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THE WHITE TRIANGLE: A PATH TOWARDS EFFICIENT AND INTEGRATED LIGHT RAIL SYSTEMS

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ABSTRACT

Australian light rail networks include significant lengths of on-street running, where frequent intersections increase passenger journey times. This paper reviews the White Triangle signals used on Sydney's light rail network. These signals allow drivers to continue up to a red signal at speed, knowing that it will change in their favour. Whilst similar systems are used elsewhere around the world, there exists limited guidance to aid signal designers and support the use of these signals. This paper presents a framework to optimise White Triangle display times to reduce intersection delays. This was found to provide a theoretical time saving of 3 to 30 seconds per intersection. Whilst this is only partially achievable in practice, the paper demonstrates that White Triangles can be used to reduce LRV phase lengths and maximise Transit Signal Priority effectiveness. The signals thus offer potential reductions in passenger journey times and cost savings to network operators.

Keywords: White Triangle, Light Rail, Signals

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Australian light rail networks include significant lengths of on-street running, where frequent intersections increase passenger journey times. This paper reviews the White Triangle signals used on Sydney's light rail network. These signals allow drivers to continue up to a red signal at speed, knowing that it will change in their favour. Whilst similar systems are used elsewhere around the world, there exists limited guidance to aid signal designers and support the use of these signals. This paper presents a framework to optimise White Triangle display times to reduce intersection delays. This was found to provide a theoretical time saving of 3 to 30 seconds per intersection. Whilst this is only partially achievable in practice, the paper demonstrates that White Triangles can be used to reduce LRV phase lengths and maximise Transit Signal Priority effectiveness. The signals thus offer potential reductions in passenger journey times and cost savings to network operators.

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1. INTRODUCTION

Australian light rail is undergoing a resurgence, with new networks recently opening in Sydney, Newcastle, Canberra, and the Gold Coast. However, Australian networks have significant lengths of on-street running where light rail vehicles (LRVs) must stop at red lights. This increases journey time, and requires additional LRVs and crew to meet contractually-mandated service frequencies.

Sydney's CBD and South East Light Rail (CSELR) is a 12 km long light rail system linking the City with Randwick and Kingsford. The CSELR utilises three different signalling systems, including:

- **Line of sight** operations where the driver is responsible for avoiding obstructions
- **Rail signals** to control turnouts and allow LRVs to cross from one track to another
- **Intersection traffic signals** linked to Sydney's Coordinated Adaptive Traffic System (SCATS)

Traffic signals are common on the line, with 33 signalised intersections on the line between Circular Quay and Randwick, and 37 on the line between Circular Quay and Kingsford. Intersection delay times are a key performance metric on the system, with Transport for New South Wales (2014) incentivising the line's operator to minimise intersection delays, to allow them to operate with fewer vehicles. CSELR traffic signals consist of standard Australian three-aspect T signals (Red, Amber and White). However, some intersections have a fourth aspect showing a White Triangle. This is illuminated with the Red T, about six seconds before a White T is displayed (Fig. 1). Thus, a White Triangle allows drivers to accelerate their LRV towards the red light, knowing that the signal is about to change for them. This signal is unique amongst Australian light rail systems, and there are only a few examples of similar systems elsewhere globally. There is also only limited information available to aid signal designers when implementing these signals and quantifying their benefits.

This paper proposes a design methodology which could be used to optimise White Triangles, and which could assist designers with applying these signals on other light rail systems. It also assesses the potential of White Triangle signals to reduce journey times, using the CSELR as a case study.

