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Priority Based Traffic Control

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Abstract

The rising ubiquity of internet connected devices and wireless networks offers a bright future for intelligent transport systems in urban environments. By equipping individual vehicles with wireless devices capable of communicating with traffic signal controllers, adaptive traffic control schemes can be used to prioritise traffic flows, minimise delay based on traffic priority, and reduce the rising costs of congestion within our urban networks.

The Priority Based Traffic Control system (PBTC) is a tool for simulating the opportunities allowed by a fully connected traffic fleet. By establishing wireless communication with vehicles approaching a controlled intersection and estimating the operational stopping cost and delay cost for each vehicle, the PBTC system can adapt to local traffic conditions in real time, minimising the congestion costs incurred by road users. Lookahead estimation allows a signal controller to extend green time dynamically to further reduce the cost associated with phase changes.

This paper presents the PBTC system architecture, methods used to estimate and minimise the costs of delaying approaching traffic at a controlled intersection, and results of evaluation against vehicle actuated and adaptive control methods.

Chapter 1

Introduction

Transportation is fundamental to the modern global economy, encouraging growth and job creation, trade, and quality of life. The success of road transportation and steady increase in the number of individual vehicles in use has resulted in an ongoing strain on societies to provide infrastructure capable of satisfying demand.

Widespread utilisation of road transport for commercial and private use has lead to significant traffic congestion in densely populated, urban environments as demand outstrips the capacity of roading networks (European Commission, 2011). As the complexity of road networks increases, so too does the need for control systems to safely and efficiently manage access to shared road by competing flows of traffic.

Intersections with signal controls allow competing traffic flows to independently make use of the limited capacity of intersecting sections of two or more roads. To avoid collisions, allowing traffic to flow through a controlled intersection requires stopping all competing traffic flows also demanding the intersection. As a result, controlled intersection delay is one of the most significant causes of congestion costs in urban road networks.

This project seeks to improve cost effectiveness of traditional traffic control techniques by considering the individual costs associated with stopping or delaying vehicles approaching a controlled intersection.

1.1 Motivations

Urban congestion is a significant problem facing the New Zealand transportation industry. In 2013, an independent consultation commissioned by the New Zealand Transport Agency (NZTA) found that the increase in transport cost due to congestion within Auckland City could be as high as 1.2 billion dollars annually when compared to freely flowing traffic (Wallis & Lupton, 2013).

The New Zealand Ministry of Transport (MoT) 2008 transport strategy identifies affordability and efficiency as two primary goals of transportation development over the next three decades and recommends future congestion management strategies should more efficient use of existing network capacity without the need to add expensive new infrastructure. Improving the effectiveness of traffic signal controls at road intersections has potential benefits for all controlled intersections in New Zealand, at significantly lower costs than infrastructure changes.

Advances in wireless technologies suggests that inter-vehicle communication technology may be commonplace on New Zealand roads within the next decade. By simulating the possibilities of a fully connected transport system, we hope to encourage development in this area.

1.2 Problem

Modern intersection signal controllers seek to minimise delay by responding to vehicle demand at each incoming link. The implementation of individual traffic actuated systems differs, but common characteristics include the use of multiple pre-determined phase and cycle plans, created in advance by a traffic engineer. Isolated traffic actuated systems are limited in practice because of the need for traffic engineers to predefine plans, which are unable to adapt to real time changes in demand.

Adaptive traffic control systems, such as the Sydney Coordinated Adaptive Traffic Control System (SCATS), operated at all controlled intersections on New Zealand cities and highways; adaptively increment phase plans in response to near-real time traffic conditions and are successful for reducing delay within high demand road networks. Existing systems are limited to minimising the number of queued cars or average delay at an intersection.

When an approaching vehicle is stopped at a controlled intersection, a cost is absorbed by the occupants or owners of the vehicle. Costs incurred may be caused by the physical characteristics of a vehicle, for example: a stopped vehicle must use more fuel to accelerate back to a cruise speed; or by the impact of the delay on the vehicle occupants in terms of added commuting time.

As an example of this problem, consider a common "cross-roads" intersection, with two competing approaches. If a large, commercial freight vehicle running late for a ferry and a small family car returning home from a shopping trip are approaching the intersection on two competing roads, who should be given right of way? There is significantly more cost incurred if the truck is forced to stop at the intersection, including cost of fuel required to accelerate and the potential of being late for the ferry and missing a shipment. In a traditional vehicle actuated or adaptive traffic control system, there is no guarantee on who will be given the opportunity to pass first. The traffic controller is not influenced by the approaching traffic and, depending on the current signal phase timing, it is likely that both vehicles are forced to stop, or the truck is forced to stop.

This project presents a new methodology for adaptive traffic control that considers individual vehicles approaching or waiting at an intersection based on a dynamically calculated *priority* value, calculated using properties of each vehicle that can be communicated to a traffic controller using wireless devices embedded in vehicles.

