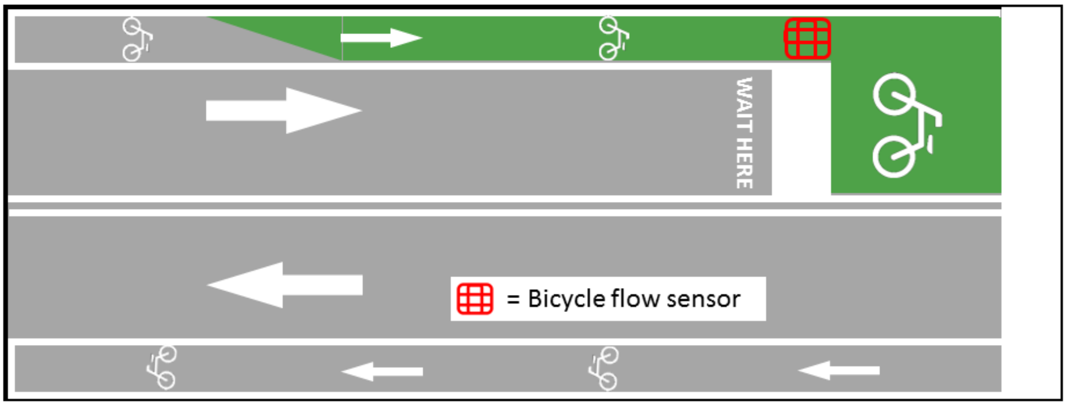

Thomas Larkin - u5561939

Improving the safety of and awareness towards cycling commuters on Canberra's roads

ENGN2226 Systems Engineering Analysis Individual Research Portfolio

Executive Summary

A comprehensive analysis involving qualitative and quantitative data was initially undertaken to examine the attitudes between motorists and commuter cyclists in Canberra. Intersections within the some of the central Canberra suburbs were identified as the most problematic road sections on which the greatest number of motorist-cyclist collisions per year occurs. A thorough analysis into additional infrastructure within intersections to improve the safety of commuter cyclists was then examined, with a particular emphasis on human design factors. Options such as improved bicycle lane visibility, wider bicycle lanes and bicycle boxes were initially considered in isolation. Through subsequent utilisation of systems engineering tools including time, materials, energy and cost factors analysis, a final design solution consisting of a bicycle boxes and traffic light bicycle sensors was selected and continuously refined. This design solution has the advantage of directly improving commuter cyclist safety but also in raising the awareness of commuter cyclists through bicycle boxes, which improves the visibility of cyclists stopped at intersections.

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1.0 Motivation

As the price of fuel increases and automobile congestion within cities becomes a more prominent issue, alternative means of commuting transport are becoming a necessity. Cycling offers one of the best alternative commuting options, providing a cheap and relatively quick mode of transport which also includes added health benefits. Despite these advantages of commuting by bicycle, a majority of people prefer to commute by car as it is much faster, more convenient and statistically, is much safer. This is because when cyclist-motorist crashes occur, a large percentage of these result in serious injury or death, and this inherent lack of safety when cycling on-roads can make this mode of transport quite unappealing (Watson & Cameron, 2006). Current research has indicated that 'safety' and 'route continuity' are the two primary factors influencing a person's tendency to commute by bicycle (Pikoraa, et al., 2003). Considering all types of road users, the Australian National Road Safety Strategy has set a target to reduce the number of serious injuries and deaths on all roads by 2020 by 30 percent, and 'improving cyclist safety' has been identified as a means of achieving this reduction (Ausralian Transport Council, 2011).

Within Canberra, often the most direct cycling routes that allow traffic flow at higher speeds are on arterial roadways (R.D Gossip Consulting Engineers; McCann Property & Planning, 2005). The fact that on arterial roadways, cyclists are not physically segregated from motorists and that there can be large speed differences between these two road users means that arterial roadways are usually the least safe areas to commute. Pedal cyclists within Canberra, when compared to national rates, are nearly twice as likely to sustain a serious injury as a result as a road vehicle accident (ACT Territory and Municipal Services, 2014). Improving both the safety of and awareness towards commuter cyclists on Canberra's arterial roads will aim to prevent further accidents and ideally, encourage more people to adopt this transport alternative. With a target on commuter cyclists, this report will focus much of the analysis and outcomes on the behaviour of cyclists during peak morning and evening traffic times (7:30 am-9:00 am and 4:30 pm – 6:30 pm respectively). This portfolio has been undertaken by way of first examining the commuter cyclist system through different lenses, particularly from a human factors, time factors and materials factors perspective. Each of the relevant tools pertaining to these lenses have been applied and, where appropriate, modified to suit the requirements of this report.

2.0 Qualitative and Quantitative Factors

2.1 Gathering Data

The research question which this portfolio seeks to address is 'Improving the safety of and awareness towards cycling commuters on Canberra's roads.' Since this research question pertains towards two distinct parties, cycling commuters and motorists, it is necessary to consider two classes of survey questions that will address these two parties. Amongst these two parties 'improving safety' is a primary consideration for the former and 'improving awareness towards cyclists' is a primary consideration for the latter. Five survey questions were posed to surveyee's in the form of an anonymous online questionnaire and these questions and associated raw data is shown in Annex A figure A1 and table A2. The sample size of the survey was 25 respondents. A selection of some of the survey results are indicated below in figure 1.

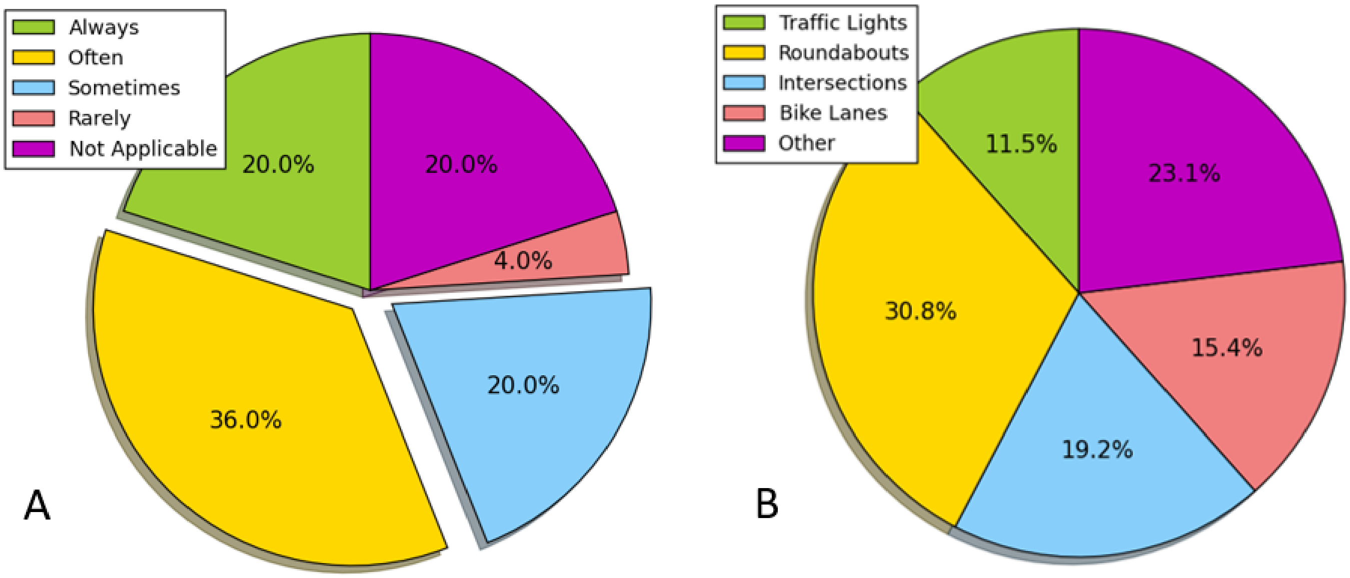

Figure 1: (A) Responses to the question 'How Strictly do you follow road rules whilst commuting by bicycle?' (B) Responses to the question 'What aspect of Canberra's roads do you think need the most improvement to best integrate commuters and road users?'