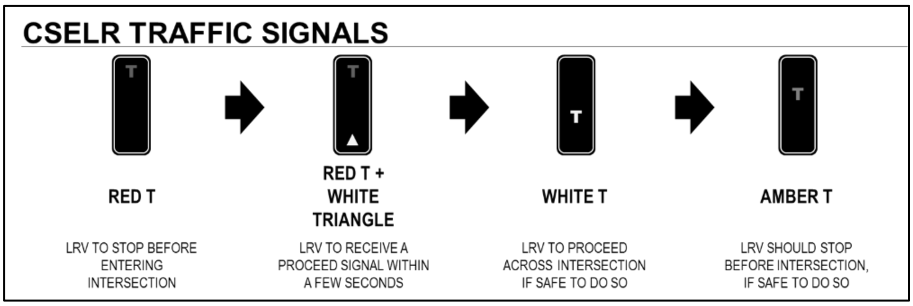

Figure 1: Sequence of Operation of CSELR Traffic Signals

2. GLOBAL CASE STUDIES

A review of light rail networks globally found some signals which were similar to Sydney's White Triangle, including on networks in France (e.g. Nice & Marseilles, as in Fig. 2), Portland, United States of America and Kaohsiung, Taiwan. Of these, only the French system had a publicly-available standard (Service Technique des Remontées Mécaniques et des Transports Guidés, 2009). Their fourth aspect, termed the **"Vertical Announcement,"** (Sydney's White Triangle), is displayed in the seconds before the "Vertical" signal is received (Sydney's White T). This system also includes a fifth "Acknowledge" aspect, indicating when the LRV's request for intersection access has been received (Savona n.d.).

The French standard notes that the Vertical Announcement should only illuminate before the vehicle reaches the point at which it would otherwise have to brake to stop at the intersection (Service Technique des Remontées Mécaniques et des Transports Guidés, 2009). It proposes using a linear deceleration rate of 1.2 m/s^2, a driver reaction time of 0 seconds, and a vehicle reaction time of 0.85 seconds. The standard gives a minimum display time of 3 seconds (to enable the driver to actually perceive the signal). No maximum display time is given; however, it notes the signal's effectiveness would be reduced if the display time was excessive and gives a preference for consistent display time across a network.

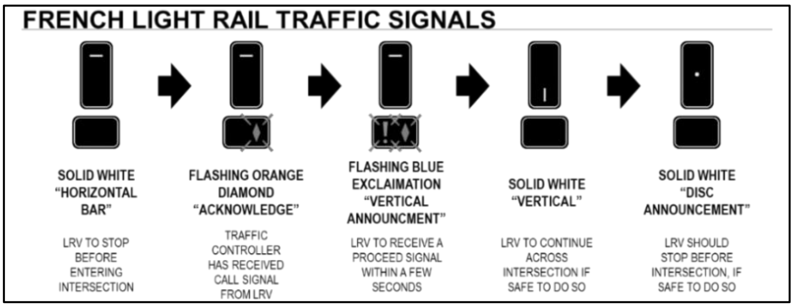

Figure 2: Sequence of Operation of French Light Rail Traffic Signals

3. LITERAURE REVIEW: ACCELERATION AND BRAKING CONSIDERATIONS

3.1 Light Rail Vehicle Data

In order to develop a design framework for White Triangle signals and assess their effectiveness, LRV data was reviewed to understand the limits of LRV acceleration and braking (refer to Table 1).

Table 1: Typical Values for Maximum Service Braking, Acceleration and Speed for Various LRVs

LRV	Max Service Brake (m/s^2)	Max Service Acceleration (m/s^2)	Max Speed (km/h)	Source
Sydney Citadis 305	1.2	1.3	80	Railway Technology 2021
Melbourne E Class	1.2	1.3	80	Yarra Trams 2020
Sheffield Supertram	1.5	1.3	80	Stage Coach 2021
Croydon Flexity Tram	1.3	1.2	80	Bombardier 2009

It is noted that most LRVs also have emergency track brakes. These consist of electromagnets which drop and attach to the track, rapidly slowing the vehicle at rates of up to 3.0 m/s^2 (Yarra Trams 2020).

3.2 Role of Non-Linear Acceleration and Braking Rates

However, it is not realistic to assume that an LRV accelerates and decelerates at its maximum service rate at each intersection. In practice, LRV drivers actually apply an increasing rate of acceleration / deceleration up until a point, before decreasing this rate as the LRV approaches their desired speed. Wang & Rakha (2018) developed a non-linear model for light rail vehicle behaviour, applying traditional rail equations such as rolling resistance (the well-known Davis equation), tractive effort and rail braking force, along with Fadhloun et al.'s (2015) throttle behaviour model for cars. They calibrated the terms of this throttle model using GPS data from the Portland light rail system, finding a good fit between their modelled speed and acceleration values, and values observed in the field. The Wang & Rakha model juxtaposes Service Technique des Remontées Mécaniques et des Transports Guidés (2009), which instead calculates Vertical Announcement time using a linear deceleration rate.