1.3 Priority Based Signal Control

Vehicle priority modelling allows for consideration of a wide range of vehicle and motorist properties, including size and weight, fuel efficiency, number of passengers, individual passenger urgency, and purpose of transit. Inter-vehicular, short range, ad hoc communication is used between vehicles and a traffic controller in order to receive responsive, real-time information about the location and properties of vehicles approaching an intersection.

1.4 Contributions

This paper presents three primary contributions to the field of traffic signal control research and implementation:

- **Vehicular Priority Model**, a model for estimating the priority of individual vehicles within a road network; based upon passenger urgency, cost of stoppage, cost of delay, and passenger occupancy.

- **Priority Based Traffic Control Algorithm**, an on-line algorithm for determining signal phase times at a controlled intersection based on priority of real-time traffic, determined by one-way, vehicle-controller communication.
- **Open-Source Simulator Implementation**, an implementation of the Priority Based Traffic Control algorithm above, as well as modifications to the Movsim Traffic Simulator to allow adding of new traffic control strategies to be tested.

Chapter 2

Motivations, Background and Related Work

2.1 Terminology

Traffic control engineering involves specific terminology to refer to different signal controls, timing plans, and controller types. This section offers a brief introduction of traffic signal control and terminology that may be used throughout the remainder of this report.

Modern intersections with traffic signals are controlled by a roadside *signal controller*. Controllers switch power to signal lanterns and determine the sequence of display for each set of lights, operating under the safety requirement that no two conflicting flows receive green signals simultaneously. A typical controller operates lights in sequences called *phases*, which are dynamic length allocations of green light time to a set of non-conflicting flows at an intersection. Typically, modern controllers include the following fixed or dynamic time allocations within a phase:

- *late start time*, a fixed length of time a green light may be delayed for safety of other movements (e.g. pedestrian protection)
- *minimum green time*, a fixed length of time that a phase must operate before changing
- *inter-green time*, a fixed length of time required to operate amber and red signals at the end of a phase, typically at least 6 seconds.
- *extension green time*, a dynamic length of time allocated to a phase determined after all required fixed times have been deducted from the total phase tie.
- *maximum green time*, if the addition of the previous four time allocations exceeds the fixed maximum green time the phase is forced to change.

A *cycle* (or *plan*) is an ordered sequence of one or more phases which is repeated by a controller. A fixed cycle traffic controller runs each phase for a fixed length of time within a static cycle. An actuated traffic controller can respond to sensor inputs from lane road loops and skip phases that are not in demand. Adaptive traffic controllers differ in implementation but typically can extend or shorten the length of a phase if a queue is completely cleared midway through a phase. The length of a cycle of an adaptive controller can be adapted to demand, typically running for a shorter length of time during quiet traffic and increasing in length to reduce queuing and satisfy high demand peaks (Thomson & Moriarty, 2013).

An intersection has a given *capacity*, defined as the maximum sustainable flow rate at which vehicles or pedestrians can travel through the intersection in a given time period.

Capacity is dependant on the geometric layout of an intersection (e.g. width of road, number of lanes), driving and surface conditions, and traffic conditions. The *degree of saturation* of an intersection is a ratio of arrival flow rate with respect to capacity of each approach for a given period. Arrival flow rate, also called *demand flow*, refers to the number of vehicles or pedestrians arriving during a given period, measured from the back of a queue (Akcelik, 2004). A section of road is said to be saturated if the traffic flow is equivalent to the capacity of the road at a given speed, such that any increase in flow will have a negative impact on the flow through the system. Any section of road where demanded traffic flow exceeds capacity is said to be *congested* (Wallis & Lupton, 2013).

2.2 Signal Control Optimisation Techniques

This section provides a review of published literature on existing implementations of adaptive traffic control systems in use globally and within New Zealand, and identifies the benefits and limitations imposed by the use of these systems. Information related to the Sydney Coordinated Adaptive Traffic System (SCATS) is partially based on personal experience at the NZTA Wellington Traffic Operations Centre, in Johnsonville.

2.2.1 Sydney Coordinated Adaptive Traffic System

SCATS is a centralised, coordinated, adaptive traffic control system (Lowrie, 1982). In New Zealand, all controlled intersections operate on isolated control or within a coordinated network under the Sydney Coordinated Adaptive Traffic System (SCATS). SCATS operations within New Zealand are controlled by the New Zealand Transport Association (NZTA), for state highways and inter-city motorways; and local body councils where appropriate.

SCATS operates on a networked computer with two-way communication to individual SCATS connected traffic controllers over broadband (or modem) connections. SCATS interfaces with roadside traffic signal control units, requesting phase times, skipping phases, or adjusting cycle lengths on an adaptive basis. A traffic control engineer can monitor traffic demand and flow rates for an intersection and manually adjust SCATS calculated phases or cycle lengths if required.

