamps that are self-reported to be nearing their end of life. This style of preventive maintenance avoids both the excessive costs of replacing individual lights when they fail and the risk of not meeting safety standards, while still maximising the utilisation of the hardware.

7.8.3 Fixed Costs

The second main limitation of the simulation is that costs of hardware and services are fixed over the lifetime of the installation. Not all the modelled components, tariffs, and/or services will retain the same cost over the lifetime of the installation. For example, LED hardware is currently considerably more expensive than HPS street lighting. However, as the technology is developed and adopted, these costs are expected to fall. The same trend is also expected for the sensor platform and hardware used in the smart LED configuration. A result of these falling hardware costs means a lower initial difference in net value between configurations, which in turn places more emphasis on the running costs and maintenance of each system. Similarly, electrical costs are also modelled as a constant in the simulation. Any expected rise in electrical costs would further increase the importance of energy reductions in the simulated model. The effect of this change would increase the effectiveness of dimming.

7.8.4 Non-monetary Factors

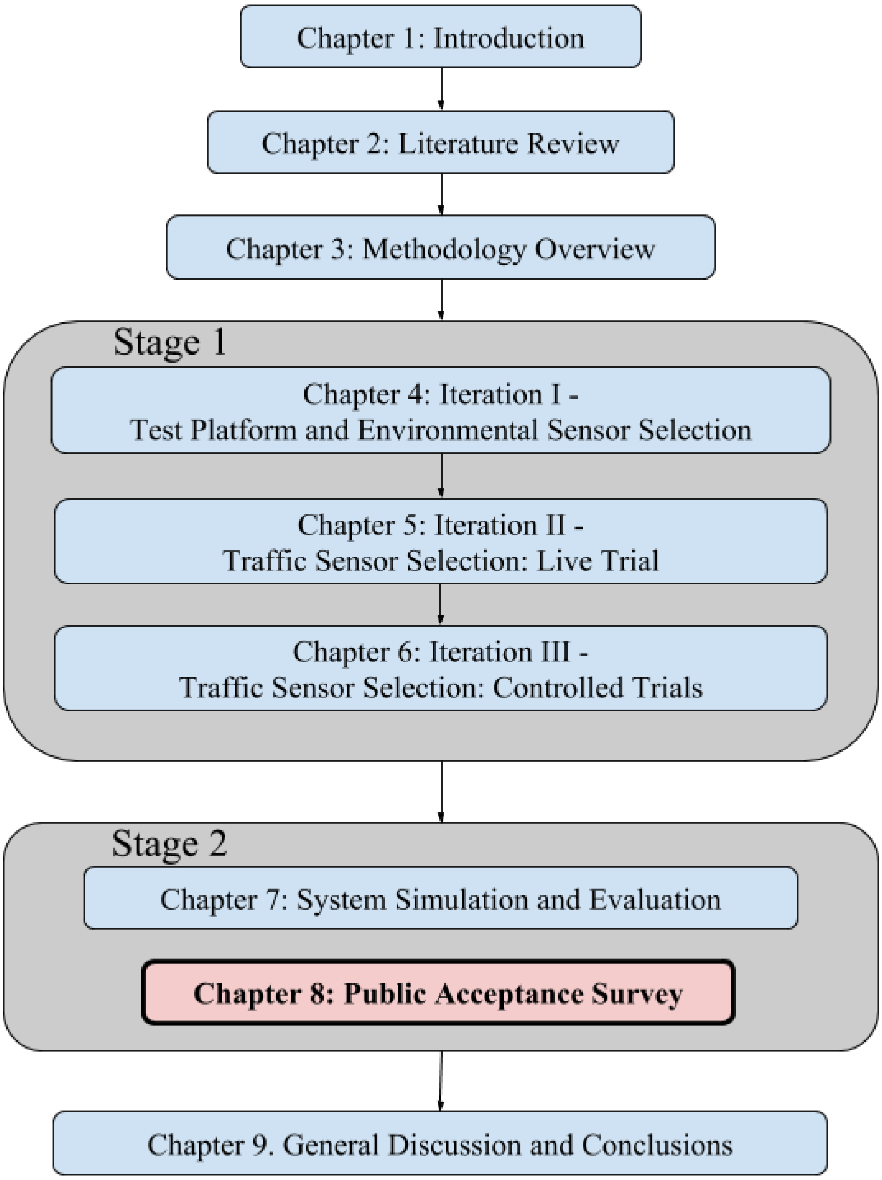
This model focuses on the direct financial costs and benefits of different lighting configurations. However, there are many costs and benefits that are non-monetary or cannot be directly captured by the simulation model. This includes any potential health, social, and environmental effects of implementing different lighting solutions, as well as opportunities for urban research. Potential revenue from the sale or use of traffic or environmental data is also not captured in this evaluation but can be included in the simulation to offset annual costs. Administration overheads for sensor and hardware development and compliance testing and certification for components were also not considered in the simulation.

7.9 CONCLUSIONS

The evaluation presented in this chapter showed that a traffic-aware lighting installation ultimately costs less and provides more value than conventional lighting. The finding implies that many road lighting replacement projects that are currently switching or have previously changed over to LED are not using the technology to its full potential. A recommendation of this chapter is that lighting authorities should adopt and further investigate active dimming solutions, particularly in small cities and in areas with low night traffic, such as residential or industrial suburbs. Large cities can also benefit from the collection of traffic information made possible by smart lighting control systems for traffic improvement purposes. Findings from the case study also suggest that policies regarding dimming and preventive maintenance should be reconsidered to allow traffic-aware lighting technologies to deliver maximum use of the hardware.

This chapter also produced a versatile simulation model for evaluating and comparing lighting installations. The model allows for much more nuanced control of lighting sites, control hardware, maintenance, and dimming schemes than other publicly available tools. Future areas of study will investigate methods to increase the accuracy of the simulation's estimates and expand its functionality. Such improvements could include the consideration of photometric data and lighting requirements, as well as additional hardware options such as photovoltaic cells to assess the viability of standalone lighting systems.

Chapter 8 - Public Acceptance of Technology



This chapter will be submitted to the IEEE Conference on Smart City as follows: ‘K. Mohring, T. Myers, I. Atkinson, A. Swinbourne “Public acceptance of a smart streetlight sensor network”’

8.1 CHAPTER OVERVIEW

Smart road lighting projects are becoming increasingly viable due to the decreasing costs of sensor hardware, as demonstrated in the previous chapter. Development of traffic sensor technologies and their supporting systems allows for city-wide coverage of a more sophisticated and low-cost detection network, which would result in improving traffic flow and saving power by dimming lights. However, a project of this scale would affect the lives of citizens and require public support. This chapter investigates the public acceptances of smart road lighting infrastructure by focusing on the three main applications of the technology that most directly affect citizens: traffic improvement, dimming, and walkability. A quantitative survey was conducted to gauge the level of support for each application and the trends that determined that support. The chapter concludes by discussing the factors that were found to influence public acceptance of smart streetlight applications, and how these factors could shape policies and marketing to ensure that an implementation of any such smart city technology is successful.

8.2 CHAPTER INTRODUCTION

Smart road lighting, equipped with traffic sensors, wireless networking capabilities, and more computational power means that streetlights can do more than just illuminate roads. This inclusion of a sensor system means that lamp controllers have a much higher degree of awareness of the surrounding conditions, which allows for opportunities in innovation in many areas. For example, using traffic detection, smart lighting can provide detailed road usage information to authorities to improve road conditions, congestion management, and road maintenance. This traffic information allows road operators to know when the road is in use, so that lights can be dimmed to save power without compromising the safety of the road. The smart controllers in the lights also provide a convenient platform to install other sensors to measure pollution or microclimate information around a city to track environmental conditions.

The previous chapter showed that smart streetlight installations can be financially viable using currently available components. With costs no longer prohibitive to installation, the decision to install smart road lighting hinges on public acceptance. Both streetlights and the roads that they inhabit are a public good that serve everyday citizens. As the public are the primary users, it is important to understand their needs, motivations, and perspectives so that the system can be designed, communicated, and implemented in an appropriate way to maximise the project's success [242]. The public must also be aware of the costs (or opportunity costs), benefits, and risks associated with the technology and accept those changes as a society.

In seeking to better understand the public opinion on smart street lighting, this chapter makes the following contributions:

- The mechanisms and likely costs and benefits from the perspectives of the public of implementing smart road lighting are outlined in Section 8.3. Goal framing was used as a lens to investigate hedonic, gain, and normative perspectives of typical citizens.
- Responses from a survey questionnaire (Section 8.4) showed that most respondents support smart street lighting in its public-facing applications (Section 8.5). Key determinants of the willingness to support and/or scale of support were determined using regression analysis and explored against the context of existing research (Section 8.6).
- Finally, the study concludes with recommendations for implementing a smart streetlight system to maximise public support and outcomes (Section 8.7).

8.3 BACKGROUND

Goal framing theory suggests that behaviour, and the way that people process and act on information, are driven by personal goals or motives [243]. These goals can be categorised into three types: hedonic, gain, and normative. Hedonic goals are driven by a desire to improve one's feelings in an environment or situation by seeking positive feelings such as enjoyment, fulfilment and safety, and/or by avoiding negative feelings such as effort, uncertainty or confrontation. Gain goals are concerned with personal resources, which can include factors such as wealth, time and personal status.

Lastly, normative goals are associated with expectations of appropriateness from society or significant others. Normative goals are often seen in the environmental context and include examples like recycling, where there is often little or no direct monetary or hedonic benefit, but behaviours can still be influenced by societal ideals. Multiple goals and motivations are generally active at any given time, but typically speaking, a single goal will dominate decision-making.

In the context of technological acceptance, hedonic goals can be expressed as satisfaction, joy, or fear of using the technology, or resulting from its use. Gain goals manifest in the form of personal costs such as changes in fees or taxes, or in the case of public goods, opportunity costs of implementing a technology at the expense of forgoing another. Normative goals can be in terms of positive or negative effects on society or the environment [242]. The following sections investigate the goal frames associated with the specific applications that smart streetlight systems could enable.

8.3.1 **Traffic Optimisation**

A streetlight-mounted sensor network may be able to improve traffic coordination by supplying a much more complete picture of road activity across an entire city, including on roads without traffic light intersections. The rich data set that is possible could allow for more sophisticated traffic signalling and control to give a shorter, smoother, and less stressful journey to road users, affecting both gain and hedonic goal frames. The network could even be used to link previously disconnected systems together to ensure that all intersections across the city are optimised to give the best results in lowering stress caused by trip times and stopping. Less time on the road or idling would also reduce carbon pollution, which can be a factor in normative goals [42]. This reasoning led to the formulation of the following two hypotheses, which reflect the prediction that the hedonic and gain advantages (reduction of stress and travel time, respectively) of traffic improvement would be dominant over the gain disadvantages (higher personal monetary cost).

Hypothesis 1: Support for traffic improvement is driven by satisfaction with road experience

Hypothesis 2: Support for traffic improvement is moderated by total road travel time

8.3.2 Streetlight Dimming

Under the context of streetlight dimming, all three goal frames may be active simultaneously. Hedonic factors are mostly centred on the safety and comfort provided by public lighting, as well as potential feelings of annoyance from spilled light and the desire to avoid or remove the stimulus. Gain goals are similarly balanced between the potential savings on rates from adaptive lighting, while also representing an opportunity cost in municipal funding for other services. Normative goals can manifest in the context of reducing light and carbon pollution, as well as reducing the negative impact that lighting has on fauna. Support for dimming services was predicted to be driven by hedonic and normative goal frames, i.e. acceptance was predicted to be higher for participants who valued environmental conservation, perceptions of personal safety, and/or were annoyed by spilled light trespassing into the home. This prediction led to the following three hypotheses:

> *Hypothesis 3: Support for dimming services is associated with perceptions of personal safety*
>
> *Hypothesis 4: Support for dimming services is associated with annoyance with light trespass from public lighting*
>
> *Hypothesis 5: Support for dimming services is associated with perceived importance of environmental conservation*

8.3.3 Walkability

Pedestrian mobility is not a problem that can be ‘solved’ with real-time data, unlike traffic coordination and streetlight dimming. Climate data cannot directly affect the built environment or climate conditions themselves. Instead, collected data such as air temperature, humidity, presence of shade, and pedestrian traffic levels can guide and inform planners of the effectiveness of developments and improvements on walkability and pedestrian comfort (e.g. the installation of cover or trees for shade). Real-time climate data can also be used to track urban heat islands and pedestrian activity around the city to suggest which areas could be improved.

As the technology proposed in this study has no direct effects on walkability, goal framing and acceptance were not particularly applicable to this aspect of the study. Hedonic and normative goals are still present from the perspectives of increasing outdoor physical activity for better health, living environments, and cohesive societies. The gain goal frame applies to housing value and the public cost of implementing a climate sensor network. However, as most of the discussed effects are an indirect result of the potential system and are unlikely to impact public acceptance, they were not explored as part of this study.

8.4 METHODOLOGY

A questionnaire was designed to gauge public support for the three main application domains of smart road lighting that directly affected citizens, which were: traffic improvement, streetlight dimming, and walkability. The questionnaire, which is shown in full in Appendix A, was split into four parts: one for each application domain, to assess the participants' level of support as well as influencing factors, and a final section that collected general demographic information. Each section started with a passage of information that explained the possible role and benefits of smart road lighting where applicable to the section.

The first part of the questionnaire was focused on traffic and road use. The focus of this section was a willingness-to-pay assessment around traffic improvement. Participants were given a hypothetical scenario of paying an annual vehicle registration fee of AU$750. In this scenario, AU$60 of that fee was taken to directly support road maintenance and traffic improvement programs. Participants were then asked for the maximum amount they would be willing to pay on top of the existing fee to further support traffic improvement programs, if at all, provided that the result of their contribution meant that their wait times at traffic light intersections reduced by half. Additional information around typical road usage was also collected. This information included the participants' primary mode of road transport, weekly travel frequency, and usual trip length. Participants were also asked to rate their satisfaction with road conditions, such as congestion, wait times, and stopping frequency, using a five-point Likert-type scale ranging from Excellent (1) to Terrible (5).

The second part of the questionnaire investigated the participants' support and experiences around streetlights and dimming. Participants were asked to rate how strongly they agreed with a series of seven statements around residential road lighting using a five-point Likert-type scale from Strongly Agree (1) to Strongly Disagree (5). These statements included items such as: ‘Well-lit roads make me feel safe’, and ‘I am bothered by streetlights when in my home’; and were intended to capture a degree of personal safety at night, dissatisfaction with existing lights, and energy consciousness. Following these statements, participants were presented with an example list of municipal services that are funded by citizens’ rates payments, which included water treatment, sewerage, and recycling. Each service was allocated a proportion of funds that reflected real-world spending in a rural town. Streetlight dimming was then added to the list of these services and participants were asked to reallocate the existing funds across all items to proportions that they thought were appropriate. Participants were informed that there would be no change to the amount of available funding, and that any increase in funding for a service would mean a decrease in funding for another service. The new funding allocations showed the level of support for dimming projects, and where participants were willing to sacrifice existing services to allow these projects to exist.

The third part of the questionnaire investigated walkability and mobility around cities. Typical weekly walking and cycling times were collected to establish a baseline level of activity for each participant. Then participants were asked for the maximum amount of time they would be willing to walk in their city with and without shade, and in summer and winter, before they would consider alternative transport to observe the possible outcome of installing more cover in public areas. The following section asked participants to indicate what factors they considered to be major barriers to walking in their city using a five-point Likert-type scale, ranging from ‘Definitely a factor’ (1) to ‘Definitely not a factor’ (5). These factors included environmental effects such as temperature and wet conditions, personal safety, and perceptions of long distances between areas of interest. Participants were then asked how often they would be likely to visit city centres and public areas, depending on whether they offered a free wireless internet service. Finally, a willingness-to-pay assessment was conducted for a smartphone application that would allow access to highly localised and accurate weather information to gauge public interest in the climate data possible with a city-wide sensor network. Willingness to pay was assessed as a once-off purchase, as opposed to a subscription-based model.

The fourth and final part of the questionnaire collected personal information and comfort levels with technology. These characteristics included age and gender, which have been known to affect the acceptance of technology [244]. Employment status, resident city, and whether the participant currently paid rates were also collected. Personal perceived importance of fitness, leisure time, and environmental conservation were collected using five-point Likert-type scales, ranging from 'Extremely Important' (1) to 'Not at all important' (5). Comfort with computer systems was also collected with a five-point Likert-type scale ranging from 'Extremely comfortable' (1) to 'Extremely uncomfortable' (5). Lastly, the frequency of smartphone application was collected by asking participants how often they typically used applications on a weekly basis.