It should be noted that within figure 1A, 'Not Applicable' was the selection given by those surveyants who indicated that they did not commute by bicycle at least once per week. Likewise in figure 1B, the 'other' category contained responses which were less infrastructure based and more along the lines of 'improving motorist knowledge of cyclist's rights on the road' and 'enforcing tougher road rules for those motorists who drive dangerously around cyclists'. Finally within this survey, 63 % of those questioned responded 'Yes' to the question 'Has the presence of cyclists on Canberra's roads ever bothered you?'

2.2 Data Analysis

The results of this survey appear to highlight some key points, allowing a suitable problem scope for this portfolio to be detailed. Firstly, cycling commuters in Canberra are reasonably compliant with road rules. Whilst this survey was deliberately ambiguous as to exactly what road rules surveyants were breaking (figure 1A), to encourage honest responses, triangulation of this data with similar research and user knowledge suggests that offences such as cycling through red lights and stop signs are the most common cyclist infringements (Johnson, et al., 2011) (Johnson, et al., 2008). This would serve to explain why both traffic lights and intersections (which in Canberra, generally contain traffic lights) represent a large percentage of the road features which respondents stated as needing the most improvement (figure 1B). To triangulate this user response with an additional data source, ACT bicycle crash statistics collected between a four year period cite 51% of all deaths involving cyclists and motorists as occurring within intersections (Whately, 1985). The survey also indicated that 63 % of motorists were bothered by the presence of cyclists on the roads and previous research has indicated that disobeying traffic signals is the type of cyclist behaviour which most annoys motorists (Fincham, 2006).

2.3 System Scoping

Although roundabouts were identified as the road feature within Canberra which required the most improvement in order to best integrate cyclists and motorists (figure 1B), trying to implement changes within a roundabout system would most likely require substantial modifications to the infrastructure. From an economic perspective, this is unviable since Canberra contains a large number of roundabouts. Likewise, whilst the results obtained within this portfolio may suggest that roundabouts are in need of improvement, the greatest number of cyclist and motorist collisions within Canberra occur at intersections (Court & Strang, 2010). From user experience, whilst roundabouts are tricky to commute through on a bicycle, the lower speeds and reduced vehicle flow density within roundabouts means that cyclist and motorist collisions are easier to avoid than within intersections. Likewise the prevalence of roundabouts within Canberra means that most road users understand relevant road rules within these road features. Consequently, intersections within Canberra will be defined as the primary system of interest within this portfolio. Table 1 below indicates the relevant endogenous, endogenous and excluded factors to consider within this system.

Table 1: System Scoping for the intersection with on-road bicycle lanes

Endogenous (inside the system boundary)	**Exogenous (likely inputs into the system)**	**Excluded (excluded from the system consideration)**
Width of the bicycle lane Bicycle lane signage Bicycle lane colouring Entry and exit to bicycle lanes within intersection Traffic light sensors Bicycle type	Brightness and visibility of the cyclist towards motorists Median strips Pedestrian crossings within intersection	Physicality/cardiovascular fitness of the cyclist Weather conditions during the time of commuting Demographics of cyclist

'Bicycle type' has been included as an endogenous system consideration. This was deemed as a relevant internal consideration as various components of the bicycle such as the brake pad wear, tire wear and bicycle handlebar width can influence how the bicycle handles and consequently, how safe it is to ride on-roads.

2.4 Further refining the scope of the portfolio through Quantitative Data analysis

With the road feature of 'Intersections' having been identified as the target area for improvement within this portfolio, it is necessary to consider further refinement of the system scope through analysis of relevant quantitative data.

As sourced from the *Australian Capital Territory's Chief Health Officer's report 2014,* of all crashes involving vehicles and cyclists in 2012, 15% occurred in the CBD, 12% in Turner and 10% in Braddon. This data is useful as it highlights a concentrated area where a large portion (39%) of all accidents occur (ACT Territory and Municipal Services, 2014). A potential source of error from this data, however, is the fact that it represents areas where cyclists and road users (commuting to work in the CBD) congregate. This is indicative that congestion, rather than physical road factors were the cause of this large percentage of accidents. By observation, the quantitative data contained within the *Australian Capital Territory's Chief Health Officer's report* is taken from primary sources including the Bureau of Statistics National Mortality Database and the ACT Emergency Department Information System, thus the data presented by the document can be considered very reputable. Based on this observation of the area within which many cyclist-motorist crashed occur, this portfolio will examine ways in which to better integrate cyclists and motorists within intersections in Canberra's Inner North. By the definition adopted within this project, this will consist of the suburbs of Braddon, Acton, Ainslie, Turner, O'Conner, Hackett and Reid.

3.0 Human and Time Factors

Facilitating better integration between cyclists and motorists within intersections around Canberra's Inner North could revolve around improving the current infrastructure, with an emphasis on human usability. Design alternatives examined below will be broadly classified as either modifications of existing infrastructure or implementation of new infrastructure.

3.1 Modifications to Existing Infrastructure

3. 1. 1 Widening of Bicycle Lanes within Intersections

The width of bicycle lanes in the road sections surrounding intersections can influence both the usability and safety of these road features. The *ACT Design Standards for Urban Infrastructure* (Territory and Municipal Services, 2007) cites a series of minimum bicycle lane widths which vary depending on both the type of road and the speed environment of the road. Aspects such as the road geometry, road surface and gutter width are listed as primary considerations when ascertaining the appropriate width of a cycle lane. Design standards for arterial roads are listed, however, with the document noting that cycle lanes constructed in areas with 60km/h and 80km/h speed limits should have cycle lanes with minimum widths of 1.2 and 1.8m respectively. Taking anthropometric data from data for an average male and female (National Aeronautics and Space Administration, 2008), the mean sitting hip breadths are 38.4 and 33.7 cm respectively. Data for sitting hip breadths have been chosen as this data best replicates the hip breadth of a cyclist sitting in a saddle. Examining a selection of popular handlebars amongst cyclists reveals that the average handlebar width for road drop-down style bars is 42.8 cm and for flat mountain bike style handlebars is 77.2 cm (Chain Reaction Cycles, 2015). Commuter bike style handlebars include both drop-down and flat handlebars and the average width of such handlebars is expected to fall within the range indicated. With the average handlebar width for both handlebar types sitting greater than the average sitting hip breadth for both males and females, it is clear that analysis involving on-road bicycle lane widths should consider the case of the theoretical widest occupant, that being a commuter on a mountain bike.

Reducing the lateral distance between on-road cyclists and motor vehicles can impose turbulent forces on cyclists, with previous analysis having shown that motor vehicles passing cyclists 0.9 m away at 72km/h can exert forces of up to 16.7 Newtons of lateral force (Federal Highway Administration, 1975). Although these forces are generally not large enough to knock cyclists off their bicycles, the fact that they are uncontrollable and largely unpredictable can impose anxiety and stress towards commuter cyclists. Recently, the ACT government has investigated the possibility of implementing new laws, which will require motorists to observe a minimum 1 metre overtaking width when driving past on-road cyclists (Sansom, 2015). In order to ascertain if current bicycle lanes entering into and exiting out of intersections are wide enough to allow for the proposed overtaking width law, a brief geometric analysis will be conducted (figure 2) using theoretical maximum widths of cyclists and vehicles. The value for the maximum vehicle width has been sourced from *Lane Widths on Urban Roads, 2010* (Bicycle Network, 2010).

