Optimising Traffic Operations at Signalised Intersections via Transit Signal Priority

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

Under the supervision of Dr. Michelle Zeibots, Prof. Xiaobo Qu, Dr. Kasun Wijayaratna

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Required wording for the certificate of original authorship

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *Mina Ghanbarikarekani* declare that this thesis, is submitted in fulfilment of the requirements for the award of *PhD*, in the *School of Civil and Environmental Engineering/Faculty of Engineering and IT* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abstract

Sustainable urban transport systems can only be achieved with a balance between private and public transport modes. Though private transport options are necessary for certain trip purposes, it is imperative to ensure that the mass transport of people using public modes achieves an acceptable level of service. Integrated road networks contain links that utilise private, public and active modes of transport. Intersections serve as the primary method of control to maintain safety and functionality of the network. However, as a result of the control, inefficiencies may occur, compromising the effectiveness of a multi-modal transport system. In particular, congestion may negatively affect public transport performance. The following dissertation develops novel strategies for the prioritisation of public transport vehicles to improve the efficiency, effectiveness and quality of service of the transport system as a whole.

Prioritisation of public transport can be achieved through the provision of dedicated road infrastructure (lanes), and operations — especially of intersections managed through a variety of signalisation strategies. Two widely used options for prioritisation of public transport can be through using pre-signals (for buses) and Transit Signal Priority (TSP). The focus of this thesis is TSP for Light Rail Vehicles (LRV)s. Pre-signals can be installed near an intersection to give priority to buses by stopping vehicles before the main intersection. LRV signal priority is a timing strategy that gives priority to LRVs at signalised intersections. It is based on changing the sequence of phases, extending the green time and reducing the red time of the LRV's phase to limit delays to the vehicle.

Bus pre-signals and LRV signal priority systems are becoming more popular in cities, reducing the average delay per passenger and making public transport more attractive.

However, they also impose additional stops, delay and travel time to private vehicles, compromising their overall efficiency.

The research conducted in this study focuses on improving pre-signals and LRV signal priority systems by changing the approach speed of public transport vehicles in order to reduce the green time needed to give public transport priority. The pre-signal model reduces the number of stops behind them so that vehicles can adjust their speed based on traffic conditions as well as the speed and approach of buses. The revised model for LRV signal priority systems minimises the green extension and red reduction of LRV phases by estimating the optimal speed needed to reach the stop line. As a consequence, the priority of LRVs and buses is maintained while at the same time improving the performance of private vehicles by keeping the red time to an absolute minimum.

This thesis advances the evolution of TSP in this way via two methods. First, a set of algorithms is developed to optimise the approach speeds of public transport vehicles to signalised intersections. Second, the algorithm set is then applied to a set of functioning, on-street light rail intersections in the city of Newcastle in the state of New South Wales in Australia. This second phase of the research has sought to test the algorithms by putting them through the early stages of testing and development that would be undertaken as part of an implementation process. This work has been undertaken in collaboration with professional technical staff from Transport for NSW with support from the agencies Research Hub.

Chapter 1 - Introduction

1. INTRODUCTION

1.1. Public transit

Communities have been negatively impacted by traffic congestion experienced in big cities, which has caused health, economic, social and environmental issues due to high levels of localised air pollution, long travel times and delays. This is why methodologies that can help mitigate traffic congestion are needed to improve the transport systems in major cities, particularly their central business districts (CBD).

Reducing traffic congestion is a primary objective for governments in urban environments due to its detrimental social, economic and environmental implications. There is already a focus on mitigating transport congestion by providing additional road infrastructure and currently by demand management through commuter behaviour initiatives such as work from home programs and various road pricing strategies. However, when developing a sustainable integrated transport system, it is also imperative to optimise and encourage greater utilisation of public transport systems that ultimately reduce demands on road networks and thus mitigate congestion.

The importance of efficient and effective public transport systems can also be viewed through the fundamental traffic characteristic of speed. At a macroscopic level, average road traffic speed is influenced by the fixed speed of independent public transport systems (such as heavy rail defined by a schedule) and the variable speed of privately owned vehicles. For example, a traveller can either travel by car or by train to their destination, which is 10km away and assuming there are no unexpected disruptions to either mode of transport, the traveller has the following range of travel times:

- *Train*: 30 minutes (fixed travel time based on the public transport schedules; this results in a speed of 20km/hr)
- *Car*: 15 to 30 minutes (variable travel time that depends on the level of congestion; this results in speeds between 20km/hr to 40km/hr)

If travel time is the most significant factor, the traveller would choose to travel by car because the travel time could be halved, but if each traveller faces the same scenario between origin and destination, they would both choose a car, and that would result in a congested situation of 30 minutes (speed = 20km/hr), which is equal to the travel time on the train. Now, consider that the rail network has been upgraded so that the train has a travel time of 20 minutes (at a fixed speed of 30km/hr). Although this is still slower than the best-case scenario for the car, travellers who experience the congested 30 minute travel times will shift to the train option because it will guarantee a faster-fixed travel speed (30km/hr as opposed to 20km/hr). This result reduces the demand for private vehicles, which then improves the performance of the road network, as outlined by Mogridge (1997). Moreover, if equilibrium conditions hold, the average travel time on the road would also converge towards 20 minutes as the travellers settle on a preferred mode of transport. Although this is a simple example, it highlights how to mitigate road congestion by improving independent public transport networks.

In addition to enhancing the independent heavy rail and metro systems that are already in place, it is equally important to optimise systems (bus and light rail) that interact with the road network. Bus and light rail options are feeders for independent public transport systems, so maximising patronage on these services will help to reduce car use and further alleviate road congestion.

One of the main causes of traffic congestion is the high rate of car ownership and their increasing use in daily travel (Cullinane 2002). On the other hand, public transport systems can actually carry more people than private vehicles, reduce traffic congestion and take up less space on the roads (Nguyen *et al*. 2020). It, therefore, makes sense to develop public transport systems and encourage patronage rather than allow people to choke up city streets with private vehicles. However, to achieve this goal, the performance of public transport systems must be improved in terms of reduced delays and travel time (Nguyen *et al*. 2020).

Since intersections act as the control mechanism for the road network, these are critical locations where that affect the performance of public and private vehicles. Current traffic control strategies often prioritise public transportation systems at intersections because they help reduce possible conflicts at intersections and also motivate people to use public vehicles rather than private cars by offering services with quicker travel times.

As mentioned above, since public transport vehicles can carry more passengers while occupying less space, they are an important part of the overall transport systems in cities, but there is always a need to improve them to reduce traffic congestion in urban areas. In many large cities, buses are an effective vehicle for transferring people because they do not need specific infrastructure, including rail or special structures for stations such as platforms (Vuchic 2002). Consequently, optimising their performance by giving them priority with pre-signals would help to reduce traffic congestion in highly populated cities.

Another form of public transport in big cities is Light Rail Vehicle (LRV) systems used to connect many central business districts with surrounding suburbs. There are several aspects of LRVs that make them an acceptable transport mode for commuting people. One aspect is power from electricity helps to reduce air pollution, and another is their higher carrying capacities and ability to reduce road traffic congestion (Houston *et al*. 2015). Hence, any method that will improve their functionality, such as prioritising them at signalised intersections, is worth considering.

While several priority methods are currently in use, they do have some drawbacks that could be modified to improve the functionality of public transport, such as buses and LRVs as well as private vehicles. Many studies have proposed different methods to optimise the operation of different priority systems (for example, Wittpohl *et al*. 2021, De Keyser *et al*. 2018). This research, therefore, focuses on prioritising buses and light rail vehicles as two common public transport systems in cities.

1.2. Public Transport Prioritisation Solutions

These days, public transport (PT) is often not selected as the most desirable transport mode due to high car ownership, the easy access and convenience of car-use and shorter travel times when compared to public transport. In order to make public transport more reliable and become a more attractive alternative to cars, priority systems have been applied to Urban Traffic Control (UTC) systems (for example, Bhouri *et al*. 2017). These systems give buses and trams a green signal once they approach the traffic light, thereby decreasing PT travel time and delay, especially during peak hours.

The priority systems applied to traffic networks depend strongly on the interaction between public and private vehicles, particularly whether there is a separated public transport lane or purely mixed lanes for both private and public transport vehicles. It should be noted that the most efficient priority systems are those servicing public transport, operating in segregated lanes enabling vehicles to avoid long wait times and congestion (Diakaki *et al*. 2015).

For scenarios where PT operates with cars in mixed lanes, there is a need to utilise the strategies that decrease PT time-in-queue and stop time at signalised intersections (Hrelja *et al*. 2020). To this end, the lane should be cleared from cars through forecasting car arrival times so that public transport services experience fewer delays.

PT priority aims to make amendments to the traffic signal timing procedure to let trams and/or buses pass the intersection without stopping, and this system necessarily requires the following features:

- Ability to detect public transport vehicles to apply the control strategy, and
- Optimise the performance of the traffic light by minimising the additional stops imposed on cars (Civitas 2010, Branco & Biora 2013).

Prioritisation of public transport vehicles not only reduces their delay and travel time. but also leads to more comprehensive benefits such as:

- Reduced air pollution by decreasing the presence of PT vehicles in traffic jams and the use of motorised vehicles by encouraging more passengers to use PT (Malandraki *et al*. 2015)
- Making PT more reliable and attractive among transportation modes by reducing its travel time (Redman *et al*. 2013).

This research specifically talks about two different priority systems used for the prioritisation of buses and trams as part of the urban traffic network named “Bus Pre-Signals” and “Transit Signal Priority (TSP)”. One of the most popular priority systems is the Transit Signal Priority (TSP) system or Adaptive Plan Signals that can be implemented to signalised intersections and level crossings for prioritising high occupancy vehicles, including trams, buses and trains. In addition to TSP, Bus Pre-Signal has been introduced as an innovative priority system applicable for buses operating in reserved lanes.

These priority methods have been selected for further investigation as the intention of these methods is to provide priority if and when a public transport vehicle is present. Unlike fixed infrastructure, such as dedicated bus lanes or separated tram corridors, these approaches offer solutions in an integrated environment. As highlighted by Guler & Menendez (2015), bus pre-signals are incredibly useful in lower frequency service scenarios and can reduce the impact on other road users. Similarly, a recent doctoral dissertation by Ardalan (2020), highlights that transit signal priority can achieve road traffic sustainability when designed correctly. The gap this research has identified is that to date, though the objective is to provide priority to public transport vehicles whilst reducing impacts on other road users, the algorithms used to date do not effectively achieve this outcome. The two algorithms (Bus Pre-Signals and a modified TSP – SOLRV) achieve such a sustainable solution, as presented in Chapters 3 and 4 of this thesis. The following sub-sections introduce the existing approaches to the focal prioritisation methods.

1.2.1. Bus pre-signal

Pre-signals are an innovative procedure for prioritising buses behind signalised intersections. It is a kind of traffic signal that is implemented in advance of a main signalised intersection that gives priority to buses as they approach main intersections by providing a red signal to private vehicles (Figure 1.1 Shows where pre-signals are installed).

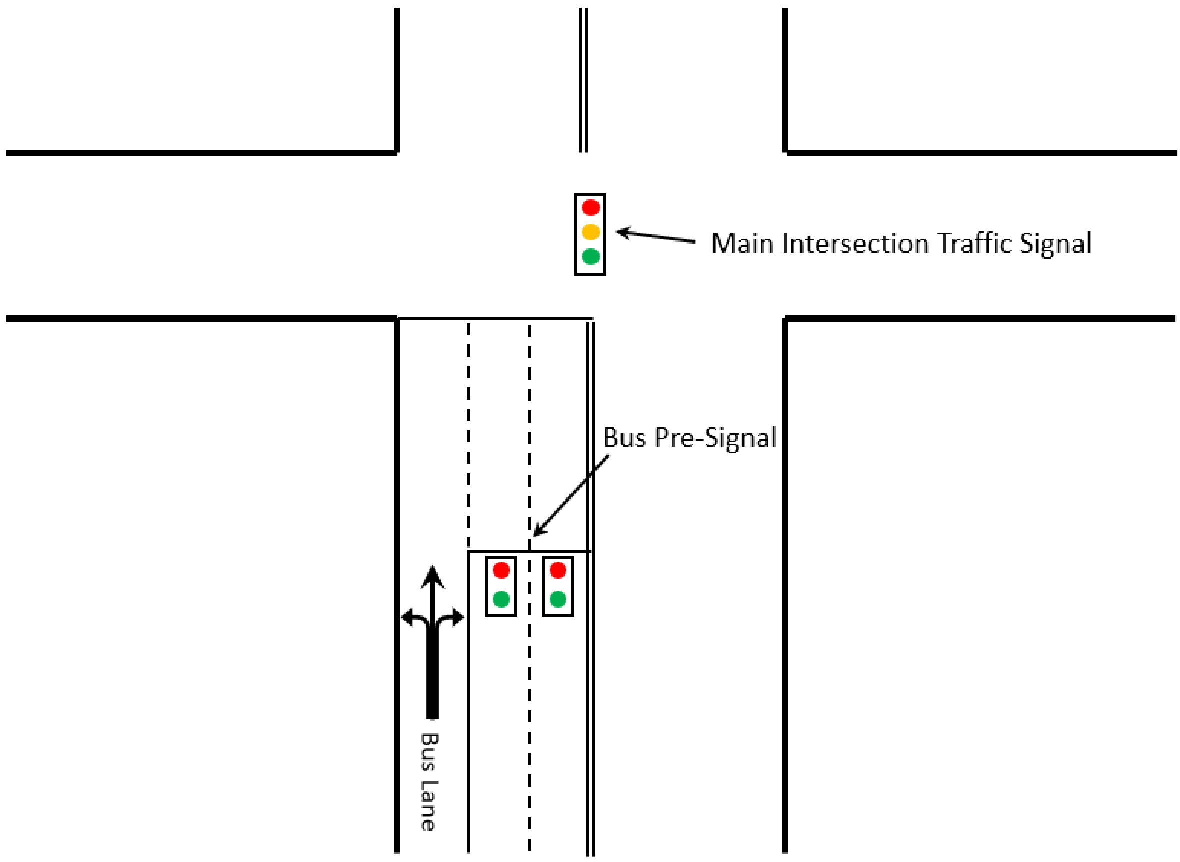


Figure 1.1 – The location of a bus pre-signal in advance of the main intersection

Pre-signals could be implemented on arterials that already have a separate bus lane, which is justified when the headways of buses are short. The other reason for installing pre-signals as well as bus lanes and short headways is the increasing demand to keep cars flowing in conditions that range from saturated to oversaturated.

Pre-signalling for buses has been considered as one of the effective strategies for reducing the average delay per passenger (Guler & Menendez 2014), which is the reason for becoming more popular in cities. Moreover, this strategy will reduce potential conflicts between buses and private vehicles at intersections because it separates them behind a stop line.

Although this method can reduce bus delays and travel time and increase their speed, it has many disadvantages in heavy traffic because pre-signals impose additional stopping time for private cars, which results in the increase of their delay and travel time (Dadashzadeh & Ergun 2018). In essence, pre-signals enhance bus functionality by prioritising them at intersections, but it does not consider private vehicles.

This research strives to minimise the aforementioned drawback for cars caused by implementing the bus pre-signals due to the longer stop time at pre-signal. To achieve this goal, two models are suggested for minimising (1) the initial queue delay (IQD) and (2) the time-in-queue (TIQ) of private vehicles behind the pre-signal.

The IQD model is to estimate the optimal distance for implementing pre-signals, determine the VMS installation distance from the pre-signal, and optimise the speed of vehicles reaching pre-signals for the sake of reducing their number of stops. By contrast, the TIQ model aims to calculate an appropriate speed for arriving vehicles to minimise car TIQ behind pre-signals.

The contribution of the proposed IQD and TIQ models is to decrease the additional stop-time imposed on cars behind the bus pre-signal by balancing the traffic operating speed in advance of pre-signals. More specifically, these models aim to manage car arrival times based on the arrival time of buses by changing car speeds before reaching the pre-signal. In this way, private vehicles can arrive at the pre-signal, preferably once the signal is green, so that a minimum stop is required and their stop time and delay is reduced.

1.2.2. LRV signal priority

Prioritising public transport within road networks increases throughput and reduces travel times and delays in congested urban environments, which means it can then transport more people quickly and efficiently (Lin *et al*. 2015). The Transit Signal Priority (TSP) mechanism, currently being considered by many traffic experts, prioritises public transport modes by manipulating traffic signal phasing. Active TSP systems are generally implemented using three main strategies based on the duration of signal phases, the location of public transport vehicles, and traffic demand at other approaches. These strategies are commonly defined as “green extension”, “red reduction” and “phase change”:

- ***Green extension*** — prolongs the green time of the public transport phase as a public transport vehicle approaches an intersection thereby limiting impedance by extending the time provided to cross an intersection
- ***Red reduction*** — decreases the red time of the public transport phase, thus reducing the wait time of a public transport vehicle stopped at an intersection
- ***Phase change*** — changes the sequence of phases when a public transport vehicle approaches an intersection by giving it the next green signal phase regardless of the sequence (Zhou and Gan, 2009).

One issue with manipulating traffic signals utilising these methods is that although it priorities a public transport vehicle, it adds significant delays to other users, particularly private vehicles. This detrimental impact of TSP is often perceived as a deterrent to its implementation (Wijayaratna *et al.* 2013). Accordingly, the study presented in this thesis focuses on advancing these traditional approaches to TSP by optimising the speed of approaching public transport vehicles, particularly light rail vehicles. This research developed the “Speed Optimisation of Light Rail Vehicle” (SOLRV) algorithm — a novel approach that manipulates the signal timing infrastructure and the speed of public transport vehicle infrastructure. In short, SOLRV is designed to achieve gains through a dual system of speed and signal timing adjustment to reduce the duration of green extensions and red reductions of traditional TSPs. This ultimately reduces the impact on other users of intersections such as private vehicles as outlined by Wijayaratna *et al.* (2013) to achieve a more sustainable prioritisation of light rail vehicles on a road network. In this way, the contribution of the SOLRV algorithm is to minimise the drawbacks of the TSP system from a motorists perspective, which would otherwise incur an increase in stop time for cars behind the traffic lights due to extending the green signal or reducing the red signal of the LRV phase. The SOLRV algorithm aims to minimise the required change in the LRV phase, green extension or red reduction, to reduce the stop time of other vehicles at other phases, which is gained by moderating the LRV's speed when approaching the intersection.

1.3. Scope of this study

This research aims to modify the bus pre-signals and LRV signal priority discussed in Sections 1.2.1 and 1.2.2 by first proposing a model to improve pre-signals that reduces the number of stops vehicles make behind them. This model would prioritise buses and improve the performance of private vehicles by minimising the number of stops when approaching the pre-signals. This will be achieved by alleviating the number of stops by having cars alter their speed based on the timing of traffic signals, the approach of buses, and the traffic conditions ahead. This will make the flow of private cars continuous and balanced, rather than discrete.

The second proposal is an adaptive model to modify the TSP strategy for LRVs at intersections equipped with actuated signals. This model would minimise the green extension and red reduction times by determining the optimum speed for LRVs approaching the intersection, thereby minimising the stops and delays for vehicles on other approaches.

The rest of this thesis is structured as follows. Chapter 2 explains the background studies related to bus pre-signals and LRV signal priority. Chapter 3 describes the methods used, i.e. a model for modifying the pre-signals for buses and a model to improve LRV signal priority.

Chapter 4 describes the future works of this research. The structure of the thesis is shown in Figure 1.2.

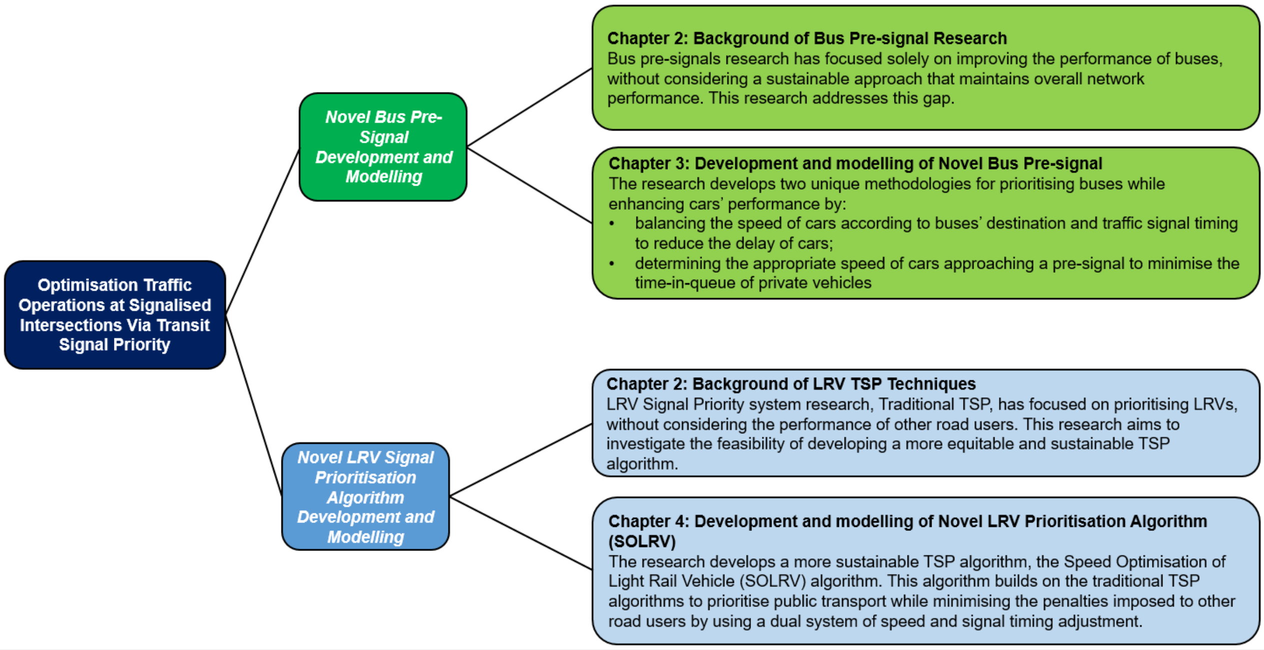


Figure 1.2 – Thesis Structure

The remaining sections of this thesis describe the development of the bus pre-signal and SOLRV algorithm, how the algorithm was tested, and a road map towards its potential implementation in New South Wales. The sections include:

- ***Chapter 2 - Literature Review***
  - Describes the background of bus pre-signals and traditional TSP algorithms, the latest research concerning them, and provides justification for the novel bus pre-signal and the LRV signal priority approach.
- ***Chapter 3 – Novel Bus Pre-signal Development and Modelling***
  - Summary of the methodology used to develop, test, and evaluate the potential of the novel bus pre-signal
  - The IQD model formulation, which describes the model development, the mathematical process for its application, and sensitivity analysis

    - The TIQ model formulation, which describes the model development, the mathematical process for its application, and sensitivity analysis.
- ***Chapter 4 – Novel LRV Signal Prioritisation Algorithm Development and Modelling***
    - Summary of the methodology used to develop, test, and evaluate the potential of the SOLRV algorithm
    - The SOLRV algorithm formulation, which describes the development of the SOLRV algorithm and the mathematical foundation for its application
    - The SOLRV algorithm application, which describes the micro-simulation modelling undertaken to determine the performance of the SOLRV algorithm for case studies of single intersections with differing configurations
    - The SOLRV algorithm application, which describes the micro-simulation modelling undertaken to determine the performance of the SOLRV algorithm for a corridor of intersections that account for network impacts.
- ***Chapter 5 – Conclusion***
    - The final chapter presents concluding remarks and a summary of the research outcomes and achievements.

Chapter 2 – Literature Review

2. LITERATURE REVIEW

The following chapter discusses the background studies conducted on the prioritisation of public transport vehicles, specifically buses and LRVs. Prioritising buses has been investigated as an approach for providing a faster, more reliable, efficient and sustainable system. In general, PT prioritisation at traffic lights is viewed as highly beneficial, especially at intersections with high traffic demand and low capacity (as outlined by Hounsell & Shrestha 2012).

With the increasing use of automatic vehicle location (AVL) systems, it is now possible to provide "differential" priority, where different levels of priority can be awarded to buses at traffic signals according to chosen criteria (for example, to improve regularity). At present, common strategies are based on the comparison of the headway time of a bus with the scheduled headway. However, this paper shows that greater regularity benefits could be achieved through a strategy where priority for a bus is based not only on its own headway but also the headway of the bus behind (the following bus). This thesis demonstrates the benefits of this on a theoretical basis and quantifies the benefits from simulation modelling of a high-frequency bus route. Such a strategy provides an opportunity to exploit the more detailed location information available from the growing number of AVL-based systems for buses being implemented around the world (Hounsell & Shrestha 2012).