8.4.1 Participants and Survey Distribution

Questionnaires were distributed online over a period of eight months, between September 2017 and April 2018, to obtain a cross-sectional sample of Australian citizens. Invitation for involvement in the survey was conducted mostly through social media using a combination of personal and public channels, including municipal council pages, James Cook University newsletters, and via a local media release. The invitation contained a link to the online questionnaire, which typically took less than 20 minutes to complete. A physical version of the survey was also made available in Townsville's public libraries. Responses were restricted to Australian residents over 18 years of age.

8.4.2 Data Analysis

The willingness to pay for traffic improvement, as well as the scale of the hypothetical contributions, were used to measure support for traffic improvement projects. Then a binary logistic regression analysis was used to determine which factors influenced whether the participant was willing to support traffic improvement. The scale of contributions was not considered at all for the regression, but a correlation analysis among those willing to pay was conducted to find which factors affected support levels.

The funding allocation for streetlight dimming was compared with existing municipal services to determine the comparative importance of the services. A hierarchical linear regression was completed to determine the relationship between support for streetlight dimming and perceptions on streetlight comfort and safety. Lastly, the determinants and barriers for walkability were investigated and discussed against the possible utilities provided by smart road lighting to examine which features would give the most benefit to the public in an urban context.

8.5 RESULTS AND ANALYSIS

Completed questionnaires were received from 167 respondents. Table 8.1 shows a detailed breakdown of the collected sample. The sample contained mostly male participants (56%) and the median recorded age was 30, compared with the national median of 37.2 years of age [245]. Residential postcodes were used to identify the city in which participants lived. Participants living in Australia's top ten most populous cities were identified as living in a metropolitan area, while less populous cities were coded as rural for the purposes of this analysis. In terms of population density, the sample was largely skewed towards rural urban centres. Most responses (67%) came from participants living in Townsville, Queensland. Only 16% of the responses were from participants living in metropolitan areas, despite those areas comprising over 73% of the national population.

The disproportion of the responses collected indicates a non-representative sample. This implies that the presented responses and findings may not necessarily reflect those living in large cities. For instance, respondents may be less reliant on public transport, experience less light pollution, and have shorter commute times, compared to the 'average' Australian citizen, who resides in a large urban centre.

Table 8.1 - General demographic information of collected sample

Variable (N=167)	Value	n	%
Gender	Male	94	56
	Female	55	33
	Missing	18	11
Location	Metropolitan	26	16
	Rural	141	84
Employment	Employed	136	81
	Unemployed	31	19
Frequent app usage	Yes	145	87
	No	22	13
Ratepayer	Yes	71	42
	No	88	53
	Missing	8	5

8.5.1 Traffic

The majority (96%) of those who completed the questionnaire used a private motor vehicle as their primary form of transport. Figure 8.1 and Figure 8.2 show the typical travel characteristics of those drivers. Most of the sampled population (58%) travelled every weekday on a regular basis, while 20% did not regularly travel at all. Typical trip times were mostly around 15 to 20 minutes *(M=18.4, SD=10.0)*, however there was a significant difference in travel time between those living in metropolitan and rural areas, *t(154)=2.81, p=.006).*

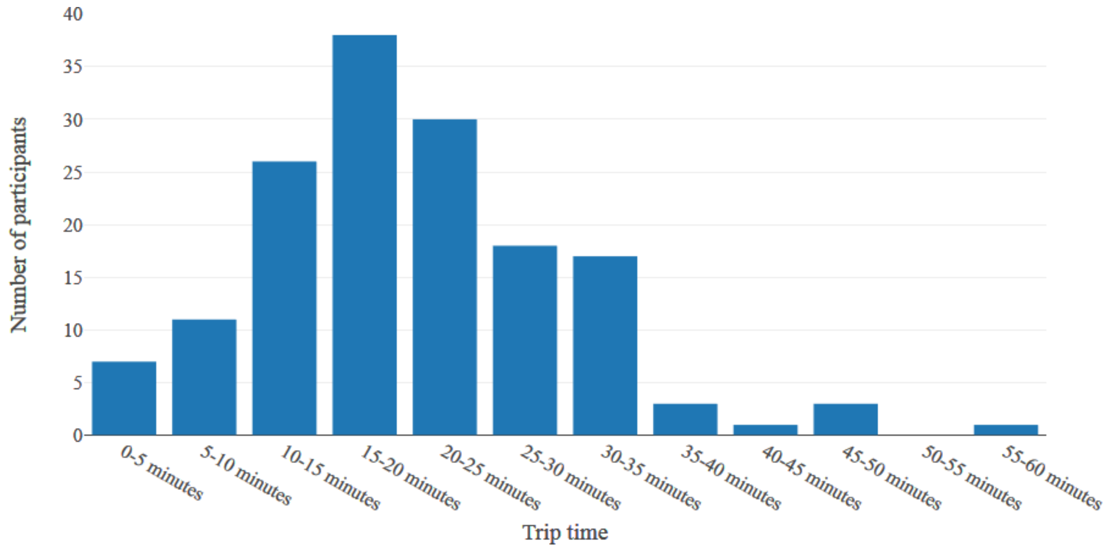


Figure 8.1 - Typical participant road trip travel time (n=156)

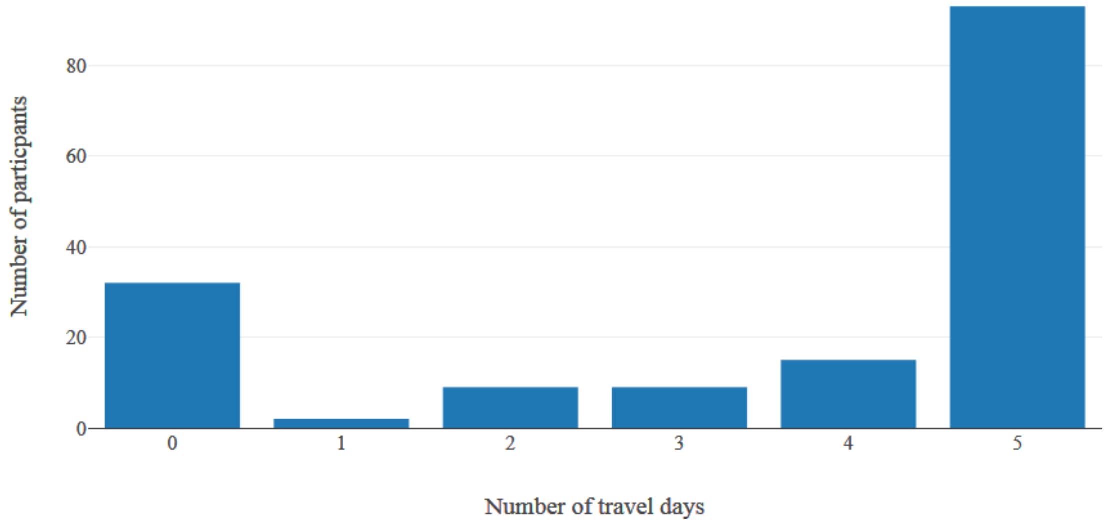


Figure 8.2 - Typical participant travel days per week (excluding weekends) (n=160)

Participants' satisfaction around road use is shown in Figure 8.3[1]. Overall, satisfaction levels were mostly balanced around a neutral level, with participants expressing a wide degree of satisfaction levels around most topics. The sample was mostly satisfied with trip times, wait at non-signalled intersections, and traffic flow in general. Collectively, participants had a mostly negative experience with wait at signalled intersections and stopping frequency on the road. The categories that

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[1] Design of diverging stacked bar chart from Heiberger et al [246]

received the most satisfaction ratings of 'Terrible' were wait times at both signalled and non-signalled intersections. These experiences with traffic may be more positive than the population's perceptions due to the sample's skew away from metropolitan areas that are normally associated with worse traffic conditions than rural areas.

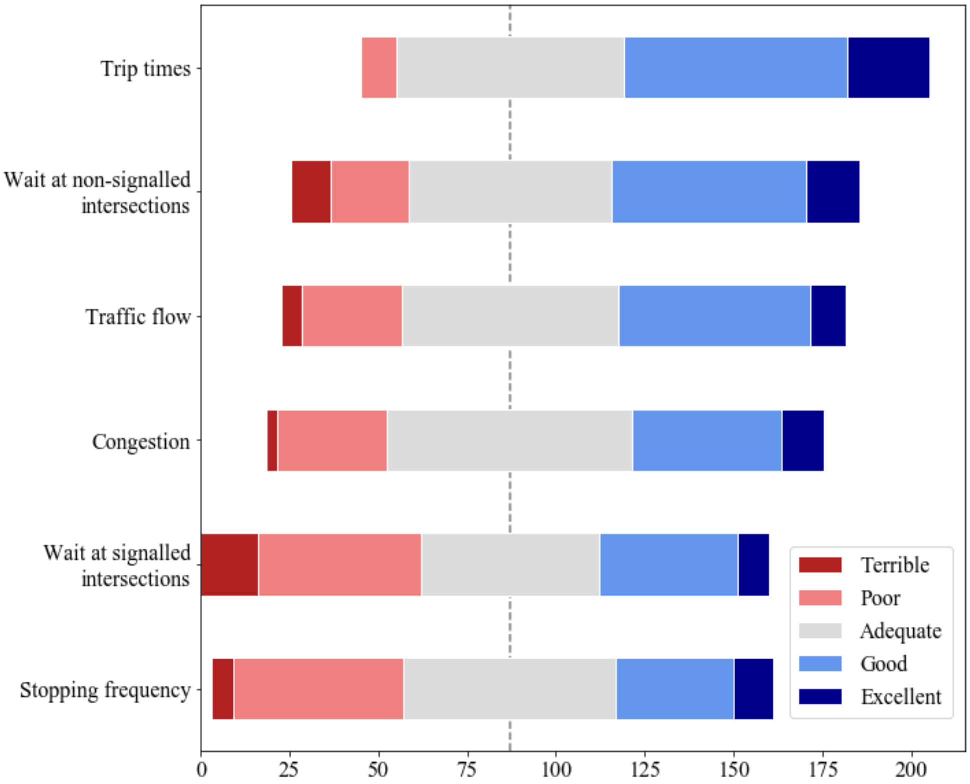

Figure 8.3 - Level of satisfaction related to road user experience

Of the 161 drivers who participated in the survey, 67% were willing to pay an excess on top of their annual vehicle registration to support traffic improvement programs. The mean contribution, among those willing to contribute, was AU$75.5 *(SD=59.47)*. Table 8.2 shows the results of the binary logistic regression, which tested which factors influenced whether the participant was willing to contribute.

Regression Model 1 included both age and gender, using dummy variables to convert gender into multiple binary categories for regression analysis. This model accounted for less than 3% of the variance in whether a contribution was made, and none of the tested variables were shown to significantly affect the outcome.

Regression Model 2 added the typical travel characteristics of the participant, namely, their trip times and travel frequency, after controlling for age and gender. Travel frequency was binarised into whether the participant regularly travelled during the week or not. The addition of these variables greatly increased the explanatory power of the model *(R-change=15.3%)*. Trip times did not have a significant effect on the variance, but a regular travel frequency was significant *(p<.001)* and was associated with an increased willingness to pay.

Regression Model 3 added participants' satisfaction with their general road experience. The recorded variables around road satisfaction were highly-intercorrelated. As a result, only factors around sources that could be objectively measured were included in the model, namely stopping frequency and wait times at signalled intersections. The inclusion of these terms explained an additional 11.5% of the variance in willingness to pay. Regular trip frequency continued to be significant *(p<.001)*, as was the satisfaction with wait times at traffic light intersections *(p=.018)*. Lower levels of recorded satisfaction were associated with an increased willingness to pay.

These results indicate that regular use of road transport, and satisfaction with wait times at traffic lights were significant in determining support for traffic improvement. A possible reason behind this result is that those who rely on road transport for commuting are more willing to improve the system for efficiency reasons. However, trip length did not significantly affect the model, whereas satisfaction at traffic lights did. This result implies that commuters are typically accepting of the length of their regular trips, but the variance in trip times and frustration caused by stopping at traffic lights provide the hedonic and gain incentives to support traffic improvement.

Correlation analysis between contributors showed a weak negative correlation between satisfaction stopping frequency and the amount of money participants were willing to pay *r(106)=-.282, p=.003*. Willingness to pay was also weakly correlated with city population[1], $r(106)=-.262$, $p=.011$, and personal comfort with computer technology, $r(106)=0.244$, $p=.017$.

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[1] City population was coded in terms of rank. An increase in population causes this rank to approach 1; i.e.: the largest city. This coding explains why the correlation coefficient is negative.

Table 8.2 - Hierarchical regression coefficients for willingness to pay for traffic improvement

	Model 1		**Model 2**		**Model 3**	
Variable	**b**	**OR**	**b**	**OR**	**b**	**OR**
Constant	0.515	-	0.725	-	-0.971	-
Age	0.178	1.02	0.016	1.02	0.030	1.03
Male (base=other)	0.439	1.55	0.244	1.28	-0.371	0.690
Female (base=other)	-0.259	0.772	-0.503	0.604	-1.07	0.344
Avg. trip length			0.023	1.01	-0.009	0.991
Regular Travel (base=irregular)			**2.42*****	11.3	**3.05*****	21.1
Satisfaction - Stopping frequency					-0.529	0.589
Satisfaction - Wait at lights					**-0.709***	0.492
N	142		139		138	
McFadden pseudo-R^2	.028		.181		0.296	
LLR p-value	.170		**<.0001**		<**.0001**	

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* p<.05
**p<.01
***p<.001

8.5.2 **Dimming**

Participant responses to statements about streetlights, personal safety, and energy consciousness are shown in Figure 8.4. Most participants (94%) indicated that streetlights made them feel safe at night. Most participants also stated that they considered themselves to be energy conscious (86%) and expressed that they considered environmental conservation to be important (74%). Most participants (64%) were concerned with crime in their area. Despite the concerns around crime and the feelings of safety associated with streetlights, most people (51%) disagreed that dimming would annoy them and the statement, "Unlit roads worry me" was met with a reasonably balanced number of responses.

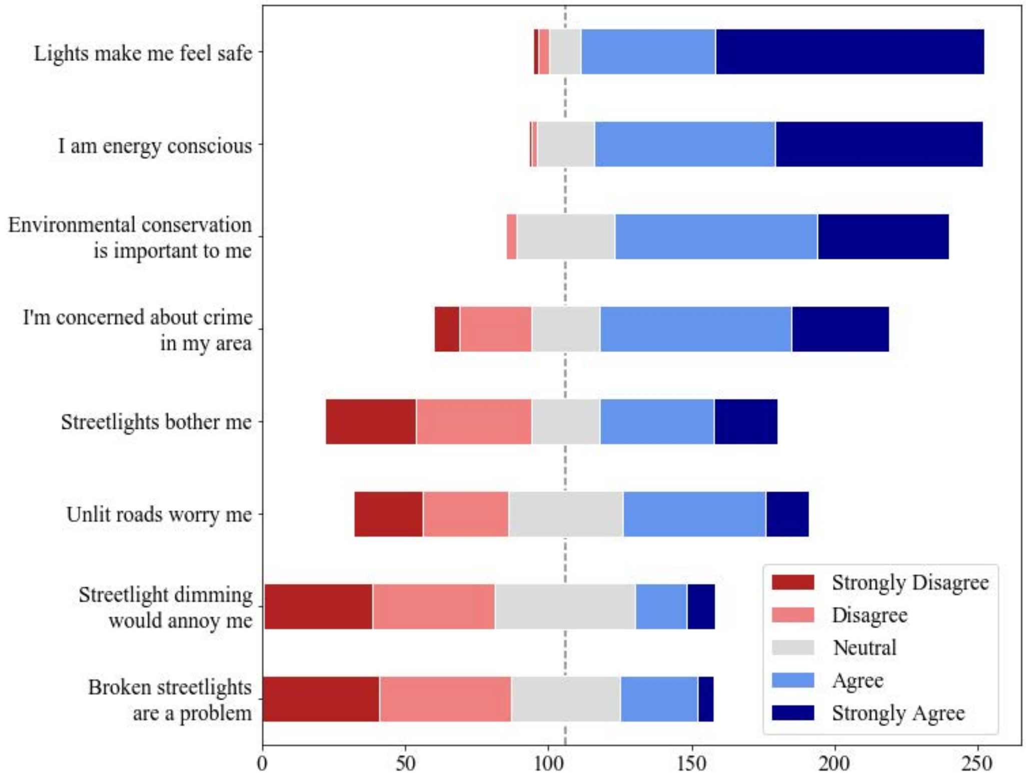

Figure 8.4 - Participant perceptions of street lights, energy, and safety

After removing outliers and invalid responses, 160 participants completed the fund reallocation task for municipal services. Of those responses, 91% of participants decided to allocate funds towards streetlight dimming projects *(M=8.92, SD=7.00)* as shown in Figure 8.5. This proportion of funding is like the amount received by recycling services before the reallocation. Interestingly, funds given to recycling services also increased on average after the reallocation *(M=13.8, SD=6.97)*, resulting in an increase in funds of 3.8 percentile points. Most participants took funds from sewerage, of which funding decreased by 7.94 percentile across all responses *(SD=7.47)*, and to a lesser extent, water treatment, which dropped an average of 4.76 percentile points *(SD=7.09)*.