SCATS incrementally adjusts the planned phase times of a traffic signal controller by responding to traffic data collected by the signal controller during the previous cycle. Inputs to SCATS from each individual controller include the number of vehicles and flow rate per each intersection approach, the expected and actual phase times, and the degree of saturation for the intersection. The SCATS system calculates and requests phase times and cycle lengths to minimise the degree of saturation of an intersection, defined as the ratio of effectively used green time to total available green time (Wolshon & Taylor, 1999). The proportion of effectively used green time is typically increased using longer cycles and higher split times for high demand approaches.

In a coordinated traffic control system, emphasis is given to ensuring that green times between two nearby intersections are scheduled in such a way as to allow for synchronised green phases, preventing vehicles arriving from an upstream intersection being required to stop downstream. The effect of this synchronisation is colloquially known as a "corridor of green" and will be familiar to most New Zealand inner city motorists. SCATS intersections are organised into groups called subsystems, typically based on proximity. A traffic control engineer identifies a critical intersection within each subsystem in a road network. The cycle time is optimised for the critical intersection and neighbouring intersections adopt the same cycle time to provide naive coordination of phases and ensure undersaturation of the critical intersection (Kilby & Johnson, 2010).

In practice, SCATS is limited by the ability to adjust timings only at the conclusion of a cycle, and the relatively small incremental adjustments made between cycles. During peaks of high intersection demand, the time for a cycle length increases, typically as long as 120 seconds or higher. Adjustments made to phase and cycle times at the end of each cycle are typically within the range of 5%-10%. As a result, SCATS can be slow to respond to disruptive periods of high demand and requires manual intervention from traffic engineers to handle such situations, for example, sporting or musical events with large numbers of fans entering and leaving a stadium at the same time.

2.2.2 Splits-Cycle-Offsets-Optimization-Technique

The Splits-Cycle-Offsets-Optimization-Technique (SCOOT) is an adaptive traffic control system first developed in the 1980s and deployed widely in the United Kingdom.

The primary objective of SCOOT is to minimise the sum of the average traffic queues in an area. A limit of this optimisation is the complete reduction of queues in a network, such that every approaching vehicle receives a green signal, not possible in practice. (Bell, 1992; Robertson & Bretherton, 1991). SCOOT modelling is based on construction of so called "cyclic flow profiles", online relative to real-time demand measured by detectors upstream of an intersection. A cyclic flow profile is a measure of a one-way flow of vehicles past a point (e.g. stop line) during a time step of a signal cycle. The use of cyclic flow profiles generated online in respond to actual traffic demand is promoted as an advantage of SCOOT over fixed-plan adaptive systems such as SCATS, as SCOOT does not require a traffic engineer to predetermine a set of plans to model traffic flow or congestion at an intersection.

The SCATS and SCOOT control systems are also limited by the reliability of communication links between signal controllers and the central optimiser. If communication is interrupted or lost, signal controllers will revert to a fallback mode, using predefined plans designed by a traffic engineer. In order to maintain integrity of a network in the event of communication loss, fallback plans are updated regularly by traffic control engineers using historical time of day data collected over a reasonable time period, a costly operation which requires continuous maintenance. In addition, SCATS and SCOOT both rely on the use of inductive loops installed within the pavement of a road at intersection stop-lines or at an upstream location, which must be replaced each time the surface of the road is maintained (Bell, 1992).

2.3 Lookahead Based Control

Recent work has explored alternatives to phase based control. van Katwijk, et al. (2008) present a "movement-based" lookahead optimisation algorithm that allows vehicle demand to pass through an intersection in distinct *movements*, which represent a passage of traffic from an approach lane to another exit lane, rather than structured phases or stages which are typically predefined sets of one or more movements. Movement-based control allows for clearance of more approaches by starting and ending individual movements of non-conflicting movements of traffic rather than a entire phases. The use of movements in control optimisation reduces the search space required by a decision tree, allowing a signal controller to look ahead to a N-second event horizon.

Similar algorithms implementing lookahead optimisation techniques have also been explored using traditional phase control, seeking to minimise total delay at an intersection, with significantly improved results over Webster's method (Porche, et al., 1996), although this work is limited by lack of comparison with traffic actuated or adaptive controllers.

2.4 Inter-Vehicular Communication

The ubiquity of mobile communication devices and modern wireless capabilities have offered new possibilities for inter-vehicle communication within road networks. Previous research suggests that short-range wireless communication devices installed in road vehicles can be used to form mobile ad-hoc networks between near proximity clusters of traffic (Gradinescu, et al., 2007; Nadeem, et al., 2004; Yang, et al., 2004).