As the prioritisation of surface public transport has been considered significantly in urban traffic management, there are many studies carried out that propose different methods of prioritisation and test their efficiency and effects on network traffic operation (Bhouri *et al*. 2017).

One of the most popular systems in prioritisation of PT is Urban Traffic Control (UTC), which provides surface PT such as trams and buses, priority at signalised intersections. Bhouri *et al.* 2015 carried out investigations on UTC systems and their disadvantages on urban traffic networks and propounded an optimal control theory applicable for traffic signals with the aim of improving PT. Testing the proposed traffic regulation plans demonstrated that a mixed request was needed for imposing least impact on cars (Bhouri *et al*. 2017).

The ways for prioritising buses can sometimes be different from LRVs in terms of the applied strategy and method. However, none of them has significant impact on mode-split once there is no effort to motivate single occupant cars to commute by PT (Hensher & Waters II 1994).

Bus priority at traffic signals is a growing area of cooperative transport system applications. Interest in bus priority continues to grow as cities pay more attention to the needs of buses to provide fast, frequent and reliable services, thus contributing to a more sustainable transport system. Bus priority at traffic signals is particularly favoured at places where road space is limited, and traffic signal density is high (Hounsell & Shrestha 2012).

Sections 2.1 and 2.2 present previous studies on the two methods considered in this research, bus pre-signals and LRV signal priority systems.

2.1. Bus pre-signal

Pre-signalling is one of the most recent innovations that have been considered over the last two decades. A bus pre-signal was defined by Peake (2006) as traffic signals implemented behind intersections to manage traffic flow and give priority to buses. The first time pre-signals were used to prioritise buses was proposed by Wu & Hounsell (1998). They proposed three different categories: 1) implementing uncontrolled pre-signals for buses, 2) pre-signals, which controlled buses and cars, and 3) giving a red signal to private vehicles while pre-signalling arriving buses, and then giving a red signal to the bus lane. Note here that according to Wu & Hounsell (1998), Kumara & Hounsell (2006), He *et al.* (2016), Xuan (2011) and Xuan *et al.* (2012), using pre-signals upstream of urban intersections reduces their discharge rate and wastes an intersection's green time. Or in other words, fewer vehicles can be discharged by pre-signals than the capacity and green time of the main intersection.

Kumara & Hounsell (2006) proposed queue relocation to avoid wasting a main intersections' green time by having pre-signalised intersections, queue relocation, and bus priority. Queue relocation keeps private vehicles in a pre-signal stop line by saving the green time of the main intersection, while bus priority is supplied by detectors embedded in the vehicles. They indicated that pre-signals help to prioritise buses in over-saturated intersections by queue relocation and bus prioritisation.

Another solution offered by Xuan *et al*. (2012) to solve the discharge rate of intersections is the use of mid-block pre-signals. They demonstrated that this solution stores traffic flow between pre-signals and main intersections. To increase the discharge rate of intersections He *et al*. (2016) proposed an adaptive algorithm that can control pre-signals during real-time demand by private and public transportation utilising accurate statistics and real-time detection. They showed that pre-signals with an adaptive control algorithm could stimulate a greater use of buses by reducing delays far better than continuous and interrupted bus lane strategies. Increasing the flow capacity at intersections is one of the most significant and fundamental parameters that affect their efficiency. Another study to improve intersection capacity is Xuan's (2011) research. Xuan proposed a method to increase the flow capacity of signalised intersections using tandem design in which left-turning and through moving vehicles were sorted by a mid-block pre-signal. Xuan carried out studies on the length of the blocks needed to reach optimal capacity and how this tandem design could minimise these requirements. Xuan showed that this tandem design increased the flow of cars and buses at intersections equipped with pre-signals.

In addition to the low discharge rate of intersections, Wu & Hounsell (1998) explained another issue with pre-signals — an extension of the queue length to an upstream intersection. They suggested vital assumptions for estimating traffic signal timing to avoid these issues.

Many solutions for mitigating traffic congestion in terms of developing different kinds of infrastructure have been suggested, but the costs are high. Fortunately, there are cheaper methods such as pre-signals that can enhance the functionality of traffic flow at intersections (Vieira *et al.* 2017). Vieira *et al.* proposed an agent-based simulation model to simulate vehicle behaviour, their results showed that this strategy decreased the length of queues, reduced overall fuel consumption, and increased traffic flow.

Kejun (2008) carried out a study that prioritised buses at a single intersection using pre-signals and passive priority by introducing a Bus Advance Area between the stop lines of pre-signalised and main intersections. Kejun (2008) also investigated the efficiency of pre-signals by simulating an intersection in VISSIM where it was shown that although pre-signals increased the efficiency of buses, they had a negative impact on private vehicles because they had additional stops behind the pre-signals. To eliminate this impact at intersections with pre-signals, He *et al.* (2015) suggested a control algorithm with online performance that was modelled in the micro-simulation software, VISSIM. In their research, they implemented the algorithm with the bus lane, mixed lanes, and pre-signal strategies. After comparing these methods, they showed that using pre-signals with the proposed algorithm not only prioritised buses, it also maintained the proficiency of private vehicles. In addition to the studies by He *et al.* (2015), Guler & Menendez (2014) played a significant role in improving the functionality of private vehicles as well as bus priority. Guler & Menendez (2014) estimated the delays of cars and buses in pre-signalised intersections analytically using queuing theory by computing delays in implemented pre-signals and allocating a lane to buses. After comparing commuter delays, they concluded that pre-signal systems will minimise a delay more than dedicated bus lanes. Consequently, implementing pre-signals has fundamental effects on buses due to their high capacities. Moreover, Guler & Menendez (2015) presented a practical instruction relating to the use of pre-signals upstream of intersections. The influence of implementing pre-signals on intersections compared to other bus priority strategies helped to determine the conditions for applying pre-signals on arterials. It should be mentioned that they proposed instructions for pre-signals to simultaneously improve transit services and private transportation systems. Guler *et al.* (2016) and also suggested an innovative strategy to prioritise buses as well as improving the functionality of cars. This strategy provides dynamic timing for pre-signals, which can be activated or deactivated depending on the traffic situation. In their research they considered that implementing pre-signals leads will increase the delay of cars in under saturated intersections and reduce their discharge rate in over saturated intersections, however, a single-lane strategy can mitigate this undesirable situation.

Bie *et al.* (2017) investigated traffic flow at a tandem intersection, and then proposed a real-time traffic signal timing method that utilised several loop detectors. They also considered the lane choosing a policy to determine the green duration for traffic signals. They showed that minimising vehicle delays optimised the traffic parameters at intersections, and helped to reduce vehicle delays and the length of queues.

Figure 2.1 provides a summary of the existing bus pre-signal methods, their disadvantages and solutions proposed by other researchers so far.

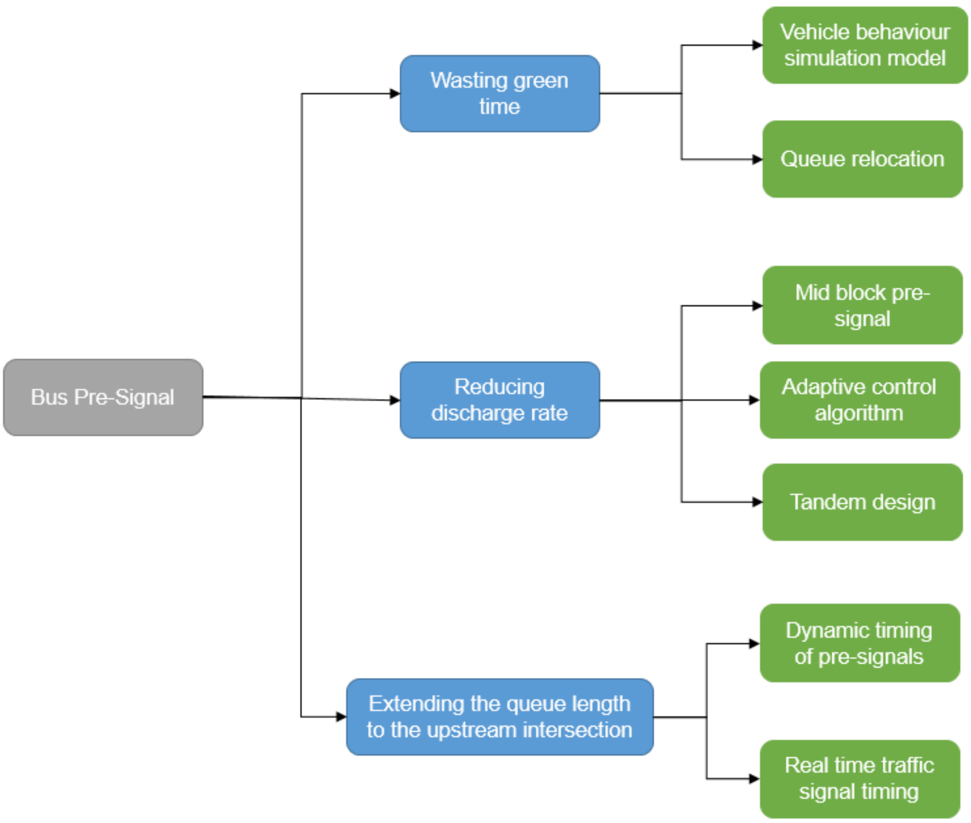


Figure 2.1 - Methods proposed for the bus pre-signal disadvantages

The studies conducted around bus priority show that the suggested methods only consider bus performance and functionality in terms of their delay and travel time at signalised intersections for the purpose of increasing passengers' reliability. However, the methods do not consider the impact of increasing the stop time and delay imposed on cars due to the pre-signal, so this research aims to improve the cars' operation at pre-signals as well as prioritise buses to fill this gap. To serve this purpose, it is suggested to moderate the speed of cars approaching the pre-signal, considering the presence of buses and the condition of main intersections' traffic lights.

2.2. LRV signal priority

The primary objective of this research is to enhance the traditional approaches to TSP to achieve greater sustainability in its implementation. This means understanding the context of TSP development and then describing the most recent research related to its improvement. The first part of this literature review provided a brief introduction to the classification of different TSP options that are available for implementation. Lin *et al.* (2015) provided a comprehensive review of TSP literature, which is useful for readers seeking further information regarding the evolution of this topic.

Figure 2.2 shows a hierarchical classification of TSP. TSP techniques can be classified as having passive and active approaches (Currie 2006, Smith *et al.* 2005). Passive approaches do not directly prioritise public transport vehicles, they optimise signal timing and coordination to assist the progression of all vehicles along public transport routes. On the other hand, active approaches directly prioritise public transport vehicles through either unconditional (sometimes referred to as pre-emption) or conditional priority (referred to simply as a priority). Pre-emption or unconditional priority provides immediate priority to public transport vehicles without considering other vehicles or users of an intersection. Conditional priority, however, considers the public transport vehicle approaching an intersection as well as the traffic conditions at an intersection (queue lengths, saturation, time since last priority was called) to determine the provision of priority (Langdon 2002, Currie 2006). The implementation of both unconditional and conditional priority generally considers the use of the “green extension”, “red reduction” or “phase insertion” mechanisms to provide an advantage for public transport vehicles.

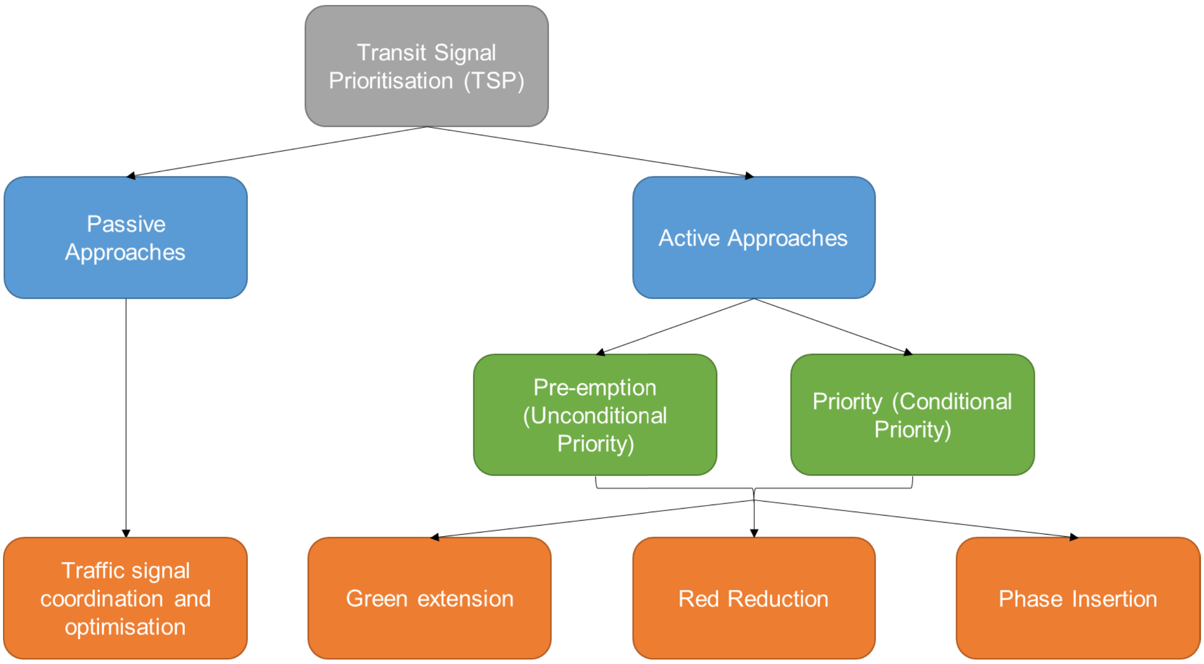


Figure 2.2 - Transit Signal Prioritisation Classification

The above classification, as well as past studies (Lin *et al.* 2015, Wijayaratna *et al.* 2013, Ngan *et al.* 2004) indicates that unconditional priority, and at times conditional priority, significantly reduces the performance of road networks by eliminating the benefits of prioritisation. These negative impacts are the result of adjustments to signal timing and a combination of complicating factors related to public transport infrastructures, such as the number of stops, and the dwell times and travel times of public transport vehicles (Li 2008). This research attempts to advance existing TSP to reduce these negative impacts to sustainably prioritise public transport on a road network. Past research regarding TSP implementation has already investigated methods to improve its efficacy, the remainder of the literature focusses on the mechanisms discussed in prior studies:

1. Coordinating traffic signals and real-time policies
2. Predicting the arrival of public transport vehicles
3. Adaptive traffic control systems.

2.2.1. Coordinating traffic signals and real-time policies

Implementing traditional TSP algorithms interrupts the coordination of signalised intersections along arterial corridors, which is why researchers have investigated methods to regain coordination through a variety of techniques. A basic approach to limit the interruption of signal coordination has been to implement real-time policies where public transport vehicles request priority as a vehicle approaches an intersection on a needs basis. One of the first examples of this is provided by Chang *et al.* (1995) where a real-time method was developed to prioritise buses at signalised intersections based on the traffic conditions, rather than using unconditional strategies. This approach significantly reduced disruption to coordinated corridors (Chang *et al.* 1995). In his research, Skabardonis (2000) presented extensions of such an approach by considering a mix of passive and active TSP approaches to alleviate the network-wide impacts of prioritisation. More recently, He *et al.* (2014) presented a clear example of using real-time policies to achieve better signal coordination with TSP. Their proposed model decreased the average delay of transit vehicles as well as the passenger car delay. This model was also shown to be more efficient in oversaturated conditions and environments with higher frequencies of public transport vehicles. The weakness of this approach however, is that intermittent prioritisation results in a variety of signal timings that can reduce safety at intersections as users must quickly adapt to the change in signal phasing.

Cesme & Furth (2014) also tried to enhance actuated traffic signal controls by using real-time policies. They developed a "self-organising signals" algorithm that allowed for secondary phases of green extension and dynamic coordination of closely spaced intersections. Micro-simulation modelling with this novel algorithm along major US corridors revealed 14% reductions in corridor delays compared to a coordinated system without public transport priority and 60% reduction in public transport delay per intersection. In the context of light rail, Zhou *et al.* (2016) tried to improve the performance of trams at signalised intersections by implementing an asymmetric multi-band optimisation method to coordinate the signals. Simulation modelling of this approach also delivered benefits for all users. Zhao *et al.* (2018) proposed a microscopic model with six modules that can be applied at level crossings. Its efficiency was investigated by comparing the length of queues and implementing a green wave for tram phasing to coordinate traffic signals. These results are incredibly promising, but as noted across these publications, the practical application of such a complicated algorithm is not common in practice. This directed the study to focus on potentially simpler algorithms.

Several studies were also carried out to evaluate the network-wide implementation of TSP strategies (Bagherian *et al.* 2015; Ahmed & Hawas 2015).

Bagherian *et al.* (2015) presented a new approach to analysing the impact of transit signal priority at the network level by developing a novel delay function. This research suggests that the delay function (based on traffic flow and signal properties) can eliminate the need for extensive operational modelling through microsimulation approaches, which offers practitioners an opportunity to test more real-time ad-hoc approaches to prioritisation, where the impacts can be quickly evaluated. Ahmed & Hawas (2015) proposed an independent system for controlling traffic, which could determine the limitations for different traffic conditions such as recurrent or non-recurrent congestion, TSP applications, and congestion resulting from downstream network pinch-points. The effectiveness of this approach has been presented using a CORSIM-microsimulation model, but its primary advantage is the utilisation of empirical data from the boundaries of the study area that offer a direct approach to measure network-wide impacts.

2.2.2. Predicting the arrivals of public transport vehicles

Removing the delays resulting from TSP due to uncertainty in the arrival of public transport vehicles at intersections can lead to better coordination and a more sustainable application of TSP. Accordingly, researchers focussed on developing predictive models of public transport arrivals that account for stops, dwell times and road network delays to enhance TSP. Islam *et al.* (2016) and Asim *et al.* (2012) carried out research in the field of prioritising LRVs at traffic signals. In the study by Islam *et al*. (2016) at Edmonton, Canada, three approaches were proposed to enhance the existing light rail system: providing simple priority for LRV; predicting LRV arrival times and implementing priority, and; prioritising LRVs and buses by estimating the arrival time of LRV. They demonstrated from their research that the second method had the best results, although the dual prioritisation of bus and light rail vehicles did not reveal any benefits to the overall system. However, this study clearly showed the advantages of predicting the arrival time of light rail vehicles. Asim *et al.* (2012) undertook research that focused on adaptive signal control of a single intersection with pre-emption for the LRV, similar to the results of Islam *et al.* (2016), arrival time prediction enhanced the performance of the TSP application.

Bin (2012) investigated the influence of traffic parameters on the operation of a transit signal priority by introducing the average delay of a passenger and the random characteristics of traffic flow. This simulation revealed that fluctuating the arrival rate will affect the timing of traffic signals, and the model reduced passenger delays (Bin 2012), thus reinforcing the results of Islam *et al.* (2016) and Asim *et al.* (2012).

Tan *et al.* (2008) presented an algorithm that estimates the time that public vehicles enter signalised intersections so that public transport systems can be prioritised. Unlike other studies, this research used the Global Positioning System (GPS) to track vehicles in the algorithm, rather than field sensors and detectors. This approach is quite comparable to traditional vehicle tracking and could be supplemented as an arrival model in existing TSP algorithms.

In Sydney, Australia, a PTIPS (Public Transport Information and Priority System) has been developed to improve real-time data collection of New South Wales's public transport system, including traffic flow, buses location and signal operation to predict arrival time of buses for priority implementation. The advent of PTIPS has helped to prioritise public transport and the road network by providing priority for buses. Jarjees & Mehaffey (2008) carried out a study on the PTIPS process and its interaction with Sydney Coordinated Adaptive Traffic System (SCATS) and highlighted the possibility of using public transport arrival times to enhance TSP. Moreover, Jarjees *et al.* (2012) analysed the effect of PTIPS on its stakeholders and indicated that the advancements in information distribution have benefited travellers. However, utilisation within TSP algorithms has not been documented clearly in the literature and should be investigated in the future, especially in the context of predicting the arrivals of public transport.

2.2.3. Adaptive traffic control systems

Adaptive traffic control systems allow traffic signal timings to "adapt" to actual changes in the traffic demand at intersections in a road network. Given the adaptive nature of signalling systems, incorporating TSPs into them has the least impact on traffic delays to other vehicles and users in the system. However, integrating a TSP algorithm into adaptive systems is also the most complicated due to their inherent variability. Since SCATS, which are present across the NSW road network, is at the forefront of adaptive control of signalised road networks, installing adaptive control TSPs will be most beneficial. The following studies reveal promising approaches to adaptive real-time prioritisation.

Yagar & Han (1994) explored the responsive phase ordering for prioritising transit vehicles in an adaptive control environment. Their research was based on decision rules so the signal orders were implemented to provide priority. This method reduced total delay better than a fixed-time signal. Some of the studies carried out to prioritise public transport vehicles are responsive to traffic conditions and demand (Dion & Hellinga 2002; He *et al.* 2014, Cesme & Furth, 2014; Chang *et al.* 1995; Asim *et al.* 2012; Li 2008), in fact according to Dion & Hellinga (2002) a real-time optimisation model that depends on traffic conditions has been proposed. This model first considered the conflicts in traffic flow caused by transit vehicles due to dwell times and accessibility, and then the number of improvements caused by prioritising transit vehicles. When their model was applied to isolated intersections it reduced delays in fixed-time and actuated signals, it also reduced delays at fixed-time intersections using responsive traffic control. Moreover, delays at actuated intersections also decreased because the model prioritised transit vehicles.

Unconditional transit signal priority systems cause many traffic delays because of insufficient adaptive data, so to optimise traffic performance at a corridor of level crossings, Wu *et al.* (2012) developed a real-time methodology, which considers the situation of a cross street. Their model minimised delays to light rail vehicles at intersections, minimising the influence of other approaches. To this end, the arrival times of LRVs was estimated using GPS, which dramatically improved operations at the intersections.

Another adaptive model for developing the operation of TSP was based on optimising the green splits to reduce delays to public and private vehicles. This model considered safety and signal control loops, decreased delays for buses and other vehicles at the intersections (Li *et al.* 2011).

Vilarinho & Tavares (2014) developed a strategy to control traffic signals and optimise the response of signal timing to traffic flow in real-time (adaptive to traffic demands). They applied the Akçelik method to find the dominant approach, the length of each cycle and the proportion of green time. The aim of their algorithm was to minimise delays at an isolated intersection, so it was written in several programming languages in order to be imported into Aimsun. The outputs of this model significantly reduced overall delays and also managed unpredictable events.

2.3. Summary

The research carried out revealed that while pre-signals have some disadvantages, traffic conditions at oversaturated intersections generally improved. Investigating the previous studies around bus pre-signals demonstrates that this priority system has three different weaknesses including wasting green time of the intersection, reducing discharge rate of the main intersection, and elongating the queue to the upstream intersection. As presented in Section 2.1, several models were also proposed to increase the capacity and discharge rate of intersections, and ultimately to eliminate the aforementioned drawbacks. Furthermore, some research also suggested utilising queuing theory and adaptive time of traffic signals to enhance the performance of private vehicles at pre-signalised intersections.

It should be considered that all the proposed methods aimed to decrease the impact of bus pre-signals on private vehicles only when there is no bus approaching the main intersection. Accordingly, there is a gap in the studies undertaken for improving cars' performance at pre-signals. In other words, no strategy has been advocated for the situation of improving cars' operation and bus priority at the same time. This research aims to keep the bus priority system activated as well as reducing cars' stop time behind the bus pre-signal. TSP has an extensive history with many research efforts and real-world applications. As described in the previous sections, the fundamental issue surrounding the implementation of TSP involves minimising additional delays to users other than users of public transport. Researchers also investigated enhanced coordination mechanisms, predicting arrival times, and incorporating TSP within adaptive control systems. Although there have been promising results from all the approaches described, and with significant reductions in delays, ***a major barrier to field implementation has been the complexity of the algorithms developed. These algorithms mainly focussed on adjusting signal timing, they lacked detailed investigations into the potential manipulation of public transport vehicles (speed or frequency variations)***.

Accordingly, the objective of this research is to develop a TSP algorithm suitable for an adaptive traffic control system, which can adjust the duration of traffic signals and also modify the speed of public transport vehicles throughout their journey. This model aims to minimise the green extension and red reduction of traditional TSP strategies by calculating the appropriate speed for LRVs in the system such that the functionality of other phases would be vastly improved.

Chapter 3 – Novel Bus Pre-signal Development and Modelling

Section 1.2.1 talked about the Bus Pre-Signal implemented in advance of the main traffic lights to prioritise buses, and also its detrimental impacts on private vehicles. This Chapter proposes two models to overcome the bus pre-signals drawbacks. These models are outlined by moderating the approaching speed of cars with the purpose of reducing their stop time behind the bus pre-signals.