3.3 Impacts on Passenger Comfort and Safety

Acceleration and braking are further complicated by passenger comfort considerations. Accelerating or braking too harshly is likely to cause passenger discomfort or injury, with LRVs particularly susceptible to this given their high proportion of standing passengers. Powell & Palacin (2015) review the physiological responses of passengers to the acceleration and braking of rail vehicles. They note that standing passengers respond using different strategies depending on both the magnitude of the acceleration, and the rate of change in acceleration (jerk). For low acceleration and jerk, passengers bend the ankles and/or hips, whilst in situations of high acceleration and jerk passengers take one or more steps. This "stepping strategy" is most dangerous, as passengers risk losing their footing and falling.

A linear acceleration model does not consider jerk, however in practice an LRV driver would manage jerk by the rate at which they move their controller. Instead, limits for comfortable acceleration rates were reviewed. Powell & Palacin (2015) note that a British Rail "rule of thumb" for comfortable acceleration was 0.1g (i.e. $0.98 m/s^2$, g is acceleration due to gravity). Karekla & Fang (2021) note that for passengers to move freely on a bus, acceleration should be kept between 0.7 & $1.2 m/s^2$. Finally, Bae et al. (2019) reviewed acceleration on an autonomous minibus, and found that a maximum of $0.9 m/s^2$ was acceptable for standing passengers. Thus $1.0 m/s^2$ appears to be a comfortable acceleration rate.

3.4 Driver & Vehicle Reaction Time

The calculation of vehicle acceleration and deceleration must also consider the time taken for a driver to perceive and react to a signal. Whilst there is limited data available on LRV driver reaction time, reaction time is well-studied for cars, with road design standards using this data. A value of 1.0 second is adopted in the United States yellow light driver reaction time (Transportation Research Board 2012). Austroads (2020) notes Australia adopts a yellow light driver reaction time of 1.0 to 1.5 seconds. This standard also states that a yellow light must be displayed for at least 3 seconds to allow for its perception (consistent with the 3 seconds minimum Vertical Announcement time in the French standard).

LRVs may also have a reaction time (time taken to respond to a drivers' command to accelerate or brake). Service Technique des Remontées Mécaniques et des Transports Guidés (2009) adopts an LRV reaction time of 0.85 seconds, from the European Standard for Mass Transit Braking Systems (EN13452). Thus, for the purpose of this design framework a total (driver + LRV) reaction time of 2 seconds will be used.

4. FRAMEWORK FOR DETERMINING WHITE TRIANGLE DISPLAY TIME

This literature review as well as observation of CSELR intersections has allowed for a framework to be developed to optimise **White Triangle Display Time**. In this framework, intersections are classified as

- **Type A**: intersections not located adjacent to a light rail stop (LRV would be decelerating), or
- **Type B:** intersections located adjacent to platforms (LRV would be accelerating).

It is noted that one intersection may be a different type in each direction (depending on station locations).

4.1 Considerations at Both Type A and Type B Intersections

For both Type A & B intersections, there is a point at which the driver has to look for a White Triangle and make a decision to alter their speed, termed the **Decision Point**. To remind drivers, some similar systems internationally (e.g. Portland, USA) actually mark this location with a physical sign (Fox 1992). In general traffic, drivers normally begin to decelerate well ahead of the last point at which they would theoretically be able to stop before the intersection. Discussing the commissioning process for similar systems with a practicing light rail signal designer, it was noted that LRV drivers are similarly conservative, even when a White Triangle-type signal is displayed. Diez (pers. comm. September 20, 2021) notes that drivers often brake early, as they feel they are at risk of entering the intersection under a Red T. She instead suggests that additional seconds of White T, displayed before the LRV enters the intersection, could resolve these concerns. This **Confidence Factor Time**, of say 2 seconds, could then be optimised during the signal commissioning phase to ensure drivers are not braking unnecessarily. Its hypothesised that this time can also be used to account for any differences between linear equations of motion and non-linear approaches to LRV motion (as in Wang & Rakha 2018). For this reason, this paper proposes using linear equations to simplify White Triangle Display Time calculation.