Gradinescu et al. (2007) discuss an implementation for car-to-car communication and car-to-controller communication as a replacement for loop detection used by adaptive traffic controllers. In the author's implementation, vehicles periodically transmit information about themselves and other nearby vehicles to a traffic controller using one-hop broadcasts. A traffic signal controller maintains a record of each known vehicle within range and optimises cycle length and phase timings based for the succeeding phase based on real-time information from each approach. Experimentation results of the study suggest that adaptive traffic control using a simple traffic actuated method out-performs a predetermined phase controller by a significant factor when total intersection delay is the primary measure of effectiveness at an intersection. While these results are promising, the work is limited in scope by the use of a predetermined phase time controller as a baseline for experimentation. The increase in performance measured by the authors does not take into account the advantages of existing traffic actuated or adaptive controller schemes over an isolated, fixed-cycle controller; which are likely to be significant.

Wireless communication between vehicles and signal controllers can provide more information at an earlier stage of approach than loop detectors, including characteristics of a vehicle (number of passengers, size, weight, type of activity), speed of approach and current position. Research in this field has explored the use of vehicle-to-vehicle communication for early warning safety systems, collision avoidance, and as a means of informing vehicle passengers about road network conditions; suggesting widespread benefits for use of the technology beyond traffic modelling at intersections (Nadeem et al., 2004; Yang et al., 2004).

Chapter 3

Design

The following chapter discusses design decisions and justifications of PBTC and the developed simulation tool. The outcomes discussed in this chapter are:

- design of an appropriate model of individual vehicle priority,
- design of a simulation tool as a platform for implementing the PBTC system,
- design of a phase control algorithm, to be operated on a 2 phase intersection,
- evaluation methodology and relevant measures of effectiveness used to compare the performance of the PBTC system to existing alternatives.

3.1 Priority Modeling

Representative modeling of the priority of vehicles and passengers approaching an intersection is required to effectively design, develop and evaluate the PBTC system within a realistic setting.

The priority of an individual vehicle is proportional the cost, measured in cents, of stopping and/or delaying the vehicle at a PBTC controlled intersection. A single cost figure is calculated by an aggregation of the current effective delay cost, potential stopping cost, and potential delay cost for the vehicle. The operational stopping cost calculation is based on the velocity, acceleration, mass, and engine efficiency of a vehicle. Delay cost is based upon the class of vehicle, an individual notion of urgency, and number of passengers.

Emphasis has been placed on approximations of cost components that can be calculated efficiently in real-time by a traffic light controller. In order to develop realistic approximations of cost components, the following assumptions have been made about the physical characteristics of vehicles and driver behaviours:

- vehicles are classed as light or heavy, with petrol and diesel engines respectively,
- vehicle mass, engine efficiency, and aerodynamic properties are considered constant per vehicle class. Table 3.1 shows the constants representing the physical properties of each vehicle class,
- the price per litre for petrol fuel is \$2.24, and diesel fuel \$1.65 (New Zealand Dollars), based upon market values at the time of writing.

Quantity	value for light vehicles	value for heavy vehicles
Mass	1,500kg	15,000kg
Engine efficiency factor	0.3	0.3
Fuel type	petrol	diesel
Fuel price	$2.24/l	$1.65/l
Fuel energy density	$3.6 \text{x} 10^6$J/l	$3.6 \text{x} 10^6$J/l

Table 3.1: Physical vehicle constants per vehicle class used as parameters for the physics based consumption model. Light vehicles are cars only, heavy vehicles can be buses or trucks within the PBTC system.

3.1.1 Operational Stopping Cost

The operational stopping cost of an individual vehicle is the economic cost expended whenever the vehicle is delayed or forced to stop at a controlled intersection. The stopping cost of a vehicle is proportional to the cruise speed of the vehicle before the stop, and recognises that a vehicle that has been forced to stop expends a certain amount of fuel after takeoff in order to reach the speed of travel before stopping. Calculating an estimation for the cost of stopping a vehicle involves estimating the number of litres of fuel consumed when decelerating and accelerating at a controlled intersection.

Modern cars are typically capable of calculating and displaying the instantaneous or cumulative fuel consumption for a journey. Treiber & Kesting (2013) present a method for calculating fuel consumption as a function of driving resistance and velocity using a physics based consumption model. This instantaneous fuel consumption model was used in simulation as part of a priority message from a vehicle upstream of a traffic signal controller, however it was found that the fuel consumption rate alone is not appropriate for estimating the operational stopping cost of a vehicle, as it is dependent on vehicle speed and acceleration at the instant of communication.

Models exist for retrospective analysis of fuel consumption over a journey, using measured speed and acceleration rates over time and could be used to find the total cost of a stopping and accelerating through a controlled intersection after a vehicle has completed a trip (Akcelik Besley, 2003; Treiber Kesting, 2013; Treiber, et al., 2008). Attempts to implement these models at various time steps to estimate consumption leaving an intersection were not successful at producing meaningful results as an assumed arbitrary rate of predicted acceleration is not appropriate for all vehicles and speed limits. In practice, driver behaviour, vehicle characteristics, and intersection geometrics are likely to significantly decrease the accuracy of a predictive acceleration estimation.