3. NOVEL BUS PRE-SIGNAL DEVELOPMENT AND MODELLING

In this Chapter, two models are proposed to calculate the appropriate speed for private vehicles reaching the pre-signals. The first model will minimise the initial queue delay (IQD) behind the pre-signal and the second model will minimise the time-in-queue (TIQ) of private vehicles behind the pre-signal.

Listed below are some essential assumptions for proposing and presenting a model:

- Without loss of generality, we assume there are two lanes
- The intersection is controlled by a fixed-time traffic signal and equipped with pre-signals
- It is assumed that the studied intersection is isolated and is not influenced by the adjacent intersections
- A Variable Message Sign (VMS) has been installed in the opposite direction of bus stops to warn private cars
- An Automatic Vehicle Location system (AVL) is utilised in each bus to determine their location, their approach and selected lane

- Detectors are needed throughout the area behind the stop line where buses can change lanes. These detectors also declare the existence of other cars and the lane selected by the bus
- Another detector is needed at the VMS point to count the number of private cars in the space between the VMS and the area behind the stop line
- The movement of buses and cars is assumed to be static, their speed is based on road rules, and is therefore constant.

We first describe the initial queue delay (IQD) model and its procedures, as well as the model's objective function based on the initial delay in the queue, and the required parameters. The time-in-queue (TIQ) model and its algorithm regarding the time-in-queue parameter is then described.

3.1. The Procedure of the IQD Model

In this part we suggest a model to modify the performance of the pre-signals used to prioritise buses at signalised intersections. This study aims to minimise the number of stops and thus optimise the performance of buses and private vehicles in urban arterials with signalised intersections equipped with pre-signals. It is therefore essential that:

- Buses be located in the first line of the queue behind the stop line. Pre-signals are the appropriate methods for meeting this requirement by prioritising buses behind intersections
- Cars be at a moderate speed and without any stops or with minimum stops behind the pre-signals. This means the initial queue behind the pre-signals must be minimised. More specifically, the initial queue delay (Highway Capacity Manual, 2000) must be minimised at the pre-signals through the objective function proposed in Equation

$$F(x) = \min[d_3] \tag{3.1}$$

-).

Objective function:

$$F(x) = \min\,[d_3] \tag{3.1}$$

Subject to:

$$d_3 = \frac{1800 \times Q_b \times (1+u) \times t}{CT} \tag{3.2}$$

If $v_{car,suggested} \geq 5\, km/h$ then $Q_b = 0$ (3.3)

where:

T = Duration of analysis period (h)

Q_b = Initial queue at the start of period T (veh),

C = Adjusted lane group capacity (veh/h),

t = Duration of unmet demand in T (h), ($t = 0$ if $Q_b = 0$, otherwise $t = \min[T, \frac{Q_b}{C[1-\min(1, \frac{V}{C})}]$ if $Q_b \neq 0$)

u = Delay parameter ($u = 0$ if $t < T$, otherwise $u = 1 - \frac{CT}{Q_b[1-\min(1, \frac{V}{C})]}$ if $t \geq T$)

$v_{car,suggested}$ = the suggested speed of the car in arterials using the model (km/h)

Some parameters must be identified in order to estimate the suggested speed of cars ($v_{car,suggested}$). These parameters can be found by following the next three steps.

Step 1: Estimate the optimal distance for implementing pre-signals:

At this distance buses could select their desirable lane at the main intersection. Moreover, the AVL used in buses declares their real-time position to private vehicles in order to reduce their speeds due to prioritising them and their selected lane (Shown in Figure 3.1 as d_{bus}). AVL systems ease the implementation of different priority levels based on the presence and headway of buses (Hounsell & Shrestha 2012).

There are several factors that must be considered for estimating this distance. These factors are based on the movements of buses as they change lanes and reach the stop line of the main intersection. In this research, the distance for implementing pre-signals (d_{bus}) is obtained by modifying the distance proposed by Guler & Menedez (2015). They assumed that a bus stopped at the pre-signal so its initial speed needed to move towards the main intersection was zero. However, in this research the buses do not stop at pre-signals and they reach the main intersection with an initial speed. It is also assumed that buses change their lane and arrive at the main intersection when the traffic signal is red. Therefore, d_{bus} can be calculated by Equation).

$$d_{bus} = [(c - r_{ms})_1 \times (\frac{C}{k_{jam}} - v_1) + (c - r_{ms})_2 \times (0 - \frac{C}{k_{jam}})] \times 1000 \quad (3.4)$$

where:

d_{bus} = Distance between the pre-signal and the main intersection (m)

c = Common cycle length of the traffic signal (h)

r_{ms} = Duration of red at the traffic signal (h)

C = Total capacity across all lanes at the main signal (veh/h)

k_{jam} = Jam density (density at zero speed) (veh/km)

$\frac{C}{k_{jam}}$ = Speed of moving bus changing lanes and reaching the intersection

v_1 = Initial speed of Bus, which is not zero

$(c - r_{ms})$ = Duration of Green traffic signal,

$(c - r_{ms})_1$ = The time required for buses to change lanes at an initial speed of v_1

$(c - r_{ms})_2$ = The time required for buses to reach the stop-line at a speed of $\frac{C}{k_{jam}}$

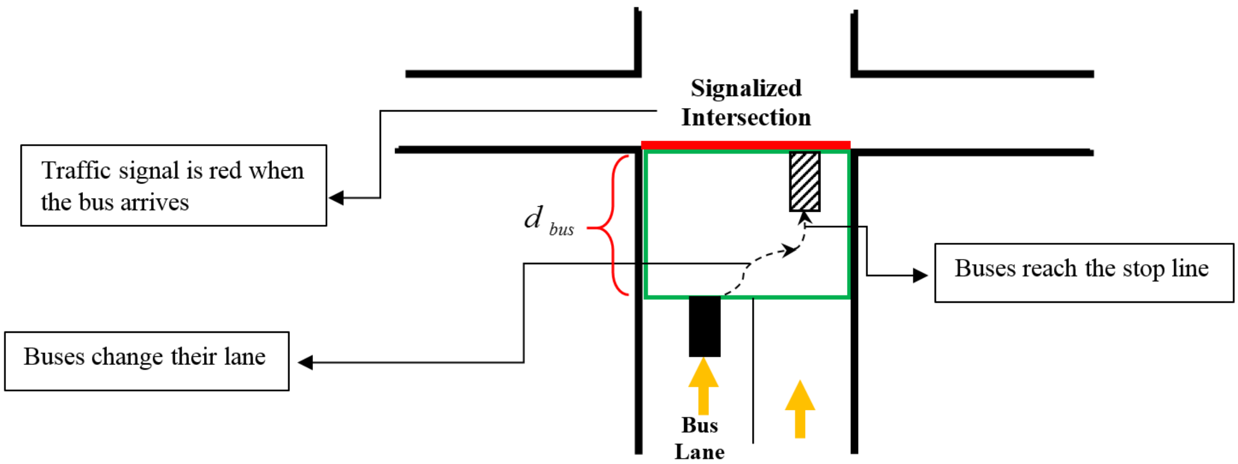


Figure 3.1 - The buses' approach for changing lane and reaching the stop line

Step 2: Determine the distance between cars and intersection for installing a VMS to give a car real-time information about its appropriate speed:

The distance required allows the lead vehicle to either increase or decrease its speed, in other words, the distance needed to moderate and/or justify its speed in a critical traffic situation. This distance (Equation (3.5)) is related to the distance between bus and intersection, and the drivers' reaction time and their current speed, which means the distance from the pre-signal (d_{bus}) estimated in Equation (3.4) must be added to this distance. The details are shown in Figure 3.2.

To calculate the distance Equations (3.5) and (3.6) are presented:

$$x = \frac{vt_{reaction}}{3.6} \tag{3.5}$$

$$d_{VMS} = x + d_{bus} \tag{3.6}$$

where:

$v_{current}$ = Speed of the lead vehicle, which is assumed to be constant and based on the road rules (km/h)

$t_{reaction}$ = Reaction time once the lead vehicle decides to change speed (s), which is assumed 2 s

x = Distance between the lead vehicle and the pre-signal

d_{VMS} = The essential distance between the lead vehicle and the intersection, which is required for the lead vehicle to stop the car in a critical situation (m).

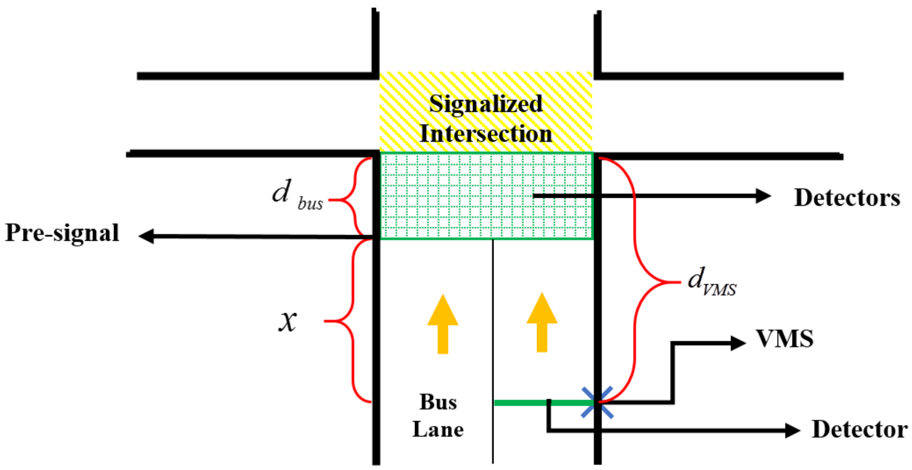


Figure 3.2 - The schematic intersection components

Step 3: Optimise the speed of vehicles before reaching pre-signals for the sake of reducing their number of stops:

To minimise the number of stops for cars, the speed and initial queue delay are considered. Alleviating private vehicle stops is done by controlling their speed, this also eliminates their initial queue delay. When a bus arrives at d_{bus}, cars would be notified that it is about change lanes. As mentioned above, cars are notified earlier in d_{VMS}, so they have the opportunity to speed according to bus travel time, speed, selected lane, d_{bus}, traffic signal timing, whether it is red or green, and the speed of the bus while crossing the intersection. These factors are used to estimate the desired arrival time for cars, and then its speed can be calculated according to the distance d_{VMS}.

In order to estimate the speed of the vehicle, and consequently the following vehicle, equations shown below are used:

$$t_B = Max\,[t_{bus}, r_{ms}] \tag{3.7}$$

$$t_{bus} = \frac{3.6 d_{bus}}{v_{bus}} \tag{3.8}$$

where:

t_B = A bus's travel time according to the traffic signal timing (s)

t_{bus} = A bus's travel time (for changing lanes) to pass the area behind the stop line (s)

d_{bus} = The distance between the pre-signal and the main intersection (m)

v_{bus} = A bus's mean speed close to the intersection (km/h)

r_{ms} = Duration of red time in traffic signal (s)

$$t_{car} = \frac{3.6 d_{VMS}}{v_{car,current}} \tag{3.9}$$

t_{car} = A car's travel time to reach the intersection (s)

d_{VMS} = The proposed distance for installing the VMS (m)

$v_{car,current}$ = A car's mean speed in arterials (km/h)

$$t_C = t_B + t_{car} \tag{3.10}$$

t_C = A car's travel time according to the leading traffic condition (s)

$$v_{car,suggested} = \frac{d_{VMS}}{t_C} \times 3.6 = v_{lead} \tag{3.11}$$

$v_{car,suggested}$ = The suggested speed of a car on arterial roads according to the leading traffic condition, and in terms of buses changing their lanes and traffic signal timing (km/h)

The suggested speed for private vehicles estimated in Equation (3.11), $v_{car,suggested}$, is the speed of the leading vehicle. As a result, private vehicles are informed about traffic conditions prior to reaching an intersection, and they are notified of the appropriate speed. Consequently, not only would the number of stops for private vehicles be reduced, buses would be prioritised to select their approach.

The point is that a VMS should be installed in the best place to inform private vehicles of an appropriate distance, even in critical traffic conditions. Traffic conditions are influenced by the following factors:

- The distance at which private vehicles travel in front of the lead vehicle
- A bus travelling in the bus lane changes its lane in d_{bus} distance, or keeps moving in its lane
- Considering time and type of traffic signal in terms of the duration time of red or green.

The speed depicted in the VMS must be updated when traffic signals change from red to green or vice versa.

3.2. The procedure of the TIQ Model

In this section, a model is proposed that will improve the performance of intersections equipped with pre-signals by minimising the time-in-queue per vehicle located behind a pre-signal. To achieve this goal, an appropriate speed for arriving vehicles with the minimum time they will spend in the queue behind pre-signals must be estimated, that is, minimise vehicles' time-in-queue based on the equation presented in the Highway Capacity Manual (HCM 2000).

Objective function:

$$F(x) = \min\,[d_{vq}] \tag{3.12}$$

Subject to:

$$d_{vq} = (I_s \times \frac{\sum V_{iq}}{V_{tot}}) \times 0.9 \tag{3.13}$$

$$v_{car,suggested} \geq 5\ km/h \tag{3.14}$$

In Equation (3.13), d_{vq} is the time-in-queue per vehicle (s), I_s is the interval between vehicle-in-queue counts (veh), $\sum V_{iq}$ is the sum of vehicle-in-queue counts (veh), V_{tot} is the total number of vehicles arriving during the survey period (veh), and 0.9 is the empirical adjustment factor.

The next phase is to estimate an appropriate speed at which private vehicles should arrive at pre-signals. Thus the optimal distance for applying pre-signals (d_{bus}), and the distance at which a Variable Message Sign (VMS) can inform cars about their speed (d_{VMS}) must be calculated using the Equations (3.15), (3.16) and (3.17) proposed in the previous part.

$$d_{bus} = [(c - r_{ms})_1 \times (\frac{C}{k_{jam}} - v_1) + (c - r_{ms})_2 \times (0 - \frac{C}{k_{jam}})] \times 1000 \tag{3.15}$$

In this equation, d_{bus} is the distance between the pre-signal and the main intersection (m), c is the common length of traffic signal cycle (h), r_{ms} is the duration of red at the traffic signal (h), C is the total capacity across all lanes at the main signal (veh/h), k_{jam} is the jam density (density at zero speed) (veh/km), $\frac{C}{k_{jam}}$ is the speed at which buses move to change lanes and reach the intersection, v_1 is the initial speed of the bus (which is not zero), $(c - r_{ms})$

is the green time, $(c - r_{ms})_1$ is the time buses need to change lanes with an initial speed of v_1, and $(c - r_{ms})_2$ is the time buses need to reach the stop-line with a speed of $\frac{C}{k_{jam}}$.

$$x = \frac{v_{current} t_{reaction}}{3.6} \tag{3.16}$$

$$d_{VMS} = x + d_{bus} \tag{3.17}$$

In this equation, $v_{current}$ is the speed of the lead vehicle, which is assumed constant and based on the road rules (km/h), $t_{reaction}$ is the reaction time of the lead vehicle once it decides to change its speed (s), which is assumed to be 2 s, x is the distance between the lead vehicle and the pre-signal, d_{VMS} is the essential distance between the lead vehicle and the intersection, which the lead vehicle needs to stop in a critical situation (m) (Schematised in Figure 3.2).

Using d_{bus} and d_{VMS}, the appropriate speed for private vehicles can be calculated. This speed can be optimised by minimising the amount of time-in-queue for each vehicle. In other words, the time-in-queue of vehicles arriving at the pre-signal is reduced by adjusting their speed, based on the arrival time of the bus and traffic conditions before the intersection. Moreover, since they must be informed about their operating speed by VMS, they can then move at the suggested speed from the VMS point to the pre-signal to minimise their time-in-queue behind the pre-signal.

In order to estimate the speed of private cars, the equations proposed by Ghanbarikarekani *et al*. (2018) are applied.

$$v_{car,suggested} = \frac{d_{VMS}}{t_C} \times 3.6 \tag{3.18}$$

While $v_{car,suggested}$ is the suggested speed of cars in arterials according to the leading traffic conditions in terms of the existence of buses changing their lanes and traffic signal timing (km/h).

And t_C is a car's travel time according to the leading traffic condition (s) that could be calculated by Equation (3.19).

$$t_C = t_B + t_{car} \tag{3.19}$$

t_B is a bus's travel time according to traffic signal timing (s), and t_{car} is a car's travel time to reach the intersection (s), which are computed through Equations (3.20) and (3.21) respectively.

$$t_B = Max\,[t_{bus}, r_{ms}] \tag{3.20}$$

$$t_{bus} = \frac{3.6 d_{bus}}{v_{bus}} \tag{3.21}$$

$$t_{car} = \frac{3.6 d_{VMS}}{v_{car,current}} \tag{3.22}$$

t_{bus} is the bus's travel time (for changing its lane) to pass the area behind the stop line (s), d_{bus} is the distance between the pre-signal and the main intersection (m), v_{bus} is the bus's mean speed near the intersection (km/h), r_{ms} is the duration of red in the traffic signal (s). $v_{car,current}$ is the car's mean speed in arterials (km/h), and d_{VMS} is the distance proposed to install the VMS (m).

3.3. Results and Discussion

In order to test the influence of the proposed IQD and TIQ models on the bus pre-signal's performance, the proposed models are analysed on a simple intersection with hypothetical traffic data compatible to the real-world intersection, presented in sections 3.3.1 and 3.3.2. Afterwards, Section 3.3.3 compares the efficiency of IQD with the TIQ model. A hypothetical, real-world test case was used for evaluation and comparison to provide overarching analysis that could be applied to specific cases in practice. This offers a more generic practical contribution that can be referred to by researchers and practitioners alike in the future.

3.3.1. IQD Model Tested on the Study Intersection

The proposed model would be analysed numerically by using a signalised intersection equipped with a pre-signal system both before and after implementing the model. Moreover, vehicle delays could be estimated in the cases mentioned, and thus the desirability of the model would be demonstrated by comparing the results. In order to analyse this model, some assumptions have been made and they are presented in Table 3.1. More specifically, the length of the signal cycle is 60 s, and the ratio of green time to cycle length (g/c) is 0.5. The density and capacity of the arterial roads are 100 veh/km and 800 veh/h respectively, and the proportion of traffic flow to capacity (V/C) is 1. The speed of buses and cars are hypothetically 20 km/h and 40 km/h before implementing the model.

The essential distance for buses to change lanes before an intersection (d_{bus}), and the distance required between the lead vehicle and the intersection for installing VMS (d_{VMS}) could be calculated using the parameters mentioned (assumed in Table 3.1) and the equations proposed in the previous section. However, the suggested speed and travel time of cars are estimated to be shown on VMS.

Table 3.1 - Assumptions for parameters used in the model

Parameters	Values (current situation)	Values (after implementing the model)
Duration	1 h	1 h
Number of buses	12	12
Number of cars (V)	800 veh	800 veh
Bus headway	300 s	300 s
Car headway	4.5 s	4.5 s
Cycle length (c)	60 s	60 s
Red duration (r_{ms})	30 s	30 s
Capacity (C)	800 veh/h	800 veh/h
Jam density (K_{jam})	100 veh/km	100 veh/km
Initial speed of bus (V_{1b})	20 km/h	20 km/h
Initial speed of car (V_{1c})	40 km/h	40 km/h
Green duration (G)	30 s	30 s
Time for bus to change lane	15 s	15 s
Time for bus to reach the stop line	15 s	15 s
Capacity/Density	8	8
d_{bus}	83.33 m	83.33 m
Distance of VMS for car (x)	--	22.22 m
Reaction time (t)	2 s	2 s
d_{VMS}	--	106 m
Bus travel time (t_{bus})	15 s	15 s
Suggested travel time of bus (t_B)	30 s	30 s
Car travel time (t_{car})	--	9.5 s
Suggested travel time of car (t_C)	--	39.5 s

Parameters	Values (current situation)	Values (after implementing the model)
Suggested speed of car ($V_{car, suggested}$)	--	9.62 km/h
Traffic flow (V)	800 veh/h	800 veh/h
X (V/C)	1.00	1.00
Initial queue ($Q_{(b)}$)	10 veh	0 veh
Uniform delay ($d_{(1)}$)	15s	15s
Incremental delay ($d_{(2)}$)	64 s	64 s
Progression adjustment factor (PF)	1.667	1.667
Initial queue delay ($d_{(3)}$)	22.5 s	0 s
Delay	111.14 s	88.64 s
Travel time bus	126.14 s	103.64 s
Travel time car	150.64 s	128.14 s
g/c	0.5	0.5
Average car occupancy	2 p	2 p
Delay/person	55.57 s/pp	44.32 s/pp

The most important difference between the current situation and applying the proposed model is forming a queue of vehicles behind pre-signals as the red signal is imposed on cars. This issue would cause initial queue delays if pre-signals are implemented without any modification, in fact there would be a huge increase in the number of delays. This means that implementing the model would eliminate the need for cars to stop behind the pre-signal, therefore car delays and per person delays related to the additional stops would be alleviated. As shown in Table 3.1, delays have been reduced by 20% by implementing the model where V/C=1 and g/c=0.5. This would illustrate how efficiently the model can alleviate delays to both cars and people.

To carry out a numerical analysis of the model, the fluctuation of g/c and V/C should be considered, and its influence on car delays would be determined. Figure 3.3 shows the number of delays in the current situation and after implementing the model at g/c=0.5 and different V/C ratios.

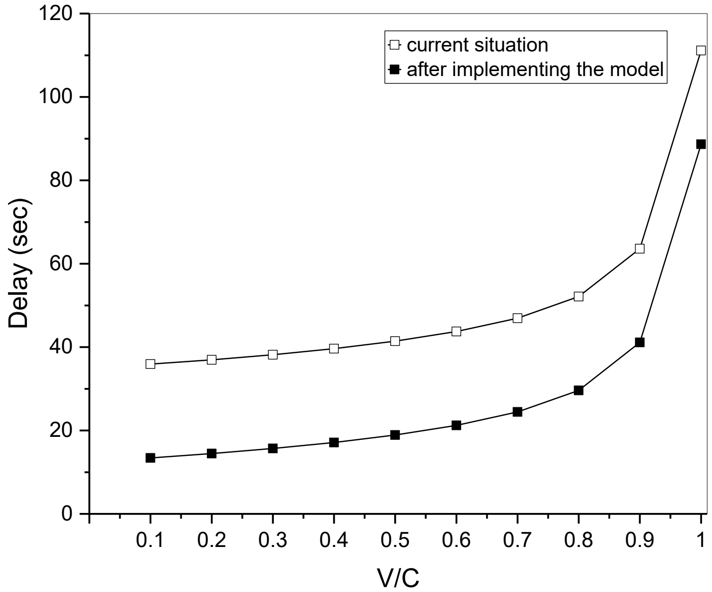


Figure 3.3 – Comparison of private vehicle delays for the current situation and the proposed pre-signal's model with different V/C ratios at g/c=0.5

As shown in Figure 3.3, implementing the proposed model has reduced the delays in all the V/C ratios. It must be mentioned that the percentage by which delays have improved decreased as the ratio of V/C increased. In other words, the number of delays reduced by 63% under saturated conditions, whereas it is 20% more over the saturated one.

3.3.2. TIQ Model Tested on the Study Intersection

A sensitive analysis of the proposed model will be done in this section to investigate the efficiency of applying the algorithm. To this end the hypothetical values presented in Table 3.2 are used.

Table 3.2- Hypothetical values of parameters used in the model

Parameters	Values (current situation)	Values (after implementing the model)
Number of cars (V)	800 veh	800 veh
Car headway	4.5 s	4.5 s
Cycle length (c)	60 s	60 s
Red duration (r_{ms})	30 s	30 s
Capacity (C)	800 veh/h	800 veh/h
Jam density (K_{jam})	100 veh/km	100 veh/km
Initial speed of bus (V_{1b})	20 km/h	20 km/h
Initial speed of car (V_{1c})	40 km/h	40 km/h
Green duration (G)	30 s	30 s
Time for bus to change lane	15 s	15 s
Time for bus to reach the stop line	15 s	15 s
Capacity/Density	8	8
d_{bus}	83.33 m	83.33 m
Distance of VMS for car (x)	--	22.22 m
Reaction time (t)	2 s	2 s
d_{VMS}	--	106 m
Bus travel time (t_{bus})	15 s	15 s
Suggested travel time of bus (t_B)	30 s	30 s
Car travel time (t_{car})	--	9.5 s
Suggested travel time of car (t_C)	--	39.5 s
Suggested speed of car ($V_{car,suggested}$)	--	10 km/h
Traffic flow (V)	800 veh/h	800 veh/h
X (V/C)	1.00	1.00
Interval between vehicle in queue I_s	4.5 (s)	4.5 (s)
Sum of vehicle in queue V_{iq} (veh)	640	154
Total number of vehicle arriving during the survey V_{tot}	200 (veh)	200 (veh)
Empirical adjustment factor 0.9	0.9	0.9
Time in queue d_{vq}	12.96 (s)	3.12 (s)
g/c	0.5	0.5

From this data parameters such as d_{bus}, d_{VMS} and $v_{car,suggested}$ and d_{vq} can be determined and then the time-in-queue would be estimated before and after implementing the proposed model. In the end, the efficiency of the algorithm can be investigated by comparing the time-in-queue value in the current situation with its value after utilising the suggested algorithm. This comparison is shown in Figure 3.4.