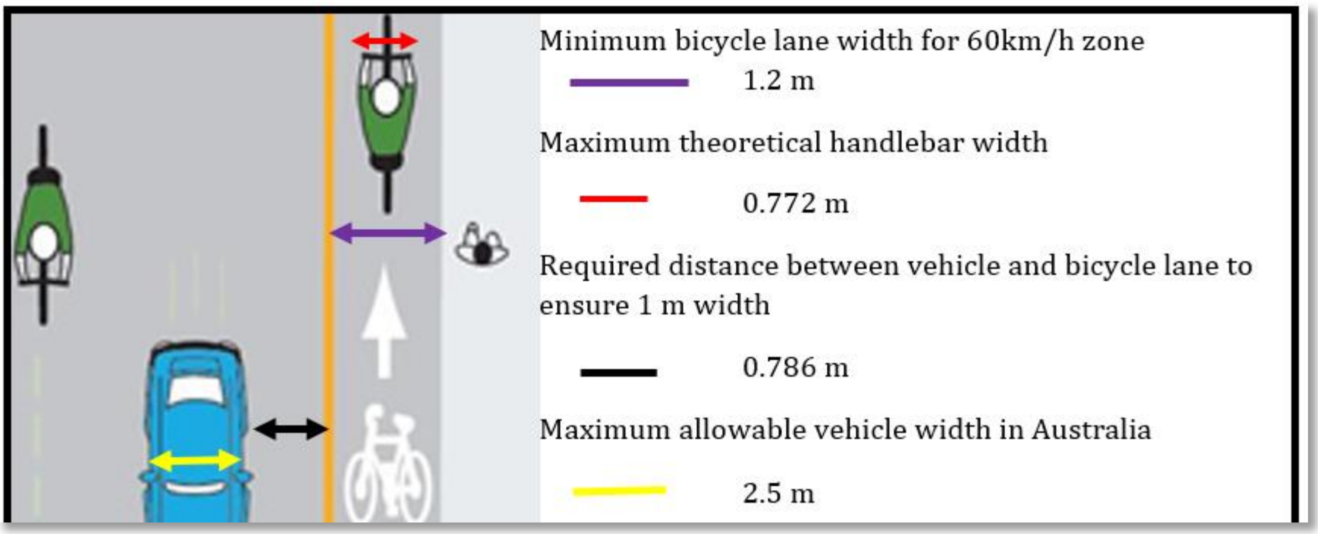

Figure 2- Examining dimensions for bicycle lane width using theoretical maximum values for bicycle width and theoretical minimum values for passing distance and bicycle lane width. Original image sourced from Google Images

If the road width in figure 2 adhered to the Urban Design standards within the ACT thus having a width of 3.5 m (Department of Territory and Municipal Services, n.d.), a vehicle with the theoretical maximum width of 2.5 m would be able to a pass a cyclist riding centred in the on-road bicycle lane whilst giving them the required 1 m of safe clearance without encroaching into either the adjacent motorist lane or bicycle lane. This is because from figure 2, 0.786 + 2.5 = 3.286 m which is slightly less than the road width standard of 3.5 m. The important outcome of this analysis is that it indicated that a potential infrastructure based design alternative would not depend on widening the road beyond the curb. Rather, a design alternative could involve slightly widening the bicycle lanes by between 0.2 – 0.4 m, dependent on the existing road width. This widening could serve to provide further separation between cyclists and motorists, and could be coupled with a physical barrier such as elevated concrete or plastic markings. The implementation of physical barriers to separate bicycle lanes and roads has shown to improve the safety of cyclists using these lanes and for motorists, clearer visual delineation is provided (Cohen, 2013).

3. 1. 2 Bicycle Lane Colouring within Intersections

The human experience of both cyclists and motorists within intersections could be enhanced by the addition of clearly marked and coloured bicycle lanes. Various colours such as blue, green, red and yellow have been used to classify on-road bicycle lanes and are utilised to ensure that motorists pay more attention when driving near these road features. At present, the colour green has been adopted nationally to indicate cycle facilities on roads and pavements (Department of Territory and Municipal Services, 2007). It is not used on all bicycle lanes, rather, only those on which there is a high risk of collision between motorists and cyclists including high speed zones, high volume traffic zones and areas where cycle lanes and vehicle lanes cross. This is because the installation and maintenance of green markings on cycle lanes is expensive and over utilisation of such coloured markings can render them ineffective as a cautionary device towards motorists (Department of Territory and Municipal Services, 2007). Previous research into the use of coloured bicycle lanes within intersections has shown that there exists an optimum number of marked lanes in any direction. It has been found that with between two to four coloured bicycle lane marking crossings in an intersections, cyclists become complacent when scanning for surrounding traffic whilst motorists focus too heavily on the bicycle lanes and disregard traffic signals (Jensen, 2008). Ideally, the use of one coloured bicycle lane within an intersection could provide the necessary visual warning for motorists without them having to sacrifice too much traffic signal perception. The use of one coloured bicycle lane is also much cheaper to install and maintain than multiple. Adopting this design alternative, however, would require thorough analysis of the directions within intersections that experience the greatest cyclist traffic flow, in order to decide upon a direction on which to implement a coloured bicycle lane. From user experience, many of the major intersections in Canberra's Inner North are situated along Northbourne Avenue, which generally experiences relatively even flows of traffic in both main directions. This means that selecting the most accident-likely direction on which to implement a coloured bicycle lane could be quite difficult.

3. 2 Implementation of New Infrastructure

3. 2. 1 Bicycle Boxes

Bicycle boxes are a type of road making which are commonly employed in conjunction with bicycle lanes within intersections. They are used to allow cyclists to bypass traffic and move to the front of intersection queues, which in turn allows their movements to be clearly visible to motorists once traffic flow resumes (Dill, et al., 2010). Bicycle boxes are most advantageous in preventing collisions where cars are turning left and bicycles are moving straight (Puente, 2010), and from user experience and observation, this collision type is very common within Canberra. Examples of some typical bicycle box designs are shown below in figure 3.

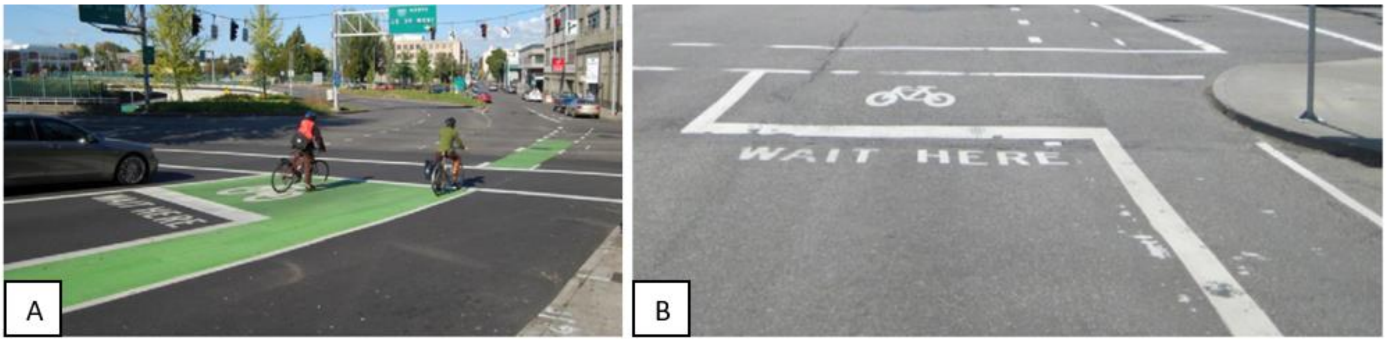

Figure 3- (A) A coloured bicycle box at an intersection and (B) a non-coloured bicycle box at an intersection. Note: Traffic flows on the right hand side of the road in both images. (Dill, et al., 2010)

With the perception of safety at intersections being enhanced through the employment of bicycle boxes, such additional infrastructure could enhance the user experience of the commuter cyclist in Canberra but for the motorist, who would have to adjust to a new road feature and experience longer waiting times within intersections (Section 3.3.1), the user experience may be diminished.

3. 2. 2 Bicycle Traffic Light sensors

A final consideration of a new road feature within intersections that could improve commuter cyclist safety is traffic light sensors which detect bicycles. Previous research into the red-light infringement behaviour of Australian cyclists has shown that 'traffic sensor did not detect bicycle' is the second most common reason for cyclists riding through red traffic signals, with 24.2% of all infringements within the study being attributed towards this (the most common reason was for cyclists turning left at an intersection on a red signal) (Johnson, et al., 2008). Similarly, research conducted overseas has shown that a majority of bicycle red-light infringements occurred after the cyclist has stopped at the intersection and waited for periods longer than 30 s, before becoming impatient and crossing during a gap in traffic flow (Pai & Jou, 2014). Aside from this behaviour being law-breaking, red-light non-compliance is likely to both reduce the confidence of motorists when interacting with cyclists and increase the perceptibility of cyclists towards motorists as being unpredictable (Johnson, et al., 2011). It is expected that instances of cyclists crossing during a red signal due to their bicycle not being detected by traffic sensors or crossing due to impatience has the potential to decrease if the aforementioned infrastructure was employed within intersections.

3. 3 Effect on queue times at intersections due to new infrastructure

3. 3. 1 Program Evaluation and Review Technique (PERT) analysis for a bicycle box at an intersection

In order to examine the temporal flow within a modified intersection consisting of a bicycle box, a PERT chart was constructed to illustrate the interrelationships between different events. This PERT chart is shown below in figure 4.