An alternative appropriate measure of operational stopping cost is achieved by the PBTC system through a physics-based consumption model considering the deceleration and acceleration stages of a stop for a particular vehicle. As most modern car engines employ fuel cutoff during deceleration to prevent unnecessary fuel use, the total fuel used can be approximated solely on the acceleration component of a stop at an intersection (Treiber & Kesting, 2013).

The PBTC system estimates the fuel consumption of a vehicle departing an intersection by calculating the kinetic energy of the vehicle before the stop. By making an assumption that the vehicle will accelerate to their previous approach speed when leaving the intersection, the calculation is a reflection of how much energy is lost if the vehicle is requested to stop as it will require at least this much energy to reach the approach speed of the vehicle before the stop. This assumption does not hold in all circumstances, for example whenever downstream links of an intersection are heavily saturated with slow moving traffic, however it is a reasonable estimation for free flowing traffic as the approach and departure speeds are likely to be equal to the speed limit of the area.

Given the kinetic energy of an approaching vehicle is known, the litres of fuel required to generate this energy can be found based on the calorimetric energy density of the fuel being burned by the engine and the mechanical efficiency factor of the vehicle engine. Equation 3.2 summarises the calculation of the operational stopping cost based on this method.

$$\text{operational stopping cost} = \frac{\text{change in kinetic energy}}{\text{engine efficiency} \times \text{calorimetric fuel density}} \times \text{fuel price per litre} \tag{3.1}$$

$$= \frac{\frac{1}{2}mv^2}{c_d \times w_{cal}} \times p_f \ / \ \mathrm{L} \tag{3.2}$$

This physics based consumption model is only an approximation of the actual fuel consumption of approaching vehicles, but appropriately differentiates between light and heavy vehicles. More sophisticated estimations of fuel consumption would be desirable in practice and could be achieved through reinforcement learning using accurate measures of fuel consumption communicated by a vehicle to a traffic controller after it has departed an intersection.

3.1.2 Delay Cost

The delay cost of a vehicle approaching a traffic light is dependent on the urgency of travel of the vehicle occupants. Delay costs for a vehicle occupant can be defined proportional to the "lateness" of a passenger to reach a given destination by a predetermined time. For example, if a passenger is travelling from Wellington CBD to the airport and has only 10 minutes available before check-in closes for a flight, the cost of delay of the journey should reflect the money the passenger will effectively lose if they miss the flight and must rebook tickets or cancel their trip.

The calculation of a delay cost for each vehicle requires user input of the urgency of travel for a passenger or passengers. This project assumes vehicles on the road network are equipped with a dashboard computer with capability of inputting any required variables. A number of alternative variables of user input have been considered during development of the PBTC system, including arrival time and relative urgency.

In an arrival time based approach, a user would be required to set their destination and desired time of arrival into the dashboard computer, to be sent to a PBTC traffic controller when approaching an intersection. The PBTC controller can estimate the travel time to the destination and based on the arrival time, assign a cost of delay to the vehicle. One of the advantages of this method is that a sophisticated network of connected PBTC controllers could share knowledge of traffic conditions at each intersection and calculate an accurate measure of the likely travel time based on a route to the destination. Extensions to such a system could also calculate and inform a driver of the best route to the destination based on the passenger urgency, i.e., routing all low priority drivers to a more congested route and redirecting high urgency vehicles to a faster alternative. A significant disadvantage of this approach is the higher complexity of input by a user. If a user does not know the travel time to a destination from their current location, they may inadvertently allocate themselves maximum urgency by setting a short time of arrival and as a result it is more difficult for the system to consider a range of vehicle urgencies.

As an alternative, a relative urgency measure is used by the PBTC system, which asks a driver to set their own perceived urgency as a discrete integer on a scale from one to five. This measure is both easy for vehicle occupants to understand, and simple for a PBTC controller to consider the urgency of an individual vehicle relative to others at an intersection. Passengers can use their knowledge of the approximate travel time to a destination and importance of the journey to make their own judgement about urgency of passage at an intersection. A potential drawback of this system is the ease of which it can be abused, for example all drivers can easily set their urgency to the maximum value. This project assumes that this does not happen, and in practice the higher price payed to pass an intersection at a higher urgency will prevent this behaviour.

For simplicity, the PBTC system assumes that all passengers in a vehicle have identical urgency and as a result, the delay cost is linearly proportional to the number of passengers in a vehicle. Consequently, vehicles with higher passenger occupancy are favoured by the PBTC system, encouraging more efficient use of road networks through ride-sharing or carpooling initiatives. Reducing the number of single occupant vehicles on our roads reduces congestion and fuel emissions, and shares the costs of maintaining and running a vehicle between multiple individuals and is similarly encouraged by High Occupancy Vehicle (HOV) lanes in use on modern highways with congestion problems.