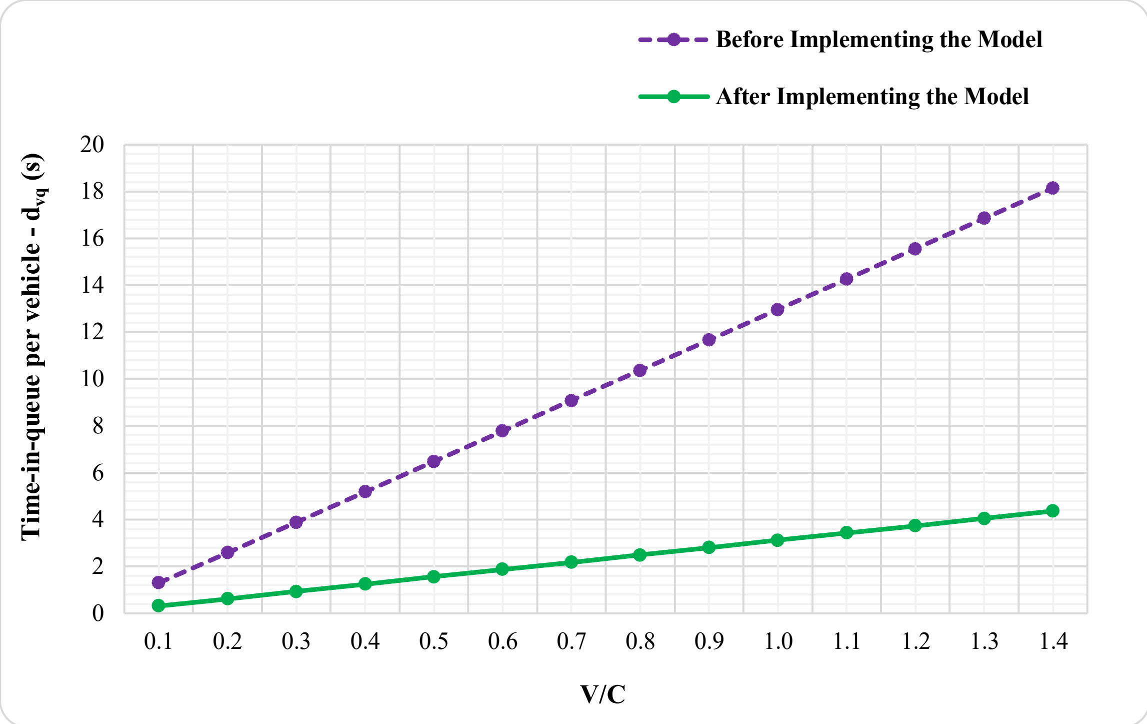


Figure 3.4 - Comparison of each vehicle's time-in-queue before and after implementing the proposed model in different V/C ratios

As shown in Figure 3.4, the proposed model has reduced the time-in-queue at all the V/C ratios, and this reduction was much higher in higher V/C ratios. In other words, in oversaturated traffic conditions the time-in-queue decreased much more than for under-saturated conditions.

3.3.3. Comparison of IQD Model and TIQ Model

Prioritising public transport vehicles is now considered to be a good response to traffic congestion, but while pre-signals at signalised intersections prioritise buses, they cause private vehicles to stop more frequently, which obviously lengthens their travel time.

This research aims to eliminate the problem of having cars make additional stops behind pre-signals by moderating the speed at which they approach the stop line of pre-signals. To achieve this aim, two models were suggested to compute the speed of cars that are reaching the pre-signals. The first model (IQD) finds the speed of cars by minimising the initial queue delay behind the pre-signal, while the second model (TIQ) estimates the reducing speed of private vehicles by minimising the time-in-queue of cars at pre-signals. These models have been presented and analysed numerically.

The initial queue delay and time-in-queue parameters found from these models have been utilised to estimate the appropriate speed of cars. These parameters incorporate the essence of delay, so the result of applying these models can be compared to each other.

The IQD model helped to reduce delays in all the V/C ratios, much more in under- saturated conditions (where V/C is under 0.9) than in over- saturated conditions (where V/C is greater than 0.9). In other words, the IQD model is better in under- saturated traffic conditions. The TIQ model reduced the time-in-queue behind the pre-signals in over- saturated and under-saturated traffic conditions. While the performance of the TIQ model is more consistent across over- and under-saturated conditions in contrast to the IQD model, it is more efficient in higher V/C ratios.

3.4. Conclusion

Installing bus pre-signals behind signalised intersections is one of the strategies suggested for improving public transport to encourage people to not use their cars. Pre-signals are installed in advance of intersections to give private cars a red signal and warn buses to select their lane as they approach behind the main intersection. In this way, conflict between cars and buses while discharging at an intersection is eliminated, and the priority for being in the first line of the queue and discharging at an intersection is given to buses. Since buses carry more people, their overall delay and travel time has decreased considerably. This strategy reduces the delay and travel time of buses, and also increases their speed. However, cars are not considered, because they are further delayed and given additional stops behind the pre-signal. More specifically, installing pre-signals enhances the functionality of buses by giving them priority and eliminating, or at least alleviating, probable conflicts between them and cars. However, it creates a deterioration in the performance of private vehicles because it increases the number of times they have to stop.

This study aims to develop this relatively modern method of pre-signals by proposing two models. The first model aims to minimise the number of stops private vehicles must make behind pre-signals, and thus optimise their speed and travel time by reducing the delay. This will be achieved by simultaneously prioritising buses while enhancing car performance by minimising the number of times that cars need to stop behind pre-signals. The approach of this model is to balance the speed of cars according to a buses' destination and traffic signal timing, both of which would reduce the delay of cars considerably. The second model seeks to minimise the time-in-queue of private vehicles behind pre-signals by determining the appropriate speed of cars as they approach a pre-signal in order to minimise their time-in-queue, and their delay, stopping time and travel time. The results in Section 3.3.3 indicate that the proposed model reduced the time-in-queue of private vehicles behind a pre-signal, which means their functionality has improved. Moreover, this model led to higher V/C ratios than smaller V/C ratios. In other words, this algorithm could improve the performance of cars in over-saturated traffic conditions much more efficiently than in under-saturated ones.

Chapter 4 – Novel Light Rail Vehicle Signal Prioritisation Algorithm Development and Modelling

Section 1.2.2 explained the traditional Transit Signal Priority (TSP) system applied to traffic lights to provide public transport priority and its drawbacks imposed on cars. This chapter proposes an algorithm added to TSP at Light Rail Vehicle level crossings in order to eliminate disadvantages of TSPs. This algorithm is based on optimising the speed of the LRVs approaching the traffic light equipped with the TSP. The methodology and structure of the algorithm named Speed Optimisation of Light Rail Vehicle (SOLRV) is recounted in this section. In addition, the SOLRV algorithm testing on both hypothetical and a real traffic network is presented as well as its numerical analysis.

4. NOVEL LRV SIGNAL PRIORITISATION ALGORITHM DEVELOPMENT AND MODELLING

Figure 4.1 shows the methodology used to develop the novel TSP algorithm, SOLRV. This process involved iterations of formulating and testing the algorithm and stakeholder engagement actions, which led to the development of a finalised algorithm with the potential for field implementation. Existing formulations of TSP combined with recent literature were also used to formulate the algorithm that was then tested using microsimulation modelling. This formulation and testing was presented to Transport for New South Wales (TfNSW) and other key stakeholders throughout its development, and modifications were made through an iterative process until the algorithm was finalised well enough to be applied in practice. The following sub-sections provide additional methodological details of each stage.

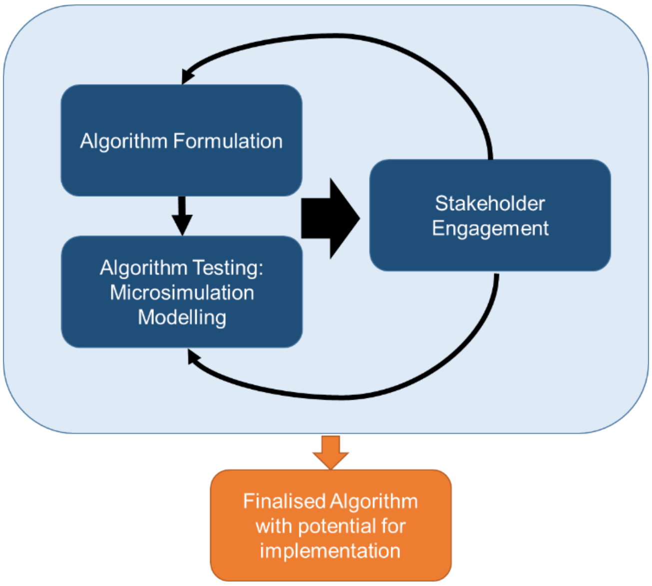


Figure 4.1 - Flow chart describing methodology used to develop novel TSP algorithm, "Speed Optimisation of Light Rail Vehicle" (SOLRV)

The SOLRV algorithm builds upon the traditional TSP algorithms that are described in the literature and applied in practice. Specifically, SOLRV draws foundational inspiration from the work of Asim *et al.* (2012) and Islam *et al.* (2016) who considered the arrival times of public transport vehicles in adaptive signal control systems. Figure 4.2 shows the key changes to the traditional TSP process that was included in the SOLRV process (highlighted in dark blue). Instead of actioning a green-extension or red-reduction based on the need for priority, the novel algorithm is first used to modify vehicle speed (speed optimisation) to gauge whether it is possible to avoid modifying signal timing, If the adjustment in speed is inadequate, a green-extension or red-reduction phase adjustment is executed. This additional step can reduce the instances and duration of phase adjustments within the signal timing, which then reduces delays for other road users. Further details of the SOLRV formulation and application are presented in Chapter 4 of this thesis.

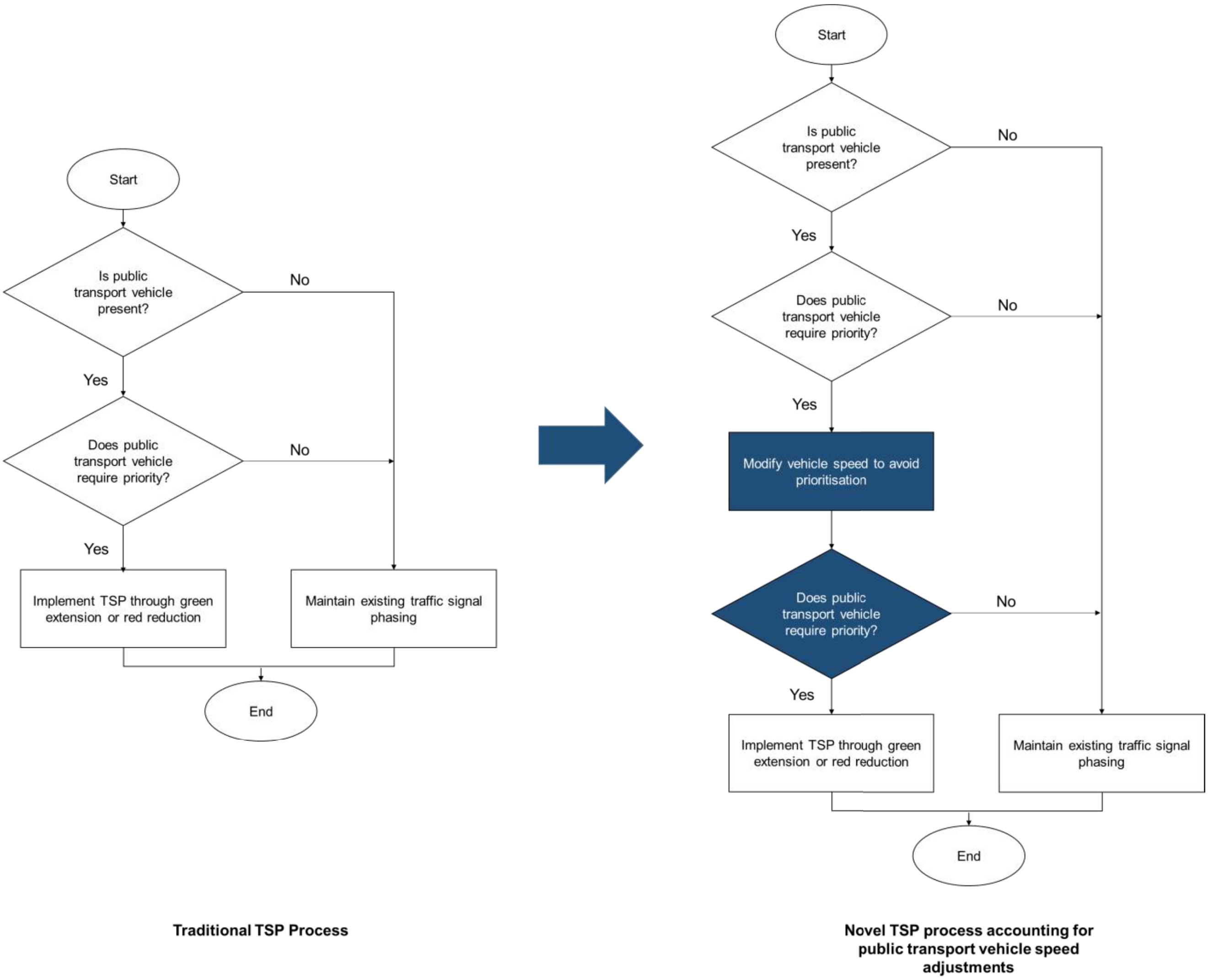


Figure 4.2 - Comparison between traditional TSP procedures and the novel TSP procedure that accounts for adjustments in speed (basis of SOLRV)

4.1. Stakeholder Engagement

Implementing public transport prioritisation algorithms requires the cooperation and support of transport agencies such as TfNSW, technical contractors and the algorithm development team. Accordingly, stakeholder engagement was vital throughout the study to ensure that the finalised algorithm presented in this thesis is on a pathway to potential future implementation. In addition to project planning and update meetings with TfNSW project managers and technical staff, two formal workshops were held to disseminate the progress and findings of the study and obtain feedback to enhance the algorithm and testing. As Figure 4.1 shows, stakeholder engagement assisted in the iterations needed to develop the algorithm.

The formal workshops included:

- **Workshop 1**: the novel TSP algorithm and the microsimulation modelling results of the Newcastle Intersection Case Study were presented. It provided an opportunity for practitioners and other key stakeholders to identify the key performance metrics deemed necessary for assessment within future microsimulation modelling exercises, and it also assisted in developing a road map for potential future integration with SCATS (see Section 8).
- **Workshop 2**: presented the overall findings of the study and provided further input to the roadmap for future potential integration with SCATS.

Unfortunately, due to COVID-19, Workshop 2 was modified to an online event with a questionnaire survey filled out by technical experts and project managers commenting on the value of and improvements to the study.

4.2. SOLRV Algorithm Formulation

The Speed Optimisation of Light Rail Vehicle (SOLRV) algorithm aims to improve traditional TSP applications by reducing delays for other road users (specifically private vehicles) while maintaining priority for light rail vehicles. To this end, the optimum speed of an arriving LRV is determined as a means of minimising green extensions and red reductions. The speed adjustment of LRVs is calculated based on the duration of the signalling phase at the time the LRV is detected. The detector is located at a specific distance from the stop-line, which is consistent with the required stopping distance for the vehicle. After reducing its speed, an LRV would reach the stop-line where the green-extension or red-reduction applied at the intersection would be minimised whilst still giving the LRV priority. This means that other vehicles on other approaches would not be penalised and their dwell time and delay would be minimised.

The functionality of the SOLRV algorithm depends on having an upstream detector installed, which can detect an LRV before it approaches the stop line. The detector must be located a set distance upstream of the stop-line in order to adjust and implement the speed of the arriving LRV (As shown in Figure 4.3).

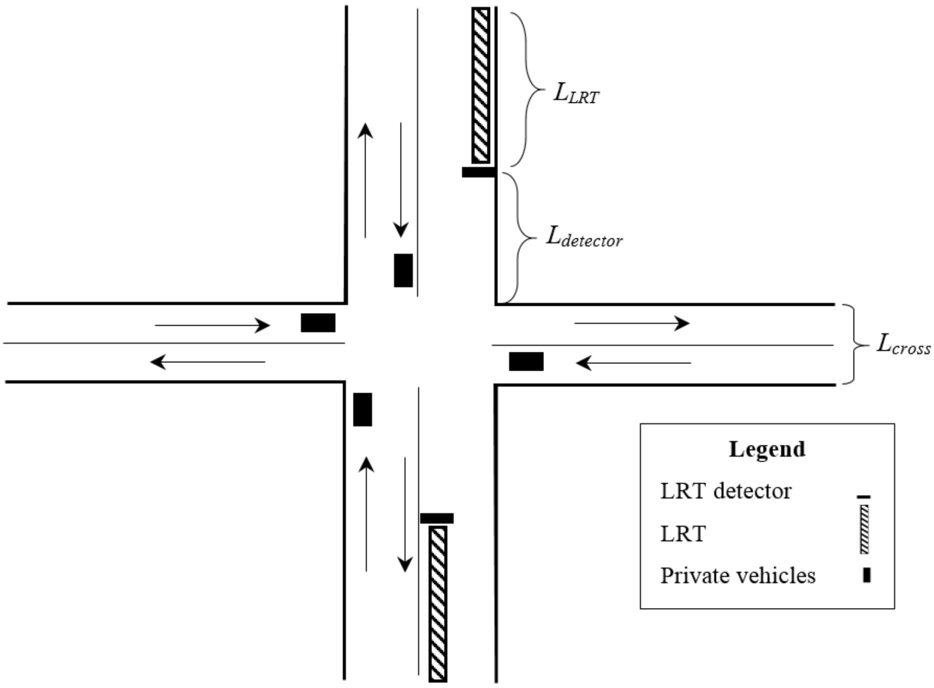


Figure 4.3 - The positioning of the LRV's detectors upstream of the stop-line on LRV route

Several parameters must be determined to formulate the SOLRV algorithm using the procedure shown in Figure 4.4. These Parameters are as follows:

1. The location at which the LRV detector is installed ($L_{detector}$)

$$L_{detector} = Max\,[\frac{V^2_{Max,LRV} - V^2_{current,LRV}}{2a_{LRV} \times 3.6^2}, \frac{V^2_{\min,LRV} - V^2_{current,LRV}}{2a_{LRV} \times 3.6^2}] \tag{4.1}$$

where $L_{detector}$ is the distance (m) needed from the stop-line to install an LRV detector, a_{LRV} is the usual acceleration and deceleration of LRV systems (m/s2) assumed 1.32 m/s2 (RTSA presentation, 2014), $V_{Max,LRV}$ is the maximum speed of LRV systems (km/h), it is assumed to be 30 km/h, $V_{min,LRV}$ is the minimum speed of LRV systems (km/h), it is assumed to be 10 km/h, and $V_{current,LRV}$ is the current speed of LRV systems (km/h) at the time the LRV has been detected.

2. The LRV phase state when the LRV has been detected, regardless of whether the phase is green (G_{LRV}) or red (R_{LRV})
3. The time remaining for the green (G_{LRV}) or red (R_{LRV}) signal as the LRV passes through the upstream detector; this is determined as the percentage of total duration of green or red. (α and β are respectively the percentage duration of green and red in the LRV phase once an LRV passes the detector)
4. t_1 is the time required (s) for the LRV to increase/decrease its speed in order to pass the intersection within the remaining green/red time, including its extension / reduction duration; it is based on the driver's reaction time and is assumed to be 2 s
5. t_2 is the time required (s) for the LRV to pass an intersection with its increased / decreased speed within the remaining green / red time and its extension / reduction
6. L_{LRV} is the length of an LRV (m), which is assumed to be 30 m (Currie and Burke, 2013)
7. L_{cross} is the width of the cross street (m).

There are two conditions that could exist as an LRV approaches a signalised intersection. The signal phasing for LRV movement could be red, meaning a red-reduction alteration would be considered, or the signal phasing for an LRV movement could be green, which would trigger the possibility of including a "green-extension" into the phasing of the intersection.

As shown in Figure 4.4, the SOLRV algorithm is based on the remaining green or red time of the signal phasing for the movement of an LRV when it is detected upstream of the intersection. After optimising the speed of the LRV and using the remaining green or red time, the algorithm will determine the green-extension or red-reduction needed to give the LRV priority at the intersection. These calculations differ depending on whether a green-extension or red-reduction is required. This is described in more detail in the following sections of this thesis.

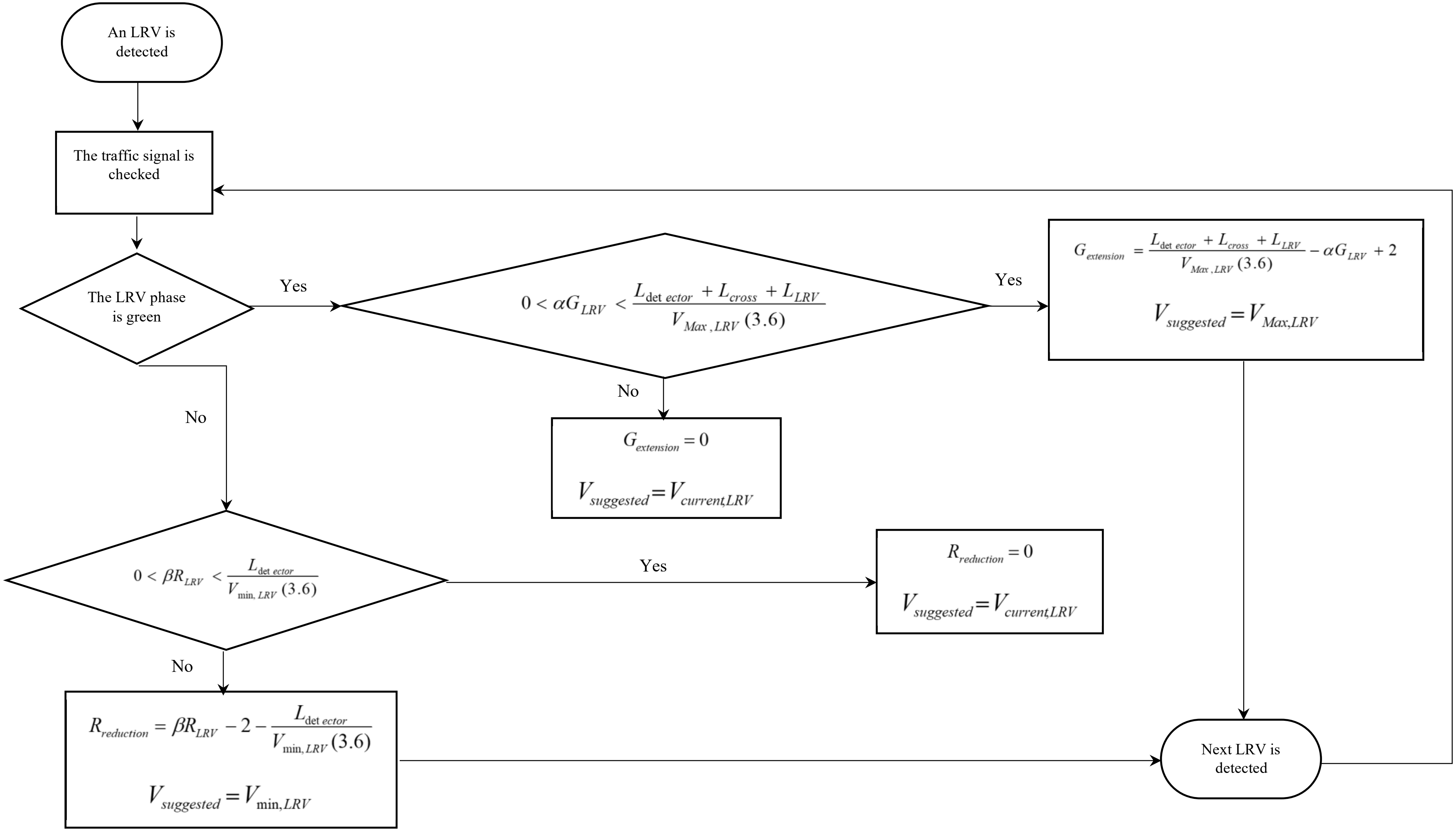


Figure 4.4 - SOLRV algorithm flow chart - Real-time control procedure for prioritising LRVs at signalised intersections

4.2.1. Green extension

This section contains the procedure used to calculate an optimal speed for LRVs approaching signalised intersections to minimise "green-extension" prioritisation. Note that this strategy is utilised when the phase of the light rail is green once an LRV has been detected. The formulation is presented as follows:

Objective function:

$$F(x) = \min\,[G_{extension}] \tag{4.2}$$

Subject to:

$$10\ km/h \le V_{suggested} \le 30\ km/h \tag{4.3}$$

$$0 \sec \le G_{extension} \le 20 \sec \tag{4.4}$$

In order to calculate the speed of an LRV to minimise the green extension, the time the LRV needs to pass through the intersection from the detector must be determined. This travel time consists of the time needed for the LRV to increase its speed at the detector (the drivers' reaction time), and the time needed to continue at the speed suggested to pass the intersection.

$$\frac{1}{2}at_1^2 + V_0 t_1 + V_{suggested}\, t_2 = L_{detector} + L_{cross} + L_{LRV} \tag{4.5}$$

$$t_1 + t_2 = \alpha\, G_{LRV} + G_{extension} \tag{4.6}$$

As shown in Equation (4.6), an LRV would pass the intersection in the remaining green time and in an acceptable green extension. Using Equations (4.5) and (4.6) and the maximum speed of LRVs results in a formula for calculating the green extension, as presented in Equation (4.7).

$$G_{extension} = \frac{L_{detector} + L_{cross} + L_{LRV}}{V_{Max,LRV}\,(3.6)} - \alpha\, G_{LRV} + 2 \tag{4.7}$$

To solve the objective function using the Linear Programming (LP) method, two cases are assumed. First, when the duration of the green signal is less than the time an LRV needs to pass through an intersection, the appropriate speed suggested for an LRV would be its maximum acceptable speed of 30 km/h. The amount of green extension for an LRV's phase is calculated using Equation (4.7). Second, if the green time for an LRV is equal to or greater than the time needed to pass through an intersection, it can continue at its current speed and no green extension is required.