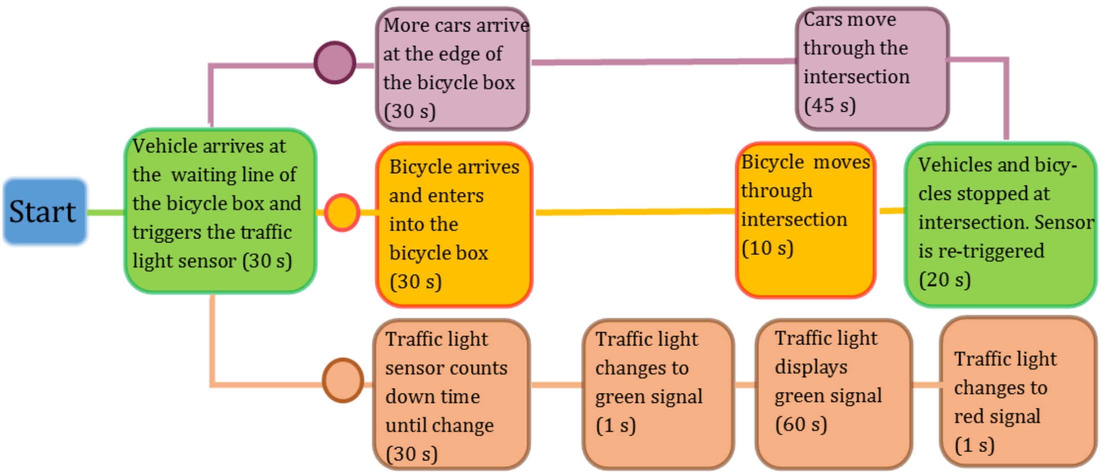

Figure 4: PERT Chart for the bicycle box implementation at an intersection

The most important time factor within the bicycle box implementation which the PERT chart encapsulates is the fact that during the operation of a bicycle box, most of the events occur independently of eachother. Aside from the initial period where both cars and bicycles are entering into and waiting at the entrance to the intersection, the fundamental operating principal of the bicycle box is that it allows bicycles to travel through the intersection prior to motor vehicles. Timewise, this is disadvantageous for motorists, as they are left with less time to travel through the intersecton.

Evidently, the critical path of the traffic light system with a bicycle box as seen in figure 4 is the maroon coloured path. Optimizing the green signal time length, given arbitrartily as 60 seconds in the PERT Chart, is necessary in order to reduce queuing times at all entrances to the intersection. This can be acthieved through the use of adaptive traffic light technology, explained further in section 5.0. Clearly, however, the primary limitation of the bicycle box system is that the speed and volume of the cyclists moving through the intersection is inversely proportional to the speed and volume of vehicles moving through the intersection. Hypothetically, if the cyclists were to take longer than the stipulated 10 seconds to move through the intersection, motor vehicle traffic could be significantly delayed. This could result in an increased number of motorists speeding through the intersection to compensate for the additional waiting times, and could further invoke tensions between cyclists and motorists. A thorough understanding of the feasibility of increased waiting times at intersections is necessary to decide upon the validity of bicycle box implementation at major intersections within Canberra's Inner North.

3. 3. 2 Queue Theory applied to major intersections in Canberra's Inner North

In order to examine the time based impact of introducing bicycle boxes within some of the major intersections within Canberra's Inner North, current average queue times should be examined. Renowned systems analyst, Donella Meadows cited 'delays' as one of the 'twelve leverage points to intervene within a system,' meaning that small changes to the delay of objects within a system can result in much larger behavioural changes within that system (Meadows, 2009). Delays are an inherent component of traffic lights within intersections but to extend upon Meadows' concept, any changes to the current delay times within intersections as a result of bicycle box implementation should be minimised to best reduce the likelihood of more pronounced system implications over time. Changing the average waiting time at traffic lights at major intersections within Canberra could result in longer vehicle commuting times, increased congestion about intersections during peak hour and potentially greater instances of motorists driving unlawfully to account for lost time. In order to quantify the waiting times associated with bicycle box implementation, queue theory will be employed.

For a motorist during peak hour, based on prior user experience, red light queues can be considered as over-saturated traffic conditions, defined as those whereby queues are established during red phases and not necessarily terminated during green phases of the traffic light (Anon., n.d.). Under such conditions, the average waiting time ($\overline{W}$) for a vehicle is defined by the following equation (Teodorovic & Trani, 2005):

$$\overline{W} = \frac{r^2}{2c(1-\rho)} \qquad (1)$$

Where $\overline{W}$ is the average service time in seconds and $c = r + g$ with c the total cycle time (seconds), r the total red light time (seconds) and g the total green light time (seconds). The variable $\rho = \frac{\lambda}{\mu}$ where μ = the service rate (average number of vehicles passing through the green signal per unit time); λ = the average number of arrivals per unit time when the traffic signal is green. In order to utilise this equation within this research project, certain major intersections commonly used by commuters in the Inner North of Canberra were analysed and the appropriate data pertaining to equation (1) was obtained.

This data is shown in annex B table B1. In order to minimise discrepancies within this data collection process, the following measures were implemented:

- All data was gathered during the estimated peak traffic period between 4:30 pm and 6:30 pm.
- All data was gathered for vehicles travelling through traffic lights facing along Northbourne Avenue. Traffic flowing in both directions of Northbourne Avenue was analysed.
- Total red light time, r, was timed between the point when the light changed red until the moment the light changed back to green. Similarly, the total green light time was commenced once the light changed green and completed when the light turned from amber to red.

Despite these controlled methods, there was inherent error present within the data collection process. Since the data collection was conducted manually using a stopwatch, often when large volumes of traffic were flowing through the intersection or stopped at the intersection, it was difficult to accurately count each vehicle. This could have been alleviated through the use of video based data collection, which has previously shown to be very effective is modelling traffic flow by (Johnson, et al., 2011) and (Kovacs & Homlok, 2010), but due to cost and privacy based constraints, manual data collection proved the most feasible.

From the analysis of data, it was found that r = 69.64 seconds, g = 55.6 seconds, λ = 15.2 vehicles/minute and μ = 33.8 vehicles/minute. Substituting these values into equation (1) it is found that the average delay time for motor vehicles on selected intersections on Northbourne Avenue is;

$$\overline{W} = \frac{69.64^2}{2(69.64 + 55.6)(1 - \frac{15.2}{33.8})} = 35.18\ seconds$$

For a revised system consisting of a bicycle box within built-in bicycle detectors and assuming that the cyclists using the technology take approximately 10 seconds to clear through the intersection (allowing cars to flow through the intersection), the queue theory analysis can be revised using the new g value of 45.6 s (based on a 10 second reduction in the amount of time a motorist will have to move through the intersection).

$$\overline{W} = \frac{69.64^2}{2(69.64 + 45.6)(1 - \frac{15.2}{33.8})} = 38.2\ seconds$$

To further demonstrate how the average waiting time, $\overline{W}$, changes as a function of service rate of vehicles, μ a plot between these two parameters is shown below in figure 5.

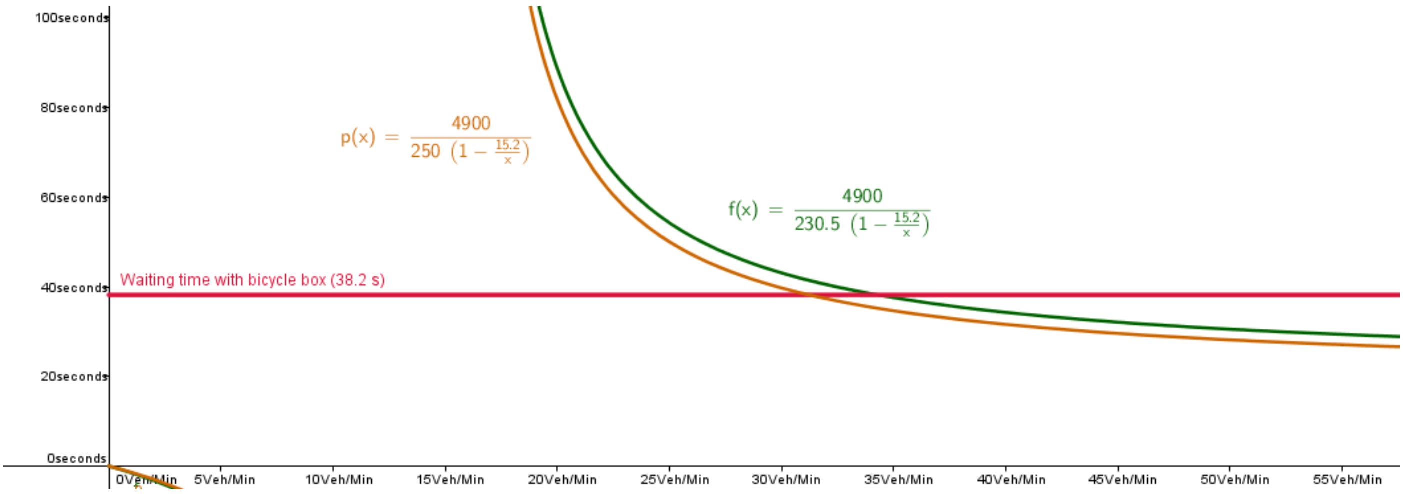

Figure 5: Waiting time (y-axis, in seconds) as a function of vehicle service rate (x-axis, in vehicles per minute) for the system without the bicycle box (orange curve) and the system with the bicycle box (green curve)