The economic cost of delay to the vehicle occupants is calculated using the NZTA's estimated average figure of \$26.20NZD per vehicle hour. The PBTC system makes the assumption that this figure is representative of the cost of delay for an average journey, and hence reflects a single-occupant vehicle with an urgency of 3. Assuming t is the time a vehicle is delayed in seconds, u is the discrete relative urgency input by the vehicle occupant/s, and p is the number of passengers in a vehicle, a formula for the overall cost of delaying a vehicle, c_{d}, is given as

$$c_{\mathrm{d}} = t^{s(u)} * 0.007(\frac{u}{3}) * p \tag{3.3}$$

Where 0.007 is the delay cost in cents per second, and $s(u)$ is a constant for each vehicle class, determined by

$$s(u) = \begin{cases} 1 & : u \leq 3 \\ 1.1 & : u = 4 \\ 1.25 & : u = 5 \end{cases} \tag{3.4}$$

Figure 3.1 shows the relationship between delay cost and time delayed for each of the five discrete urgency values for up to sixty seconds of delay.

For simplicity, the PBTC system assumes all urgency values are constant and do not change during the time a vehicle is waiting at an intersection. In a real-world system this model is likely to be too simplistic. Depending on the initial urgency of the vehicle, as the length of time that vehicle has been delayed increases, their urgency to pass the intersection will also increase and the costs of delay will compound. There is also a limit to this relationship, for example, if the occupants of a vehicle are delayed to the point that they miss their meeting, flight, or other appointment, their urgency may reduce significantly and/or they may change destination and return home. Modeling these conditions is beyond the scope of this project and not relevant within the simulation environment.

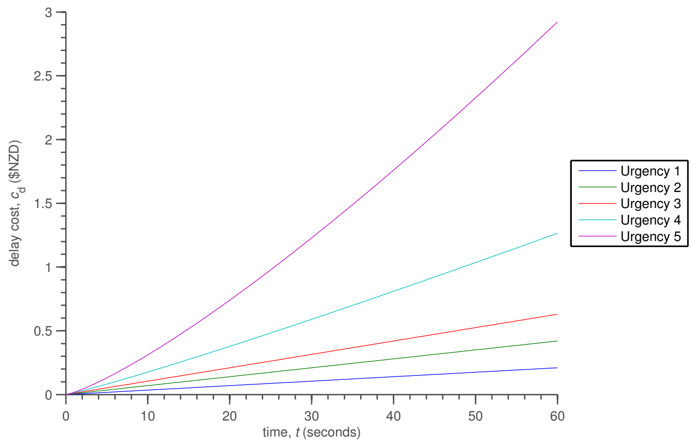

Figure 3.1: Cost of delay per time for a range of occupant urgency values, from time of zero seconds up to sixty seconds.

3.2 Simulator Design

3.2.1 MovSim

A primary challenge of measuring and evaluating performance of an adaptive traffic control system is the requirement to simulate realistic traffic conditions with sufficiently measurable results. Software for simulating traffic control methods is typically developed by vendors of a particular system and as such is proprietary and not available for research. Because of this, an open-source tool called MovSim has been used to develop and evaluate the PBTC system.

MovSim (Multi-model Open-source Vehicular-traffic Simulator) is an open-source, Java-based traffic simulator implementing multiple time-continuous, car-following traffic models designed for investigating traffic dynamics; currently under active development. MovSim is based upon the work of Treiber & Kesting (2013) and implements a wide range of configurable vehicle-following, acceleration, and lane changing models that determine individual vehicle movement within the simulation. MovSim also has a stand-alone visualisation engine that is used to view the progress of a simulation at runtime. Visualising the state of running simulations is beneficial for validating intersection layouts and exploring the interaction between individual vehicles and traffic signals.

Limitations of using the MovSim project as a base simulation tool for the PBTC system include lack of support for bi-directional traffic flow and turning behaviour at intersections, both requirements for accurate modeling of a real world road network. Both of these features are areas of future development for the MovSim project. The sophisticated vehicle modeling capabilities of the MovSim application have outweighed these limitations during development of the PBTC system.

3.3 PBTC System Design

Treiber & Kesting (2013) describes the 'Golden Rule of Traffic Flow Optimisation' as trying to homogenise traffic flow with respect to time, spatial arrangement, and local speed differences.

3.3.1 Assumptions

Design of a system for producing an optimal, minimal cost solution to phase assignment at any arbitrary controlled intersection is a difficult problem and evaluating such a system requires a sophisticated simulator capable of realistically modeling real world intersection geometrics, driver behaviours, and traffic flows. Development of these capabilities for simulation is an effort beyond the scope of this project. For this reason, the following assumptions have been made to simplify development of the PBTC control algorithm within this project:

- the control algorithm operates over a two-phase intersection, with each phase allocating green to one of two flows of traffic approaching the intersection only,
- approaching vehicles represent straight through demand for the intersection only, no left/right split phases (i.e "arrow lights") are required,
- the algorithm is limited to a single, isolated intersection only and does not consider any aspects of coordination between neighbouring intersection controllers.