4.2.2. Red reduction

Similar to estimating the minimum green extension, reducing the red signal of an LRV's phase is achieved by optimising its speed. This method is applied when an LRV is detected and the phase of LRV movement of the upstream intersection is red.

Objective function:

$$F(x) = \min\,[R_{reduction}] \tag{4.8}$$

Subject to:

$$10\ km/h \le V_{suggested} \le 30\ km/h \tag{4.9}$$

$$0\,\text{sec} \le R_{reduction} \le 20\,\text{sec} \tag{4.10}$$

To determine the speed of an LRV by minimising the duration of red reduction, the time it needs to reach the stop line from the detector is calculated. Therefore, the time needed to reduce the speed of the LRV at the detector and the time required for it to continue on its way to reach the stop line can be estimated.

$$-\frac{1}{2}at_1^2 + V_0 t_1 + V_{suggested}\, t_2 = L_{\det ector} \tag{4.11}$$

$$t_1 + t_2 = \beta\, R_{LRV} - R_{reduction} \tag{4.12}$$

According to Equation (4.12), the time needed for an LRV to reach the stop line is calculated by subtracting the red reduction and the remaining red signal. Using Equations (4.11) and (4.12) and the minimum speed of LRVs, the formula used to calculate the red-reduction is presented in Equation (4.13).

$$R_{reduction} = \beta\, R_{LRV} - 2 - \frac{L_{\det ector}}{V_{\min, LRV}\,(3.6)} \tag{4.13}$$

Similar to the Green Extension model in the previous section, two conditions are presented to solve the objective function using the Linear Programming (LP) method. When the red time is greater than the time an LRV needs to reach the stop line at an intersection, the appropriate speed for an LRV is minimum acceptable speed of 10 km/h. The amount of red reduction for an LRV's phase is calculated using Equation (4.13). Conversely, if an LRV's red time is equal to or less than the time needed to pass through an intersection, the LRV will not need a red-reduction or any change in speed.

The SOLRV approach provides priority irrespective of other road users, so it is an unconditional approach. However, due to speed optimisation, the algorithm minimises the green-extension or red-reduction priority controls, which minimises potential delays for other road users, particularly the dwell time for private vehicles at each leg of an intersection. This formulation can potentially offer a sustainable TSP, which in turn will enhance the performance of the road network as a whole. Chapter 5 and Chapter 6 of the thesis describes how the SOLRV algorithm was applied in a microsimulation environment.

4.3. Numerical Analysis

In order to investigate the influence of the SOLRV algorithm on traffic operating with transit signal priority systems at signalised intersections, an intersection with a transit signal priority for LRVs is presented as an example. For the sake of analysing this model, some parameters have been assumed and they are presented in Table 4.1. More specifically, these assumptions include the duration of remaining green and red time once an LRV passes through the detector, the maximum, minimum and current speed of LRVs, the reaction time of the driver (t_1), the acceleration and braking rates of LRVs, the length of an LRV and the width of the cross street. $L_{detector}$, $G_{extension}$, $R_{reduction}$ and t_2 could be calculated using the parameters mentioned and the equations proposed in the flowchart.

Table 4.1 - Assumptions for parameters used in the model

Parameters	Values
Green duration of the LRV phase (G_{LRV})	30 s
Red duration of the LRV phase (R_{LRV})	90 s
Current speed of LRV (V_0)	20 km/h
$L_{detector}$	15 m
L_{cross}	15 m
L_{LRV}	30 m
t_1	2 s
Suggested speed of LRV ($V_{suggested}$) for green signal	30 km/h
Suggested speed of LRV ($V_{suggested}$) for red signal	10 km/h

According to the parameters in Table 4.1, this model aims to determine the minimum green extension or red reduction of an LRV's phase based on the maximum or minimum speed needed to pass through an intersection. The speed suggested by the model would be the optimum speed for an LRV to pass through an intersection during its minimum green extension or red reduction. Hence, the number of stops, delays, and travel time of private vehicles in other phases would be minimised. Figure 4.5 and Figure 4.6 show the procedure and the result of using this model. They each depict the minimum green extension and red reduction of rail's phase in different green time and red time once an LRV reaches the detector.

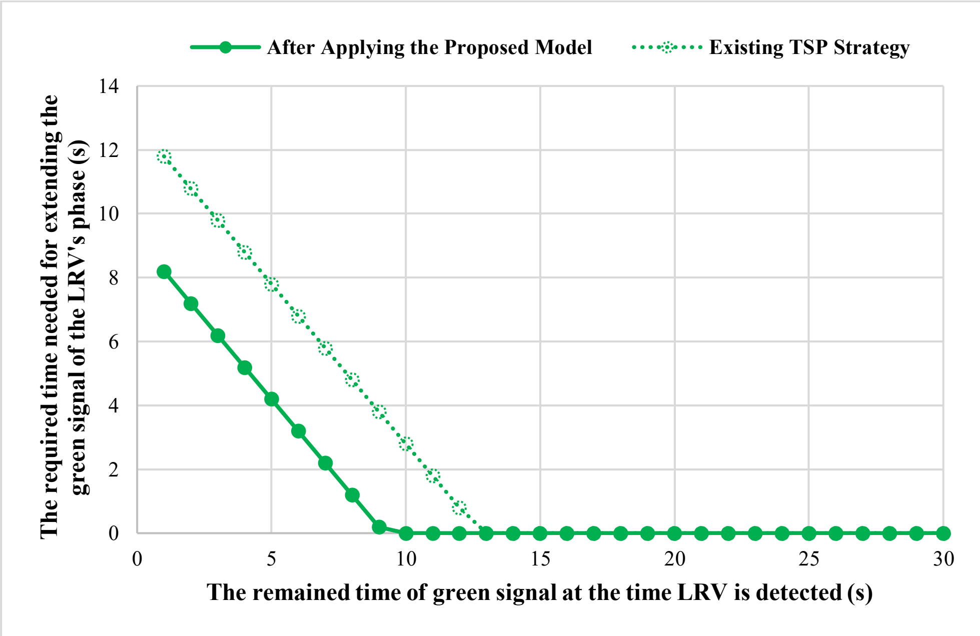


Figure 4.5 - Sample of minimising the green extension of the LRV's phase on its remained green signal and maximum acceptable speed of LRVs using SOLRV algorithm.

Figure 4.5 shows that the maximum extension of the green signal on the LRVs' phase reduced by 33% during the minimum remaining green time by applying the proposed model. Moreover, the minimum time remaining for the green signal when an LRV has been detected means the green extension needs to decrease by 23% by implementing the algorithm. Hence, other traffic modes in other phases would receive less red signal time because the green extension of the LRVs' phase has decreased. Furthermore, the total delay and travel time for the whole intersection has been reduced.

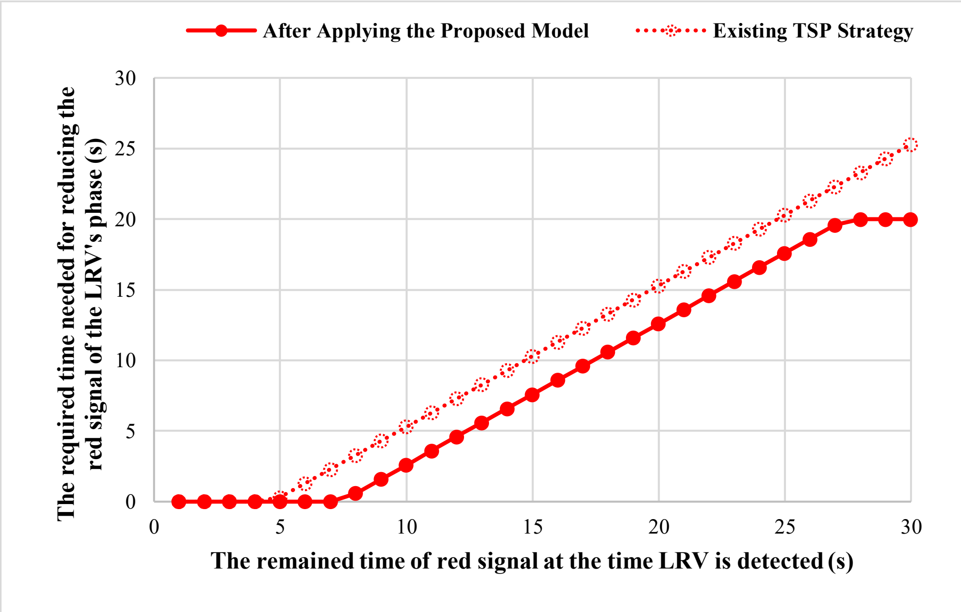


Figure 4.6 - Sample of minimising the red reduction of the LRV's phase on its remained red signal and minimum acceptable speed of LRVs using SOLRV algorithm.

Figure 4.6 shows that as a consequence of applying the suggested algorithm, the need of LRV phase for the maximum amount of red reduction — over the maximum remaining red signal — has been reduced by 20%. The algorithm has enhanced the operation of intersections by reducing the remaining LRVs' red time. This model has also improved the functionality of the intersection by increasing the minimum remaining red time that is needed to change the speed and red reduction. In other words, by changing the speed of an LRV from its current value to its minimum acceptable value, the red reduction must be applied in the higher remaining red signal.

4.4. Algorithm Testing: Microsimulation Modelling

Analytical and operational modelling approaches were considered as potential platforms to test the proposed SOLRV algorithm. This means that microsimulation software, which models individual vehicle movements and is ideal for operational assessment, is an appropriate platform to demonstrate the model. API plugins were developed within the AIMSUN microsimulation software to model both traditional TSP and the SOLRV algorithm, and all the scenarios were modelled on the same microsimulation modelling platform.

The SOLRV algorithm should ideally be tested for a multitude of intersection configurations and light rail corridors, but given the time and resources available, only the following case studies were modelled to evaluate the algorithm:

- **Single Intersection Case Studies**
  - Hunter Street/Darby Street, Newcastle (3-Leg intersection)
  - Hypothetical 4-leg intersection
- **Network Case Study**
  - Newcastle light rail corridor.

These case studies were selected because the data needed to develop the models was available, and it would provide the breadth of testing required to conclusively determine the impact and effectiveness of the SOLRV algorithm. Single intersection testing was essential to evaluate the performance and the functionality of the algorithm. Corridor testing revealed the impact of network wide traffic as a result of applying the algorithm.

The following three operational scenarios were considered for each of the case studies evaluated:

- **Base case scenario:** road infrastructure without any priority system
- **Traditional Transit Signal Priority (TSP) algorithm:** road infrastructure with a traditional TSP algorithm
- **Speed Optimisation of LRV (SOLRV) Algorithm:** road infrastructure with the SOLRV algorithm.

To account for variations in traffic demand, a sensitivity analysis was carried out across the following demand cases:

1. **Existing situation** using collected SCATS data and field survey data for turn proportions
2. **25% increase in demand** relative to the "Existing Situation" case
3. **50% increase in demand** relative to the "Existing Situation" case
4. **100% increase in demand** relative to the "Existing Situation" case.

The procedure for testing the proposed SOLRV algorithm is shown in Figure 4.7.

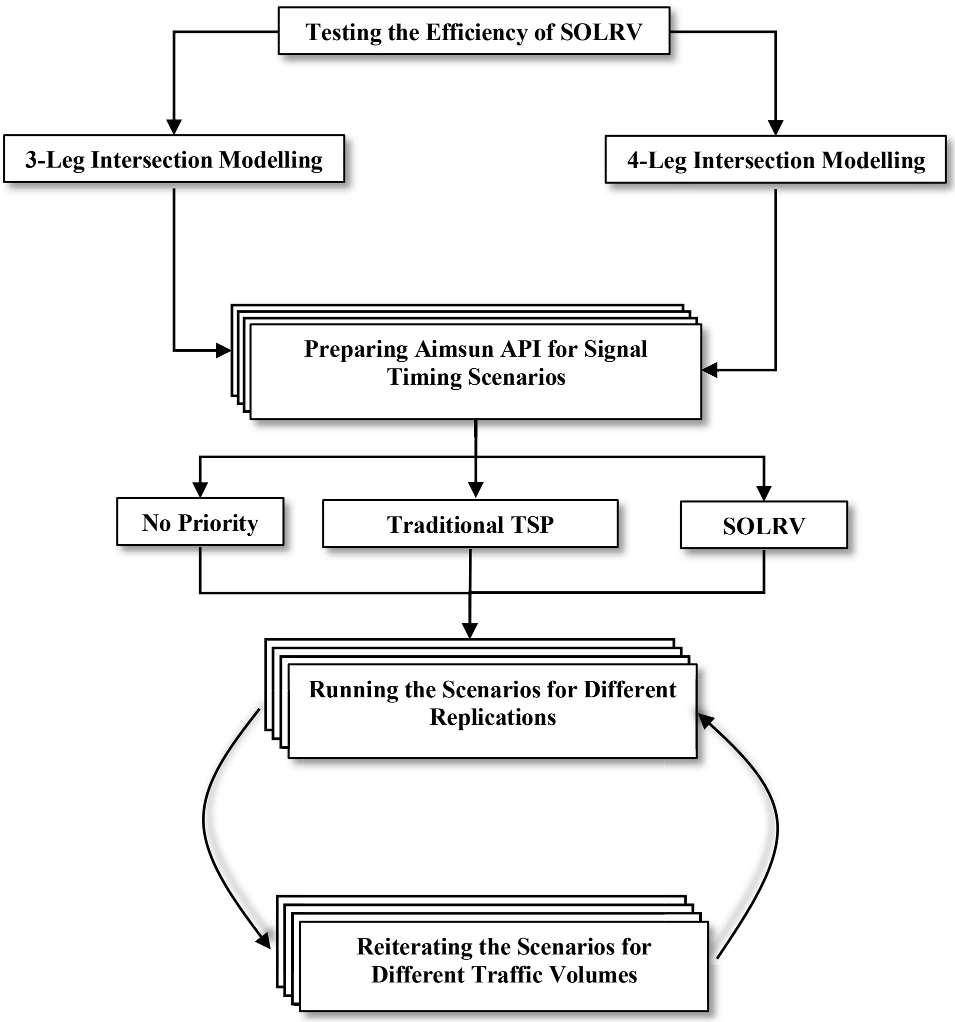


Figure 4.7 – The procedure of testing the SOLRV algorithm.

Finally, to cater for perturbations in traffic operations and variability in demand profiles, Road and Maritime Services (RMS) suggested modelling the five "seed" values presented in

Table 4.2. The stability of results across the seeds indicates reliability in the modelling outputs, and the average performance metrics across the seed values were used to describe the overall modelling results.

Table 4.2 - The seed values suggested by RMS (RMS Modelling Guideline, 2013)

Seed Order Number	Seed Value
1	560
2	28
3	7771
4	86524
5	2849

4.5. SOLRV Algorithm Application: Single Intersection Case Study

The formulated SOLRV algorithm was implemented by using an API plug-in specifically scripted to satisfy the requirements of the AIMSUN software platform. The first set of algorithm testing was completed on two signalised intersections, this enabled an understanding of the performance implications as well as determining the functionality of the algorithm. These case studies provided an opportunity to modify components of the algorithm to enhance performance and ensure realism because the complicated network-wide effects were not present. Once the algorithm had been finalised, network-wide testing was completed through the corridor study presented in Chapter 6 of this thesis.

4.5.1. Study Area Description

Two intersections were used as test cases:

- The 3-leg intersection of Hunter Street/Darby Street in Newcastle Light Rail Network (Figure 4.8), and
- A hypothetical 4-leg intersection (Figure 4.9).

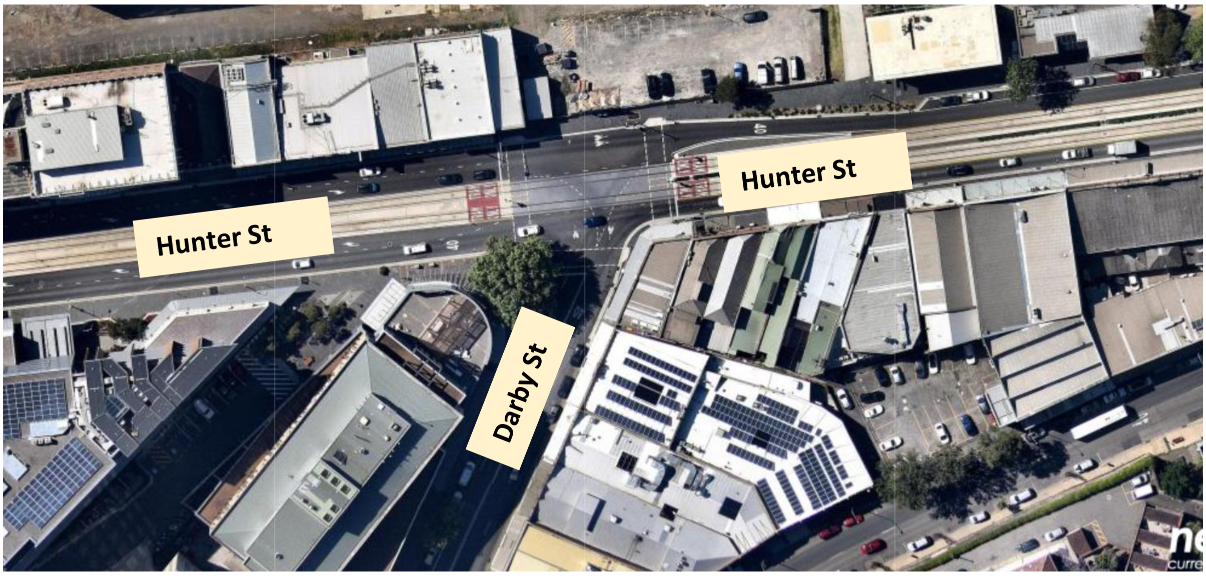


Figure 4.8 - Hunter Street/Darby Street Intersection

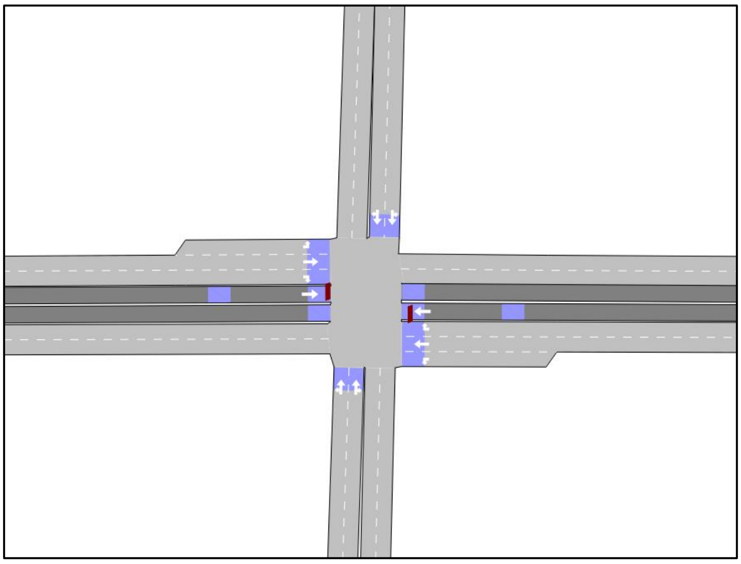


Figure 4.9 - Hypothetical 4-Leg Intersection

The Hunter Street/Darby Street intersection is a real-world intersection so the algorithm provides an expectation of actual performance upon implementation. The algorithm was also tested on a hypothetical 4-leg intersection so that the limitations of the algorithm could be understood in potential scenarios that experience greater levels of congestion. Furthermore, a 4-leg intersection poses additional complexity as the signal phasing structure further tests the adaptability of the SOLRV algorithm.

4.5.2. Modelling Parameters Set and Scenario Testing Approach

As discussed in Section 4.4 the algorithm was compared with a traditional TSP and a "no-TSP" case. Further to testing this scenario, the following modelling assumptions and parameters were set for the Hunter Street/Darby Street intersection:

- SCATS data of the intersection of Hunter Street/Darby Street was gathered from Roads and Maritime Services (RMS). The data includes traffic volume and traffic signal timing and phasing. Traffic volumes are usually lower on Mondays and Fridays due to different traffic behaviour on these first and last weekdays. Consequently, SCATS data for Tuesday, Wednesday and Thursday, October 15 to 17, 2019 was used for modelling.
- Using the SCATS data, the morning and evening peak hours were extracted, 8:00AM – 9:00AM and 4:50PM – 5:50 PM. Traffic volumes were also recorded for the morning peak hour 8:00AM – 9:00AM on 20 November 2019 through site inspection. Traffic counts were recorded for light vehicles, heavy vehicles and buses. The traffic volumes, queue length, stop time, traffic signal timing and phasing and behaviours were collected via the site visit
- Figure 4.10 shows the distribution of vehicles on each leg of the intersection based on movements extracted from SCATS data for the current case. The proportion of turns from the Eastern arm in Hunter Street was gained from the survey data

- Figure 4.11 shows the phasing and signal timing structure of the intersection.