Additionally, the White Triangle Display Time must be long enough for a driver to perceive the signal. It is therefore reasonable to adopt a **Minimum White Triangle Display Time** of 3.0 seconds (based on the literature reviewed in Section 3.4 above). In the case of an adaptive traffic signal control system like SCATS, there is also likely to be a **Maximum White Triangle Display Time**. The length of any individual traffic light phase at an intersection in the SCATS system varies based upon both demand for other phases at that intersection, as well as instructions from a regional computer (detecting demand at other intersections and adjusting intersections accordingly) (Austroads 2020). A White Triangle cannot be displayed until it is certain that a light rail phase is about to commence (as otherwise the LRV could enter the intersection under a Red T). This is generally only possible once the previous phase has begun to end, effectively limiting the White Triangle Display Time to the length of the intersection's intergreen period (i.e. the yellow + all red clearance time). The length of this intergreen period may vary by an intersection's speed and geometry, and the calculation methodology may differ between jurisdictions. Adopting the calculation methodology given by Austroads (2020), for a typical a 30 m wide, level intersection, with a design speed of 50 km/h, the intergreen period would be approx. 6 seconds.

The French Standard also notes that it is preferable that Vertical Announcement signals are displayed for the same length of time at all intersections (Service Technique des Remontées Mécaniques et des Transports Guidés, 2009). However, an increased speed increases the distance an LRV will take to stop (Type A) and increases the time taken to accelerate to line speed (Type B). Higher speeds also generally result in longer intergreen periods (yellow and all-red times become longer), allowing for longer White Triangle Display Times. Over many light rail lines, there can be considerable difference in speed, for example, the CSELR has intersections with speeds varying from 10 km/h to 60 km/h. In these networks, it may be advantageous to adopt a **Dynamic White Triangle Display Time**, varying the display time based on the speed of the intersection. To aid in driver training, it may be useful to group intersections (which could be adjacent and/or of similar speed), to provide consistent speed across each group.

4.2 Type A Intersections

An idealised velocity time graph was produced for an LRV approaching a Type A Intersection, showing the best, worst and some intermediate cases (Fig. 3). In the Best Case, the LRV receives the White Triangle whilst travelling at line speed, entering and exiting the intersection without decelerating. This would occur if the current signal phase was a light rail phase, or if a light rail phase was ready to start (e.g. if full active Transit Signal Priority was in effect). However, in the Worst Case there is no LRV phase immediately available, and the LRV doesn't receive a White Triangle until it has come to a complete stop. There also exists an infinite number of intermediate cases, where the LRV receives a White Triangle after it begins decelerating, but before it comes to a stop. This occurs if a light rail phase starts after the LRV begins decelerating (it is noted that if conditional Transit Signal Priority is provided, the LRV is kept moving at a higher speed, when compared to if no White Triangle is provided). Thus, for a safe solution, a Type A intersection must satisfy both of the following criteria:

- **If a White Triangle is sighted,** the LRV must not be able to travel the full distance from Decision Point to intersection stop line, before a White T is shown (critical for normal solution).
- **If no White Triangle is sighted**, the LRV must be able to safely stop from line speed, in the distance between the Decision Point and intersection stop line (critical for constrained solution).

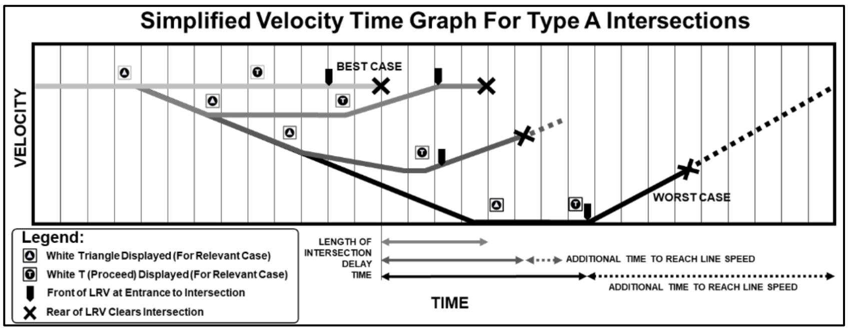

Figure 3: Idealised Velocity-Time Graph for an LRV Approaching a Type A Intersection

In a **Normal Solution**, the White Triangle Display Time and Confidence Factor Time set the Decision Point (Fig 4). This allows LRVs which don't receive a White Triangle to stop well before the intersection stop line when decelerating at a comfortable rate (say, 1.0 m/s^2, based on Section 3.3 above, noting that in practice drivers would just decelerate more gradually over this distance). The driver is not at risk of entering the intersection before the White T is observed, as the Confidence Factor Time ensures some time between when the White T is displayed and the vehicle actually entering the intersection.