3.3.2 Vehicle-Controller Communication

Communication between approaching or waiting vehicles and a PBTC controller at an intersection is required to provide inputs to the control algorithm to make a cost effective choice of phase timings based on the real-time traffic conditions. The implementation details of the required communication network is beyond the scope of this project and suggested as an area for future research. This project assumes that all of the necessary technology required for vehicles to send small packets of information to a controller exists in every vehicle using the road network, and each vehicle sends its own state information directly to the roadside intersection controller.

In the simulation developed as part of this project, vehicles approaching or waiting a PBTC controlled intersection broadcast their current state to the intersection controller every two seconds if the distance to the intersection stop line is less than 150 metres. There are two justifications for this behaviour, firstly; although in a simulated environment any object can feasibly read the properties of any other object at any time, it is important to consider the real world application of the system where network latency and limited network capacity are real problems that prevent instantaneous, real-time messaging with no delay.

Secondly, consider a situation where a single vehicle is approaching a red light at an intersection where there is no demand for the competing green phase; in a stop-line actuated control system the vehicle will be forced to stop, wait at least six seconds for the lights to react and change phase, and then take off. By allowing a 150 metre broadcast window, a PBTC controller is able to respond to this situation and change the phase before the approaching vehicle has reached the lights, preventing them from stopping. The 150 metre window is based on assuming an approaching vehicle is traveling at a constant speed below 80km/h (approximately 22 m/s), requiring at least 133 metres of clearance given a typical controller requires 6 seconds of inter-green time to change a phase. In practice, it might be useful to be able to tweak the distance at which cars would be considered by the PBTC system based on the speed limit of the area.

3.3.3 Control Algorithm Design

The PBTC control algorithm is a primary component of the PBTC system, designed to be executed by a roadside traffic controller to determine which phases should operate, the order of operation, and duration of each phase; in real-time. The primary objective of the

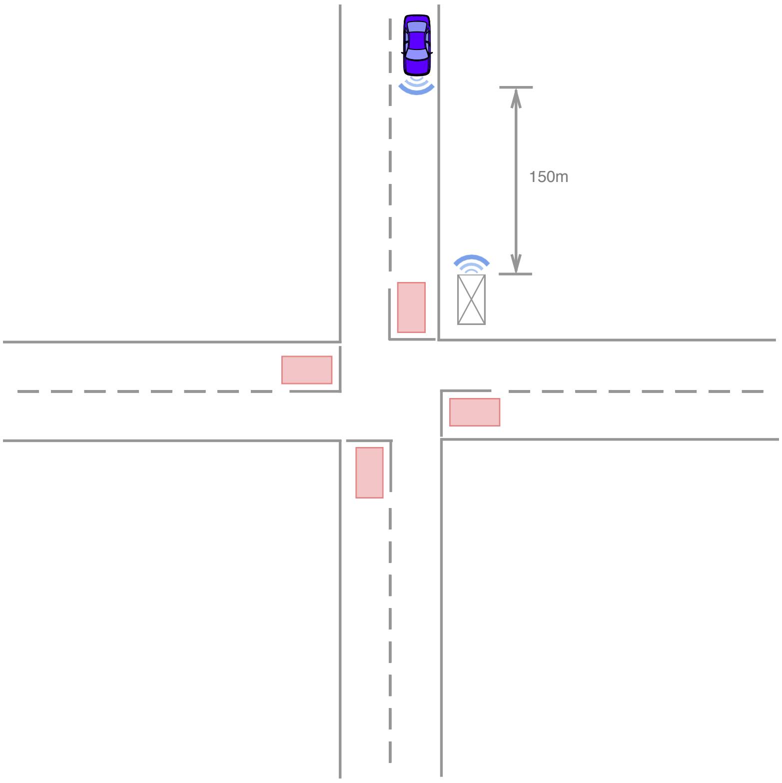

Figure 3.2: Plan elevation of a simple four way intersection showing an approaching vehicle communicating with a PBTC controller. The distance of initial communication is shown as 150 metres. The position of stop-line detectors typically used by SCATS systems are shown in red. The PBTC controller is able to adapt to vehicle actuations in advance of the vehicle arrival at the stop line.

PBTC control algorithm is to reduce the total economic cost incurred by vehicle movements at PBTC controlled intersection, using traffic composition information communicated to a controller by vehicles in the network.