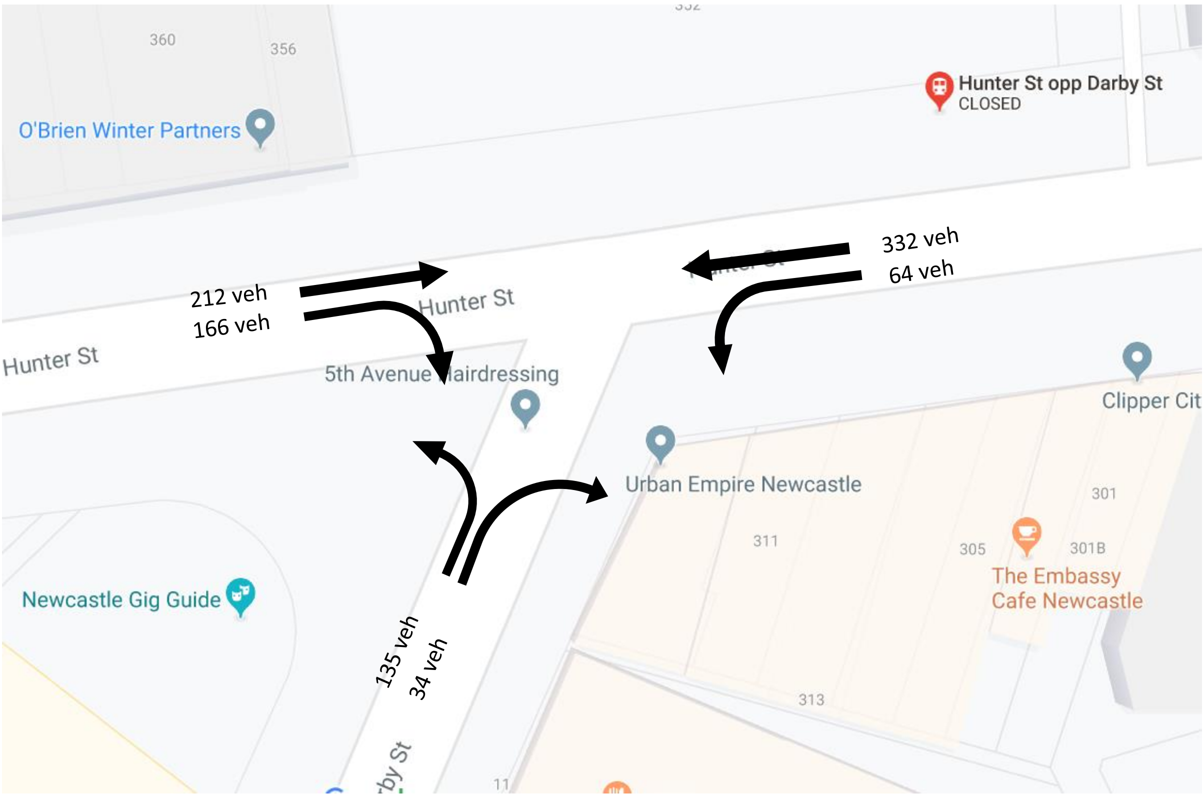


Figure 4.10 - Current cars' volume at the intersection of Hunter Street/Darby Street during AM peak hour from SCATS data

Figure 4.11 – Traffic signal phasing at the intersection of Hunter Street/Darby Street from SCATS data

4.6. SOLRV Algorithm Application: Corridor Case Study

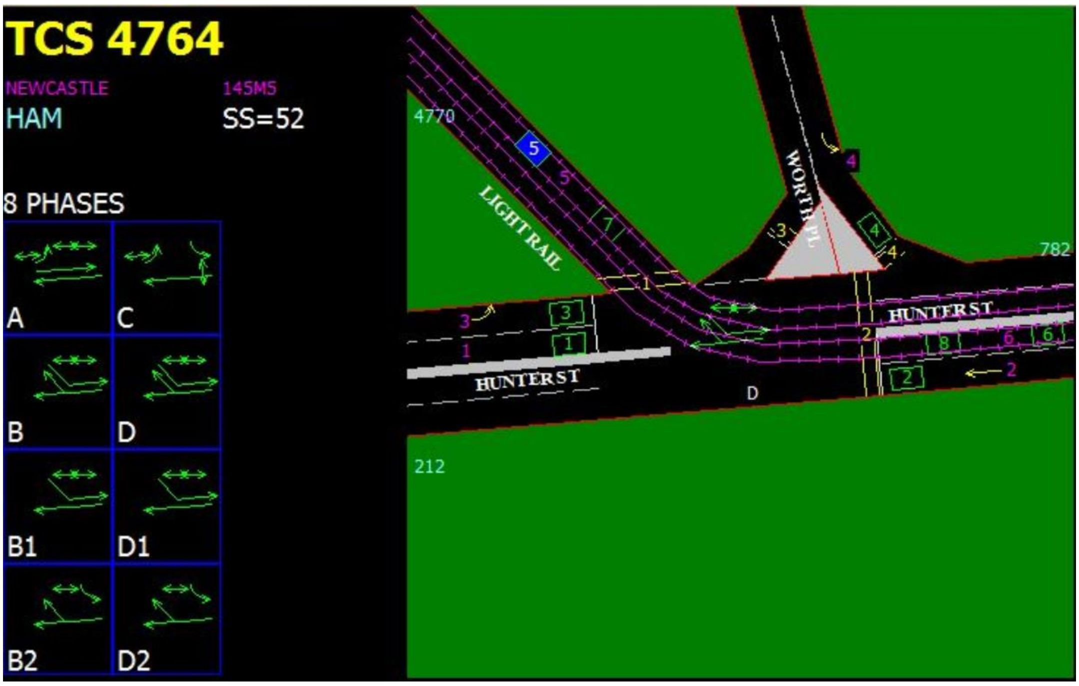
4.6.1. Description of Study Area

Since investigating how the algorithm would perform on an isolated intersection does not capture its effect on the entire network, or the impact of the case study on the adjacent intersections, the algorithm was also tested across a light rail corridor. Indeed, the proposed algorithm needed to be tested on a network of intersections and coordinated traffic signals. Since the Newcastle light rail network has six stations and six signalised intersections, it was used as a case study. Figure 4.12 shows the location of the light rail stations and all the signalised junctions over the Newcastle light rail route; in reality only four of these intersections were considered as the study area in this study.

Figure 4.12 - The study area at Newcastle light rail corridor

4.6.2. Modelling Parameters Set and Scenario Testing Approach

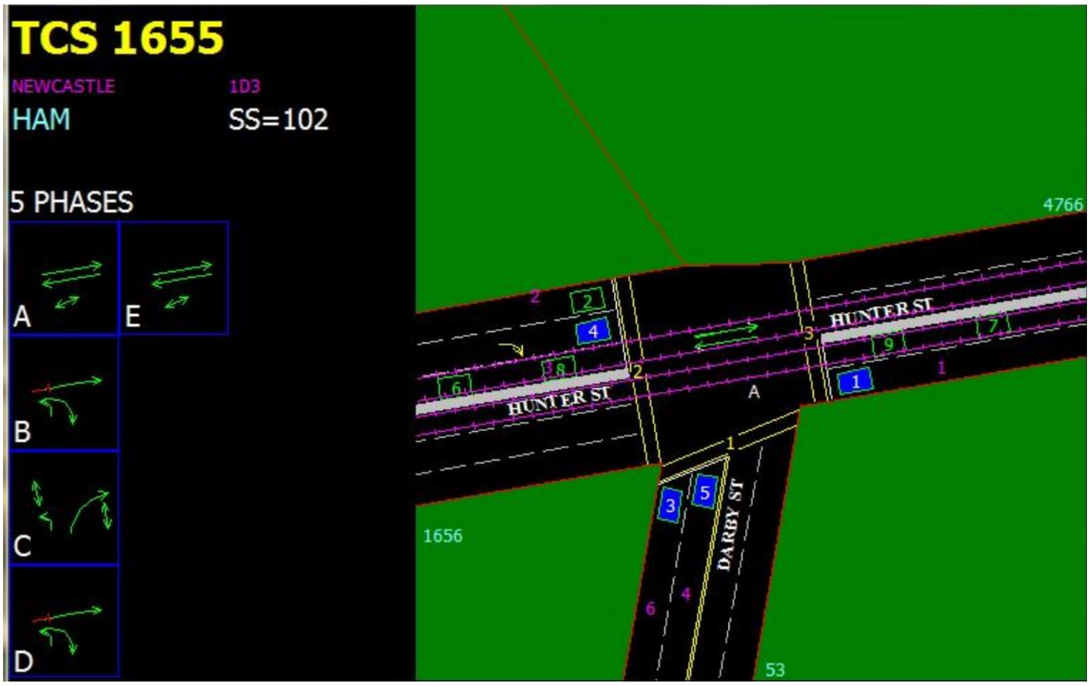
All the traffic lights at Newcastle are actuated and controlled by SCATS, so all the information required, including traffic volumes, and signal timing and phasing were extracted from SCATS data.



a. Intersection of Hunter Street/Worth Place

b. Intersection of Hunter Street/Auckland Street

c. Intersection of Hunter Street/Merewether Street



d. Intersection of Hunter Street/Darby Street

Figure 4.13 - Traffic signals phasing from SCATS data

Figure 4.13 shows the signalised intersections on the Newcastle Light Rail network, which are embedded within SCATS. We modelled four of these intersections, as shown in Figure 4.12, they include:

- Intersection of Hunter Street / Worth Place
- Intersection of Hunter Street / Auckland Street
- Intersection of Hunter Street / Merewether Street
- Intersection of Hunter Street / Darby Street.

4.7. Results

The following sections present the results from the microsimulation modelling methodology described in Section 3.2. The results focus on the fundamental traffic characteristics of delay, speed, and travel time, and they also consider the impact from a vehicle and user perspective with "person based" delays also estimated. Moreover, the impact of the SOLRV algorithm on pedestrian movements was also discussed.

4.7.1. Hunter Street/Darby Street Intersection

4.7.1.1. Assessment of Traffic Characteristics

Table 4.3 shows the results of the delays modelled for each seed value, and the difference in percentage between the SOLRV algorithm (considering the optimal detector location) and the TSP for the current volumes of traffic observed at the intersection. It also depicts the impact of traditional TSP on how the intersection performs by comparing the difference in percentage in vehicle delays from the base scenario to the TSP system.

Table 4.3 - Intersection of Hunter Street/Darby Street delay for the current traffic volumes based on different replications

Replication	Vehicle Groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
15074	All	32.48	34.69	7%	33.23	33.24	32.08	30.99	-11%
	Cars	32.97	35.39	7%	33.98	34.04	32.78	31.72	-10%
	Trams	16.77	11.99	-29%	8.88	7.55	9.38	7.42	-38%
28	All	37.33	37.64	1%	37.22	37.51	35.56	35.11	-7%
	Cars	37.83	38.16	1%	37.78	38.06	36.13	35.64	-7%
	Trams	8.3	7.82	-6%	4.66	5.69	3.11	4.59	-41%
560	All	33.34	35.98	8%	36.6	35.78	36.19	38.17	-1%
	Cars	33.47	36.45	9%	37.07	36.29	36.72	38.74	0%
	Trams	25.3	6.4	-75%	7.26	3.76	3.18	2.68	-41%
2849	All	31.96	33.67	5%	33.67	33	34.91	35.26	-2%
	Cars	32.23	34.18	6%	34.19	33.51	35.45	35.78	-2%
	Trams	17.23	5.47	-68%	4.36	4.56	4.71	6.04	-17%
7771	All	35.51	35.6	0%	39.58	39.68	37.74	39.01	6%
	Cars	35.95	36.26	1%	40.36	40.48	38.5	39.85	6%
	Trams	16.31	6.98	-57%	5.42	4.11	4.53	2.05	-35%
86524	All	35.28	34.95	-1%	36.26	37.1	37.29	37.84	4%
	Cars	35.55	35.5	0%	36.83	37.68	37.88	38.46	4%
	Trams	18.83	2.32	-88%	1.87	2.54	2.13	0.87	-19%
AVG	All	34.34	35.42	3%	36.1	36.08	35.62	36.03	0.565%
	Cars	34.69	35.99	4%	36.72	36.71	36.24	36.68	0.695%
	Trams	16.89	7.48	-56%	5.8	5.04	5.13	4.29	-31.417%

According to Table 4.3 the delay for cars increased due to prioritising the intersection using a traditional TSP algorithm, but when the SOLVR algorithm was implemented, the LRVs continued to be prioritised but the delays for cars decreased significantly. By comparing the “AVG” results (average modelling results across all the seeds tested), the car delays reduced from an increase of 4% to a much smaller increase of 0.695% in the SOLVR environment, and there was a further 32% improvement in LRV delays. Based on the results achieved from Aimsun modelling, car and LRV delays have decreased across most replications. It is important to note that LRVs can carry about 270 passengers so a 31% decrease in delay has a greater impact on more people than an 0.7% increase in delays for cars with an occupancy rate of 1.2/vehicle. The greatest improvements in performance as a result of the SOLVR algorithm occurred in replications “15074” and “28” where detectors were installed 40 metres from the stop line ($L_{detector}$ = 40 m).

To investigate the impact of TSP and the SOLRV algorithm on the study intersection, current traffic demand performance parameters were extracted from Aimsun, as shown in Table 4.4.

Table 4.4 - Traffic parameters of the intersection of Hunter Street/Darby Street for the current traffic volumes modelled in base scenario, TSP and SOLRV algorithm with best $L_{detector}$

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Delay (sec/km)	All	32.48	34.69	7%	30.99	-11%
	Cars	32.97	35.39	7%	31.72	-10%
	Trams	16.77	11.99	-29%	7.42	-38%
Speed (km/h)	All	40.94	40.46	-1%	41.14	2%
	Cars	41.66	41.16	-1%	41.84	2%
	Trams	17.81	18.1	2%	18.74	4%
Stop time (sec/km)	All	23.36	24.84	6%	21.25	-14%
	Cars	23.08	25.16	9%	21.58	-14%
	Trams	32.57	14.65	-55%	10.66	-27%
Travel time (sec/km)	All	105.02	107.23	2%	103.52	-3%
	Cars	101.5	103.93	2%	100.25	-4%

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
	Trams	218.58	213.73	-2%	209.21	-2%

Table 4.4 reiterates the previous findings by suggesting that traditional TSP has increased the delay, stop time and travel time of cars, and reduced their speed and flow, but it improved the functionality of LRVs through prioritisation. However, implementing the SOLRV algorithm reduced the delay, stop time and travel time of cars, and yet the prioritised LRVs experienced further improvements. In other words, the algorithm would reduce the delays, stop times and travel times of LRVs while increasing their speed by prioritisation, as well as improving the performance of the intersection for cars, thus resulting in a net gain for the whole system.

The delay of LRVs and cars at the study intersection with a 25% increase in the current volume is depicted in Table 4.5 across the operational scenarios.

Table 4.5 - Intersection of Hunter Street/Darby Street delay for case 2 (25% increase) based on different replications

Replication	Vehicle groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
15074	All	36.52	37.96	4%	36.95	36.4	38.04	41.53	-4%
	Cars	37.07	38.71	4%	37.7	37.18	38.78	42.32	-4%
	Trams	14.45	8.46	-41%	7.25	5.8	8.61	9.87	-31%
28	All	33.02	34	3%	34.36	34.61	34.63	33.87	-0.4%
	Cars	33.28	34.35	3%	34.78	35.04	35.06	34.28	-0.2%
	Trams	14.38	9.22	-36%	4.89	3.69	3.95	5.33	-42.2%
560	All	38.3	38.74	1%	38.98	38.27	39.95	42.02	-1%
	Cars	38.65	39.15	1%	39.39	38.68	40.42	42.49	-1%
	Trams	10.01	5.75	-43%	6.44	5.14	2.34	3.81	-11%

Replication	Vehicle groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
2849	All	35.49	37.53	6%	38.06	37	36.7	36.09	-4%
	Cars	35.72	37.99	6%	38.54	37.47	37.2	36.55	-4%
	Trams	18.79	5.83	-69%	4.51	3.82	1.86	4.06	-30%
7771	All	37.61	41.73	11%	38.68	39.24	39.05	38.32	-8%
	Cars	37.98	42.36	12%	39.3	39.93	39.74	38.98	-8%
	Trams	17.64	7.31	-59%	4.74	1.6	1.9	2.92	-60%
86524	All	34.96	38.47	10%	41.43	37.87	38.53	38.45	-2%
	Cars	35.27	38.92	10%	41.92	38.32	39	38.9	-2%
	Trams	12.57	5.48	-56%	4.75	4.15	4.39	4.86	-24%
AVG	All	35.99	38.11	6%	38.09	37.25	37.84	38.41	-2%
	Cars	36.34	38.62	6%	38.63	37.79	38.39	38.95	-2%
	Trams	14.86	7.22	-51%	5.6	4.1	4.35	5.63	-43%

Table 4.5 presents similar results to Table 4.3 where the traditional TSP systems reduced LRV delay by providing priority, while cars faced more delays. However, the SOLRV algorithm improved the performance of this intersection for cars across all the replications run, specifically 15074, 2849 and 7771, and it maintained LRV priority. These replications were applied for detectors were placed 30 metres, 40 metres and 40 metres from an intersection to get the best results. The average of these replications suggests a 43% improvement in LRV delays, which is significant, especially regarding the passenger capacity of this mode of transportation.

Table 4.6 shows the modelling outputs of the study intersection on Aimsun related to the base case scenario, TSP and best $L_{detector}$ of the SOLRV algorithm for case 2 of traffic demand.

Table 4.6 - Traffic parameters of the intersection of Hunter Street/Darby Street for case 2 (25% increase) modelled in base scenario, TSP and SOLRV algorithm with best $L_{detector}$

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Delay (sec/km)	All	37.61	41.73	11%	38.32	-8%
	Cars	37.98	42.36	12%	38.98	-8%
	Trams	17.64	7.31	-59%	2.92	-60%
Speed (km/h)	All	39.95	39.62	-1%	39.76	0%
	Cars	40.35	40	-1%	40.13	0%
	Trams	18.27	18.8	3%	19.44	3%
Stop time (sec/km)	All	26.52	30.47	15%	27.24	-11%
	Cars	26.66	30.87	16%	27.69	-10%
	Trams	19.22	8.63	-55%	3.07	-64%
Travel time (sec/km)	All	108.29	112.41	4%	109	-3%
	Cars	106.3	110.68	4%	107.29	-3%
	Trams	216.42	206.09	-5%	201.69	-2%

According to Table 4.6, the SOLRV algorithm added to TSP modified the priority system by reducing delays, travel time and stop time for cars and LRVs. However, applying the traditional TSP system to the study intersection penalised cars by increasing their delays, stop time and travel time, and prioritising LRVs.

The optimisation algorithm (SOLRV) was applied to the study intersection with higher traffic demand i.e. 50% and 100% increase in the current case volume. Table 4.7 and Table 4.8 show the delay outputs and traffic parameters of Aimsun simulation for the 50% scenario and Table 4.9 and Table 4.10 present the results for the 100% scenarios.

Table 4.7 - Intersection of Hunter Street/Darby Street delay for case 3 (50% increase) based on different replications

Replication	Vehicle groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
15074	All	38.71	41.77	8%	43.15	42.4	41.21	42.23	-1%
	Cars	39.06	42.46	9%	43.94	43.18	41.9	42.94	-1%
	Trams	22.08	8.35	-62%	4.91	4.53	8.21	8.16	-2%
28	All	39.53	37.48	-5%	38.03	40.93	41.72	39.74	1%
	Cars	39.75	37.86	-5%	38.45	41.4	42.17	40.18	2%
	Trams	20.87	5.74	-72%	2.67	1.51	3.44	2.81	-53%
560	All	38.35	40.51	6%	39.78	42.93	43.89	45.92	-2%
	Cars	38.54	40.86	6%	40.13	43.34	44.32	46.36	-2%
	Trams	20.53	7.2	-65%	5.11	3.08	1.5	3.39	-29%
2849	All	36.65	39.07	7%	38.51	36.32	37.89	38.73	-7%
	Cars	36.91	39.48	7%	38.93	36.72	38.3	39.16	-7%
	Trams	15.4	4.66	-70%	2.93	3.41	3.38	2.92	-27%
7771	All	42.88	46.31	8%	45.67	45.74	45.94	44.96	-3%
	Cars	43.19	46.92	9%	46.28	46.4	46.59	45.6	-3%
	Trams	22.28	6.4	-71%	5.22	2.39	2.93	2.96	-54%
86524	All	37.98	43.5	15%	42.52	42.36	43.28	41.42	-5%
	Cars	38.07	43.91	15%	42.95	42.8	43.74	41.84	-5%
	Trams	30.34	7.31	-76%	4.65	3	2.22	3.99	-45%
AVG	All	39.05	41.52	6%	41.36	41.85	42.36	42.21	-0.39%
	Cars	39.29	41.99	7%	41.87	42.38	42.89	42.72	-0.29%
	Trams	21.98	6.8	-69%	4.37	3.14	4.18	4.5	-35.74%

Table 4.8 - Traffic parameters of the intersection of Hunter Street/Darby Street for case 3 (50% increase) modelled in base scenario, TSP and SOLRV algorithm with best $L_{detector}$

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Delay (sec/km)	All	36.65	39.07	7%	36.32	-7%
	Cars	36.91	39.48	7%	36.72	-7%
	Trams	15.4	4.66	-70%	3.41	-27%
Speed (km/h)	All	39.79	39.25	-1%	39.84	2%
	Cars	40.05	39.49	-1%	40.09	2%
	Trams	17.96	18.7	4%	18.91	1%
Stop time (sec/km)	All	25.51	27.22	7%	24.84	-9%
	Cars	25.49	27.34	7%	25.11	-8%
	Trams	27.12	17.04	-37%	2.38	-86%
Travel time (sec/km)	All	106.57	108.98	2%	106.23	-3%
	Cars	105.28	107.84	2%	105.08	-3%
	Trams	214.33	203.58	-5%	202.22	-1%

The results indicate similar outcomes to the previous demand scenarios, however it is clear that the advantages of the SOLVR algorithm are greater in a congested environment with reductions in delays for LRVs and across all the other types of traffic modelled.

Table 4.9 - Intersection of Hunter Street/Darby Street delay for case 4 (100% increase) based on different replications

Replication	Vehicle groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
15074	All	44.33	47.7	8%	47.96	47.19	49.49	47.77	-1%
	Cars	44.61	48.26	8%	48.59	47.83	50.14	48.37	-1%
	Trams	25.99	11.75	-55%	6.99	5.57	8.19	9.32	-53%
28	All	43.05	50.27	17%	46.66	50.6	49.2	49.42	-7%
	Cars	43.22	50.66	17%	47.03	51.03	49.63	49.84	-7%
	Trams	23.71	5.94	-75%	4.58	1.58	0.48	2.23	-23%
560	All	51.7	52.64	2%	53.36	56.92	52.19	57.48	-1%
	Cars	51.86	52.98	2%	53.67	57.31	52.55	57.89	-1%
	Trams	31.83	8.26	-74%	12.47	6.18	4.6	4.19	-44%
2849	All	42.99	46.76	9%	46.7	47.53	44.35	43.67	-7%
	Cars	43.24	47.11	9%	47.07	47.93	44.68	44.02	-7%
	Trams	15.85	7.61	-52%	4.92	2.04	7.01	4.55	-40%
7771	All	51.36	56.47	10%	56.32	61.02	58.61	70.54	-0.27%
	Cars	51.83	56.98	10%	56.9	61.68	59.26	71.29	-0.14%
	Trams	10.02	10.76	7%	5.1	2.22	0.39	3.29	-52.60%
86524	All	45.42	49.97	10%	48.11	46.02	47.46	48.87	-8%
	Cars	45.59	50.3	10%	48.46	46.38	47.82	49.26	-8%
	Trams	25.95	10.48	-60%	6.67	3.05	4.42	2.46	-71%
AVG	All	46.52	50.68	9%	49.91	51.59	50.31	53.13	-2%
	Cars	46.77	51.1	9%	50.35	52.08	50.78	53.62	-1%
	Trams	21.88	9.55	-56%	6.62	3.59	4.47	4.9	-31%

Table 4.10 - Traffic parameters of the intersection of Hunter Street/Darby Street for case 4 (100% increase) modelled in base scenario, TSP and SOLRV algorithm with best $L_{detector}$

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Delay (sec/km)	All	45.42	49.97	10%	46.02	-8%
	Cars	45.59	50.3	10%	46.38	-8%
	Trams	25.95	10.48	-60%	3.05	-71%
Speed (km/h)	All	37.37	36.8	-2%	37.16	1%
	Cars	37.52	36.93	-2%	37.29	1%
	Trams	19.72	20.93	6%	21.72	4%
Stop time (sec/km)	All	31.67	35.97	14%	32.08	-11%
	Cars	31.7	36.16	14%	32.33	-11%
	Trams	28.09	13.55	-52%	1.6	-88%
Travel time (sec/km)	All	114.66	119.21	4%	115.26	-3%
	Cars	114	118.71	4%	114.79	-3%
	Trams	193.53	178.06	-8%	170.56	-4%

In summary, the modelling results revealed that the intersection performed much better for LRVs and other vehicles when the SOLVR algorithm is compared to the traditional TSP approach. TSP systems will improve the performance of LRVs by prioritising them without considering the impact on other vehicles in the system. This means that cars are penalised by increased delays, longer travel times and stop times and reduced speeds. The SOLRV algorithm considers the impact on other vehicles in the system and therefore creates a more equitable solution by minimising the penalty on private vehicles whilst maintaining the priority benefits for LRVs.

To better grasp how the proposed SOLRV algorithm impacts on the case study intersection under different traffic scenarios, Figure 4.14 shows the changes in average delays of tested seeds for cars and LRVs between traditional TSP and the SOLRV algorithm.