With a **Constrained Solution**, the distance taken for an LRV to stop at a comfortable deceleration rate sets the Decision Point (Fig. 4). There appears no need to add an additional safety factor to this distance, as the driver could apply the LRV's maximum service braking to stop earlier at say 1.2 m/s^2, rather than a 1.0 m/s^2 (notwithstanding this, designers should always consider ways to reduce the risk of vehicles and pedestrians obstructing tracks). However, in the Constrained Solution, an LRV which does receive a White Triangle is unable to cover the Decision Point Distance in the White Triangle Display Time and Confidence Factor Time. This results in extra unnecessary distance between the point where the Confidence Factor Time expires, and the intersection stop line. This effectively wastes time as part of the LRV phase. For this reason, designers should seek to adopt the Normal Solution, where possible.

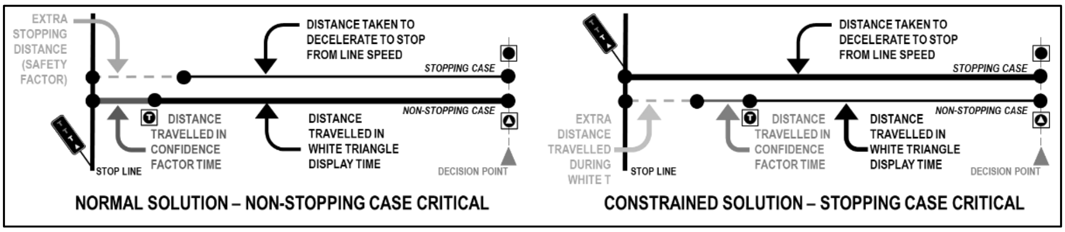

Figure 4: Diagrammatic Comparison of Normal and Constrained Solution

Therefore, an iterative process is required to optimise the White Triangle Display Time, as in Fig. 6. Taking a trial White Triangle Display Time, the non-stopping time can be found as:

$$t_{non-stopping} = t_{trial} + t_{confidence\ factor} \tag{1}$$

And hence the non-stopping distance is:

$$s_{non-stopping} = t_{non-stopping} * v_{linespeed} \tag{2}$$

The stopping distance is then found using:

$$s_{stopping} = \frac{-v_{linespeed}^{2}}{2a_{deceleration}} + \frac{v_{linespeed}}{t_{reaction}} \tag{3}$$

And hence the time taken to travel the stopping distance at line speed is found as:

$$t_{stopping@linespeed} = \frac{s_{stopping}}{v_{linespeed}} \tag{4}$$

The designer must check that the trial time lies within the Minimum and Maximum Display Times. A Normal Solution occurs if $t_{stopping@linespeed}$ is less then $t_{non-stopping}$, and hence the decision point is set by

Equation 2. If a Constrained Solution is obtained, then the designer should firstly iterate, trying to obtain a Normal Solution (as this would be more efficient). However, if a Constrained Solution must be adopted then the stopping distance should be taken as the greater of the values yielded by Equations 2 and 4.

4.3 Type B Intersections

A similar velocity-time graph was developed for Type B intersections (Fig. 5). The Best-case scenario involves an LRV receiving the White Triangle as it moves off from the platform. Over the **Available Distance** between the platform and intersection, the LRV accelerates to line speed, maintaining this speed as it enters the intersection under a White T. In the Worst-case scenario, the LRV accelerates and decelerates to stop at the intersection, where it has to wait to receive a White Triangle and White T. Only then can it enter the intersection, experiencing a delay in reaching line speed. There exists an infinite number of cases between Best and Worst, depending on when the LRV receives the White Triangle.