Phases of an intersection are preconfigured based upon the geometry of the intersection. Each phase within the PBTC system contains an allocation of green or red signals to each light at a controlled intersection, such that no two competing traffic flows receive a green light at the same time in a phase. Two traffic flows are said to be competing if a collision would occur if vehicles on each flow entered the intersection at the same time. Each phase also defines a minimum time the phase must run for. The minimum time condition is a safety consideration of the system, designed to allow enough time for at least one vehicle to pass safely through the intersection before the phase is changed.

The order and duration of phases at a PBTC controlled intersection is determined by calculating aggregate costs of delay and operation for each approach of an intersection. A PBTC controller maintains a list of messages received from approaching or delayed vehicles that are used for calculation of the delay costs and operational stopping costs for each vehicle and aggregated to find the total costs for an approach.

The primary cost of changing phases at a controlled intersection is the cost of stopping and delaying free flowing traffic. As a result, the standard operation for a PBTC controlled intersection is to run a set phase continuously until a phase change is determined to be cost effective and scheduled by the PBTC control algorithm. This behaviour is designed to produce minimal changes to the system, effectively maximising the homogeneity of free flowing traffic until the cost of interfering becomes low relative to the cost of doing nothing.

A phase change is scheduled by a PBTC controller if the sum of the cost of stopping the traffic flow currently approaching a green signal, defined as the phase change cost or c_{pc}, is less than the total incurred cost of delay for all vehicles queued and waiting at any approaches displaying a red signal, defined as the phase delay cost or c_{pd}. The cost of stopping the traffic flow on a green signal also includes an estimation of the potential delay cost for each vehicle assuming they must be delayed *at least* as long as the minimum condition for the newly scheduled phase. Equations X and X define the phase change cost and phase delay cost in a mathematical notation.

$$c_{\mathrm{pc}} = \sum_{v \in approaches.green.vehicles} c_{\mathrm{stop}} + c_{\mathrm{delay(min)}} \tag{3.5}$$

$$c_{\mathrm{pd}} = \sum_{approach \in approaches.red} \; \sum_{v \in approach.vehicles} c_{\mathrm{stop}} + c_{\mathrm{delay(min)}} \tag{3.6}$$

If this condition is true at any time, the algorithm enters a phase change sequence. During a phase change sequence, a lookahead heuristic is applied to find the minimum potential cost incurred as a result of the change. Based on a predefined lookahead table size, the controller estimates the total cost of changing phase for each second from zero up to the table size, constructing a table with each row representing a time in seconds and the cost of stopping the phase at that time. The controller then dynamically extends the current phase duration by the number of seconds that corresponds with the lowest cost value in the lookahead table.

The lookahead method used in the PBTC control algorithm is an optimisation method performing a local search for a time of changing phases that incurs the least cost to the system. For example, consider an intersection where two vehicles have been waiting at a red signal for 60 seconds, and the cost of delay has exceeded the cost of stopping the opposing traffic flow receiving a green signal. If two vehicles are approaching the intersection on the freely flowing approach but are close enough to stop if the phase is changed immediately, the cost of the change includes the operational cost of stopping the two vehicles and the cost of delaying the vehicles for the minimum duration of the next phase.

Due to their distance from the intersection and current velocity, after one additional second the two moving vehicles may pass through the intersection and these costs are avoided, with the trade-off cost being one more second of delay for the two waiting vehicles which is likely to be significantly less. The lookahead procedure of the PBTC control algorithm will evaluate the total cost of extending the current phase by a fixed number of seconds to allow the moving vehicles to pass, and extend the current phase by the calculated minimum time if it is found to be less than the cost of an immediate change.

Algorithm 1 PBTC phase scheduling algorithm

Data: c_p : $currentphase, n_p$: $nextscheduledphase, a$: $setofapproaches, K$: $lookaheadwindowsize$
Result: minimal cost time until phase should be change executed

```
begin
    set totalStoppingCost = 0
    set totalDelayCost = 0
    for approach in approaches do
        if approach signal is red then
            add cost of delay for all vehicles queued on approach to delayCost
        end
        else
            add cost of stopping and cost of minimum delay for all vehicles on approach to
            stoppingCost
        end
    end
    if stoppingCost ¡ delayCost then
        set lookaheadTable = []   for i := 0 to K do
            lookaheadTable[i] = cost of delay for all stopped approaches over i + cost of stop-
            ping for all vehicles that cannot clear the intersection after i seconds
        end
        set extendedGreenTime = index of minimum value in lookaheadTable   return ex-
        tendedGreenTime
    end
    return -1 ;                                        /* no change scheduled */
end
```

3.4 Evaluation Methodology

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Appendices

Appendix A

Gantt Chart of Project Achievement

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Figure A.1: The Gantt chart above shows expected approximate work breakdowns for the trimester break and trimester two. Velocity of the project (work completed per week) is expected to be significantly higher during the trimester break than period after the beginning of trimester two. It is expected that the time allocations provided are sufficient for the required work.