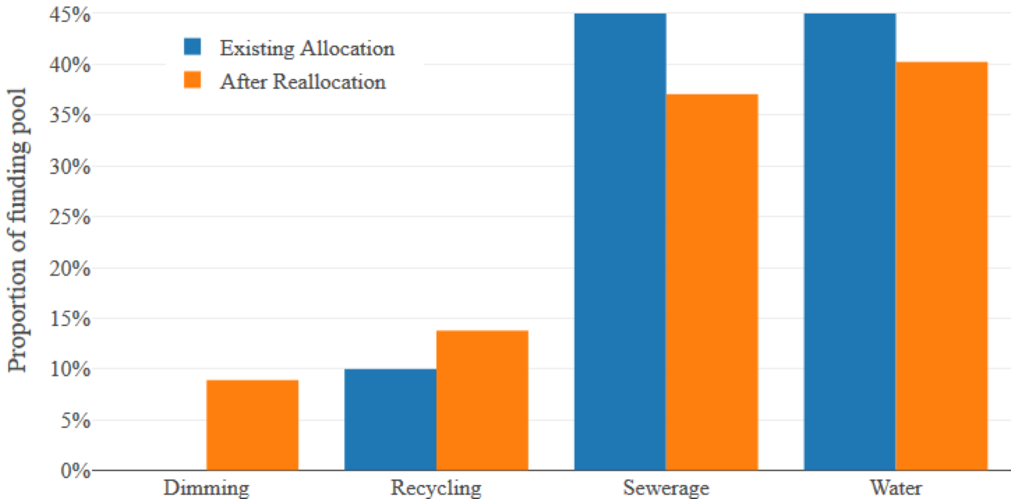

Figure 8.5 - Average funds given to municipal services after reallocation

Table 8.3 shows results of the multiple linear regression that was conducted to find which factors influenced the level of support for dimming projects. The first step of the regression model used age and gender as factors, which explained 6.3% of the variance. In Regression Model 1, age was significant in explaining the outcome *(p=0.003)* and an increase in age was associated with a decreased level of support for dimming as a municipal service. This effect continued through all three models. Regression Model 2 added in ratepayer and employment status using dummy variables. The addition of these two factors only barely increased the explanatory power of the model (<1% change in R^2). As a result, these two terms were deemed to have no significant effect and were summarily removed from the model.

Regression Model 3 added in the participants' opinions on streetlights, energy consciousness, and safety concerns in their neighbourhood. Concerns regarding broken lights, and feelings of safety due to lit roads, were omitted from the model due to high collinearity with concerns with crime in general, and because they did not independently account for a significant portion of the outcome variance when controlling for the other variables in the model.

Of the included variables, age *(p=.005)*, hypothetical annoyance from dimming lights *(p=.006)*, existing level of displeasure caused by spill lighting *(p=.046)*, and the perception of personal safety during the day *(p=.01)* were significant in explaining the variability of dimming support. An increase in support levels was associated with a decrease in the participants' age, how much they viewed daytime safety as a barrier to walking, and how much they thought streetlight dimming would bother them if it were implemented. An increased amount of support was also associated with a higher degree of displeasure regarding light spilling into participants' homes from the road.

Table 8.3 - Hierarchical regression coefficients for public dimming support

	Model 1			Model 2			Model 3		
Variable	**b**	**SE**	**t**	**b**	**SE**	**t**	**b**	**SE**	**t**
Constant	-0.871	2.2	-0.851	-0.849	2.572	-0.330	-1.53	2.16	-0.708
Age	-0.123	0.041	**-3.00****	-0.1367	0.048	**-2.87****	-0.120	0.040	**-2.99****
Male (base=other)	1.726	2.32	0.745	1.638	2.34	0.701	1.58	2.28	0.691
Female (base=other)	2.84	2.4	1.18	2.92	2.42	1.21	1.91	2.40	0.795
Employed				-1.60	1.70	-0.941	-	-	-
Ratepayer				0.878	1.36	0.622	-	-	-
Bothered by spill light							0.925	0.415	**2.23***
Annoyed by dimming							-1.59	0.521	**-3.05****
Energy conscious							0.664	0.763	0.869
Night safety as barrier to walking							-0.002	0.593	-0.003
Daytime safety as barrier to walking							1.02	0.517	**1.98***
Concerned by crime in area							0.626	0.520	1.20
N	153			153			151		
Model R²	.063			.070			.173		
F-change	3.347			-1.145			0.354[1]		
p-value	.021			.0570			.0006		

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[1] F-change calculated from Model 1, as opposed to Model 2

* p<.05

** p<.01

*** p<.001

8.5.3 **Walkability**

The typical walking behaviours collected from participants are shown in Table 8.4. On average, participants were willing to walk for 18.6 minutes longer in summer due to the presence of shade (SD=47.8). This effect was less pronounced in winter, where the maximum time that people were willing to walk only increased by an average of 9.26 minutes due to shade (SD=19.2). The increase in walking time due to shade was not significantly different between participants living in tropical or temperate areas for both summer, *t(140)=0.223, p=.824*, and winter, *t(140)=-0.657, p=.512.* Participants were willing to walk the longest in winter in shade, which implies that weather and temperature have a pronounced effect on willingness to walk. This implication is further reflected in what participants viewed as barriers to walking in their city (Figure 8.6).

Table 8.4 - Maximum time participants were willing to walk in different climate and shade scenarios

Variable (N=167)	Mean (minutes)	SD
Walking time in summer in shade	28.1	47.4
Walking time in summer without shade	9.5	11.1
Walking time in winter in shade	32.9	34.3
Walking time in winter without shade	23.6	30.2
Weekly walking time	49.3	74.7

Most participants strongly believed that temperature (69%), other weather effects (59%), distance between areas of interest (53%), and travel time by foot (48%) were significant barriers to walking in their town or city of residence. Personal safety at night, the availability of alternative transport, and the absence of cover were considered relatively moderate barriers to walking. The belief that long distances between areas of interest was significantly different between participants living in metropolitan and rural areas, t(144)=-2.68, p=.009.

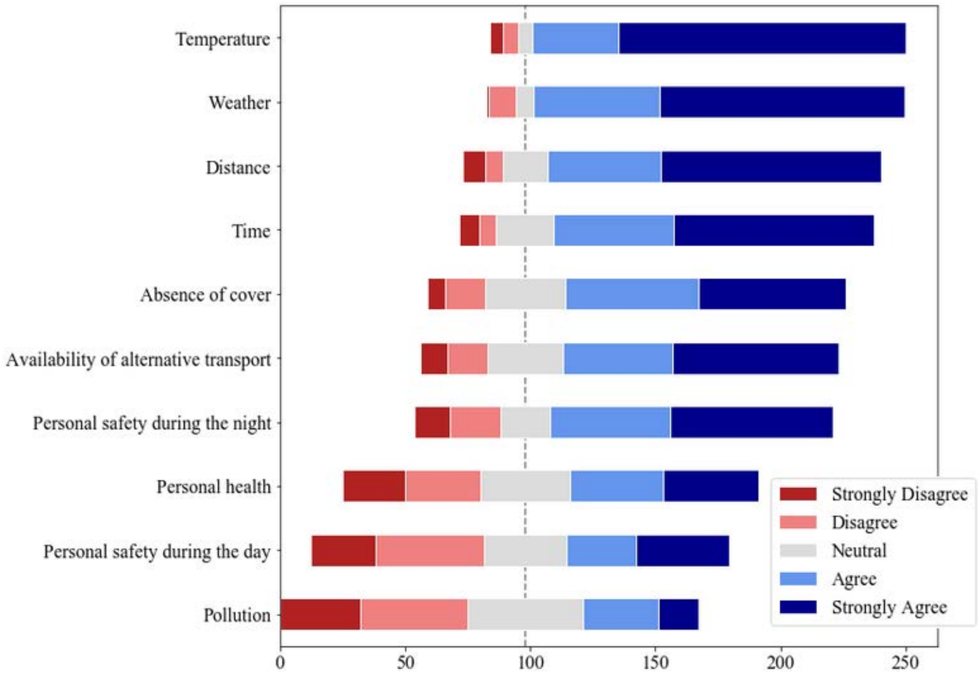

Figure 8.6 - Participant perceptions of barriers to walkability in their urban environment

The correlation matrix between the participants' walking characteristics and perceptions of walkability barriers is shown in Table 8.5. The correlation shows that the maximum time the participant was willing to walk in summer, winter, and with or without shade, were highly inter-correlated. Walking times between shade and no shade had a strong positive correlation in summer, *r(144)=.663, p<.0001 and* winter, *r(144)=.735, p<.0001*. Similarly, walking times in shade between summer and winter also had a strong positive correlation, *r(144)=.718, p<.0001*. This implies that the maximum amount of walking that participants were willing to do under the various conditions was partly due to habit.

Participants' perceptions of whether weather was a barrier were negatively correlated with maximum walking in all scenarios, *r(142)= -.23 ~ -.34, p<.0001*. There was a weak negative correlation between walking distances in summer and how much the participant viewed temperature to be a barrier to walking, *r(142)=-.27 ~ -.41, p<.01*. Lack of cover and time needed for foot travel were only important in summer without shade. In all other scenarios, distance between areas of interest was the only other barrier, with a substantial correlation with maximum walking duration. Overall, the data suggests that beside habitual behaviours, perceptions on weather and long walking distances tend to influence the amount of time participants were willing to walk. Perceptions of temperature as a barrier to walking only appeared to affect how long the participant was willing to walk in summer months

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Table 8.5 - Correlation matrix of walking behaviours and perceived barriers to walkability

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Summer walking time (shaded)	-														
2. Summer walking time (unshaded)	**0.66*****	-													
3. Winter walking time (shaded)	**0.71*****	**0.39*****	-												
4. Winter walking time (unshaded)	**0.64*****	**0.51*****	**0.73*****	-											
5. Barrier - Temperature	**-0.27****	**-0.41*****	**-0.17***	**-0.19***	-										
6. Barrier - Weather	**-0.23****	**-0.31*****	**-0.26****	**-0.34*****	**0.40*****	-									
7. Barrier - Pollution	-0.03	-0.1	-0.1	-0.09	0.1	**0.19***	-								
8. Barrier - Cover	-0.14	**-0.30*****	-0.1	**-0.18***	**0.33*****	**0.32*****	**0.23****	-							
9. Barrier - Distance	**-0.25****	-0.13	**-0.25****	**-0.20***	**0.27*****	**0.21***	0.04	**0.26****	-						
10. Barrier - Transport	-0.11	-0.07	-0.06	-0.08	**0.28*****	0.01	-0.02	0.15	**0.24****	-					
11. Barrier - Health	-0.05	-0.14	-0.08	-0.1	0.05	0.06	**0.27****	**0.20***	0.04	**0.18***	-				
12. Barrier - Safety during day	-0.09	**-0.17***	-0.14	**-0.26****	0.03	0.13	**0.36*****	0.12	0.05	-0.13	**0.39*****	-			
13. Barrier - Time	-0.11	**-0.22****	-0.02	-0.09	**0.25****	**0.22****	0.06	**0.29*****	**0.40*****	0.12	**0.21***	**0.22****	-		
14. Barrier - Safety at night	-0.04	-0.13	-0.06	-0.16	0.1	0.13	**0.25****	**0.25****	**0.24****	-0.05	**0.22****	**0.61*****	**0.34*****	-	
15. Weekly Walking Time	**0.24****	0.15	**0.27****	**0.33*****	-0.08	-0.11	-0.12	0.02	-0.03	-0.01	-0.05	-0.14	0.07	-0.04	-
16. Is Regular Cyclist	**0.18***	0.06	**0.22****	**0.32*****	**-0.27*****	-0.07	0.15	-0.07	**-0.43*****	-0.15	0.01	0.01	-0.14	-0.14	**0.18***

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* p<.05

**p<.01

***p<.001

Only a small proportion of participants expressed that they would be willing to travel to city centres (10%) or public spaces (22%) more often due to the availability of a free wireless internet service. The proportion of respondents who were more willing to visit city centres and public spaces was significantly less in metropolitan areas compared to rural areas, $\chi^2(1, N=167)=93.8, p<.0001$.

Finally, 69% of participants were willing to pay for a weather app that gave them access to street-level accurate climate data. The willingness to pay any amount for the weather app had a weak positive correlation to whether the participant was already using a smartphone application as a source for weather information, $rs(159)=.235, p=.002$. This correlation indicates that participants who were already using weather apps, and perhaps had more experience with using smartphone applications for weather, were more likely to spend money for higher-resolution information.

8.6 DISCUSSION

Table 8.6 shows a summary of the hypotheses tested in this chapter. The following sections outline the results and the reasons why each hypothesis was either accepted or rejected in light of the analysis and findings.

Table 8.6 - Summary of hypotheses from survey analysis

#	**Hypothesis**	**Accepted?**
H1	Support for traffic improvement is driven by satisfaction with road experience	Accepted
H2	Support for traffic improvement is moderated by total road travel time	Rejected
H3	Support for dimming services is associated with perceptions of personal safety	Accepted
H4	Support for dimming services is associated with annoyance with light trespass from public lighting	Accepted
H5	Support for dimming services is associated with perceived importance of environmental conservation	Rejected

8.6.1 **Traffic**

The most significant determinants for willingness to pay was whether the participant regularly used the road, and their satisfaction with wait times at traffic lights. This result suggests that those who rely on road travel, possibly for commuting purposes, are more willing to pay, likely because they directly benefit from traffic improvement. This partially goes against the expectation in Hypothesis 2, which predicted that support would increase with total travel time rather than frequency. However, this result may differ for larger cities, where participants recorded a higher mean travel time. Unfortunately, the sample of responses from metropolitan areas was too small to explore this avenue of investigation.

The association between decreased satisfaction with wait times at traffic lights and increased willingness to pay implies that hedonic goals play a substantial role in predicted public support. This finding partially confirms Hypothesis 1, which predicted that support would be associated with road satisfaction. While road satisfaction perceptions tended to be correlated, wait times at traffic lights were the item that impacted support the most. This factor is also the main area that stands to benefit from traffic light synchronisation. A possible limitation of this finding is that objective wait times at signalled intersections were not measured, nor is it certain that reducing actual wait times would increase satisfaction with road conditions.

In terms of scale of support, those with low road satisfaction, particularly around stopping frequency, were likely to be willing to pay a larger fee to improve traffic. A higher degree of comfort with computers, as well as living in a larger city, also increased willingness to pay. As with the satisfaction with wait times, satisfaction with stopping frequency represents a gain goal that is expressed by spending less time on the road, or a hedonic gain in simply stopping less to avoid annoyance or inconvenience. Satisfaction with stopping frequency was also correlated with satisfaction with trip times, congestion, and traffic flow, all of which fell as city population increased. Participants with a high degree of computer comfort tended to have a higher willingness to pay, which is a finding echoed in other models such as the '*Unified Theory of Acceptance and Use of Technology*' as a reduction of effort expectancy or anxiety [244, 247].

8.6.2 **Dimming**

The regression analysis showed that support for streetlight dimming had four significant determinants: 1) views on spilled light, 2) hypothetical annoyance for dimming lights, 3) views of safety during the day as a barrier to walking, and 4) age.

Support for dimming increased with the view that spilled light bothered participants within their homes. A likely explanation for this result is that respondents who were bothered by spilled light in their homes are experiencing the negative health or hedonic effects of lighting at night on comfort or possibly sleep. Those who felt that spilled light was more of a bother would be more likely to place a higher importance on dimming to remove the source of their discomfort, which was predicted by Hypothesis 4.