As illustrated by figure 5, when the vehicle service rate is less than approximately 20 vehicles/minute or greater than approximately 40 vehicles per minute, the additional 3 seconds of waiting time incurred due to bicycle boxes has a very minimal influence on $\overline{W}$. This is because at such vehicle service rate extremities, the average waiting time displays either an exponential increase or decrease and the gaps between the orange and green curves shown in figure 5, representative of the waiting time, decrease. Clearly, the additional waiting time imposed by the bicycle boxes has the greatest influence on $\overline{W}$ when the vehicle flow rate is between 23-33 vehicles/minute, a range just below the average vehicle service rate observed during peak hour within Canberra.

A means of best mitigating this additional waiting time could be through the combining two of the design alternatives outlined previously, that is, through the implementation of traffic light sensors for bicycles within bicycle boxes. If an adaptive traffic light technology, which varied the traffic signal lengths based on cyclist in-flows into the bicycle box, was employed in conjunction the bicycle box system, there is the potential that additional waiting times could be minimised alongside an improvement in cyclist safety. Bicycle-specific traffic light sensors could be placed at the cycle-lane entry into the bicycle box as shown below in figure 6, thus accounting to all cyclists who cycle into the bicycle box from the on-road lane.

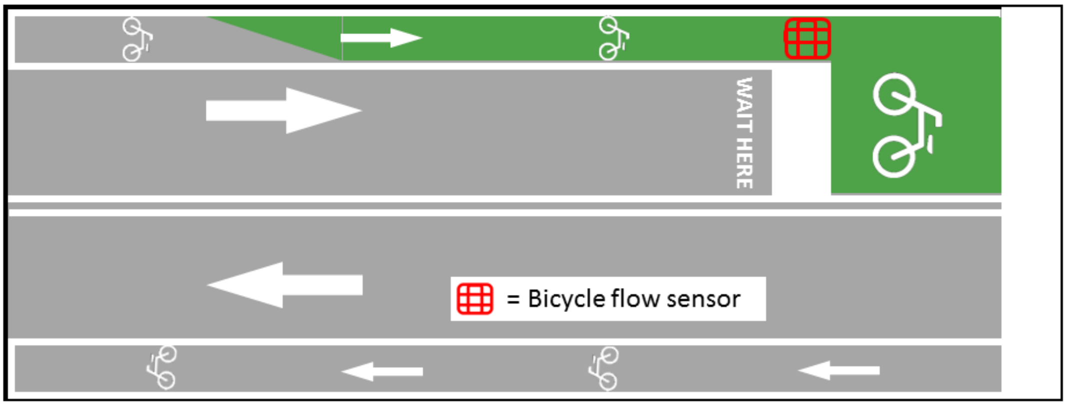

Figure 6: Proposed design alternative, combining a bicycle box with bicycle flow sensors

To extend upon this idea of a bicycle flow sensor, illustrated in figure 6, a concept generation tree was constructed (Annex E, figure E1) and from this, a variety of possible bicycle detection methods became apparent. To minimize the costs and impact on the surrounding intersection based infrastructure, below-road detection based technologies were considered to be the most feasible. Due to the fact that current car detecting sensors utilise inductive loop sensors, this was the detection type chosen for use within the design solution.

3.3.3 Case Study 1- Bicycle box implementation in Portland, United States

Before and after studies of bicycle boxes at signalized intersections was conducted in Portland, a city with a comparable population to that of Canberra (583,000 to 381,000) (UN Data, 2015). In this study, nine green coloured bicycle boxes and three non-coloured bicycle boxes were installed with thermoplastic marking the preferred choice of road marker. In a survey conducted after the bicycle boxes had been installed, 42% of motorists felt that the bicycle boxes made driving through the intersection safer and 77% of cyclists felt safer riding through intersections with bicycle boxes (Dill, et al., 2010). This study also concluded that both motorists and cyclists more frequently used the coloured bicycle boxes for their intended purpose.

3.3. 4 Case Study 2- Bicycle box implementation in Christchurch, New Zealand

With a population of 362,000, quite comparable to that of Canberra's 381,000, the city of Christchurch also represents a similar city to examine bicycle box success within (UN Data, 2015). A three year study was conducted in Christchurch to determine the effects towards cyclists and motorists after the implementation of non-coloured bicycle boxes within the majority intersections within this city. Over the three year study period, reductions in cyclist and vehicle collisions were found to decrease, although motorists surveyed stated that they did not like the fact that cyclists were allowed to queue ahead of them at intersections (Newman, 2002). The success of bicycle boxes in Christchurch towards reducing collisions indicates that similar success could be observed if these road features were implemented in a demographically similar city like Canberra.

3. 3. 5 The Proposed Design Solution

Based on the outcomes of the human and time factors analysis, it is decided that a design solution consisting of a coloured bicycle box with a built in inductive loop bicycle flow detector will offer the best solution towards the problem of improving cycling commuter safety. The effectiveness of bicycle boxes at existing intersections in other countries towards improving the safety of commuter cyclists warrants this design alternative for further examination within Canberra.

4.0 Material and Energy Factors

4.1 Energy Mass Flow Map analysis

In order to analyse the energy and mass flows within the proposed design solution, an Energy-Mass flow map was constructed and is shown below in figure 7. This approach is beneficial in determining where energy is inputted, outputted and lost and can assist in making the system more energy efficient (Department of Resources, Energy and Tourism, 2010).

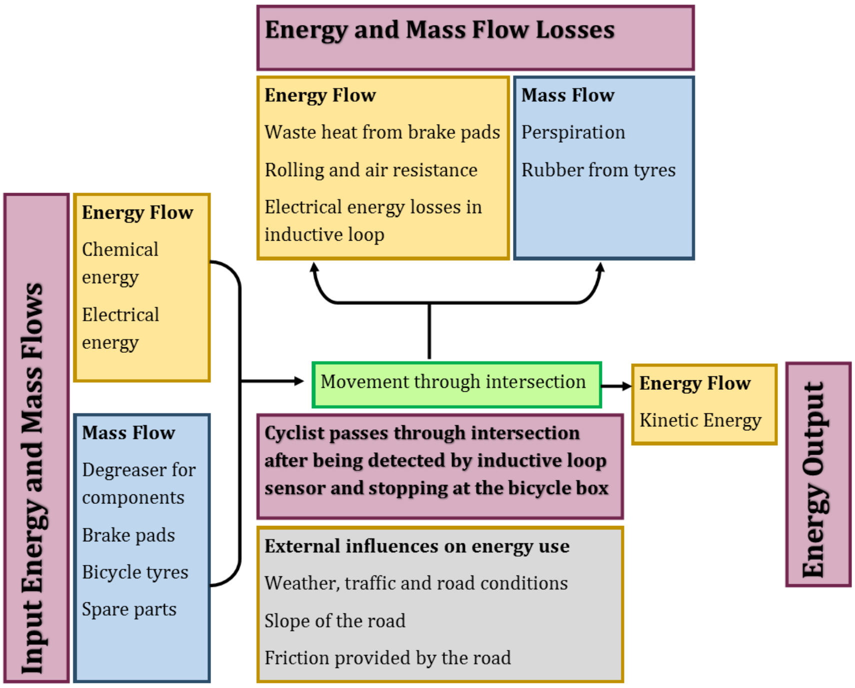

Figure 6: Energy Mass Flow Map for the System consisting of a bicycle box with build in inductive loop sensor at an intersection

By examining this Energy-Mass Flow map, it is evident that unless the commuter cyclist was using an electric bicycle, all of the energy and mass inflows are fixed. Although there are multiple mass inflows to consider, each of these would only be required to input to the bicycle every few months as part of bicycle maintenance and would not impose a significant cost to the user. Likewise, in terms of energy flow losses, significantly reducing both the rolling resistance and air resistance is difficult. This is because it is mostly external factors such as the slope of the road and friction provided by the road which influence the rolling resistance, in addition to tyre pressure which is determined by the cyclist.