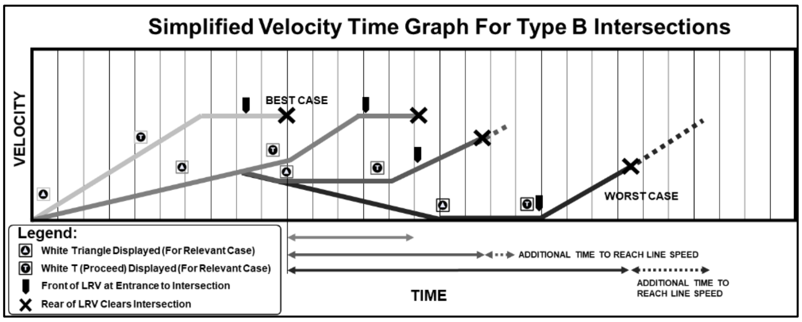

Figure 5: Idealised Velocity-Time Graph for an LRV Approaching a Type B Intersection

There is also an iterative process to arrive at the White Triangle Display Time for Type B intersections (refer Fig. 6). However, for these intersections the Decision Point is always fixed at the end of the platform. Designers should firstly determine if the LRV can reach line speed in the available distance:

$$s_{accel2linespeed} = \frac{v_{linespeed}^2}{2a_{max}} \tag{5}$$

Noting that the vehicle's maximum service acceleration rate should be used, to give a more conservative result. If $s_{accel2linespeed}$ is greater than $s_{available}$ then there is only one component in the subtotal time:

$$s_{subtotal} = \sqrt{2a_{max}s_{available}} \tag{6}$$

Otherwise the subtotal time requires two components, one for acceleration and one for constant speed:

$$s_{subtotal} = \frac{v_{linespeed}}{a_{max}} + \frac{s_{available} - s_{accel2linespeed}}{v_{linespeed}} \tag{7}$$

Deducting the Confidence Factor Time from the subtotal gives a **Trial Display Time.** If this is less than the Minimum Display Time, then no White Triangle should be provided (as the LRV accelerating from the platform would otherwise be at risk of entering the intersection before the White T is displayed). This was observed on the CSELR, where Type B intersections located immediately adjacent to a platform did not appear to have White Triangles. From here, the lesser of the Trial Time and the Maximum Display Time should be adopted as the final White Triangle Display Time.

5. QUANTIFYING THE TIME SAVINGS FROM ADOPTING WHITE TRIANGLES

To quantify the benefits of White Triangle signals, the theoretical framework proposed was applied to three CSELR intersections. Linear equations of motion were then used to calculate the difference between the Best and Worst Cases in Figs. 4 & 5, giving a Maximum Theoretical Time Saving.

5.1 Type A Intersection: George St at Market St, Southbound

At this intersection, the LRV speed limit is 20 km/h, and width of the intersection is about 20 m. For this scenario, a White Triangle Display Time of 3.0 seconds, and Decision Point Distance of 28 m was found giving a Normal Solution. The time taken for an LRV to approach, cross and clear the intersection