From another perspective, spilled light is not always perceived negatively. For example, a case study in Sweden revealed that energy-efficient lighting was rejected in a cooperative housing estate, ultimately because less light was being spilled into yards and homes, which decreased perceptions of safety and mobility among its residents [248]. A limitation of this study was that no distinction was made between how much participants were bothered by spilled light and whether their views on spilled light were positive or negative. This lack of distinction means that there is no way to determine whether individuals who were not bothered by spilled light would view streetlight dimming as negative (from those who positively perceive spilled light) or with indifference (from those not affected by spilled light). Further studies should aim to establish the views on spilled light, rather than just the perceived hedonic effects.

The view that participants would be annoyed by streetlight dimming tended to decrease support, but motivations behind this effect are unclear. On one hand, citizens could be annoyed by prospective adaptive lighting because of the changing light levels in response to activity. Alternatively, the weak correlation between being bothered by dimming and concern about unlit streets, $r(156) = .343, p< .0001$, implies that the decrease in support is at least partially due to personal safety reasons at night. Yet neither worry about unlit streets nor personal safety at night as a barrier to walking were significant determinants of support.

Personal safety during the day as a barrier to walking, however, was significant in determining level of support, which confirms Hypothesis 3. A study by Bennett et al. in 2007 [249] showed that a decrease in daytime perceptions of safety was associated with a decrease in confidence to be physically active outdoors. This association implies that activity, or at least self-efficacy of outdoor activity, may influence support for streetlight dimming. The survey did measure typical walking activity, but the activities were limited to transport rather than leisure, and did not capture the difference between day and night-time activity. These factors should be considered for future studies to measure support for dimming projects.

Age was the last significant determinant in the model and corresponded with decreasing funding support as age increased. Age did not appear to be correlated with any of the recorded variables in the survey section, apart from whether the participant was employed or a ratepayer; neither of which has an independent effect on support (as shown in Regression Model 2, Table 8.3). The lack of any other correlation, especially with that of perceptions of safety, suggests that other age-related factors not captured by the survey influenced the support of dimming among the elderly. Perceptions of increased vulnerability have been associated with a reduced level of physical activity [250]. This effect may be pronounced in the elderly, who tend to have a high self-perception of vulnerability, particularly at night [251, 252]. Other avenues to explore in this field could be classic safety indicators, such as perceptions around escape and concealment [51, 253], as well as social trust in the surrounding environment [254].

Overall, the regression model was only able to explain 17% of the variability in how much funding participants believed streetlight dimming should receive. The inclusion of perceptions on spill lighting, objective amount of physical activity during the day and night, and intentions for outdoor activity have already been discussed in this study. The self-perceived level of environmental awareness was captured, but not the extent of knowledge around dimming and lighting applications, which has been shown to have a marked effect on support for dimming [255]. However, without this information the collected data showed that environmental and energy awareness were not significant determinants for support, which means that Hypothesis 5 must be rejected and that normative goal frames were not dominant in this context.

Another possible limitation of the study is that the costs involved for implementing a streetlight dimming scheme were not presented or discussed within the survey. Therefore, participants did not have a defined cost reference when comparing the importance of services. For example, a participant may believe that recycling was the most important service but did not give it the highest proportion of funding because of the perception that recycling services are not as expensive as the other options presented.

8.6.3 **Walkability**

Most of the results from the walkability section of the survey confirmed the findings already present in the literature. Microclimate conditions, particularly the presence of shade, and thermal comfort were perceived as significant barriers to outdoor physical activity. This perception, which was overwhelming in proportion, may stem from the fact that most participants lived in Australia’s dry tropical regions, which experience hot and uncomfortable summers. Similarly, responses from rural areas, which are characterised by low density and sprawling neighbourhoods, viewed distance between destinations to be more of a barrier than their high-density, metropolitan counterparts.

The more interesting result is that many participants were willing to pay for a weather application that gave them access to fine-grained climate information. This high potential adoption rate indicates that there is interest in higher-granularity climate data than is currently available. There could also be a potential market in enhancing walkability scores with real-time climate data, which would advise citizens of the best places and times for pedestrian or other outdoor activities around their city.

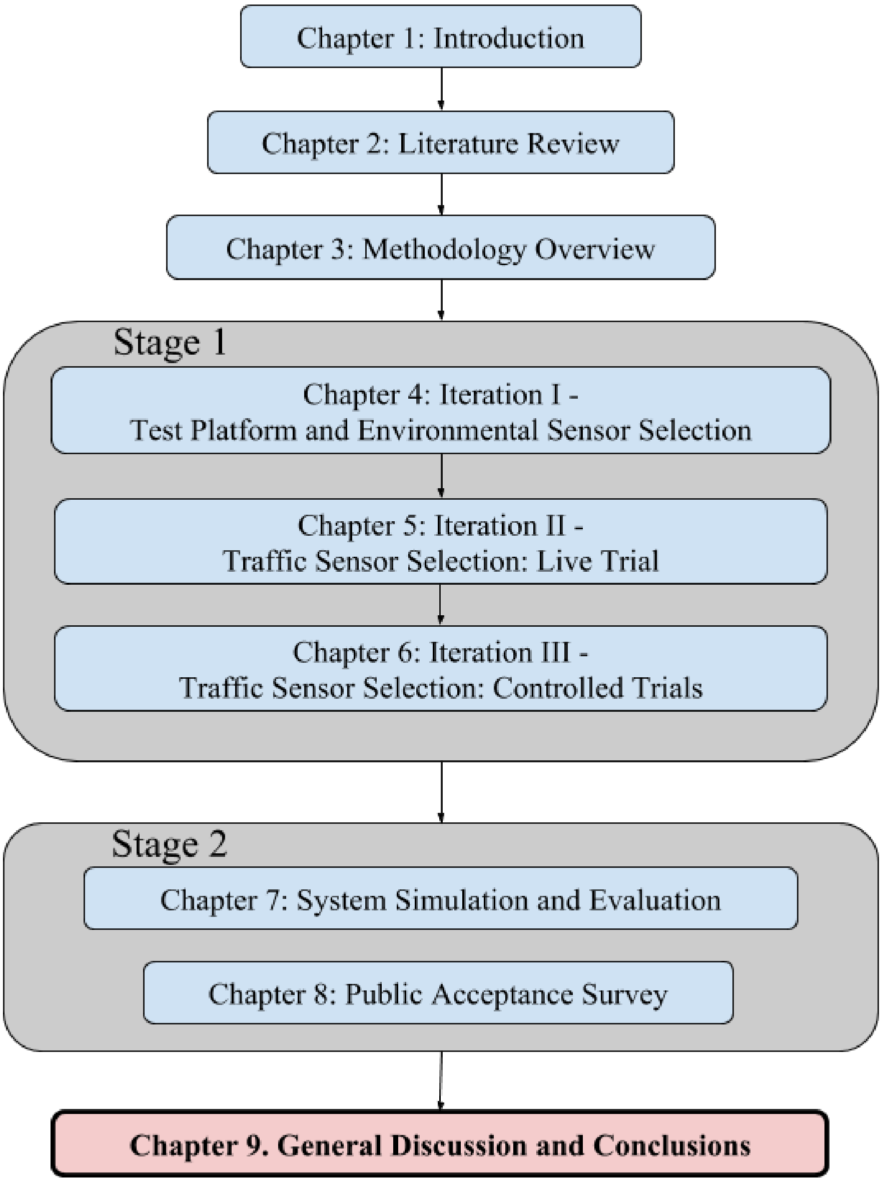
8.7 CONCLUSIONS

This study showed that participants were mostly accepting of the technologies and applications that a smart streetlight network could afford. For traffic optimisation, the communities most likely to show support for traffic improvement were those that relied on vehicles as their primary form of transport, as opposed to public or pedestrian transport. This finding indicates that rural areas, which tend to have fewer public transport options and are less likely to have implemented traffic optimisation solutions of their own, are prime candidates for trialling the smart streetlight network. Due to the low number of responses from metropolitan areas, future research should concentrate on major cities to determine if support can be determined by the same factors.

Most of the variability around support for dimming projects was not captured by the tested variables. However, the literature suggests that there is a possible link between support and feelings of vulnerability within the home, and level of physical activity, which both warrant further investigation in future studies. The dimming scenarios presented to participants were also purely hypothetical, so the impact of actual streetlight dimming on both crime and citizen comfort is not currently known, especially for vulnerable groups such as the elderly or disabled citizens. With that in mind, the groups that showed the highest level of support for dimming projects were young and/or adversely affected by streetlight trespass in their homes. By this reasoning, the dimming applications of the smart streetlights should at least be considered in neighbourhoods that generate a high volume of complaints around light trespass. Further studies should also aim to establish how spilled light is viewed by the community, either in a positive or negative context.

The findings of this chapter can serve as a guide to approaching the implementation of smart streetlight policies. For example, the public acceptance of traffic improvement was highest among participants who commuted regularly. This result could indicate that the financing for traffic improvement services should be implemented as a fee or levy on vehicle registration or public road transport ticketing. Hedonic goals in this instance were shown to be dominant over personal finances for commuters, meaning that they would be more accepting of any added costs than other demographics that use other forms of transport. In the context of dimming, light reduction schemes should be introduced under the context of reducing residential discomfort, as annoyance was a significant determinant for dimming support. However, the public also needs to be reassured that personal security and safety are being maintained, which may require that some areas, such as park entrances and areas with a high risk of crime, remain permanently lit.

Chapter 9 - General Discussion and Conclusions



9.1 CHAPTER OVERVIEW

Chapter 9 presents the conclusion to the study. A summary of each research stage is presented in response to the research questions. The results from previous chapters demonstrate that a smart road lighting system for traffic and environmental monitoring is indeed possible using currently available technologies and is both financially and socially viable. The prototype design and software, and financial analysis tool developed as part of the thesis project, are discussed and presented as the major contributions of this research. The limitations and possible directions of future study are then outlined before concluding the thesis with a reflection on how to proceed with smart road technologies.

9.2 OVERVIEW OF OBJECTIVES AND RESEARCH QUESTIONS

Growing population and increased urbanisation pose a threat to sustainable living in cities worldwide. The quality of life of citizens may be jeopardised due to high population densities, inefficiencies of city services and mobility, and wasteful management or behaviours regarding local resources. Smart city initiatives use technology to quantify, monitor, and improve city services and to empower citizens to make better decisions by providing timely and actionable information. This study focused on evaluating the concept of integrating sensor equipment into streetlight housings, which would permit the construction of a city-wide monitoring network for traffic and the environment to enable a variety of smart city services at an accessible cost.

This research attempted to solve the following research questions:

1) *Can a streetlight-integrated traffic detection system reliably detect vehicles and pedestrians, produce accurate counts, and distinguish between traffic types for use with smart road applications?*
2) *Is a streetlight-integrated traffic detection and environmental monitoring system viable for a community?*

Within the context of a streetlight implementation and within the size, mounting, and cost constraints imposed by such, the following sections respond to these research questions in detail and discuss the overall outcomes of the study.

9.2.1 Research Question 1 - Can a streetlight-integrated traffic detection system reliably detect vehicles and pedestrians, produce accurate counts, and distinguish between traffic types for use with smart road applications?

9.2.1.1 Iteration I - Test Platform and Environmental Sensor Selection

Chapter 4 started with the exploration of a base hardware control platform for data collection and sensor management. In this first development iteration of the sensor system, the requirements and conditions of control hardware and environmental sensors in a streetlight-mounted deployment were investigated. This investigation was accomplished by deploying an outdoor urban sensor network of 11 environmental sensor nodes on the external surfaces of an inner-city municipal building. Three main outcomes were found from this stage in development:

1. Heat build-up inside electronics enclosures during the day could pose a fire risk to components such as batteries. This finding discounted the possibility of using rechargeable batteries during the day to power sensor electronics while the streetlights were switched off. The high internal temperatures also highlighted the possible risk of damage to sensitive components; however, subsequent deployments in streetlight housings showed that electronics were too well insulated against heat for this risk to be a concern.

2. The sensor controller hardware was not capable of handling the number of sensors required for traffic and environmental monitoring purposes. The limited number of pins and low memory of the microcontrollers used in the trial prompted a hardware change to a more powerful, yet still low-cost, microcontroller platform to handle the increased number of sensors, and to handle data-logging operations.

3. Not all the tested environmental sensors were suitable for urban environments. Some of the sensor models included in the test had to be mounted externally to the electronics enclosure in order to operate. This mounting configuration exposed the electronics to the elements and caused some sensors to corrode and fail. These failures

led to a design ruling to not allow any sensors with exposed traces or components to be mounted externally, which required some sensors to be swapped out for more enclosed systems.

9.2.1.2 Iteration II - Traffic Sensor Selection: Live Trial

Chapter 5 marked the second stage of the prototype sensor platform's development. This stage began incorporating sensors for traffic detection into the design, including sonar, lidar, and passive infrared motion-based detection to assess their usefulness in vehicle and pedestrian counting and classification applications. After multiple rounds of preliminary testing, the prototype sensor system was deployed in an actual streetlight on a medium-to-low traffic, single-lane road to determine the effectiveness of each sensor type.

From this deployment, sonar was found to be ineffective at both detecting and counting traffic of any type due to the sensor being deployed beyond its rated range and possibly due to power supply problems. This inability to operate at height caused sonar to be removed from the prototype in subsequent tests. Similarly, problems with the mounting configuration caused the lidar to fail to detect most road traffic. However, sporadic detections of vehicles and cyclists revealed that the hardware was capable of vehicle detection with a low false-positive rate if the mounting was properly configured. Passive infrared (PIR) motion detection was useful at detecting all traffic types across a wide area from the vantage point of the streetlight housing, but unable to provide accurate vehicle counts or estimates due to variability of road traffic.

9.2.1.3 Iteration III - Traffic Sensor Selection: Controlled Trials

Chapter 6 covered the third and final development iteration of the prototype system, which refined the platform's traffic detection capabilities. Rather than continuing with live traffic tests on active roads, this development stage used tests with controlled traffic types, speeds, and densities to measure the effectiveness of each sensor type in varying scenarios. Tests continued using technologies from the previous design iteration but included multiple PIR sensors to establish zone-based motion detection, and a thermographic sensor for thermal traffic detection with a dedicated controller for processing. Tests involving over 600 vehicle passes, as well as 600 pedestrian and 400 cyclist passes, were conducted at various speeds, vehicle densities, and in both directions of travel.

PIR sensors provided very reliable detection of all traffic types and in all testing scenarios, but performed poorly in counting and classifying traffic types, even with multiple detection zones. Lidar was found to be very accurate in both detecting and counting vehicles, but not other traffic types. Cyclists and pedestrians not travelling in the centre of the lane would often miss the narrow detection zone of the sensor, causing the sensor to not record a traffic event. Finally, the thermographic sensor was able to detect, count, and classify traffic across the entire lane. However, the sensor was unable to detect vehicles in cold weather when the vehicle was first switched on due to the lack of thermal contrast against the background of the road surface.

The conclusion of the third development iteration showed that no single sensor was able to reliably detect, count, and classify traffic in every circumstance. Instead, all sensors from the final testing stage were kept in the prototype system to allow the different sensor types to compensate for the shortcomings and characteristics of one another under different road conditions. The use of multiple sensor types would also allow for data fusion and internal cross-checking, classification, and validation of traffic detections. Even with the hardware from all three sensor types and processing required by each, the final prototype design was able to fulfil the size, weight, cost, and detection requirements outlined in Chapter 1. The results from these three testing stages also confirm the research question that a traffic detection system mounted within the constraints of a streetlight housing is indeed viable, at least within the context of single-lane roadways.

9.2.2 **Research Question 2 - Is a streetlight-integrated traffic detection and environmental monitoring system viable for a community?**

Chapter 7 uses the characteristics of the developed traffic and environmental detection system to determine the cost-effectiveness of the system at scale. An evaluation tool for simulating lighting installations was created to measure the financial impacts that the prototype system would have on electrical and maintenance costs by enabling traffic-adaptive road lighting schemes. Within this tool, three lighting installations were simulated for a small, medium, and large city along main roads to determine if the different traffic levels affected the financial viability of the system. The simulation showed that the sensor platform outperformed traditional lighting options by providing a traffic-aware adaptive lighting installation. The cost-effectiveness of the traffic-aware dimming scheme was reduced with higher levels of traffic, but the resulting savings recovered the initial hardware costs in all scenarios within a period of five to 12 years. This result means that the prototype system and traffic-aware dimming schemes are more affordable in areas that have low traffic at night, such as small cities and residential and industrial areas. Regardless, the simulation showed that a streetlight-integrated sensor network would be financially viable with currently available systems and hardware, but not always within the 10-year payback period objective specified in Chapter 1.