One energy outflow which can be reduced is the waste heat generated by the braking subsystem of the bicycle.

The thermal energy produced when decelerating on a bicycle as a result of braking can be quite substantial, with studies having shown that an 80kg rider and bicycle system can generate 2.68 kJ of heat when slowing gradually from 32km/h to 16km/h (Bloomfield, 1999). Consequently, design measures should be employed within the bicycle box system to ensure heavy braking is minimized. Once possible way to minimize this is to only implement bicycle boxes within intersections that are flat or slightly sloping uphill in the direction of traffic flow. Within flat intersections, it is assumed that cyclists will not require to apply their brakes when accelerating from a stationary position in the bicycle box towards the exit of the intersection with the same argument applying for uphill sloping intersections. Furthermore, the fact that the bicycle box is positioned at the entrance to intersections means that unexpected braking as a result of sudden car movements in front of cyclists will be eliminated.

4.2 Materials Audit and end-of-life considerations

Since this design project is concerned with implementing bicycle boxes into a series of major intersections in Canberra's Inner North, the primary materials based considerations surround the choice of road marking material. As observed within the case study listed in section 3.3.3, coloured bicycle boxes implemented in Portland were found to be used more for their intended purpose than non-coloured ones, therefore the total surface area which any road marking material will be required to cover for the installation of one bicycle box will include both while edge markings and larger coloured sections. This total surface area was calculated to be 53.5m^2, taking into account a typical bicycle box depth of 5m, a width spanning the width of one 3.5m vehicle lane and a 30 m coloured bicycle lane 'run-in' of a width of 1.2m (Wall, et al., 2003). The values for bicycle lane width and road width have been previously outlined and justified in section 3.1.1. A schematic indicating these dimensions is shown in annex F figure F1. Before factors such as the cost, longevity and lifespan of the road marking material can be examined, a materials audit will be conducted below in table 2 to examine the impact of different coating methods.

Table 2: Materials Audit for road surface marking materials

Road Marking Type	**Material**	**Mass (using a mass of 10kg of road marking material)**	**Embodied Energy (EE) (MJ/kg)**	**Actual EE (MJ)**
Paint (dispersions) (Pirotta, et al., 2000)	Primal E-2706	24%	-	-
	Titanium dioxide	13.1%	65	650
	Calcium Carbonate	40%	0.85	8.5
	Silica	14.6%	230	2300
	Additives	8.3%	-	-
Thermoplastic road marking (Greer & Askjaer, 2012)	Resin (thermoplastic polyurethane)	25%	-	-
	Pigment (titanium dioxide and lead chromate)	5%	65, -	650, -
	Filler (calcium carbonate, glass beads, silica)	70%	0.85, 15, 230	8.5, 150, 2300
Road line marking tape (May, 1987)	Silicone rubber	50%	120	1200
	Fibreglass	20%	28	280
	Unknown materials	25%	-	-
	Glass beads	5%	15	150

Unfortunately, due to the very specific nature of many of the components that make up road marking mixtures, the EE of certain constituents was not able to be determined. Notwithstanding, the data presented in table 1 gives a good indicator of which road marking materials, cumulatively, will have the least embodied energy. From this observation, it appears as though road marking tape will present the optimum material choice based on embodied energy for use as a road marker for the bicycle box however further examination of the application techniques, typical usage and end-of-life considerations will need to be undertaken before a design recommendation for road marking material type is made.

Solvent based paints require the right weather conditions when they are applied to a road (moderate temperatures, no rain) and also require a few days to dry, meaning that roads being treated with such paints need to be cordoned-off during the treating process (Department of Transport and Main Roads, 2013). Also, solvent based paints are prone to fading over time, sometimes in as little as three months with factors such as high traffic flow accelerating this process (Witt, et al., 2000). Due to this, solvent based paints need to be continually reapplied.

Thermoplastics have the major advantage of having a very quick drying time, in the range of minutes after being initially heated and set into place, meaning that disruption to traffic when applying thermoplastic road markings is minimal (Witt, et al., 2000). Thermoplastics also contain no volatile organic compounds, meaning that removal and disposal of these road marking types is straightforward (Department of Transport and Main Roads, 2013). Thermoplastic road marking can be removed through a water blasting process, a method by which highly pressurized water is directed at the road tape in order to disintegrate the tape from the road surface (Avante Linemarking, 2015). This process has the advantage of being both cheap and it offers minimal erosive effects on the underlying asphalt.

Road tape marking materials are advantageous in their durability and ease of application on roads. This road marking alternative is quite expensive, however, up to twenty times the cost of applying solvent based paints over the same area (Witt, et al., 2000).

Based on this analysis of three different road marking material types, despite its relatively high embodied energy, the fact that it poses minimal disruption to surrounding road areas, has the longest lifespan and a minimal environmental impact, thermoplastic tapes will be used as the road marking material for the bicycle boxes.

5.0 Dynamics and Control

One of the most prevalent control systems present within this system is the adaptive traffic light control system. Adaptive traffic lights (ATL's) are able to analyse traffic flow in real time and compute appropriate green signal lengths based on this analysis (Fernando, et al., 2013). Consequently, ATL technology is utilised in busy intersections in order to reduce waiting times and increase the flow of traffic. One of the most prevalent forms of ATL's currently at use within Canberra is the Sydney Coordinated Adaptive Traffic System (SCATS), with 306 signalised intersections employing this technology (Territory and Municipal Services, 2015). The SCATS technology is explained below with the aid of a dynamic control system diagram in figure 7.

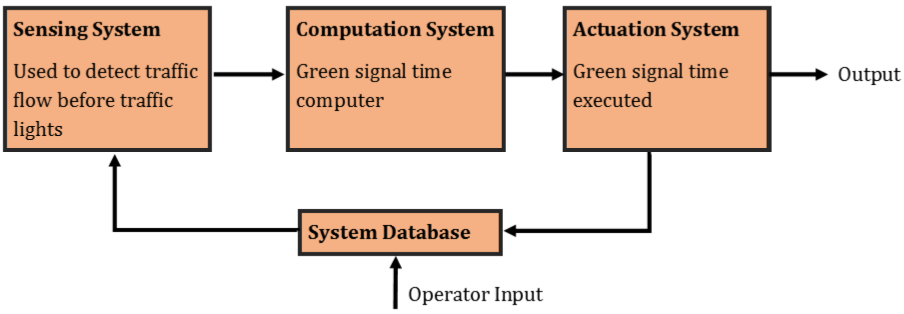

Figure 7: Basic Dynamic Control system showing typical SCATS operation

The simplified SCATS control loop as shown in figure 7 clearly indicates the three basic elements of sensing, computation and actuation. The computation system within the SCATS control loop is the most sophisticated component of this technology as it relies on past system behaviour as stored within the system database. This data is generally very recent (in the matter of minutes), allowing constant automated calibration of the traffic signals (Sims & Dobinson, 1980). Although the actual location of the ACT's 306 signalized intersections employing SCATS technology is unknown, judging from the significant variation in red and green light signal times obtained through manual intersections analysis along Northbourne Avenue, (Annex B, table B1), it is likely that the three different intersections examined all employed this technology.