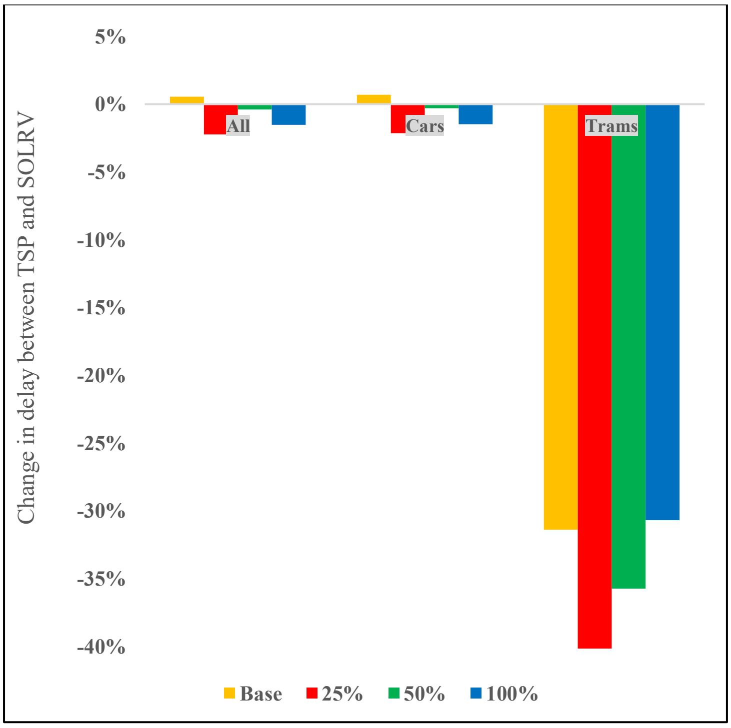


Figure 4.14 - Change in average delay of the tested seeds between TSP and SOLRV for cars and trams

4.7.1.2. Pedestrian Assessment

Pedestrians have a significant influence on modelling traffic behaviour so in this research any potential changes that the proposed SOLRV algorithm might have on pedestrian movement must be considered.

The influence that the SOLRV algorithm has on pedestrians crossing an intersection were examined by extracting the actuated signal timings for all the approaches during the model run. Table 4.11 to Table 4.14 show the signal timing at the intersection at 10-minute intervals over a one-hour period.

Table 4.11 - Pedestrian signal timing for 10-minute intervals with traditional TSP and SOLRV algorithm for the current traffic volumes

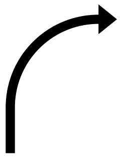
Approach	TSP		SOLRV	
	Time Interval	Green Time	Time Interval	Green Time
South to East 	1	69.6	1	70.4
	2	57.6	2	58.4
	3	83.2	3	77.6
	4	48	4	77.6
	5	28.8	5	38.4
	6	38.4	6	28.8

Table 4.12 - Pedestrian signal timing for 10-minute intervals with traditional TSP and SOLRV algorithm for case 2 (25% increase)

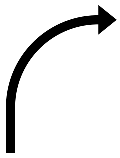
Approach	TSP		SOLRV	
	Time Interval	Green Time	Time Interval	Green Time
South to East 	1	80.8	1	80.8
	2	71.2	2	60
	3	76.8	3	67.2
	4	82.4	4	68.8
	5	79.2	5	61.6
	6	64	6	67.2

Table 4.13 - Pedestrian signal timing for 10-minute intervals with traditional TSP and SOLRV algorithm for case 3 (50% increase)

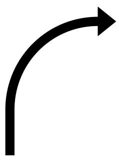
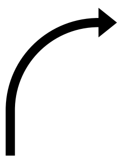
Approach	TSP		SOLRV	
	Time Interval	Green Time	Time Interval	Green Time
South to East 	1	88	1	88
	2	50.4	2	50.4
	3	88.8	3	67.2
	4	67.2	4	57.6
	5	67.2	5	57.6
	6	76.8	6	83.2

Table 4.14 - Pedestrian signal timing for 10-minute intervals with traditional TSP and SOLRV algorithm for case 4 (100% increase)

Approach	TSP		SOLRV	
	Time Interval	Green Time	Time Interval	Green Time
South to East 	1	68	1	49.6
	2	100	2	98.4
	3	117.6	3	105.6
	4	122.4	4	96
	5	89.6	5	86.4
	6	112	6	105.6

Whether pedestrian green phasing is negatively affected by the SOLRV algorithm can be examined by comparing the green time allocated to pedestrians crossing the street (shown in Table 4.11 to Table 4.14) with the actual time they need to cross the street. To calculate their speed means considering the following parameters:

- Physical properties such as gender, age, body height, bodyweight
- Emotional and cultural influences such as race, land-use, city size, country, continent
- Environmental influences such as weather conditions, time of day, peak periods, purpose of trips

The average speed of pedestrians at crossing is between 1.43m/s and 1.55m/s in Australia (Bosina & Weidmann, 2017). In this research, using the above parameters and speeds based on land-use and the locality of the case study, we assumed a walking speed of 1.40m/s. Therefore, at 1.40m/s walking speed and a 20m crossing distance, the minimum time required = 14.29 seconds. Table 4.11 to Table 4.14 show all the values presented in this diagram and indicate green times, which exceed 14.29 seconds (minimum value = 28.8 seconds). This allows the opposing movement to have adequate green time for pedestrian movements under both prioritisation schemes. Consequently, the proposed SOLRV algorithm would not impact on pedestrian mobility and safety.

4.7.2. Hypothetical 4-leg Intersection

4.7.2.1. Traffic Parameters Assessment

To further test the impact of the SOLVR algorithm, a hypothetical 4-leg intersection with greater traffic demands was considered. Table 4.15 to Table 4.22 presents the traffic outputs from modelling across the following pages of this thesis.

Table 4.15 - Delay of 4-leg intersection for current traffic volumes based on different replications

Replication	Vehicle Groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
15074	All	84.95	84.18	-1%	86.77	86.72	85.07	91.22	1%
	Cars	85.24	85.5	0%	88.21	88.2	86.53	92.79	1%
	Trams	68.62	12.29	-82%	8.53	6.17	5.68	5.72	-54%
28	All	83.04	83.81	1%	82.25	85.34	84.73	89.63	-2%
	Cars	83.55	84.58	1%	83.02	86.2	85.57	90.54	-2%
	Trams	33.63	9.21	-73%	7.28	2.54	2.9	0.64	-21%
560	All	75.97	84.43	11%	85.51	82.93	84.45	78.87	-7%
	Cars	76.18	85.11	12%	86.21	83.66	85.18	79.55	-7%
	Trams	52.07	9.03	-83%	7.29	1.83	2.73	2.18	-76%
2849	All	84.39	85.89	2%	83.88	89.02	82.75	82.26	-4%
	Cars	84.24	86.7	3%	84.67	89.91	83.57	83.11	-4%
	Trams	99.72	7.6	-92%	7.28	2.99	3.86	0.56	-93%
7771	All	86.89	86.98	0%	90.9	91.22	91.95	94.3	5%
	Cars	87.51	88.02	1%	92.04	92.4	93.15	95.53	5%
	Trams	40.23	9.5	-76%	5.19	2.97	2.13	2.47	-45%
86524	All	83.51	80.65	-3%	81.06	81.05	83.08	91.61	0.5%
	Cars	83.71	81.34	-3%	81.81	81.82	83.88	92.51	0.6%
	Trams	61.95	13.12	-79%	8.05	5.24	5.42	4.14	-60.1%
AVG	All	83.17	84.35	1%	85.14	86.1	85.4	88.07	0.94%
	Cars	83.45	85.23	2%	86.07	87.08	86.38	89.09	0.99%
	Trams	59.25	10.38	-82%	7.31	3.93	3.95	3	-30%

Table 4.15 presents the delays after modelling a 4-leg intersection, which considered three operational scenarios (No Prioritisation (Base), TSP, SOLRV) under the base case demand conditions. In addition to varying demand, the impact of distance between the stop line and detector was tested (detector length ($L_{detector}$ variation). The modelling was carried out across 6 seeds to depict a variety of traffic instances that are consistent with RMS practice for

microsimulation modelling. The table also presents the average results across all 6 seeds as the final row of the table (displayed as "AVG"). The results indicate the following key points:

- As expected, car delays increased by prioritising the intersection using a traditional TSP algorithm
- With the SOLRV algorithm, LRVs continue to be prioritised, but the impact of the delay on cars is reduced significantly. Comparing the "AVG" results (average modelling results across all seeds tested), car delays reduced from an increase of 2% to a smaller increase of 0.99% in the SOLRV environment while there was a further 30% reduction in LRV delays
- Car and LRV delays reduced across most of the replications. However, a tram's capacity is about 270 passengers, so a 30% decrease in delay has a greater impact on more people than 0.99% increase in the delay of cars with an occupancy rate of 1.2/vehicle.
- The greatest improvement in performance as a result of the SOLRV algorithm occurred in replications "560" and "2849" where detectors were installed 40 metres from the stop line ($L_{detector}$ = 40 m).

Table 4.16 - Traffic parameters of the 4-leg intersection for the current traffic volumes modelled in base scenario, TSP and SOLRV algorithm with best $L_{detector}$

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Delay (sec/km)	All	75.97	84.43	11%	78.87	-7%
	Cars	76.18	85.11	12%	79.55	-7%
	Trams	52.07	9.03	-83%	2.18	-76%
Speed (km/h)	All	31.84	31.01	-3%	32.26	4%
	Cars	31.98	31.13	-3%	32.38	4%
	Trams	15.8	17.64	12%	18.51	5%
Stop time (sec/km)	All	61.71	69.63	13%	64.41	-7%
	Cars	61.31	70.05	14%	64.97	-7%
	Trams	106.16	23.28	-78%	2.16	-91%

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Travel time (sec/km)	All	143.96	152.43	6%	146.86	-4%
	Cars	142.92	151.84	6%	146.28	-4%
	Trams	261.46	218.02	-17%	211.58	-3%

Table 4.16 extracts the average results of the replications modelled on Aimsun for some traffic parameters as representative of traffic operations at an intersection such as delays, speed, stop times and travel times. As shown in Table 4.16, the SOLRV algorithm reduced the penalties imposed on cars while maintaining LRV priority.

Table 4.17 - Delay of 4-leg intersection for case 2 (25% increase) based on different replications

Replication	Vehicle Groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
15074	All	93.17	94.77	2%	94.36	95.63	95.31	95.15	-0.4%
	Cars	93.74	95.98	2%	95.64	96.96	96.62	96.47	-0.4%
	Trams	54.69	13.25	-76%	8.32	6.24	6.79	6.5	-37%
28	All	86.41	91.89	6%	90.4	92.07	94.69	90.98	-2%
	Cars	86.82	92.58	7%	91.11	92.81	95.44	91.72	-2%
	Trams	37.74	8.34	-78%	4.67	3.49	4.37	1.61	-44%
560	All	87.68	94.72	8%	97.55	95.28	98.38	94.05	-1%
	Cars	87.94	95.33	8%	98.21	95.93	99.07	94.73	-1%
	Trams	52.23	10.17	-81%	6.33	6.16	2.52	0.82	-92%
2849	All	91.1	95.23	5%	93.97	92.19	94.6	93.23	-3%
	Cars	91.42	95.97	5%	94.7	92.94	95.36	93.98	-3%
	Trams	53.17	6.16	-88%	4.7	1.54	2.45	2.6	-75%
7771	All	95.47	99.25	4%	100.58	99.11	101.6	100.06	-0.1%
	Cars	95.71	100.21	5%	101.58	100.12	102.64	101.06	-0.1%
	Trams	72.49	8.34	-88%	5.98	4.24	3.05	5.07	-49%

Replication	Vehicle Groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
86524	All	88.09	91.24	4%	91.24	91.49	91.5	90.76	-0.5%
	Cars	88.31	91.9	4%	91.92	92.22	92.21	91.49	-0.4%
	Trams	60.36	9.71	-84%	7.26	2.93	3.93	1.47	-85%
AVG	All	90.4	94.57	5%	94.74	94.36	96.06	94.12	-0.5%
	Cars	90.73	95.38	5%	95.59	95.23	96.94	94.99	-0.4%
	Trams	56.03	9.74	-83%	6.46	4.33	4.19	3.59	-63%

Table 4.17 shows the delays after modelling a 4-leg intersection that considered the three operational scenarios (Base, TSP, SOLRV) under the “25% increase” in demand conditions (demands increased by 25% compared to the base case).

Table 4.17 presents similar results to the previous slide table where the traditional TSP systems reduced LRV delay by providing priority, while cars faced an increase in delay. However, the SOLRV algorithm would improve the performance of cars at the intersection across all the replications run, specifically “2849”, “28” and “560”, and maintain LRV priority. These replications were applied for detectors at 30m, 25m and 40m away to obtain the best results from applying SOLRV. Overall, the optimum detector length across the replications is 30m.

The average of the replications suggests a 63% improvement in LRV delays, which is significant, especially when the passenger carrying capacity of this mode of transportation is considered.

Table 4.18 - Traffic parameters of the 4-leg intersection for case 2 (25% increase) modelled in base scenario, TSP and SOLRV algorithm with best $L_{detector}$

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Delay (sec/km)	All	91.1	95.23	5%	92.19	-3%
	Cars	91.42	95.97	5%	92.94	-3%
	Trams	53.17	6.16	-88%	1.54	-75%
Speed (km/h)	All	29.25	29.06	-1%	29.65	2%
	Cars	29.37	29.14	-1%	29.74	2%
	Trams	15.73	18.56	18%	19.02	2%
Stop time (sec/km)	All	74.98	78.94	5%	76.2	-3%
	Cars	75	79.53	6%	76.82	-3%
	Trams	72.53	7.91	-89%	0.82	-90%
Travel time (sec/km)	All	158.88	163.01	3%	159.97	-2%
	Cars	158.11	162.66	3%	159.64	-2%
	Trams	252.1	205.08	-19%	200.46	-2%

According to Table 4.18, all the indicative traffic parameters have been improved by implementing the SOLRV algorithm, especially when compared to the TSP system with a 25% increase in traffic demand.

Table 4.19 presents the delays after modelling the 4-leg intersection that considered three operational scenarios (Base, TSP, SOLRV) under the "50% increase" demand conditions (demands increased by 50% compared to the base case).

These results are similar to the 25% increase in demand and display improvements for cars and LRVs in the system. On average, there was almost a 1% improvement in delays for cars, a 56% improvement in delays for trams, and the optimum detector length was 35m.

Table 4.19 - Delay of 4-leg intersection for case 30 (50% increase) based on different replications

Replication	Vehicle Groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
15074	All	108.53	116.8	8%	116.06	117.29	116.16	118.55	-1%
	Cars	109.1	118.08	8%	117.38	118.66	117.52	119.95	-1%
	Trams	63.14	13.53	-79%	9.59	6.2	6.6	5.69	-29%
28	All	102.8	105.04	2%	104.24	110.17	104.05	103.25	-2%
	Cars	103.06	105.71	3%	104.91	110.89	104.74	103.95	-2%
	Trams	64.1	7.3	-89%	6.21	6.18	4.42	2.16	-70%
560	All	101.83	100.57	-1%	99.46	104.65	102.55	99.72	-1%
	Cars	102.07	101.13	-1%	99.99	105.22	103.14	100.32	-1%
	Trams	61.73	7.26	-88%	10.12	8.84	3.79	0.47	39%
2849	All	100.39	108.87	8%	108.77	106.29	101.28	101.76	-7%
	Cars	100.8	109.55	9%	109.49	106.99	101.95	102.44	-7%
	Trams	41.34	8.19	-80%	2.5	3.25	2.67	2.56	-67%
7771	All	117.82	115.2	-2%	115.09	119.98	112.98	112.48	-2%
	Cars	118.41	116.15	-2%	116.05	121	113.94	113.44	-2%
	Trams	50.88	7.27	-86%	5.85	4.88	3.25	3.88	-47%
86524	All	101.03	97.84	-3%	110.77	103.76	101.11	107.56	3%
	Cars	101.42	98.39	-3%	111.45	104.4	101.76	108.26	3%
	Trams	42.39	15.39	-64%	10	7.82	4.91	1.92	-68%
AVG	All	105.55	107.51	2%	109.2	110.49	106.47	107.36	-0.97%
	Cars	105.96	108.28	2%	110.01	111.32	107.29	108.19	-0.91%
	Trams	54.76	10.19	-81%	7.52	6.08	4.51	3.23	-56%

Table 4.20 - Traffic parameters of the 4-leg intersection for case 3 (50% increase) modelled in base scenario, TSP and SOLRV algorithm with best $L_{detector}$

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Delay (sec/km)	All	100.39	108.87	8%	101.28	-7%
	Cars	100.8	109.55	9%	101.95	-7%
	Trams	41.34	8.19	-80%	2.67	-67%
Speed (km/h)	All	27.56	27.43	0%	28.28	3%
	Cars	27.63	27.49	-1%	28.34	3%
	Trams	16.35	18.27	12%	18.82	3%
Stop time (sec/km)	All	82.87	90.98	10%	83.65	-8%
	Cars	83	91.46	10%	84.21	-8%
	Trams	63.3	20.25	-68%	1.65	-92%
Travel time (sec/km)	All	167.91	176.4	5%	168.79	-4%
	Cars	167.42	176.19	5%	168.57	-4%
	Trams	240.19	207.02	-14%	201.6	-3%

Table 4.20 shows that that SOLRV algorithm would enhance the traffic operations at the intersection by reducing delays, stop times and travel times of cars and LRVs, while increasing their overall operational speed.

Table 4.21 presents the delays from modelling a 4-leg intersection that considered three operational scenarios (Base, TSP, SOLRV) under the "100% increase" demand conditions (demands increased by 50% compared to the base case). The outputs indicate the performance was similar to the previous demand scenarios, but the advantages of the SOLRV algorithm are greater in a congested environment with improvements in delays for LRVs and all the other traffic modelled. On average, there was almost a 4% reduction in delays for cars and a 55% reduction in delays for LRVs; the optimum detector length was 25m.

Table 4.21 - Delay of 4-leg intersection for case 4 (100% increase) based on different replications

Replication	Vehicle Groups	Base	TSP	TSP - Base	SOLRV				SOLRV - TSP
					$L_{detector}$ = 25m	$L_{detector}$ = 30m	$L_{detector}$ = 35m	$L_{detector}$ = 40m	
15074	All	218.81	163.65	-25%	212.11	199.66	176.57	183.42	8%
	Cars	220.24	165.05	-25%	213.99	201.45	178.14	185.07	8%
	Trams	68.86	14.03	-80%	10.82	7.78	8.86	7.99	-37%
28	All	203.78	199.73	-2%	222.82	198.74	185.98	184.76	-7%
	Cars	204.47	200.7	-2%	223.95	199.74	186.93	185.7	-7%
	Trams	70.33	9.47	-87%	4.53	2.77	1.3	1.14	-88%
560	All	209.96	155.84	-26%	151.46	146.33	158.79	155.24	-6%
	Cars	210.63	156.5	-26%	152.12	146.98	159.51	155.94	-6%
	Trams	64.31	9.38	-85%	4.3	2.09	1.26	0.14	-78%
2849	All	242.24	203.63	-16%	202.01	183.31	190.67	183.71	-10%
	Cars	243.23	204.64	-16%	203.02	184.23	191.62	184.63	-10%
	Trams	54.36	7.62	-86%	4.17	2.5	5.9	2.62	-67%
7771	All	295.54	199.16	-33%	210.55	176.61	197.55	203.71	-11%
	Cars	297.2	200.43	-33%	211.93	177.76	198.86	205.07	-11%
	Trams	59.98	11.52	-81%	6.25	6.34	4.09	3.27	-45%
86524	All	214.43	201.87	-6%	173.41	175.95	173.72	187.28	-14%
	Cars	215.23	202.84	-6%	174.24	176.82	174.58	188.24	-14%
	Trams	49.63	12.03	-76%	8.97	5.17	2.93	0.15	-25%
AVG	All	230.93	187.33	-19%	195.6	180.21	180.65	183.2	-4%
	Cars	231.95	188.39	-19%	196.74	181.26	181.71	184.28	-4%
	Trams	62.17	11.15	-82%	7.06	4.99	4.7	3.3	-55%

Table 4.22 - Traffic parameters of the 4-leg intersection for case 4 (100% increase) modelled in base scenario, TSP and SOLRV algorithm with best $L_{detector}$

Traffic Parameters	Vehicle groups	Base	TSP	TSP - Base	SOLRV	SOLRV - TSP
Delay (sec/km)	All	242.24	203.63	-16%	183.31	-10%
	Cars	243.23	204.64	-16%	184.23	-10%
	Trams	54.36	7.62	-86%	2.5	-67%
Speed (km/h)	All	17.13	18.68	9%	20.07	7%
	Cars	17.13	18.68	9%	20.07	7%
	Trams	16.08	18.3	14%	18.94	3%
Stop time (sec/km)	All	215.23	176.21	-18%	156.44	-11%
	Cars	215.87	177.01	-18%	157.23	-11%
	Trams	93.03	19.97	-79%	1.89	-91%
Travel time (sec/km)	All	309.6	270.97	-12%	250.63	-8%
	Cars	309.9	271.3	-12%	250.88	-8%
	Trams	253.29	206.55	-18%	201.18	-3%

As with Table 4.16, Table 4.18 and Table 4.20, Table 4.22 shows that SOLRV could reduce delays, stop times and travel times, and increase the speed of cars and LRVs within the modelling. Comparing Table 4.16, Table 4.18, Table 4.20 and Table 4.22 with each other indicates that the proposed SOLRV algorithm would result in further improvements under over-saturated traffic demand scenarios.

According to the modelling outputs shown in Table 4.15 to Table 4.22, applying SOLRV not only improved private vehicle operations by minimising delays and stop times, it also provided priority for LRVs. It also demonstrated that the effectiveness of the SOLVR algorithm is enhanced in over-saturated conditions, in fact under increasing levels of demand, there was a greater positive impact on car delays while improvements for LRVs remained between 50% and 60%.

4.7.2.2. Pedestrian Assessment

Table 4.23 to Table 4.26 show timings for pedestrians crossing an intersection under the traditional TSP and SOLRV algorithm.

Table 4.23 - Pedestrian signal timing for 10-minute intervals with traditional TSP and SOLRV algorithm for the current traffic volumes

Approach	TSP		SOLRV	
	Time Interval	Green Time	Time Interval	Green Time
South to East	1	108	1	121
	2	91	2	109
	3	106	3	91
	4	106	4	91
	5	152	5	106
	6	112	6	106
North to South and South to North	1	110	1	115
	2	115	2	120
	3	106	3	115
	4	104	4	112
	5	101	5	100
	6	118	6	123

Table 4.24 - Pedestrian signal timing for 10-minute intervals with traditional TSP and SOLRV algorithm for case 2 (25% increase)

Approach	TSP		SOLRV	
	Time Interval	Green Time	Time Interval	Green Time
South to East	1	123	1	123
	2	162	2	145
	3	137	3	143
	4	137	4	122
	5	76	5	91
	6	137	6	128
North to South and South to North	1	107	1	107
	2	112	2	111
	3	109	3	121
	4	110	4	106
	5	127	5	97
	6	108	6	124

Table 4.25 - Pedestrian signal timing for 10-minute intervals with traditional TSP and SOLRV algorithm for case 3 (50% increase)

Approach	TSP		SOLRV	
	Time Interval	Green Time	Time Interval	Green Time
South to East	1	123	1	123
	2	115	2	130
	3	129	3	146
	4	145	4	144
	5	122	5	108
	6	137	6	131
North to South and South to North	1	114	1	114
	2	126	2	117
	3	101	3	121
	4	114	4	115
	5	90	5	103
	6	102	6	130

Table 4.26 - Pedestrian signal timing for 10-minute intervals with traditional TSP and SOLRV algorithm for case 4 (100% increase)

Approach	TSP		SOLRV	
	Time Interval	Green Time	Time Interval	Green Time
South to East	1	160	1	160
	2	154	2	140
	3	152	3	149
	4	152	4	146
	5	144	5	145
	6	152	6	137
North to South and South to North	1	107	1	107
	2	113	2	109
	3	96	3	114
	4	112	4	114
	5	113	5	104
	6	105	6	114

As with the assumptions suggested for walking speed at the intersection of Hunter Street/Darby Street, to investigate the green time allocated to pedestrians, the minimum time needed to cross is 14.29 seconds. To test the impact of the SOLRV algorithm on pedestrian safety and mobility, the green time of the two approaches at the 4-leg intersection was considered; the minimum green time needed was 91 seconds, which was much less than the minimum time needed for pedestrians to cross the intersection. Therefore, the proposed SOLRV algorithm would reduce the stopping times of private vehicles at other approaches and it would not jeopardise pedestrian safety while crossing the street.

4.7.3. Newcastle Light Rail Corridor Case Study

As with the results of the single intersection case study, the corridor of the intersections for Newcastle Light Rail have been modelled and assessed. Table 4.27 shows the network delays after modelling the Newcastle Light Rail corridor with three operational scenarios: no prioritisation (Base), TSP and the SOLRV algorithm. Modelling was carried out across 10 seeds to depict a variety of traffic conditions that are consistent with RMS practice for microsimulation modelling. The table presents the average results across all 10 seeds.