Chapter 8 investigated whether smart streetlight applications would be accepted by a community. A survey questionnaire was publicly distributed to Australian citizens to quantify public support for smart streetlight applications. These applications revolved around city aspects that currently affected citizens, including traffic improvement and road experience, streetlight dimming, and measures of walkability. Support for each application was measured by a personal willingness to pay for the improvements to current services, or in some cases, reallocation of public funds to support new projects. The results of the survey showed that citizens were generally supportive of the potential applications enabled by a smart road-lighting network, despite an increased personal or public cost associated with the applications. Willingness to support these applications was particularly strong from individuals who were likely frustrated with city functions such as road transport or spilled public lighting. This outcome shows that within a social context, the applications provided by smart road lighting would be mostly accepted and therefore viable for a community.

9.3 OUTCOMES AND CONTRIBUTIONS

Overall, this thesis delivers two main contributions to the research in smart city implementations: Firstly, the study demonstrated that low-cost commodity sensors can be used as a cost-effective form of ubiquitous traffic and environmental monitoring from the vantage point of a streetlight housing. All the soft assets of the developed prototype have been made publicly available, including controller software, new or modified sensor libraries, detection algorithms, and circuit board schematics and designs. Most notable of these assets is the thermographic tracking library, which was developed for this study to enable low-cost image processing to run quickly and efficiently on a microcontroller. The second major contribution to the literature from this study is the development of a financial analysis tool for smart lighting. The tool can take traffic-adaptive dimming schemes into account when performing cost benefit analyses based on actual traffic figures for a given area. Another novel feature of the financial model is that it takes changes in lamp lifetime into account for spot and preventive maintenance schemes, which is rarely seen in similar analysis tools.

9.4 LIMITATIONS OF STUDY AND FUTURE WORK

The developed prototype for traffic detection was designed mostly around the circumstances and restrictions of residential roads. In other words, the sensors are intended to work over a single lane and mounted at a height not exceeding six metres. Traffic tests were also limited to speeds that would be typical of non-arterial roads, such as those found in residential areas and campuses (Chapter 5 & Chapter 6). A possible direction for future research would be to investigate the usefulness of the current prototype on main arterial roads. This scenario would include a higher top vehicle speed, a wider variety of traffic densities, multiple lanes, and a higher mounting configuration. Expanding the research in this manner would be useful to determine the extent to which the low-cost commodity sensor package remains viable in more scenarios.

This study also focused mostly on the counting performance of the tested traffic sensors. The sensors chosen for the final design of the hardware prototype were certainly capable of traffic classification due to the data they were able to collect. For instance, the lidar could measure the vertical profiles of objects and the narrow detection zone localised traffic to a precise area. Likewise, the thermographic sensor could determine the position, size, shape, approximate speed, and the travel direction of each object. However, an avenue of future research is to assess the classification accuracy of the traffic detection system when considering the data from all sensors. Automated classification of traffic from this type of system would enable better insights into road usage.

A third direction for future research is to reassess the functionality and affordability of technology as it changes. Over the course of this study, the hardware technologies for both sensors and control systems have been made more publicly available, have become more powerful, and have dropped in price. The processing power of microcontrollers has increased over the course of this study to the point that the thermographic detection and tracking algorithms used in the third prototype design iteration would not have been viable at the project's inception. Yet, at the time of writing, the processing unit used in testing has already been superseded by a more powerful and equally inexpensive equivalent. Similarly, sensors such as the lidar and thermographic sensor have each had newer versions and upgraded hardware released since the time of testing to enable faster and more precise detection. This high rate of technological improvement in this space, and in other areas such as vehicular networks, means that viability of smart road applications needs to be periodically assessed on an almost yearly basis. For instance, local and state governments may be more inclined to implement smart street lighting technologies if the upfront costs were lowered to the point where the installation would pay for itself within an election cycle and/or become more affordable for lighting installations with comparatively low budgets. Furthermore, public opinion of smart streetlights may evolve with that of their supporting technologies and must also be continually reassessed to ensure that any installations meet the needs and expectations of the community.

Future research could also concentrate on quantifying the less direct costs and benefits of smart road lighting systems. The financial evaluation in Chapter 7 only considered the cost savings as a result of dimming. Further effects of the smart lighting network, such as time reclaimed from trip times due to improved traffic flow or better public health as a result of light reduction at night, were not included in the study. Other less direct consequences of the enriched traffic and environmental data were also not considered, including the possibility of widespread smart home services, research into urban climate change, revitalisation of green spaces, and the use of a city-wide network for public utilities and community activities.

9.5 FINAL REMARKS

The technologies needed to implement smart streetlights are becoming more affordable every day. However, despite the continually lowering costs, communities should be encouraged to adopt and actively develop smart city technologies as soon as possible. Delaying for the sake of cheaper hardware comes at a larger opportunity cost. This thesis has shown that long-term savings are possible with smart road lighting, but the infrastructure and information made available by such a system would also provide the tools needed for innovation. Adoption can encourage the creation of new products, policies, and practices to allow and expand what is possible with smart city technologies. The sooner that these technologies are embraced, the faster they can be applied and specifically tailored to the city and its people, geography, climate, and culture to enact solutions for better city living. The smart streetlight network can act as a platform to accommodate and implement those innovations.

Cities must become more sustainable if we are to keep living within them, which is a likely future. Smart city technologies such as those presented in this thesis are vital in ensuring that cities, and their inhabitants, are prepared for that future by providing better information. Citizens can be empowered to make better decisions and formulate healthier habits and lifestyles by being more aware of their surroundings, including traffic conditions, nearby events, and climate conditions, without sacrificing their right to privacy. City services and resource management can be made better by identifying and cutting wasteful practices for more efficient and cost-effective roadways and utilities. Homes, workplaces, and community spaces can be made better by gaining further understanding about how the urban environment is affected by human influence, and how to leverage the natural environment to create more comfortable spaces to live, work, and connect with others. The deployment of a city-wide smart streetlight network ensures that relevant and useful information is available to all for a more vibrant and prosperous future.

References

[1] K. Mohring, T. Myers, and I. Atkinson, “A controlled trial of commodity sensors for a streetlight-mounted traffic detection system”, in *Proceedings of the Australasian Computer Science Week Multiconference*, 2018, p. 10: ACM.

[2] K. A. Mohring, T. S. Myers, and I. M. Atkinson, “Playing in traffic: an investigation of low-cost, non-invasive traffic sensors for street light luminaire deployments”, *International Journal of Grid and Utility Computing,* vol. 9, no. 4, pp. 333-344, 2018.

[3] K. Mohring, T. Myers, I. Atkinson, J. VanDerWal, and S. van der Valk, “Sensors in heat: A pilot study for high resolution urban sensing in an integrated streetlight platform”, in *Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2015 IEEE Tenth International Conference on*, 2015, pp. 1-6: IEEE.

[4] United Nations Publications, *The World's Cities In 2016*. United Nations Publications, 2016.

[5] J. Vargo, “Metro sapiens: an urban species”, *Journal of Environmental Studies and Sciences,* vol. 4, no. 4, pp. 360-363, 2014.

[6] M. Gross, “The urbanisation of our species”, *Current Biology,* vol. 26, no. 23, pp. R1205-R1208, 2016.

[7] I. Vojnovic, “Urban sustainability: Research, politics, policy and practice”, *Cities,* vol. 41, pp. S30-S44, 2014.

[8] U. Al-mulali, H. G. Fereidouni, J. Y. M. Lee, and C. N. B. C. Sab, “Exploring the relationship between urbanization, energy consumption, and CO2 emission in MENA countries”, *Renewable and Sustainable Energy Reviews,* vol. 23, pp. 107-112, 2013.

[9] R. Smit, A. L. Brown, and Y. C. Chan, “Do air pollution emissions and fuel consumption models for roadways include the effects of congestion in the roadway traffic flow?”, *Environmental Modelling & Software,* vol. 23, no. 10, pp. 1262-1270, 2008.

[10] X. Ouyang and B. Lin, “Carbon dioxide (CO2) emissions during urbanization: A comparative study between China and Japan”, *Journal of Cleaner Production,* vol. 143, pp. 356-368, 2017.

[11] Bureau of Infrastructure Transport and Regional Economics, “Information Sheet 74: Traffic and congestion cost trends for Australian capital cities”, Department of Infrastructure and Regional Development, Australian Government, 2015

[12] H. M. Kim and S. S. Han, “Seoul”, *Cities,* vol. 29, no. 2, pp. 142-154, 2012.

[13] D. T. C. Cox, D. F. Shanahan, H. L. Hudson, R. A. Fuller, and K. J. Gaston, “The impact of urbanisation on nature dose and the implications for human health”, *Landscape and Urban Planning,* vol. 179, pp. 72-80, 2018.

[14] X. Q. Zhang, “The trends, promises and challenges of urbanisation in the world”, *Habitat International,* vol. 54, pp. 241-252, 2016.

[15] S. Coleman, "Built Environment: Livability: Housing", in "Australia state of the environment 2016", Australian Government Department of the Environment and Energy, Canberra 2016, Available: https://soe.environment.gov.au/theme/built-environment/topic/2016/livability-housing.

[16] E. Öhrström, E. Hadzibajramovic, M. Holmes, and H. Svensson, "Effects of road traffic noise on sleep: Studies on children and adults", *Journal of Environmental Psychology,* vol. 26, no. 2, pp. 116-126, 2006.

[17] T. Nam and T. A. Pardo, "Conceptualizing smart city with dimensions of technology, people, and institutions", in *Proceedings of the 12th annual international digital government research conference: digital government innovation in challenging times*, 2011, pp. 282-291: ACM.

[18] I. Zubizarreta, A. Seravalli, and S. Arrizabalaga, "Smart City Concept: What It Is and What It Should Be", *Journal of Urban Planning and Development,* 2015.

[19] P. Neirotti, A. De Marco, A. C. Cagliano, G. Mangano, and F. Scorrano, "Current trends in Smart City initiatives: Some stylised facts", *Cities,* vol. 38, pp. 25-36, 2014.

[20] I. A. T. Hashem, V. Change, N.B. Anuar, K. Adewole, I. Yaqoob, A. Gani, E. Ahmed, H. Chiroma, "The role of big data in smart city", *International Journal of Information Management,* vol. 36, no. 5, pp. 748-758, 2016.

[21] V. Albino, U. Berardi, and R. M. Dangelico, "Smart cities: Definitions, dimensions, performance, and initiatives", *Journal of Urban Technology,* vol. 22, no. 1, pp. 3-21, 2015.

[22] B. N. Silva, M. Khan, and K. Han, "Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities", *Sustainable Cities and Society,* vol. 38, pp. 697-713, 2018.

[23] R. G. Hollands, "Will the real smart city please stand up? Intelligent, progressive or entrepreneurial?", *City,* vol. 12, no. 3, pp. 303-320, 2008.

[24] S. Allwinkle and P. Cruickshank, "Creating Smart-er Cities: An Overview", *Journal of Urban Technology,* vol. 18, no. 2, pp. 1-16, 2011.

[25] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey", *Computer networks,* vol. 54, no. 15, pp. 2787-2805, 2010.

[26] S. Chen, H. Xu, D. Liu, B. Hu, and H. Wang, "A vision of IoT: Applications, challenges, and opportunities with China perspective", *IEEE Internet of Things Journal,* vol. 1, no. 4, pp. 349-359, 2014.

[27] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of things for smart cities", *IEEE Internet of Things Journal,* vol. 1, no. 1, pp. 22-32, 2014.

[28] S. P. Mohanty, U. Choppali, and E. Kougianos, "Everything you wanted to know about smart cities: The internet of things is the backbone", *IEEE Consumer Electronics Magazine,* vol. 5, no. 3, pp. 60-70, 2016.

[29] M. Yun and B. Yuxin, "Research on the architecture and key technology of Internet of Things (IoT) applied on smart grid", in *International Conference on Advances in Energy Engineering (ICAEE),* 2010, pp. 69-72: IEEE.

[30] T. Myers, K. Mohring, and T. Andersen, "Semantic IoT: Intelligent water management for efficient urban outdoor water conservation", in *Joint International Semantic Technology Conference*, 2017, pp. 304-317: Springer.

[31] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, “Sensing as a service model for smart cities supported by internet of things”, *Transactions on Emerging Telecommunications Technologies,* vol. 25, no. 1, pp. 81-93, 2014.

[32] M. Rajashekhar, “A literature study on internet of things for smart cities”, *International Journal of Innovative Technology and Reserach,* vol. 4, no. 1, pp. 2752-2756, 2016.

[33] M. M. Rathore, A. Ahmad, A. Paul, and S. Rho, “Urban planning and building smart cities based on the internet of things using big data analytics”, *Computer Networks,* vol. 101, pp. 63-80, 2016.

[34] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, “Internet of Things (IoT): A vision, architectural elements, and future directions”, *Future Generation Computer Systems,* vol. 29, no. 7, pp. 1645-1660, 2013.

[35] L. D. Xu, W. He, and S. Li, “Internet of things in industries: a survey”, *IEEE Transactions on Industrial Informatics,* vol. 10, no. 4, pp. 2233-2243, 2014.

[36] A. Schieweck*,* E. Uhde, T. Salthammer, L.C. Salthammer, L. Morawska, M.M. Mazaheri, P. Kumar, “Smart homes and the control of indoor air quality”, *Renewable and Sustainable Energy Reviews,* vol. 94, pp. 705-718, 2018/10/01/ 2018.

[37] P. Kumar, A.N Skouloudis, M. Bell, M. Viana, M.C. Carotta, G. Biskos, L. Morawska, “Real-time sensors for indoor air monitoring and challenges ahead in deploying them to urban buildings”, *Science of The Total Environment,* vol. 560-561, pp. 150-159, 2016.

[38] P. Kumar, C. Martani, L. Morawska, L. Norford, R. Choudhary, M. Bell, M. Leach , “Indoor air quality and energy management through real-time sensing in commercial buildings”, *Energy and Buildings,* vol. 111, pp. 145-153, 2016.

[39] H. Prothmann*,* J. Branke, H. Schmeck, S. Tomforde, F. Rochner, J. Hahner, C. Muller-Schloer, “Organic traffic light control for urban road networks”, *International Journal of Autonomous and Adaptive Communications Systems,* vol. 2, no. 3, pp. 203-225, 2009.

[40] A. G. Sims and K. W. Dobinson, “The Sydney coordinated adaptive traffic (SCAT) system philosophy and benefits”, *IEEE Transactions on vehicular technology,* vol. 29, no. 2, pp. 130-137, 1980.

[41] M. Haider, K. Kerr, and M. Badami, “Does commuting cause stress? The public health implications of traffic congestion”, 2013.

[42] M. Madireddy*,* B. De Coensel, A. Can, B. Degraeuwe, B. Beausen, I. De Vlieger, D. Botteldooren, “Assessment of the impact of speed limit reduction and traffic signal coordination on vehicle emissions using an integrated approach”, *Transportation Research Part D: Transport and Environment,* vol. 16, no. 7, pp. 504-508, 2011.

[43] K. Zhang, S. Batterman, and F. Dion, “Vehicle emissions in congestion: Comparison of work zone, rush hour and free-flow conditions”, *Atmospheric Environment,* vol. 45, no. 11, pp. 1929-1939, 2011.

[44] M. Tahon*,* S. Verbrugge, B. Lannoo, J. Van Ooteghem, P. De Mil, D. Colle, M. Pickavet, P. Demeester, “Parking sensor network: Economic feasibility study of parking sensors in a city environment is well”, in

Telecommunications Internet and Media Techno Economics (CTTE), 2010 9th Conference on, 2010, pp. 1-8: IEEE.

[45] Libelium. (2014). *Smart Parking - Technical guide*. Available: http://www.libelium.com/development/smart-parking/documentation/plug-sense-smart-parking-technical-guide/

[46] S. Lee, D. Yoon, and A. Ghosh, “Intelligent parking lot application using wireless sensor networks”, in *2008 International Symposium on Collaborative Technologies and Systems*, 2008, pp. 48-57.

[47] P. Waide and S. Tanishima, *Light's labour's lost: policies for energy-efficient lighting*. OECD Publishing, 2006.

[48] K. J. Gaston, S. Gaston, J. Bennie, and J. Hopkins, “Benefits and costs of artificial nighttime lighting of the environment”, *Environmental Reviews,* vol. 23, no. 1, pp. 14-23, 2014.

[49] R. Chepesiuk, “Missing the dark: health effects of light pollution”, *Environmental Health Perspectives,* vol. 117, no. 1, pp. A20-A27, 2009.

[50] T. Longcore and C. Rich, “Ecological light pollution”, *Frontiers in Ecology and the Environment,* vol. 2, no. 4, pp. 191-198, 2004.

[51] K. Painter, “The influence of street lighting improvements on crime, fear and pedestrian street use, after dark”, *Landscape and Urban Planning,* vol. 35, no. 2, pp. 193-201, 1996.