Whilst SCATS technology has proved to be very effective in optimizing traffic flow through busy intersections, presently, it is not designed to detect or factor in flows of cyclists. The inductive loop sensing technology commonly employed by traffic light sensors is designed to detect large metallic bodies, meaning that bicycles are usually not detected. A method of modifying the inductive loops in order to detect bicycle is quite straightforward, with smaller inductive loops providing a simple, cost-effective solution (Goodridge, n.d.). Such inductive loops have been implemented successfully in areas of Sydney and the next step is in developing a feedback loop computation system with a focus on bicycles. Since cyclists would be travelling on average slower than vehicles, the computation system within SCATS could be improved to differentiate between cyclists and motorists. Ideally, this modified SCATS technology would account for cyclists travelling at high speeds approaching intersections by allowing extra time on the green signal to prevent these cyclists from either running red lights through the intersections or trying to brake suddenly at high speeds in narrow cycle lanes and within bicycle boxes. Additionally, cyclists waiting alone at one side of busy intersections would trigger the traffic light sensors themselves, ensuring that there is no need for such cyclists to cross the intersection on the red signal. Overall, it is expected that these improvements to the SCATS technology, to be implemented concurrently with bicycle boxes along Northbourne Avenue, would assist in improving the safety of commuter cyclists on roads.

An interesting lens to view the proposed design solution through is one which takes into account Donella Meadows' 'Twelve leverage points to intervene within a system.' As previously outlined within section 3.3.2, 'delays' are a pertinent leverage point within this system but an additional leverage point to consider in some depth is 'system rules' (Meadows, 2009). Rather than introducing new road rules into the system, the addition of bicycle boxes will modify the way in which motorists approach intersections on a red signal. Since the bicycle box takes up space at the entrance to an intersection, cars which approach the bicycle box on a red signal, whether it is occupied by cyclists or not, will have to come to a stop further back from the traffic lights than at typical intersections. If this system rule is not adhered to, with motorists encroaching into the bicycle boxes, the bicycle boxes will not be able to function as desired. Video analysis from previous before and after research into bicycle box implementation has shown that 73.2% of all motorists observed did not encroach into the bicycle box (Dill, et al., 2010). Since this post-installation surveillance only occurred over a three month period, it is expected that over a longer time span, this percentage of compliance would increase. This particular study underwent an extensive public awareness campaign prior to the bicycle box installation, involving posters, billboards and flyers. In order to appropriately inform motorists within Canberra of changes to 'system rules' associated with bicycle box installation, it is recommended that a similar public awareness campaign with the addition of advertisement through social media and print media be conducted. This way, the entire project system should experience a smooth integration of new system rules and in accordance with Meadows' theory, the least disruptive intervention.

6.0 Cost Factors

6.1 Cost Benefit Analysis

In order to examine the feasibility of implementing modified SCATS technology on all of Canberra's main intersections in the Inner North in addition to bicycle boxes to improve cyclist commuter safety, a cost benefit analysis (CBA) is conducted below. In adherence with typical CBA standards, the analysis has been approached as objectively as possible. A base case scenario with regards to this project is the situation whereby current traffic light technology in Canberra is kept the same and no additional road markings within intersections are implemented. Under this scenario, associated maintenance and replacement costs of the traffic lights will remain the same. Likewise, the percentage of cycling fatalities that occur due to cyclists failing to observe traffic signals (≈6.3%) will likely remain the same or increase as a result of Canberra's increased motorist and commuter cyclist population over time (Australian Transport Safety Bureau, 2006). The primary policy option under consideration is the option whereby both bicycle boxes and modified SCATS traffic light cyclist-sensors are installed in major signalized intersections within Canberra's Inner North. A tabulation of the costs and benefits associated with this policy option is shown below in table 3. The key for assessment value (AV) rankings is contained within Annex C table C1.

Table 3- Costs-Benefits Analysis Table. AV = Assessment Value, AUD used where applicable

Costs					
Government	**AV**	**Business**	**AV**	**Community**	**AV**
New traffic light infrastructure	1562	Time and subsequent productivity losses for motorists who have to queue longer at intersections	-2	Disruption in traffic on selected intersections due to implementation of new traffic light technology	-1
Thermoplastic road markings (covering 53.5 m^2 per bicycle box, section 4.2)	1808	Reduced visibility of businesses on the corner of intersections towards motorists	-1	Increased waiting times for motorists at intersections with bicycle boxes	-3
Implementing public awareness campaign towards new road features	-2				
Benefits					
Government	**AV**	**Business**	**AV**	**Community**	**AV**
Medical costs incurred due to cyclist-motorist collisions reduced	1	Reduced stress levels from commuter cyclist who utilise technology translated into the workplace	1	Reduction in the number of cyclist-motorist collisions within intersections	3
Targeted policy to promote greener forms of commuter transport	2	Reduced instances of people taking leave from work due to injuries associated with cyclist-motorist collisions	1	Increased awareness towards commuter cyclists	2
				Increased number of commuter cyclists due to the improved safety	2
Total AV	-		-1		3

To explain the origin of the two quantitative costs include within table 3, the cost of new traffic light infrastructure was calculated based upon a Fermi estimation, using the cost of installing a single SCATS technology traffic light (calculations shown in Annex C). The cost of laying the appropriate amount of thermoplastic tape was calculated based on costs listed on a supplier's website, although the prices listed were in pounds, thus converting the values into Australian Dollars did not take into account fluctuating currencies over time (Promain, 2015). No quantitative government based metric was able to be evaluated due to the difficulty in comparing actual costs with assessment values.

From this CBA table and associated total AV values, it is evident that the primary costs are incurred towards the government whilst the primary benefits are towards the community. When examining businesses, the costs outweigh the benefits. Whilst this is not a desirable outcome, it can largely be attributed towards the fact that the AV's assigned to the benefits were relatively conservative since these benefits would only become apparent after some time period. The significance of the benefits towards the community, however, cannot be underestimated. As the flow-on benefits of increasing the number of commuter cyclists could include; reduced congestion on the roads, reduced greenhouse gas emissions, cost savings within healthcare and overall increased business productivity. Canberra has an appreciable climate and topography for cyclists, and the results of the CBA indicate that through implementation of bicycle boxes with build in bicycle-flow sensors, the benefits over time will outweigh the initially incurred costs. It is for this reason that the main recommendation from the CBA is to proceed with the implementation of this system.

7.0 Portfolio Conclusions

Applying the systems engineering tools in an effort to improve the safety of and awareness towards commuter cyclists in Canberra has yielded some suggestions for improvement. Human and time factors analysis resulted in the recommendation that bicycle boxes combined with cyclist flow detectors are the best infrastructure based design alternative to address the aforementioned problem. Subsequent application of analytical techniques surrounding materials, energy and dynamics systems considerations resulted in the recommendation that thermoplastic tape markings should be used to colour the bicycle boxes, which should in turn be implemented on flat intersection surfaces, whilst an inductive loop sensing device should be used to detect cyclist flow. A final cost-benefits analysis of the proposed solution provided further validation towards the design process undertaken, indicating that benefits to the community from improved commuter cyclist safety could be significant.

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9.0 Appendices

Annex A- Survey questions from the Online Questionnaire

Questions for the cyclist:

1. Have you ever had an unsafe experience whilst commuting on Canberra's roads which was uncontrollable? Explain.
2. How strictly do you follow automobile designed road rules while commuting?
   a) Never
   b) Rarely
   c) Sometimes
   d) Often
   e) Always

Question for the road user:

3. Has the presence of cyclists on Canberra's roads ever bothered you
   a) Yes b) No

Questions for both the road user and cycling commuter:

4. What aspects of Canberra's roads do you think need the most improvement to best integrate cycling commuters and road users?
   a) Roundabouts
   b) Intersections
   c) Traffic lights
   d) Other (please specify)
5. Have you ever had a disagreement or confrontation with a cycling commuter (for the road user) or a road user (for the cycling commuter) due to an on-road incident? Explain

Table A2- Raw Data from online survey

	Question 1	**Question 2**	**Question 3**	**Question 4**	**Question 5**
1	Yes	Sometimes	No	Yes	Traffic Lights
2	No	Often	Yes	No	A clearer delineation between the domain of cars and bikes.
3	Not Applicable (I don't regularly commute by bicycle)	Not Applicable (I don't regularly commute by bicycle)	Yes	No	the bit where you have to cross the green section to turn off a major road
4	Yes	Always	Yes	No	Roundabouts
5	No	Often	No	No	More bike lanes
6	No	Often	Yes	Yes	Cycling commuter awareness of road rules
7	Not Applicable (I don't regularly commute by bicycle)	Not Applicable (I don't regularly commute by bicycle)	Yes	No	Roundabouts