Table 4.27 - Average delay of the tested replications from modelling the Newcastle Light Rail corridor in three operational scenarios and under four demand conditions

Demand Scenario	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
Base	All	175.66	159.82	156.74	-9%	-10.8%
	Cars	176.42	160.56	157.45	-9%	-10.8%
	Trams	22.73	6.97	11.06	-69%	-51.3%
25%	All	196.85	198.76	188.76	1%	-4.1%
	Cars	197.65	199.67	189.59	1%	-4.1%
	Trams	26.92	4.51	10.3	-83%	-61.7%
50%	All	210.09	217.41	205.98	3%	-2.0%
	Cars	210.94	218.37	206.86	4%	-1.9%

Demand Scenario	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
	Trams	26.28	5.66	12.07	-78%	-54.1%
100%	All	252.38	272.77	261.24	8%	3.5%
	Cars	253.35	273.93	262.31	8%	3.5%
	Trams	25.27	3.9	10.37	-85%	-59.0%

Table 4.27 shows that the performance of the corridor improved significantly for LRVs and other vehicles when the changes made by the SOLVR algorithm on the base case of the corridor are compared to the changes made by the traditional TSP approach. Comparing the delays to cars and LRVs after implementing the traditional TSP approach with the SOLRV algorithm under three different scenarios shows the efficiency of the algorithm in over-saturated conditions. The last column shows that traffic operations actually improved as the corridor became more congested. Figure 4.15 depicts the modelling outcomes for an average of the ten seeds run on Aimsun. This figure has four sections that compare the impact of the SOLRV algorithm with TSP on the case study corridor through delays, speed, stop times and travel times.

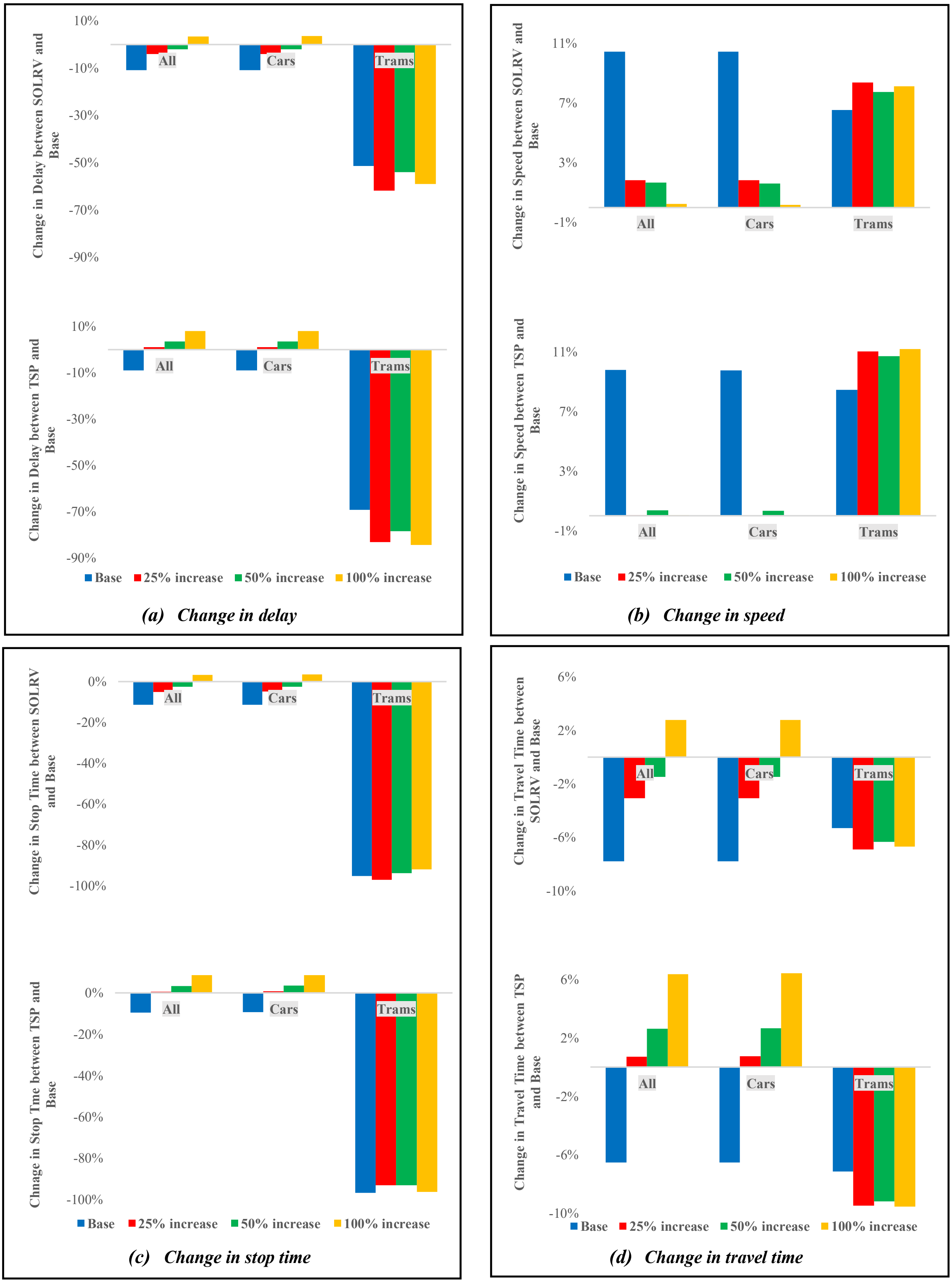


Figure 4.15 - Comparing the SOLRV and TSP results in Aimsun modelling

The bar charts shown in Figure 4.15 indicate how the proposed SOLRV algorithm improved traffic operations better than TSP, particularly in more congested conditions.

Table 4.28 shows the delays for each seed value, and the difference in percentage between the SOLRV algorithm and Base for the volumes of traffic currently observed at the intersection. It also depicts the performance of traditional TSP on the corridor by comparing the percentage difference in vehicle delays from the base scenario to the TSP scenario.

Table 4.28 - Delay results of modelling the Newcastle Light Rail corridor in three scenarios in base demand case

Replication	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
28	All	172.57	167.07	155.25	-3%	-10.0%
	Cars	173.29	167.83	155.93	-3%	-10.0%
	Trams	20.99	5.71	12.81	-73%	-39.0%
560	All	188.27	181.4	159.01	-4%	-15.5%
	Cars	189.05	182.23	159.71	-4%	-15.5%
	Trams	27.14	3.79	11.68	-86%	-57.0%
2849	All	170.5	155.72	151.83	-9%	-11.0%
	Cars	171.29	156.48	152.54	-9%	-10.9%
	Trams	16.99	3.39	8.74	-80%	-48.6%
7771	All	176.33	151.44	155.94	-14%	-11.6%
	Cars	177.04	152.08	156.61	-14%	-11.5%
	Trams	19.79	5.51	7.7	-72%	-61.1%
86524	All	156.07	142.02	148.43	-9%	-4.9%
	Cars	156.68	142.66	149.04	-9%	-4.9%
	Trams	28.29	4.77	17.66	-83%	-37.6%
137	All	176.23	163.17	162.22	-7%	-7.9%
	Cars	176.96	163.92	162.93	-7%	-7.9%
	Trams	25.42	4.36	11.51	-83%	-54.7%

Replication	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
559	All	180.83	159.42	165.84	-12%	-8.3%
	Cars	181.6	160.13	166.57	-12%	-8.3%
	Trams	18.58	5.63	9.48	-70%	-49.0%
5321	All	181.88	167.84	163.35	-8%	-10.2%
	Cars	182.63	168.6	164.09	-8%	-10.2%
	Trams	24.72	4.8	8.45	-81%	-65.8%
98812	All	173.8	152.22	153.03	-12%	-12.0%
	Cars	174.53	152.91	153.72	-12%	-11.9%
	Trams	22.11	4.57	7.36	-79%	-66.7%
601027	All	180.29	151.44	152.65	-16%	-15.3%
	Cars	181.25	152.31	153.46	-16%	-15.3%
	Trams	23.29	3.52	14.32	-85%	-38.5%
AVG	All	175.66	159.82	156.74	-9%	-10.8%
	Cars	176.42	160.56	157.45	-9%	-10.8%
	Trams	22.73	6.97	11.06	-69%	-51.3%

Table 4.28 presents the network delays after modelling the Newcastle Light Rail corridor with the three operational scenarios (No prioritisation (Base), TSP, SOLRV) under base case demand conditions. The modelling was carried out across 10 seeds to depict the various traffic conditions consistent with RMS practice for microsimulation modelling. The table also presents the average results across all 10 seeds in the final row of the table (displayed as "AVG").

The performance of the TSP and SOLVR algorithm was similar with both options improving the performance of cars and LRVs. The SOLVR algorithm was slightly more beneficial for private vehicles, whereas the TSP has reduced the delays of LRVs.

Table 4.29 - Delay results of modelling the Newcastle Light Rail corridor in three scenarios for case 2 (25% increase)

Replication	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
28	All	197.18	199.47	192.31	1%	-2.5%
	Cars	197.98	200.34	193.14	1%	-2.4%
	Trams	22.55	4	10.95	-82%	-51.4%
560	All	200.27	196.35	192.59	-2%	-3.8%
	Cars	201.04	197.22	193.4	-2%	-3.8%
	Trams	33.15	5.07	13.7	-85%	-58.7%
2849	All	196.97	198.24	193.23	1%	-1.9%
	Cars	197.81	199.17	194.13	1%	-1.9%
	Trams	26.43	3.77	7.02	-86%	-73.4%
7771	All	192.14	186.04	187.29	-3%	-2.5%
	Cars	192.78	186.8	188.05	-3%	-2.5%
	Trams	32.78	4.58	8.27	-86%	-74.8%
86524	All	203.18	211.29	194.01	4%	-4.5%
	Cars	204	212.23	194.84	4%	-4.5%
	Trams	24.39	5.41	14.13	-78%	-42.1%
137	All	192.18	193.2	178.42	1%	-7.2%
	Cars	192.97	194.06	179.14	1%	-7.2%
	Trams	22.01	5.07	18	-77%	-18.2%
559	All	197.64	196.36	187.23	-1%	-5.3%
	Cars	198.44	197.23	188.05	-1%	-5.2%
	Trams	26.8	4.96	8.48	-81%	-68.4%
5321	All	194.86	229.29	189.9	18%	-2.5%
	Cars	195.63	230.33	190.73	18%	-2.5%
	Trams	27.82	3.94	6.94	-86%	-75.1%
98812	All	196.62	186.19	186.09	-5%	-5.4%
	Cars	197.43	187	186.9	-5%	-5.3%
	Trams	21.6	5.32	6.72	-75%	-68.9%
601027	All	198.29	192.16	186.76	-3%	-5.8%

Replication	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
	Cars	199.27	193.23	187.76	-3%	-5.8%
	Trams	31.25	3.34	9.2	-89%	-70.6%
AVG	All	196.85	198.76	188.76	1%	-4.1%
	Cars	197.65	199.67	189.59	1%	-4.1%
	Trams	26.92	4.51	10.3	-83%	-61.7%

Table 4.29 shows the delays after modelling the Newcastle Light Rail corridor with the three operational scenarios (Base, TSP, SOLRV) under the "25% increase" demand conditions (demands increased by 25% compared to the base case).

The outputs indicate similar performance to the base case demand scenario. However, the advantage of the SOLVR algorithm is highlighted because the delays for cars with TSP increased while the delays for cars with SOLVR decreased; this resulted in a more equitable result.

Table 4.30 - Delay results of modelling the Newcastle Light Rail corridor in three scenarios for case 3 (50% increase)

Replication	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
28	All	215.72	206.49	216.62	-4%	0.4%
	Cars	216.53	207.38	217.5	-4%	0.4%
	Trams	33.36	5.25	13.9	-84%	-58.3%
560	All	210.85	244.75	201.05	16%	-4.6%
	Cars	211.68	245.84	201.88	16%	-4.6%
	Trams	26.07	3.49	10.44	-87%	-60.0%
2849	All	208.73	230.68	210.57	11%	0.9%

Replication	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
	Cars	209.59	231.75	211.52	11%	0.9%
	Trams	27.44	3.21	8.48	-88%	-69.1%
7771	All	208.18	204.22	206.75	-2%	-0.7%
	Cars	208.95	205.04	207.58	-2%	-0.7%
	Trams	25.98	5.35	6.4	-79%	-75.4%
86524	All	209.12	225.5	213.56	8%	2.1%
	Cars	209.95	226.5	214.39	8%	2.1%
	Trams	23.8	3.46	25.73	-85%	8.1%
137	All	214.03	230.34	196.94	8%	-8.0%
	Cars	214.88	231.34	197.72	8%	-8.0%
	Trams	24.66	3.79	16.64	-85%	-32.5%
559	All	206.73	224.82	204.41	9%	-1.1%
	Cars	207.55	225.81	205.28	9%	-1.1%
	Trams	24.39	4.55	7.68	-81%	-68.5%
5321	All	207.51	212.21	205.53	2%	-1.0%
	Cars	208.33	213.11	206.39	2%	-0.9%
	Trams	23.1	3.77	7.93	-84%	-65.7%
98812	All	208.1	230.26	209.95	11%	0.9%
	Cars	208.92	231.26	210.83	11%	0.9%
	Trams	25.81	5.28	6.97	-80%	-73.0%
601027	All	192.16	219.75	194.56	14%	1.2%
	Cars	193.23	220.97	195.55	14%	1.2%
	Trams	3.34	3.23	15.51	-3%	364.4%
AVG	All	210.09	217.41	205.98	3%	-2.0%
	Cars	210.94	218.37	206.86	4%	-1.9%
	Trams	26.28	5.66	12.07	-78%	-54.1%

Table 4.30 presents the delays after modelling the Newcastle Light Rail corridor with three operational scenarios (Base, TSP, SOLRV) under the "50% increase" demand conditions (demands increased by 50% compared to the base case).

The outputs indicate similar performance to the previous demand scenario, and again the SOLVR algorithm provided a more equitable multi-modal performance.

Table 4.31 - Delay results of modelling the Newcastle Light Rail corridor in three scenarios for case 4 (100% increase)

Replication	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
28	All	254.35	296.25	270.78	16%	6.5%
	Cars	255.33	297.49	271.88	17%	6.5%
	Trams	18.72	4.97	7.38	-73%	-60.6%
560	All	270.61	269.75	282.1	0%	4.2%
	Cars	271.63	270.87	283.26	0%	4.3%
	Trams	27.4	3.41	6.8	-88%	-75.2%
2849	All	265.97	282.13	250.53	6%	-5.8%
	Cars	267.06	283.38	251.59	6%	-5.8%
	Trams	20.41	3.59	7.73	-82%	-62.1%
7771	All	246.05	268.13	260.36	9%	5.8%
	Cars	246.91	269.16	261.35	9%	5.8%
	Trams	25.02	3.4	6.7	-86%	-73.2%
86524	All	244.18	281.74	265.8	15%	8.9%
	Cars	245.07	282.92	266.82	15%	8.9%
	Trams	30.42	5.14	20.65	-83%	-32.1%
137	All	254.4	271.87	269.58	7%	6.0%

Replication	Vehicle Groups	Base	TSP	SOLRV Algorithm	TSP - Base	SOLRV Algorithm – Base
	Cars	255.34	273	270.64	7%	6.0%
	Trams	29.99	4.86	16.09	-84%	-46.3%
559	All	256.88	264.51	250.56	3%	-2.5%
	Cars	257.88	265.61	251.57	3%	-2.4%
	Trams	21.09	4.51	8.75	-79%	-58.5%
5321	All	246.39	263.82	251.82	7%	2.2%
	Cars	247.3	264.91	252.82	7%	2.2%
	Trams	26.27	2.4	7.29	-91%	-72.2%
98812	All	239.15	259.11	249.74	8%	4.4%
	Cars	240.05	260.17	250.73	8%	4.4%
	Trams	22.12	4.89	10.27	-78%	-53.6%
601027	All	245.94	270.99	261.75	10%	6.4%
	Cars	247.07	272.42	263.05	10%	6.5%
	Trams	30.28	2.28	11.67	-92%	-61.5%
AVG	All	252.38	272.77	261.24	8%	3.5%
	Cars	253.35	273.93	262.31	8%	3.5%
	Trams	25.27	3.9	10.37	-85%	-59.0%

Table 4.31 presents the delays after modelling the Newcastle Light Rail corridor with the three operational scenarios (Base, TSP, SOLRV) under the “100% increase” demand conditions (demands increased by 100% compared to the base case).

4.7.4. Summary

4.7.4.1. Single Intersection

The modelling outputs shown in the tables presented in section 5.3 that are related to the 3-leg intersection and the hypothetical 4-leg intersection show that applying SOLRV not only improved the operation of cars by minimising their delays and stop times, it also provided priority for LRVs. This means the SOLRV algorithm improved the functionality of both trams and cars in oversaturated traffic conditions, while maintaining existing safety conditions and the time needed by pedestrians to access the intersections.

The most critical traffic conditions occur with the greatest levels of demand. As such, the average results of modelling for oversaturated conditions across both intersections (3-leg and 4-leg case studies) are highlighted below to reiterate the benefits of the SOLRV algorithm:

- Delay: The SOLRV algorithm provided a 31% to 55% and 1% to 4% improvement in delay compared to traditional TSP for LRVs and cars
- Speed: The SOLRV algorithm led to a 2% to 5% and 3% increase in speed compared to traditional TSP for LRVs and cars
- Stop Time: The SOLRV algorithm decreased stopping times by 30% and 2% to 4% for LRVs and cars compared to traditional TSP
- Travel Time: The SOLRV algorithm reduced the travel time of LRVs and cars by 1% to 3% compared to traditional TSP
- Pedestrian Walk Time: The SOLRV algorithm provided almost 35 seconds of crossing time more than the minimum time required of 14.29.

4.7.4.2. Corridor of the Intersections

The modelling outputs shown in the tables presented in Section 6.3 that are related to the corridor of the intersection at Newcastle Light Rail show that applying SOLRV not only improved the operation of cars by minimising their delays and stopping times, it also prioritised LRVs .

The average results of modelling all levels of traffic demand are highlighted below to reiterate the benefits of the SOLRV algorithm:

- Delay: The SOLRV algorithm provided a 2% to 8% reduction in car delays relative to traditional TSP without any significant change in delay for LRVs
- Speed: The SOLRV algorithm led to a 2% increase in the speed of cars relative to traditional TSP
- Stop Time: The SOLRV algorithm decreased the stopping times by 6% for cars compared to the traditional TSP
- Travel Time: The SOLRV algorithm reduced the travel time of cars by 4% relative to traditional TSP.

4.8. Conclusion

TfNSW Future Transport 2056 vision aims to provide “a productive economy”, “liveable communities” and achieve a “sustainable society”. These goals can only be obtained through the proliferation of public transport options such as light rail. The development of TSP algorithms is a key component in effectively integrating light rail options within the overall transport system. Current research indicates that although these algorithms will provide priority to public transport vehicles, there are significant delays and deteriorating conditions for other users of the road network. Therefore, the primary objective of this research was to investigate the feasibility of developing a more equitable and sustainable TSP algorithm.

This thesis describes the development of a more sustainable TSP algorithm, the Speed Optimisation of Light Rail Vehicle (SOLRV) algorithm. The SOLRV algorithm builds on the traditional TSP algorithms described in the literature and applied in practice, which utilise “green-extension” and “red-reduction” rules to prioritise public transport. The SOLRV algorithm minimises the penalties of prioritising other road users by using a dual system of speed and signal timing adjustment to reduce the duration of green extensions and red reductions. This ultimately reduces the impact on other users, such as private vehicles, to achieve more sustainable prioritisation of LRVs on a road network.

A microsimulation modelling platform was used to test the formulated SOLRV algorithm across 3 case studies (Hunter Street/Darby Street, Newcastle 3-leg intersection, Hypothetical 4-leg intersection, Newcastle Light Rail Corridor), by considering 3 operational scenarios (No TSP – base case, application of traditional TSP, application of SOLRV) and 4 demand scenarios. This resulted in 36 different simulated environments, which were then tested across a variety of traffic perturbations (random seeds) to ensure the robustness of the modelling. **This modelling revealed there were reductions in delays for LRVs that ranged from 30% to 60%, which was comparable or better than traditional TSP. However, the true benefit of the SOLRV algorithm was the 5% to 10% saving in delays for other users of the intersection. This also translated to a greater net benefit for the overall system from a personal delay perspective.**

Throughout history, NSW has benefited from traffic signal optimisation, as shown by the development and application of the SCATS system. Based on the modelling results, the SOLRV algorithm has the potential to add to SCATS and provide further gains in efficiency.

The next steps to future implementation focus on the level of resourcing and technical complexity surrounding SCATS integration, and then selecting a pilot site for implementation. With continued support from TfNSW and research from the UTS research team, the application of SOLRV is possible and could lead to significant improvements in road congestion and customer satisfaction.

Chapter 5 – Conclusions and Discussions

5. CONCLUSIONS AND DISCUSSIONS

Prioritising public transport vehicles at signalised intersections is one of the methods being considered to induce passengers to travel more on public transport. The main issue regarding prioritisation of public transport systems is the social pressures within the policy sphere relating to the perceived problem of time penalties imposed on private vehicles by reducing public vehicles' dwell time and extending cars' stop time behind the intersections. This research aimed to minimise the impact of these priority systems on vehicles, mainly by bus pre-signals and Transit Signal Priority systems for LRVs. It should be noted that these two transport modes have been selected due to their shared infrastructure with other road users and, as a consequence, their direct impact on private vehicles at roads and intersections.

Bus pre-signals are additional signals installed in advance of main intersections to stop cars and give priority to buses before reaching the main intersection. This means that vehicles are penalised through additional stops at pre-signals. LRV signal priority systems are a type of traffic light timing procedure, which reduces the dwell time of LRVs based on green extension, red reduction and changing the phase of LRVs. Unfortunately, these strategies potentially increase the stop time of cars at intersections.

In this study, mathematical algorithms for each type of public transport priority system have been suggested to reduce their impact on private cars. The algorithms proposed to improve the performance of bus pre-signals and LRV signal priority systems have been presented in Sections 3 and 4 respectively.

To eliminate the negative impact of bus pre-signals on cars, the IQD (Initial Queue Delay) model outlined in Chapter 3 aims to reduce the stopping time of private vehicles at pre-signals by moderating their speed in advance of the traffic light. This estimated speed is announced to drivers using a (VMS) Variable Message Sign. The sensitivity analysis of this model indicated that the proposed IQD model reduced the time-in-queue of private vehicles behind the pre-signal, so their functionality improved significantly. In reality, the effect of this model on higher V/C ratios was more than for smaller V/C ratios, which means that IQD improved the performance of cars better in more congested conditions than in less congested conditions.

Chapter 4 of this research suggested a mathematical algorithm for improving the performance of cars at signalised intersections equipped with LRV Signal Priority systems. Encouraging people to commute by public transport instead of private vehicles by applying methods for improving PTs' efficiency and safety such as TSP will inevitably lead to a significant decrease in traffic congestion. Current research and application have revealed that although these algorithms can prioritise public transport vehicles, they result in substantial delays and deteriorating traffic conditions for other road users. Therefore, the primary objective of this research was to investigate the feasibility of developing a more equitable and sustainable TSP algorithm.

This thesis describes the development of the more sustainable Speed Optimisation of Light Rail Vehicle (SOLRV) algorithm. This SOLRV algorithm builds on the traditional TSP algorithms, which utilise "green-extension" and "red-reduction" rules to provide priority for public transport. The SOLRV algorithm, on the other hand, minimises the penalties of prioritisation for other road users by using a dual system of speed and signal timing adjustments to reduce the duration of green extensions and red reductions. This ultimately reduces the impact on other users of intersections, e.g. private vehicles to achieve more sustainable prioritisation of LRVs on a road network.

A microsimulation modelling platform was used to test the formulated SOLRV algorithm across 3 case studies (Newcastle 3-leg intersection, hypothetical 4-leg intersection, and Newcastle Light Rail Corridor), considering 3 operational scenarios (no TSP – base case, application of traditional TSP, application of SOLRV) and 4 demand scenarios. This resulted in 36 different simulated environments, which were further tested across a variety of traffic perturbations (random seeds) to ensure the modelling was robust. The results revealed` considerable reductions in delays for LRVs ranging from 30% to 60%, which was comparable or better than traditional TSP. However, the true benefit of the SOLRV algorithm was the saving in delays for other users of the intersection, in the order of 5 to 10%. This also translated to a greater net benefit for the overall system from a personal delay perspective.

As concluded in Chapters 3 and 4, the proposed strategies for improvement of priority systems performance, i.e. both bus pre-signal and LRVs, can substantially reduce the priorities' impact on private cars at signalised intersections. Furthermore, compared to other methods, the complexity level of the proposed algorithms is low, and their implementation does not need additional specific facilities.

Although the simplicity and advantages of the studied and tested algorithms are not negligible, it has to be admitted that they need to be adjusted to the Sydney Coordinated Adaptive Traffic System (SCATS), which requires an extensive effort for future research.

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