[52] Standards Australia, “AS/NZS 1158: Lighting for roads and public spaces, Part 6: Luminaires”, 2010.

[53] P. Vitta, L. Dabasinskas, A. Tuzikas, A. Petrulis, D. Meskauskas, and A. Zukauskas, “Concept of intelligent solid-state street lighting technology”, *Electronics & Electrical Engineering,* vol. 18, no. 10, 2012.

[54] Relume, “Comparing Light Technologies - LED vs. Induction & HPS Lamp”, ed: Relume Technologies, 2012.

[55] E. L. Stone, S. Harris, and G. Jones, “Impacts of artificial lighting on bats: a review of challenges and solutions”, *Mammalian Biology - Zeitschrift für Säugetierkunde,* vol. 80, no. 3, pp. 213-219, 2015.

[56] F. Leccese and Z. Leonowicz, “Intelligent wireless street lighting system”, in *Environment and Electrical Engineering (EEEIC), 2012 11th International Conference on*, 2012, pp. 958-961: IEEE.

[57] S. P. Lau, G. V. Merrett, A. S. Weddell, and N. M. White, “A traffic-aware street lighting scheme for Smart Cities using autonomous networked sensors”, *Computers & Electrical Engineering,* no. 0, 2015.

[58] F. Falchi, P. Cinzano, C. D. Elvidge, D. M. Keith, and A. Haim, “Limiting the impact of light pollution on human health, environment and stellar visibility”, *Journal of Environmental Management,* vol. 92, no. 10, pp. 2714-2722, 2011.

[59] Q. Weng, “Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends”, *ISPRS Journal of Photogrammetry and Remote Sensing,* vol. 64, no. 4, pp. 335-344, 2009.

[60] P. Schneider, N. Castell, M. Vogt, F. R. Dauge, W. A. Lahoz, and A. Bartonova, “Mapping urban air quality in near real-time using observations from low-cost sensors and model information”, *Environment International,* vol. 106, pp. 234-247, 2017.

[61] G. Gualtieri, F. Camilli, A. Cavalieri, T. De Filippis, F. Di Gennaro, S. Di Lonardo, F. Dini, B. Gioli, A. Matese, W. Nunziati, L. Rocchi, P. Toscano, C. Vagnoli, A. Zaldei, "An integrated low-cost road traffic and air pollution monitoring platform to assess vehicles' air quality impact in urban areas", *Transportation Research Procedia,* vol. 27, pp. 609-616, 2017.

[62] B. Liang and Q. Weng, "Assessing urban environmental quality change of Indianapolis, United States, by the remote sensing and GIS integration", *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of,* vol. 4, no. 1, pp. 43-55, 2011.

[63] M. Mousa, E. Oudat, and C. Claudel, "A novel dual traffic/flash flood monitoring system using passive infrared/ultrasonic sensors", in *Mobile Ad Hoc and Sensor Systems (MASS), 2015 IEEE 12th International Conference on*, 2015, pp. 388-397: IEEE.

[64] M. Zinzi and S. Agnoli, "Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region", *Energy and Buildings,* vol. 55, pp. 66-76, 2012.

[65] A. Chatzidimitriou and S. Yannas, "Microclimate design for open spaces: Ranking urban design effects on pedestrian thermal comfort in summer", *Sustainable Cities and Society,* vol. 26, pp. 27-47, 2016.

[66] D. Ni, "Traffic sensing technologies", in *Lecture Notes in Traffic Flow Theory - A Unified Perspective,* University of Massachusetts Amherst, USA, 2013.

[67] Z. Marszalek, T. Zeglen, R. Sroka, and J. Gajda, "Inductive loop axle detector based on resistance and reactance vehicle magnetic profiles", *Sensors,* vol. 18, no. 7, 2018.

[68] S. Coleri, S. Y. Cheung, and P. Varaiya, "Sensor networks for monitoring traffic", in *Allerton conference on communication, control and computing*, 2004, pp. 32-40.

[69] US Department of Transportation. Unit costs for inductive loop surveillance on corridor [Online]. Available: https://www.itscosts.its.dot.gov/its/benecost.nsf/DisplayRUCByUnitCostElementUnadjusted?ReadForm&UnitCostElement=Inductive+Loop+Surveillance+on+Corridor+&Subsystem=Roadside+Detection+(RS-D)

[70] US Department of Transportation, "Traffic detector handbook: third edition", 2006, vol. 1 Available: https://www.fhwa.dot.gov/publications/research/operations/its/06108/01.cfm.

[71] I. Wojnicki, S. Ernst, and L. Kotulski, "Economic impact of intelligent dynamic control in urban outdoor lighting", *Energies,* vol. 9, no. 5, p. 314, 2016.

[72] A. Collins, T. Thurrell, R. Pink, and J. Feather, "Dynamic dimming: the future of motorway lighting?", *Lighting Journal,* vol. 67, no. 5, p. 25, 2002.

[73] US Department of Transportation. Equipment costs for roadside detection [Online]. Available: http://www.itscosts.its.dot.gov/its/benecost.nsf/SubsystemCosts?ReadForm&Subsystem=Roadside+Detection

[74] E. Minge, J. Kotzenmacher, and S. Peterson, “Evaluation of non-intrusive technologies for traffic detection”, Minnesota Department of Transportation, Research Services Section 2010.

[75] B. W. Grone, “An evaluation of non-intrusive traffic detectors at the NTC/NDOR detector test bed”, *Civil Engineering Theses, Dissertations, and Student Research. University of Nebraska,* 2012.

[76] US Department of Transportation. Equipment costs for non-intrusive roadside traffic detection systems [Online]. Available: https://www.itscosts.its.dot.gov/its/benecost.nsf/DisplayRUCByUnitCostElementUnadjusted?ReadForm&UnitCostElement=Remote+Traffic+Microwave+Sensor+on+Corridor+&Subsystem=Roadside+Detection+(RS-D)

[77] Department of Transport and Main Roads, “Technical Specification - MRTS97 Mounting structures for roadside equipment”, 2017.

[78] Department of Transport and Main Roads, “Technical Specification - MRTS94 Road lighting”, 2017.

[79] Department of Transport and Main Roads, “Specification - MRS98 Standalone solar (PV) powered lighting”, 2017.

[80] Philips. (2015). *Citytouch Fact Sheets*. Available: http://www.lighting.philips.com/main/systems/lighting-systems/citytouch

[81] Ergon Energy and Energex, “Public lighting design manual (EX 00767 Ver 3)”, 2010.

[82] Philips. (2015). *Los Angeles becomes first city in the world to control its street lighting through mobile and cloudbased technologies from Philips*.

[83] GE. (2015). *GE Lightgrid Fact Sheets*. Available: https://products.currentbyge.com/control-systems/lightgrid-outdoor-wireless-control-system

[84] Standards Australia, “AS/NZS 1158: Lighting for roads and public spaces, Part 1: Vehicular Traffic (Category V) Lighting”, 2005.

[85] Standards Australia, “AS/NZS 1158: Lighting for roads and public spaces, Part 3: Pedestrian Traffic (Category P) Lighting”, 2005.

[86] J. Green, C. Perkins, R. Steinbach, and P. Edwards, “Reduced street lighting at night and health: A rapid appraisal of public views in England and Wales”, *Health & Place,* vol. 34, pp. 171-180, 2015/07/01/ 2015.

[87] Commonwealth of Australia, “Street lighting strategy - draft strategy paper”, in *Equipment Energy Efficiency Program*, EEE Comittee, Australian Government, 2011.

[88] J. Tunney, “Sustainable public lighting action plan”, *Sustainability & Innovation, City of Melbourne* 2005.

[89] F. Hölker, T. Moss, B. Friefahn, W. Kloas, C.C. Voigt, D. Henckel, A. Hanel, P.M. Kappeler, *et al.*, “The dark side of light: a transdisciplinary research agenda for light pollution policy”, *Ecology and Society,* vol. 15, no. 4, 2010.

[90] S. M. Pauley, “Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue”, *Medical Hypotheses,* vol. 63, no. 4, pp. 588-596, 2004.

[91] R. G. Stevens, G. C. Brainard, D. E. Blask, S. W. Lockley, and M. E. Motta, “Adverse health effects of nighttime lighting: comments on american medical

association policy statement", *American Journal of Preventive Medicine,* vol. 45, no. 3, pp. 343-346, 2013.

[92] Y. Cho, S.-H. Ryu, B. R. Lee, K. H. Kim, E. Lee, and J. Choi, "Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment", *Chronobiology International,* vol. 32, no. 9, pp. 1294-1310, 2015.

[93] R. B. Gibbons, F. Gui, A. Medina, T. Terry, J. Du, P. Lutkevich, D. Corkum, P. Vetere, "Guidelines for the implementation of reduced lighting on roadways", United States. Federal Highway Administration2014.

[94] Standards Australia/Standards New Zealand, "DR AS/NZS 1158: Lighting for roads and public spaces - Part 6: Luminaires", Australia, 2013.

[95] R. Steinbach, C. Perkins, L. Tompson, S. Johnson, B. Armstrong, J. Green, C. Grundy, P. Wilkinson, and P. Edwards, "The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis", *Journal of Epidemiology and Community Health,* vol. 69, no. 11, pp. 1118-1124, 2015.

[96] H.S.H Chung, N.M. Ho, S.Y.R Hui, and W.Z. Mai, "Case study of a highly-reliable dimmable road lighting system with intelligent remote control."

[97] F. Marino, F. Leccese, and S. Pizzuti, "Adaptive street lighting predictive control", *Energy Procedia,* vol. 111, pp. 790-799, 2017.

[98] M. Popa and C. Cepişcă, "Energy consumption saving solutions based on intelligent street lighting control system", *UPB Sci. Bull., Series C,* vol. 73, no. 4, 2011.

[99] Philips. (2018). *Chronosense - the flexible stand-alone dimming solution - family leaflet*. Available: https://www.assets.lighting.philips.com/is/content/PhilipsLighting/comf2116-pss-global

[100] Philips. (2018). *Dynadimmer - different ways - family leaflet*. Available: http://www.lighting.philips.com/main/prof/lighting-controls/outdoor-stand-alone/dynadimmer

[101] S. Pizzuti, M. Annunziato, and F. Moretti, "Smart street lighting management", *Energy Efficiency,* vol. 6, no. 3, pp. 607-616, 2013.

[102] A. A. Filimonova, T. A. Barbasova, and D. A. Shnayder, "Outdoor lighting system upgrading based on smart grid concept", *Energy Procedia,* vol. 111, pp. 678-688, 2017.

[103] PG&E, "A Pacific Energy Center factsheet: high pressure sodium lamps", Pacific Gas & Energy Company 1997, Available: http://www.pge.com/pec.

[104] Lumec. (2008). *LEDs for outdoor lighting applications*. Available: http://www.lumec.com/pdf/white_paper/WhitePaper_LEDs.pdf

[105] National Electrical Manufacturers Association, "Guidelines on the application of dimming to high-intensity discharge lamps", 2010.

[106] Y. Ji, and R. Wolsey, "Lighting answers - dimming systems for high-intensity discharge lamps", *National Lighting Product Information Program,* vol. 1, no. 4, 1994.

[107] K. Gordon, "LED application series: outdoor area lighting", U.S. Department of Energy, United States of America, 2008.

[108] Silver Spring Networks, "The business case for smart street lights", Silver Spring Networks 2013, Available:

http://www.iitmicrogrid.net/microgrid/pdf/csmart/SilverSpring-Whitepaper-Smart-Street-Light-Bizcase.pdf, Accessed on: 2018-08-31.
[109] R. Lingard, “Lifetime of white LEDs”, 2009.
[110] Lumileds, “Street lighting - LEDs: coming soon to a street light near you “, ed, 2016.
[111] Trans-Lux. (2013). *Illuminating the benefits of LED street lights* [White Paper]. Available: http://www.trans-lux.com/content/2-products/3-tl-energy-led-lighting/Trans-Lux-Energy-LED-Lighting-White-Paper.pdf
[112] G. M. Gomis, “Green paper: Policy options to accelerate the global transition to advanced lighting”, United Nations Environmental Programme, Global Efficient Lighting Forum2014.
[113] Northeast Energy Efficiency Partnerships, “LED street lighting assessment and strategies for the northeast and mid-atlantic”, 2015.
[114] City of Ipswich. (2016). *Ipswich LED street lighting retrofit*. Available: http://www.environment.gov.au/apps/energy/ceep/ceep-ipswich-city-council-final-report.pdf
[115] P. Valdivia, “Mayor Villaraigosa announces completion of largest LED street light replacement program”, Office of the Mayor, Los Angeles, USA, 2012.
[116] B. Kinzey, “Restoring Detroit's street lighting system”, Pacific Northwest National Laboratory (PNNL), Richland, WA (US)2015.
[117] Department of Transport and Main Roads. (2017). *Technical Note 158 - Guide to the use of LED road lighting luminaires*. Available: https://www.tmr.qld.gov.au/-/media/busind/techstdpubs/Technical-notes/ITS-Electrical-technology/TN158.pdf?la=en
[118] P. Curley, “The big switch: Why it's time to scale up led street lighting”, The Climate Group 2015.
[119] L. Guo, M. Eloholma, and L. Halonen, “Luminance monitoring and optimization of luminance metering in intelligent road lighting control systems”, *Ingineria Illuminatului,* vol. 9, pp. 24-40, 2007.
[120] A. K. Jägerbrand, “LED (Light-emitting diode) road lighting in practice: An evaluation of compliance with regulations and improvements for further energy savings”, *Energies,* vol. 9, no. 5, p. 357, 2016.
[121] G. Shahzad, H. Yang, A. W. Ahmad, and C. Lee, “Energy-efficient intelligent street lighting system using traffic-adaptive control”, *IEEE Sensors Journal,* vol. 16, no. 13, pp. 5397-5405, 2016.
[122] Cisco. (2016). *Smart+Connected Lighting*. Available: https://iotevent.eu/wp-content/uploads/2016/09/Cisco-Smart-Connected-Lighting-IoT-AI-Workshop-LpS-2016.pdf
[123] Cisco. (2018, 2018-10-18). *Cisco Kinetic for cities lighting*. Available: https://www.cisco.com/c/en/us/solutions/industries/smart-connected-communities/city-lighting.html
[124] F. J. Bellido-Outeiriño, F. J. Quiles-Latorre, C. D. Moreno-Moreno, J. M. Flores-Arias, I. Moreno-García, and M. Ortiz-López, “Streetlight control system based on wireless communication over DALI protocol”, *Sensors,* vol. 16, no. 5, p. 597, 2016.
[125] Ergon Energy. (2018, 2018-09-10). *Tariffs & Prices - Other Tariffs - Tariff 71*. Available: https://www.ergon.com.au/retail/business/tariffs-and-prices/other-tariffs

[126] M. Ceriotti, M. Corra, L. D'Orazio, R. Doriguzzi, D. Facchin, *et al.*, “Is there light at the ends of the tunnel? Wireless sensor networks for adaptive lighting in road tunnels”, in *Information Processing in Sensor Networks (IPSN), 2011 10th International Conference on*, 2011, pp. 187-198: IEEE.

[127] R. Gibbons, M. Palmer, and A. Jahangiri, “Connected vehicle applications for adaptive overhead lighting (on-demand lighting)”, 2016.

[128] M. E. Palmer, R. Gibbons, and A. Jahangiri, “An experimental on-demand roadway-lighting system”, 2015.

[129] E. Juntunen, E. Tetri, O. Tapaninen, S. Yrjana, V/ Kondratyev, A. Sitomaniemi, H. Siirtola, E.M. Sarjanoja, J. Aikio, and V. Heikkinen, “A smart LED luminaire for energy savings in pedestrian road lighting”, *Lighting Research and Technology, vol. 47, pp. 103-115, 2013.*

[130] S. P. Lau, G. V. Merrett, and N. M. White, “Energy-efficient street lighting through embedded adaptive intelligence”, in *Advanced Logistics and Transport (ICALT), 2013 International Conference on*, 2013, pp. 53-58: IEEE.

[131] N. Kaptein, J. Hogema, and E. Folles, “Dynamic public lighting (DYNO)”, in *The 8th European Lighting Conference Lux Europa*, 1997.

[132] L. Guo, “*Intelligent road lighting control systems-experiences, measurements, and lighting control strategies”,* Teknillinen Korkeakoulu, 2008.

[133] R. Müllner and A. Riener, “An energy efficient pedestrian aware Smart Street Lighting system”, *International Journal of Pervasive Computing and Communications,* vol. 7, no. 2, pp. 147-161, 2011.