8	Not Applicable (I don't regularly commute by bicycle)	Not Applicable (I don't regularly commute by bicycle)	Yes	No	Intersections
9	Yes	Always	Yes	No	Intersections
10	Yes	Often	Yes	No	Roundabouts
11	Not Applicable (I don't regularly commute by bicycle)	Not Applicable (I don't regularly commute by bicycle)	Yes	No	Traffic Lights
12	Yes	Often	No	No	Specific cycling lanes
13	Yes	Always	No	Yes	Education. More bike lanes. Drivers need to learn that cyclists are allowed on the road. Tougher penalties need to be introduced for people who abuse, run of the road and throw things at cyclists.
14	No	Rarely	Yes	No	Parking in the bike lane forcing cyclists into car lanes.
15	Yes	Often	Yes	No	Traffic Lights
16	Yes	Often	Yes	No	Bike lanes
17	Yes	Often	No	No	Pedestrian crossings
18	Not Applicable (I don't regularly commute by bicycle)	Sometimes	No	No	Roundabouts
19	Yes	Always	Yes	No	Intersections
20	Not Applicable (I don't regularly commute by bicycle)	Not Applicable (I don't regularly commute by bicycle)	No	No	Intersections
21	Yes	Sometimes	No	Yes	Roundabouts
22	Yes	Always	No	Yes	Roundabouts
23	Yes	Often	Yes	No	Roundabouts
24	Yes	Sometimes	Yes	No	Roundabouts
25	Yes	Sometimes	Yes	Yes	Intersections

Annex B

Table B1- Time Factors collected data from intersections

	Duration of the red light signal (seconds)	Duration of green light signal (seconds)	λ (vehicles/seconds)	μ (vehicles/hour)
Gould Street/ Northbourne Intersection	67	61	22/67	47/61
	63	62	18/63	55/62
	62	82	20/62	74/82
	66	55	9/66	36/61
	80	61	11/80	27/45
	71	45	24/71	54/58
	75	58	12/75	30/49
Northbourne and Barry Drive	83	39	45/43	35/83
	85	43	57/40	33/80
	80	44	55/44	38/85
	85	42	47/45	33/84
	83	42	33/43	22/83
	84	42	36/42	14/85
	85	43	29/42	25/85
Masson St/Northbourne Intersection (1)	57	77	6/57	68/64
	75	64	5/59	67/71
	65	42	27/75	74/76
	53	54	27/65	65/80
	74	51	50/74	32/61
	49	44	36/49	27/60
	60	80	37/60	39/55
Northbourne/Masson St (2)	54	46	23/46	5/54
	87	50	38/50	25/80
	57	70	20/57	43/70
	84	45	48/45	20/84
	72	79	56/80	22/47
	47	56	55/80	23/47
	47	80	54/74	21/54

Annex C

Table C1- Assessment Value qualitative rankings used in the CBA. Sourced from (Business Council of Australia, 2012)

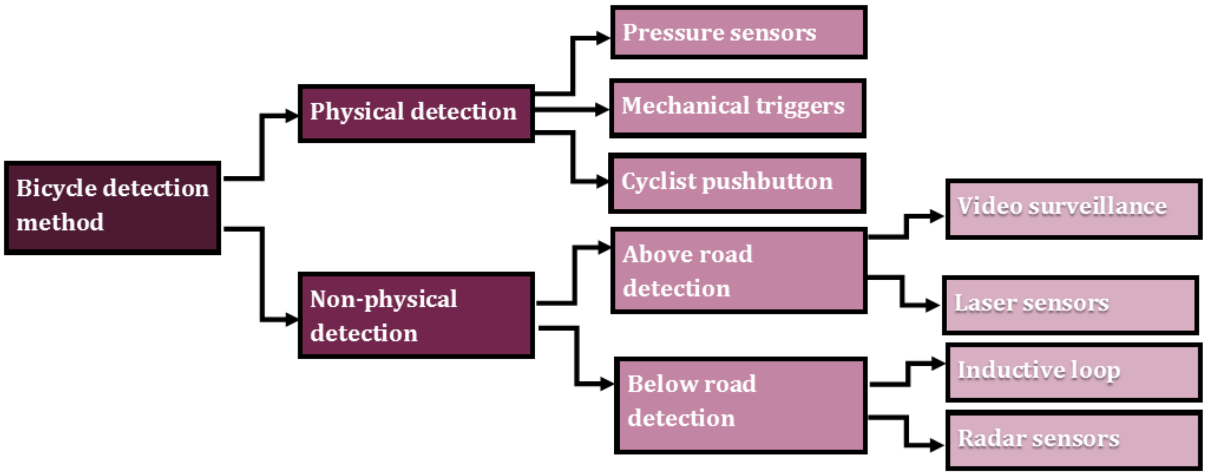
Assessment value	Score
Very much better than the base case	+ 4
Much better than the base case	+ 3
Moderately better than the base case	+ 2
Little better than the base case	+ 1
Same as the base case	0
Little worse than the base case	- 1
Moderately worse than the base case	- 2
Much worse than the base case	- 3
Very much worse than the base case	- 4

Table C2- Forecasted costs of the installation of a single SCATS traffic light control system (Dutta, et al., 2010)

<table>
<tr><th>Factor</th><th>Cost (AUD)</th></tr>
<tr><td>Initial cost</td><td>18,745</td></tr>
<tr><td>Maintenance cost/year</td><td>1,406</td></tr>
<tr><td>lifespan</td><td>15 years</td></tr>
<tr><td>Cost of cyclist detector in cycle lanes</td><td>1,562</td></tr>
<tr><td colspan="2">Based on the size of the SCATS technology, typically covering the width of three vehicles lanes at each intersection entry, the total area of SCATS inductive loop sensors will have an approximate area spanning 12 vehicle lanes (as well as traffic lights). It is expected that at a minimum, the cost of installing a bicycle-flow inductive loop sensor will be $1/12^{th}$ of this cost, since the bicycle box only covers one vehicle lane, thus the cost of $1562 (AUD) per bicycle sensor is obtained.</td></tr>
<tr><td colspan="2">To cover 53.5 m^2 of road surface with thermoplastic tape markings will require the equivalent amount of thermoplastic marking. Based on current costs taken from a supplier, which cite 0.5 m^2 as $16.9 (AUD), covering the specified area should cost approximately $1808 (AUD) (Promain, 2015).</td></tr>
</table>

Annex E

Table E1- Concept generation tree for examining bicycle detection method options



Annex F

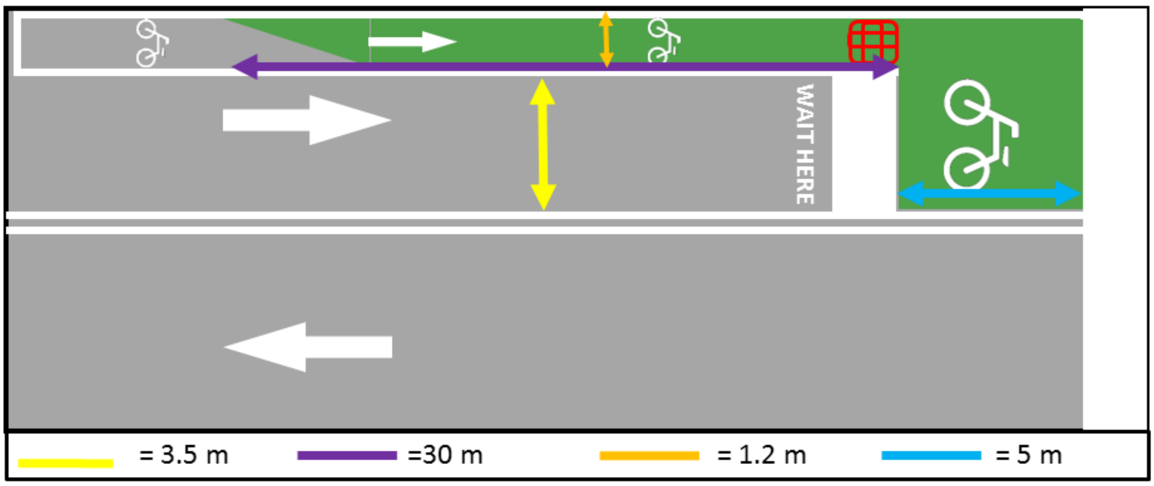


Figure F1- Bicycle box design with dimensions indicated.