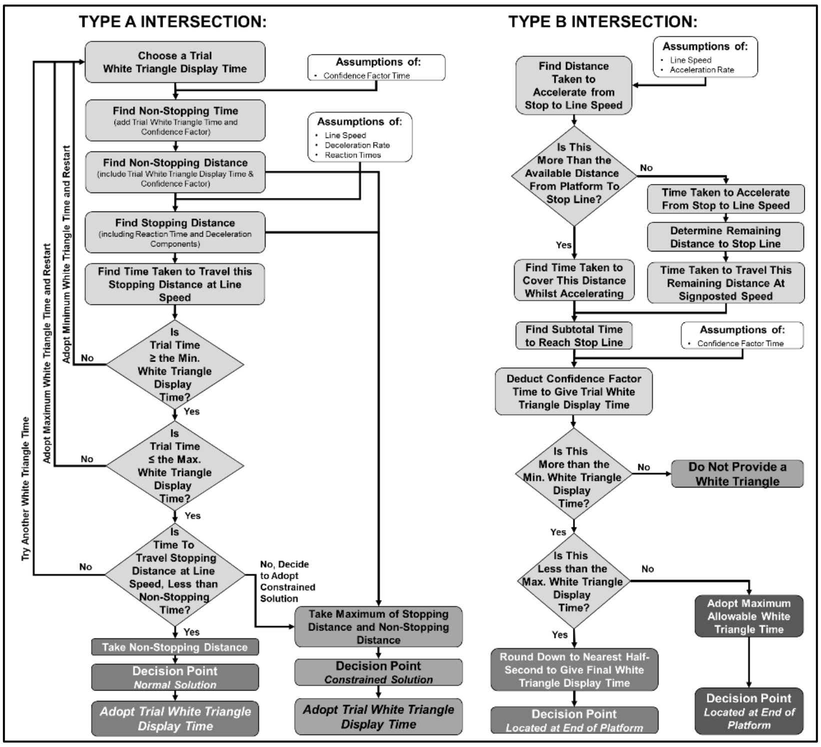

Figure 6: Summary of Proposed Design Framework for Type A and Type B intersections.

travelling at line speed was found to be 22.5 seconds (i.e. Best Case). Whilst the time taken for the LRV to decelerate to stop at the light, and accelerate back to line speed (before clearing the intersection) was found to be 33.9 seconds (Worst Case). This gives a maximum theoretical time saving of **11.4 seconds**.

5.2 Type A Intersection: ANZAC Parade at Barker St, Southbound

Here the LRV speed limit is 50 km/h, and width of the intersection is about 30 m. For this scenario, the intergreen time gave a Constrained Solution, limiting the White Triangle Display Time to 6 seconds, giving a Decision Point Distance of 125 m. The time taken for an LRV to approach, cross and clear the intersection travelling at line speed was found to be 16.0 seconds (i.e. Best Case). Whilst the time taken for the LRV to decelerate to stop at the light, and accelerate back to line speed (before clearing the intersection) was found to be 43.8 seconds. This gives a maximum theoretical time saving of **27.8 seconds**. This theoretical time saving would easily exceed 30 seconds at higher design speeds.

5.3 Type B Intersection: ANZAC Parade at Borrowdale Rd, Southbound (Kingsford Station)

The distance between the end of Kingsford station and start of the intersection is about 60 m, and width of the intersection is about 30 m. LRVs are limited to 25 km/h here. This gave a White Triangle Display Time of 6 seconds (limited by the intergreen period), with the Decision Point at the end of the platform. This allows the LRV to reach line speed before crossing and clearing the intersection, giving a cross and clear time of 14 seconds (i.e. Best Case). The Worst Case would see the LRV start from a standing stop at the entrance to the intersection, taking 17.4 seconds to cross and clear the intersection (returning to line speed before clearing the intersection). This gives a maximum theoretical time saving of **3.5 seconds**.

6. CONCLUSIONS

By developing a theoretical design framework for both Type A and B intersections, White Triangles have been shown to be effective at reducing LRV intersection delay times. Maximum Theoretical Time Savings of 3 to 30 seconds were found, and whilst this saving is unlikely to be fully achieved in practice, this simplified assessment acts as a proof of concept. White Triangles have the potential to increase Transit Signal Priority effectiveness, by keeping LRVs at a higher speed for longer (compared to if no

White Triangle is provided). Even if only a portion of the theoretical time savings is achieved in practice at each intersection, a reduction across many intersections could allow operators to reduce journey times and thus the number of LRVs and crew needed to operate a given frequency. Further, any reduction in intersection delay for an LRV also reduces the amount of time cross-traffic spends facing a red light.

6.1 Considerations for Designers Seeking to Use White Triangle Signals

In addition to the theoretical design framework presented in this paper, signal designers should consider other aspects of White Triangle signals at different points in a project's lifecycle. White Triangles, and incentives to optimise them to reduce journey time, should be included in a project's contract from the outset. An integrated approach should be adopted to mitigate safety risks during the design stage, and adjust the Display Time and Confidence Factor Time in commissioning. Finally, operators must ensure drivers receive comprehensive training to ensure they effectively respond to White Triangle indications.

6.2 Areas for Future Research

There exists a number of areas for future research into White Triangle signals, including to (1) quantify their benefits through microsimulation traffic models, (2) investigate LRV driver behaviour when faced with a White Triangle signal, (3) to propose methods and strategies to aid in commissioning of these signals and (4) develop training programs to support LRV drivers in responding to these signals.

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