[134] S. Cygan, B. Borowik, and B. Borowik, “Street lights intelligent system, based on the internet of things concept”, *Applied Computer Science,* vol. 14, no. 1, 2018.

[135] G. Leduc, “Road traffic data: Collection methods and applications”, *Working Papers on Energy, Transport and Climate Change,* vol. 1, p. 55, 2008.

[136] Tvilight. (2015). *Intelligent Lighting Solutions* Available: https://www.tvilight.com/citysense/

[137] Tvilight. (2014). *Adaptive roadway lighting saves over 60% energy; Case-Study. City of Nijmegen*. Available: https://www.tvilight.com/wp-content/uploads/2016/12/Case-Study_Nijmegen_EN_2014_Tvilight-Intelligent-Lighting.pdf

[138] P. Arani. (2014). *Adaptive LED street & area lighting - selecting, financing, and implementing best-practice solutions*. Available: http://www.partnershipdemonstrations.org

[139] A. K. Sikder, A. Acar, H. Aksu, A. S. Uluagac, K. Akkaya, and M. Conti, “IoT-enabled smart lighting systems for smart cities”, in *Computing and Communication Workshop and Conference (CCWC), 2018 IEEE 8th Annual*, 2018, pp. 639-645: IEEE.

[140] S. Anand and N. Jain, “Intelligent street light system using wireless transmission: a review”, *International Journal of Advanced Research in Electronics and Communication Engineering,* vol. 4, no. 2, 2015.

[141] K. A. Bajaj and T. S. Mote, “Review on intelligent street lightening system”, *International Journal of Science and Research, vol. 4, issue. 2,* 2015.

[142] A. Kovács, R. Batai, B.C. Csaji, P. Dudas, B. Hay, G. Pedone, T. Revesz, and J. Vancza, “Intelligent control for energy-positive street lighting”, *Energy,* vol. 114, pp. 40-51, 2016.

[143] I. Wojnicki, S. Ernst, L. Kotulski, and A. Se¸dziwy, “Advanced street lighting control”, *Expert Systems with Applications,* vol. 41, no. 4, Part 1, pp. 999-1005, 2014.

[144] M. Pipattanasomporn, S. Rahman, I. Flory, and Y. Teklu, “Engineering design and assessment of a demand-sensitive LED streetlighting system”, *Sustainable Energy Technologies and Assessments,* vol. 7, pp. 136-146, 2014.

[145] C.-F. Tsai and C.-H. Huang, “Streetlight monitoring system based on wireless sensor networks”, 2010.

[146] F. Leccese, M. Cagnetti, and D. Trinca, “A smart city application: A fully controlled street lighting isle based on Raspberry-Pi card, a ZigBee sensor network and WiMAX”, *Sensors,* vol. 14, no. 12, pp. 24408-24424, 2014.

[147] D. Middleton and P. R. Longmire, “State of the art evaluation of traffic detection and monitoring systems”, Arizona Department of Transportation, US Department of Transportation, Federal Highway Administration, Texas Transportation Institute, Texas A and M University, 2007.

[148] S.Y. Cheung and P. P. Varaiya, "*Traffic surveillance by wireless sensor networks: Final report"*. California PATH Program, Institute of Transportation Studies, University of California at Berkeley, 2007.

[149] Siemens, “Siemens SCOOTS adaptive system - Western Systems - Innovative transportation solutions for Washington”, 2010.

[150] TransMax. (2018). *STREAMS ITS Platform*. Available: https://www.transmax.com.au/what-we-do/streams/

[151] F. Boillot, S. Midenet, and J.-C. Pierrelee, “The real-time urban traffic control system CRONOS: Algorithm and experiments”, *Transportation research part C: Emerging technologies,* vol. 14, no. 1, pp. 18-38, 2006.

[152] C. Li and S. Shimamoto, “An open traffic light control model for reducing vehicles co2 emissions based on etc vehicles”, *IEEE Transactions on Vehicular Technology,* vol. 61, no. 1, pp. 97-110, 2012.

[153] M. Tubaishat, Y. Shang, and H. Shi, “Adaptive traffic light control with wireless sensor networks”, in *Proceedings of IEEE Consumer Communications and Networking Conference*, 2007, pp. 187-191.

[154] S. T. M. Gudmundur A. Bodvarsson, “Effects of loop detector installation on the portland cement concrete. pavement lifespan: Case study on I-5”, Washington State Department of Transport 2010.

[155] Y. F. Peter T. Martin, Xiaodong Wang, “Detector technology evaluation”, University of Utah, 2003.

[156] Wavetronix. *SmartSensor HD Datasheet*. Available: http://www.signalcontrol.com/products/wavetronix/Wavetronix_SmartSensor_HD.pdf

[157] G. Padmavathi, D. Shanmugapriya, and M. Kalaivani, “A study on vehicle detection and tracking using wireless sensor networks”, *Wireless Sensor Network,* vol. 2, no. 02, p. 173, 2010.

[158] K. Nellore and G. Hancke, “A survey on urban traffic management system using wireless sensor networks”, *Sensors,* vol. 16, no. 2, p. 157, 2016.

[159] R. Gade and T. B. Moeslund, “Thermal cameras and applications: a survey”, *Machine vision and applications,* vol. 25, no. 1, pp. 245-262, 2014.

[160] R. Gade, T.B. Moeslund, S.Z. Nielsen, H. Skov-Petersen, H.J. Andersen, K. Basselbjerg, H.T. Dam, O.B. Jensen, A. Jorgensen, H. Lahrmann, T.K.O. Madsen, E.S. Bala, and B. Povey, “Thermal imaging systems for real-time applications in smart cities”, *International Journal of Computer Applications in Technology,* vol. 53, no. 4, pp. 291-308, 2016.

[161] T. S. Perry, “San Diego installs smart streetlights to monitor the metropolis”, in *IEEE Spectrum*, ed, 2018.

[162] Current - Powered by GE. (2018). *CityIQ IoT Platform Capabilities*. Available: https://developer.currentbyge.com/cityiq

[163] Current - Powered by GE. (2017, 2018-10-12). *San Diego to deploy world’s largest smart city IoT platform with Current, powered by GE*. Available: https://www.currentbyge.com/ideas/san-diego-to-deploy-world-s-largest-smart-city-iot-platform-with-current-powered-by-ge

[164] Y. Jo and I. Jung, “Analysis of vehicle detection with WSN-based ultrasonic sensors”, (in English), *Sensors (Switzerland),* vol. 14, no. 8, pp. 14050-14069, 2014.

[165] L. E. Y. Mimbela and L. A. Klein, “Summary of vehicle detection and surveillance technologies used in intelligent transportation systems”, 2000.

[166] Y. Jo, J. Choi, and I. Jung, “Traffic information acquisition system with ultrasonic sensors in wireless sensor networks”, *International Journal of Distributed Sensor Networks,* vol. 2014, 2014.

[167] H. Kim, J.H. Lee, S.-W. Kim, J.I. Ko, and D. Cho, “Ultrasonic vehicle detector for side-fire implementation and extensive results including harsh conditions”, *Intelligent Transportation Systems, IEEE Transactions on,* vol. 2, no. 3, pp. 127-134, 2001.

[168] A. Kianpisheh, N. Mustaffa, P. Limtrairut, and P. Keikhosrokiani, “Smart parking system (SPS) architecture using ultrasonic detector”, *International Journal of Software Engineering and Its Applications,* vol. 6, no. 3, pp. 55-58, 2012.

[169] E. Oudat, M. Mousa, and C. Claudel, “Vehicle detection and classification using passive infrared sensing”, in *(MASS), IEEE 12th International Conference on Mobile Ad Hoc and Sensor Systems*, pp. 443-444, 2015.

[170] J. Fernández-Lozano, M. Martín-Guzmán, J. Martín-Ávila, and A. García-Cerezo, “A wireless sensor network for urban traffic characterization and trend monitoring”, *Sensors,* vol. 15, no. 10, pp. 26143-26169, 2015.

[171] Velodyne Acoustics Inc., “Velodyne's HDL-64E: A high definition LIDAR sensor for 3-D applications”, I. Velodyne Acoustics, Ed., ed. www.velodynelidar.com, 2007.

[172] PulsedLight Ltd. (2014, August). *LiDAR Lite Datasheet*. Available: https://cdn.sparkfun.com/datasheets/Sensors/Proximity/LIDAR-Lite-Laser-Datasheet.pdf

[173] C. Harlow and S. Peng, “Automatic vehicle classification system with range sensors”, *Transportation Research Part C: Emerging Technologies,* vol. 9, no. 4, pp. 231-247, 2001.

[174] D. A. Noyce, A. Gajendran, and R. Dharmaraju, “Development of bicycle and pedestrian detection and classification algorithm for active-infrared

overhead vehicle imaging sensors", *Transportation Research Record: Journal of the Transportation Research Board,* vol. 1982, no. 1, pp. 202-209, 2006.

[175] Robotshop Inc., *Hokuyo UTM-30LX-EW Scanning Laser Rangefinder*. Available: https://www.robotshop.com/en/hokuyo-utm-30lx-ew-laser-rangefinder.html

[176] C. V. P. Watts and R. Michael, "MIT and DARPA pack lidar sensor onto single chip",, *IEEE Spectrum: Technology, Engineering, and Science News,* 2016.

[177] T. Stathopoulos, H. Wu, and J. Zacharias, "Outdoor human comfort in an urban climate", *Building and Environment,* vol. 39, no. 3, pp. 297-305, 2004.

[178] I. Eliasson, "The use of climate knowledge in urban planning", *Landscape and Urban Planning,* vol. 48, no. 1–2, pp. 31-44, 2000.

[179] P. Rajagopalan, K. C. Lim, and E. Jamei, "Urban heat island and wind flow characteristics of a tropical city", *Solar Energy,* vol. 107, no. 0, pp. 159-170, 2014.

[180] H. Akbari, M. Pomerantz, and H. Taha, "Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas", *Solar energy,* vol. 70, no. 3, pp. 295-310, 2001.

[181] K. Deilami and M. Kamruzzaman, "Modelling the urban heat island effect of smart growth policy scenarios in Brisbane", *Land Use Policy,* vol. 64, pp. 38-55, 2017.

[182] A. Mohajerani, J. Bakaric, and T. Jeffrey-Bailey, "The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete", *Journal of Environmental Management,* vol. 197, pp. 522-538, 2017.

[183] L. Chen and E. Ng, "Outdoor thermal comfort and outdoor activities: A review of research in the past decade", *Cities,* vol. 29, no. 2, pp. 118-125, 2012.

[184] I. Eliasson, I. Knez, U. Westerberg, S. Thorsson, and F. Lindberg, "Climate and behaviour in a Nordic city", *Landscape and Urban Planning,* vol. 82, no. 1, pp. 72-84, 2007.

[185] J. Gehl, *Cities for people*. Island Press, 2013.

[186] J. Gehl, *Life between buildings: using public space*. Island Press, 2011.

[187] A. Soltani and E. Sharifi, "Daily variation of urban heat island effect and its correlations to urban greenery: A case study of Adelaide", *Frontiers of Architectural Research,* vol. 6, no. 4, pp. 529-538, 2017.

[188] World Health Organisation. (2018, Jul). *Non-communicable diseases and their risk factors - Physical activity*.

[189] H.-J. Jun and M. Hur, "The relationship between walkability and neighborhood social environment: The importance of physical and perceived walkability", *Applied Geography,* vol. 62, pp. 115-124, 2015.

[190] L. J. Carr, S. I. Dunsiger, and B. H. Marcus, "Walk Score™ as a global estimate of neighborhood walkability", *American Journal of Preventive Medicine,* vol. 39, no. 5, pp. 460-463, 2010.

[191] V. Mehta, "Walkable streets: pedestrian behavior, perceptions and attitudes", *Journal of Urbanism,* vol. 1, no. 3, pp. 217-245, 2008.

[192] J. I. Gilderbloom, W. W. Riggs, and W. L. Meares, “Does walkability matter? An examination of walkability’s impact on housing values, foreclosures and crime”, *Cities,* vol. 42, pp. 13-24, 2015.

[193] B. E. Saelens, J. F. Sallis, and L. D. Frank, “Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures”, *Annals of Behavioral Medicine,* vol. 25, no. 2, pp. 80-91, 2003.

[194] N. Owen, E. Cerin, E. Leslie, L. duToit, N. Coffee, L.D. Frank, A.E. Bauman, G. Hugo, B.E. Saelens, and J.F. Sallis, “Neighborhood walkability and the walking behavior of australian adults”, *American Journal of Preventive Medicine,* vol. 33, no. 5, pp. 387-395, 2007.

[195] L. D. Frank, T. L. Schmid, J. F. Sallis, J. Chapman, and B. E. Saelens, “Linking objectively measured physical activity with objectively measured urban form”, *American Journal of Preventive Medicine,* vol. 28, no. 2, pp. 117-125, 2005.

[196] M. Mead, O.A.M. Popoola, G.B. Stwart, P. Landshoff, M. Callega, M. Hayes, J.J. Baldovi, M.W. McLeod, T.F. Hodgson, J. Dicks, A. Lewis, J. Cohen, R. Baron, J.R. Saffell, R.L. Jones, “The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks”, *Atmospheric Environment,* vol. 70, pp. 186-203, 2013.

[197] F. Ingelrest, G. Barrenetxea, G. Schaefer, M. Vetterli, O. Couach, and M. Parlange, “SensorScope: Application-specific sensor network for environmental monitoring”, *ACM Transactions on Sensor Networks (TOSN),* vol. 6, no. 2, p. 17, 2010.

[198] R. B. Miller and C. Small, “Cities from space: potential applications of remote sensing in urban environmental research and policy”, *Environmental Science & Policy,* vol. 6, no. 2, pp. 129-137, 2003.

[199] J. A. Voogt and T. R. Oke, “Thermal remote sensing of urban climates”, *Remote Sensing of Environment,* vol. 86, no. 3, pp. 370-384, 2003/08/15/ 2003.

[200] X. Mao, X. Miao, Y. He, X.-Y. Li, and Y. Liu, “CitySee: urban CO2 monitoring with sensors”, in *INFOCOM, 2012 Proceedings IEEE*, 2012, pp. 1611-1619: IEEE.

[201] B. Rashid and M. H. Rehmani, “Applications of wireless sensor networks for urban areas: A survey”, *Journal of Network and Computer Applications,* vol. 60, pp. 192-219, 2016.

[202] R. Murty, A. Gosain, M. Tierney, A. Brody, A. Fahad, and J. Bers, “Citysense: A vision for an urban-scale wireless networking testbed”,, *IEEE International Conference on Technologies for Homeland Security, Waltham, MA*, 2008.

[203] D. Cuff, M. Hansen, and J. Kang, “Urban sensing: out of the woods”, *Communications of the ACM,* vol. 51, no. 3, pp. 24-33, 2008.

[204] R. H. Von Alan, S. T. March, J. Park, and S. Ram, “Design science in information systems research”, *MIS quarterly,* vol. 28, no. 1, pp. 75-105, 2004.

[205] *Seeeduino Stalker v2.3*. Available: http://wiki.seeedstudio.com/Seeeduino_Stalker_v2.3/

[206] G. Barrenetxea, Fran, O. Ingelrest, G. Schaefer, and M. Vetterli, “The hitchhiker's guide to successful wireless sensor network deployments”,, ACM conference on Embedded Network Sensor Systems, Raleigh, NC, USA, 2008.

[207] *DR AS/NZS 1158: Lighting for roads and public spaces*, 2013.

[208] C. Shenzhen Cholip Power. *1000mAh Lithium Battery Specification*. Available: https://www.seeedstudio.com/document/603450P%201000mAh.pdf

[209] D. Honegger, L. Meier, P. Tanskanen, and M. Pollefeys, “An open source and open hardware embedded metric optical flow CMOS camera for indoor and outdoor applications”, in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, 2013, pp. 1736-1741: IEEE.

[210] *Wboard Pro Arduino MEGA ESP8266 Wifi Development Board Module*. Available: https://www.itead.cc/wboard-pro.html

[211] MaxBotix Inc. (2012). *XL-MaxSonar - EZ Series Datasheet*. Available: https://www.maxbotix.com/documents/XL-MaxSonar-EZ_Datasheet.pdf

[212] K. Mohring. (2016). *Visual traffic counting for low-resolution video files: Leenix/CarCrow*. Available: https://github.com/Leenix/CarCrow

[213] Queensland Government. (5 July 2016). *Safe following distances*. Available: https://www.qld.gov.au/transport/safety/rules/road/distances/index.html

[214] R. C. Luo and O. Chen, “Wireless and pyroelectric sensory fusion system for indoor human/robot localization and monitoring”, *IEEE/ASME Transactions on Mechatronics,* vol. 18, no. 3, pp. 845-853, 2013.

[215] X. Luo, B. Shen, X. Guo, G. Luo, and G. Wang, “Human tracking using ceiling pyroelectric infrared sensors”, in *Control and Automation, 2009. ICCA 2009. IEEE International Conference on*, 2009, pp. 1716-1721: IEEE.

[216] P. Zappi, E. Farella, and L. Benini, “Tracking motion direction and distance with pyroelectric IR sensors”, *IEEE Sensors Journal,* vol. 10, no. 9, pp. 1486-1494, 2010.

[217] B. Donovan, Y. Li, R. Stern, J. Jiang, C. Claudel, and D. Work, “Vehicle detection and speed estimation with PIR sensors”, in *Proceedings of the 14th International Conference on Information Processing in Sensor Networks*, 2015, pp. 370-371: ACM.

[218] *HC-SR501 Motion Sensor Datasheet*. Available: https://www.mpja.com/download/31227sc.pdf

[219] Panasonic. *AMN(NaPiOn) Series Motion Sensor Datasheet*. Available: http://www3.panasonic.biz/ac/e_download/control/sensor/human/catalog/bltn_eng_papirs_final_amn.pdf

[220] Melexis. (2015, 02 June). *MLX90621 16x4 Infrared Array Datasheet*. Available: https://www.melexis.com/-/media/files/documents/datasheets/mlx90621-datasheet-melexis.pdf

[221] A. Tyndall, R. Cardell-Oliver, and A. Keating, “Occupancy estimation using a low-pixel count thermal imager”, *IEEE Sensors Journal,* vol. 16, no. 10, pp. 3784-3791, 2016.

[222] Y. Iwasaki, M. Misumi, and T. Nakamiya, “Robust vehicle detection under various environmental conditions using an infrared thermal camera and its application to road traffic flow monitoring”, *Sensors,* vol. 13, no. 6, pp. 7756-7773, 2013.

[223] Office of Energy Efficiency and Renewable Energy, “Retrofit Financial Analysis Tool “ United States Government2017, Available: https://www.energy.gov/eere/ssl/retrofit-financial-analysis-tool.

[224] N. Humphrey, “SEAD Street Lighting Tool”, version. 1.8.1, International Partnership for Energy Efficiency Cooperation: Super-efficient Equipment and Appliance Deployment Initiative, 2016.

[225] L. Tähkämö and L. Halonen, “Life cycle assessment of road lighting luminaires - Comparison of light-emitting diode and high-pressure sodium technologies”, *Journal of Cleaner Production,* vol. 93, pp. 234-242, 2015.

[226] L. Tähkämö, R.-S. Räsänen, and L. Halonen, “Life cycle cost comparison of high-pressure sodium and light-emitting diode luminaires in street lighting”, *The International Journal of Life Cycle Assessment,* vol. 21, no. 2, pp. 137-145, 2016.

[227] S. M. Schmidt, “A feasibility analysis of retrofitting existing roadway lighting infrastructure with LED technology”, 2012.

[228] S. Abdul Hadi, M. R. Al Kaabi, M. O. Al Ali, and H. A. Arafat, “Comparative life cycle assessment (LCA) of streetlight technologies for minor roads in United Arab Emirates”, *Energy for Sustainable Development,* vol. 17, no. 5, pp. 438-450, 2013.

[229] Y. Jiang, S. Li, B. Guan, and G. Zhao, “Cost effectiveness of new roadway lighting systems”, *Journal of Traffic and Transportation Engineering (English Edition),* vol. 2, no. 3, pp. 158-166, 2015.

[230] E. Juntunen, E.-M. Sarjanoja, J. Eskeli, H. Pihlajaniemi, and T. Österlund, “Smart and dynamic route lighting control based on movement tracking”, *Building and Environment,* 2018.

[231] F. Knobloch and N. Braunschweig, “A traffic-aware moving light system featuring optimal energy efficiency”, *IEEE Sensors Journal,* vol. 17, no. 23, pp. 7731-7740, 2017.

[232] Department of Transport and Main Roads, “Queensland traffic data averaged by hour of day and day of week “, ed. Australia: Queensland Government Data, 2017.

[233] State of Queensland, “Traffic and road use management - Part 2: Road lighting maintenance”,, Volume 4 - Intelligent Transport Systems and Electrical Technology, Department of Transport and Main Roads, 2015.

[234] S. Thorsen, Time and Date AS, '*Sunrise and sunset times - Australia', 2018* [Online]. Available: https://www.timeanddate.com/sun/australia

[235] Australian Bureau of Statistics, “Regional population growth, Australia, 2016-2017”, 2018, Available: http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/3218.0Main+Features12016-17?OpenDocument.

[236] Cree Inc. (2018). *Why Cree LED?* Available: https://lighting.cree.com/why-cree-led

[237] LoRa Alliance, “A technical overview of LoRa and LoRaWAN”, *White Paper, November,* 2015.

[238] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, “Understanding the limits of LoRaWAN”, *IEEE Communications Magazine,* vol. 55, no. 9, pp. 34-40, 2017.

[239] Elecom Electronics Supply. (2018). *LoRaWAN Module Pricing*. Available: http://www.elecomes.com/category.php?id=55

[240] State of Queensland, "Road planning and design manual", Department of Transport and Main Roads, 2nd Edition, Queensland Government, Australia, 2016.

[241] Standards Australia, "AS/NZS 1158: Lighting for roads and public spaces", 2010.

[242] N. M. A. Huijts, E. J. E. Molin, and L. Steg, "Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework", *Renewable and Sustainable Energy Reviews,* vol. 16, no. 1, pp. 525-531, 2012.

[243] S. Lindenberg and L. Steg, "Normative, gain and hedonic goal frames guiding environmental behavior", *Journal of Social Issues,* vol. 63, no. 1, pp. 117-137, 2007.

[244] V. Venkatesh, M. G. Morris, G. B. Davis, and F. D. Davis, "User acceptance of information technology: Toward a unified view", *MIS quarterly,* pp. 425-478, 2003.

[245] Australian Bureau of Statistics. (2016). *Population by Age and Sex, Regions of Australia, 2016*. Available: http://www.abs.gov.au/ausstats/abs@.nsf/mf/3235.0

[246] R. M. Heiberger and N. B. Robbins, "Design of diverging stacked bar charts for Likert scales and other applications", *Journal of Statistical Software,* vol. 57, no. 5, pp. 1-32, 2014.

[247] V. Venkatesh, J. Y. L. Thong, and X. Xu, "Consumer acceptance and use of information technology: Extending the unified theory of acceptance and use of technology", *MIS Quarterly,* vol. 36, no. 1, pp. 157-178, 2012.

[248] M. Johansson, M. Küller, and E. Pedersen, "Understanding a housing cooperatives' reasons for rejecting energy-efficient outdoor lighting", *Lighting Research & Technology,* vol. 47, no. 7, pp. 876-892, 2015.

[249] G. G. Bennett, L. H. McNeill, K. Y. Wolin, D. T. Duncan, E. Puleo, and K. M. Emmons, "Safe to walk? Neighborhood safety and physical activity among public housing residents", *PLOS Medicine,* vol. 4, no. 10, p. e306, 2007.

[250] P. Mason, A. Kearns, and M. Livingston, "“Safe Going": The influence of crime rates and perceived crime and safety on walking in deprived neighbourhoods", *Social Science & Medicine,* vol. 91, pp. 15-24, 2013/08/01/ 2013.

[251] D. Banister and A. Bowling, "Quality of life for the elderly: the transport dimension", *Transport Policy,* vol. 11, no. 2, pp. 105-115, 2004.

[252] C. G. Roman and A. Chalfin, "Fear of walking outdoors: A multilevel ecologic analysis of crime and disorder", *American Journal of Preventive Medicine,* vol. 34, no. 4, pp. 306-312, 2008.

[253] A. Haans and Y. A. de Kort, "Light distribution in dynamic street lighting: Two experimental studies on its effects on perceived safety, prospect, concealment, and escape", *Journal of Environmental Psychology,* vol. 32, no. 4, pp. 342-352, 2012.

[254] M. Johansson, M. Rosén, and R. Küller, “Individual factors influencing the assessment of the outdoor lighting of an urban footpath”, *Lighting Research & Technology,* vol. 43, no. 1, pp. 31-43, 2011.

[255] C. Boomsma and L. Steg, “The effect of information and values on acceptability of reduced street lighting”, *Journal of Environmental Psychology,* vol. 39, pp. 22-31, 2014.

Appendix A - Public Acceptance Survey

The Smart Streetlights - Smarter Cities Survey

More precise traffic information can be given to traffic lights to help smooth out road travel and make for quicker trips with fewer stops.

This section looks at your experiences with road transport to estimate how much you would benefit more intelligent traffic lights.

Q1 - Which automobile type do you use the most for regular **road travel**?
Road travel does not include the use of footpaths or bike lanes.

- ○ Private vehicle (as driver)
- ○ Other private vehicle (e.g. carpooling)
- ○ Taxi/Uber
- ○ Bus / Public road transport
- ○ Other ____
- ○ I do not regularly travel by road

Q2 - Excluding weekends, how many days do you usually travel to your place of work/study/regular destination by road?

Q3 - Excluding weekends, how many minutes does a typical one-way trip to or from your place of work/study/regular destination take?

Q4 - Considering your average experience with road travel, how would you rate your experiences in the following categories?

	Excellent	Good	Adequate	Poor	Terrible
Trip times	○	○	○	○	○
Traffic flow/speed	○	○	○	○	○
Congestion	○	○	○	○	○
Stopping frequency	○	○	○	○	○
Wait times at signalled intersections	○	○	○	○	○
Wait times at non-signalled intersections and roundabouts	○	○	○	○	○

Q5 - Imagine a scenario where you must pay $750 for 12-months of vehicle registration.
Out of this total amount, $60 currently goes towards road maintenance and traffic improvement.

What is the most you'd be willing to pay on top of your current registration fees if it meant that your wait time at traffic lights was reduced by half (regardless if you currently pay for registration or not)?

$

With developing technology, every streetlight has the potential to become a mini weather station, which means you could get weather information specific to your street rather than your suburb or city. Weather information at this level means that town planners can identify areas that need shade or cover to make cities more walker-friendly. Planning cities in this way gives benefits to citizens and visitors alike. For example, building covered walkways in areas that receive a lot of rain or sun would make walking or cycling around the city more pleasant and accessible.

Q6 - How many minutes do you usually spend walking per week for transport purposes, rather than for leisure or exercise?

Q7 - How many minutes per week do you spend cycling for transport purposes, rather than for leisure or exercise?

Q8 - How many minutes would you be willing to walk to a destination in the following scenarios in your city of residence before considering alternative (automotive) transport?

☐ minutes in summer **without shade**

☐ minutes in summer **with shade**

☐ minutes in winter **without cover**

☐ minutes in winter **with cover**

Q9 - How many minutes would you be willing to cycle to a destination before considering alternative (automotive) transport?

☐ minutes in summer

☐ minutes in winter

Q10 - What factors do you consider as barriers to you walking or cycling around your city more often? This can be for either transport or leisure purposes?

	Definitely a factor	Probably a factor	Neutral	Probably not a factor	Definitely not a factor
Temperature	○	○	○	○	○
Weather effects (rain, wind, humidity)	○	○	○	○	○
Pollution	○	○	○	○	○
Availability of cover from rain/sun/cold	○	○	○	○	○
Long distances between areas of interest	○	○	○	○	○
Availability of alternative transport	○	○	○	○	○
Personal health and/or fitness	○	○	○	○	○
Personal safety (day time)	○	○	○	○	○
Personal safety (night time)	○	○	○	○	○
Travel times	○	○	○	○	○
Other(s)	○	○	○	○	○

Q11 - Which of the following sources do you regularly use for weather information? Tick as many that apply

- ☐ TV
- ☐ Radio
- ☐ Newspaper
- ☐ Website
- ☐ Mobile application
- ☐ Other ____

Q12 - How satisfied are you with the accuracy of the information you get from your weather sources for your suburb/location?

- ○ Extremely satisfied
- ○ Somewhat satisfied
- ○ Neither satisfied nor dissatisfied
- ○ Somewhat dissatisfied
- ○ Extremely dissatisfied
- ○ Not applicable

Q13 - What the is the most you would be willing to pay for a mobile app or web service (in dollars) that could give you weather information, including temperature, humidity, and cloud cover down to the street level in real-time anywhere in your city?

Please assume that this is a once-off purchase and not subscription-based.

$

Streetlight waste a lot of energy by staying on overnight when there are no cars on the road. Instead of running them at a constant brightness, streetlight can be dimmed down when roads are empty and turned back to normal ahead of any cars or pedestrians to save energy without road users noticing the difference.

This section talks about your experiences with street lighting right now, and your views on dimming lights during the night.

Q14 - How much do you agree with the following statements?

	Strongly agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Strongly disagree
Well-lit roads make me feel safe	○	○	○	○	○
I am bothered by streetlight when in my home	○	○	○	○	○
I'm concerned about crime in my area	○	○	○	○	○
I would be annoyed with dimming streetlight at home	○	○	○	○	○
Non-working streetlights are a problem where I live	○	○	○	○	○
I am worried what will happen if the roads are not always lit	○	○	○	○	○
I'm energy conscious around my home and try to save power	○	○	○	○	○

Q15 - Imagine that for each dollar that a ratepayer was charged by the local council, 45 cents was for water, 45 cents was for sewerage, and the remaining 10 cents was for waste and recycling. If the council wanted to redistribute those amounts to add streetlight dimming, how much of that dollar should they dedicate to that service?

Please keep in mind that the proportion of the dollar spent on streetlight dimming must be taken away from the existing services. Cost to the ratepayers would remain the same in this scenario.

How should the funds be reallocated? The total amount must equal 1 dollar (100 cents).

	Current Distribution	Your Distribution
Water	45	
Sewerage	45	
Waste & Recycling	10	
Streetlight Dimming	0	

Streetlight could be upgraded to fit a Wi-Fi access point to give out free or subscription-based internet access in public areas.

This section asks how free Wi-Fi internet access would affect how often you visit public areas and public events.

Q16 - How often do you usually travel to the city centre or public spaces and parks for leisure reasons?

○ Once a day

○ More than once per week

○ Once a week

○ Once a month

○ Once every 6 months

○ Fewer than once every 6 months

○ Never

Q17 - How often would you travel to the city centre or public spaces and parks for leisure reasons if free Wi-Fi was provided in more locations?

○ Once a day

○ More than once a week

○ Once a week

○ Once a month

○ Once every 6 months

○ Fewer than once every 6 months

○ Never

Q18 - How often do you usually go to community events such as markets, public art exhibitions, and sporting events?

- ○ Once a day
- ○ More than once a week
- ○ Once a week
- ○ Once a month
- ○ Once every 6 months
- ○ Fewer than once every 6 months
- ○ Never

Q19 - How often would you be willing to travel to public areas or to community events if free Wi-Fi was provided in more locations in the areas you were interested in visiting?

- ○ Once a day
- ○ More than once a week
- ○ Once a week
- ○ Once a month
- ○ Once every 6 months
- ○ Fewer than once every 6 months
- ○ Never

The last part of this survey is about you. Our circumstances, views, and confidence all affect how we feel about technology and how we include it in our decisions.

Q20 - What is your age in years at your last birthday?

Q21 - What is the postcode of your current residence?

Q22 - What is your gender?

○ Prefer not to say

Q23 - What is your current employment status?

○ Employed full time

○ Employed part time

○ Casually employed

○ Self-employed

○ Unemployed, looking for work

○ Unemployed, not looking for work

○ Retired

Q24 - Please identify how important each of the following topics are to you:

	Extremely important	Very important	Moderately important	Slightly important	Not at all important
Fitness and wellbeing	○	○	○	○	○
Environmental conservation	○	○	○	○	○
Leisure time	○	○	○	○	○

Q25 - Are you a property owner that is required to pay for rates and utilities?

○ Yes

○ No

Q26 - How comfortable are you using computers and internet-related technologies?

○ Extremely comfortable

○ Somewhat comfortable

○ Neither comfortable nor uncomfortable

○ Somewhat uncomfortable

○ Extremely uncomfortable

Q27 - How often do you use smartphone applications (apps) per week?

- ○ More than once per day
- ○ Once per day
- ○ Once per week
- ○ Once per month
- ○ Less than once per month
- ○ Never

Thank you for completing the survey.

Your responses will be used to evaluate public interest in supporting smart streetlight projects and using the services that it could offer.