

# **Better service through runtime savings – Inner West Light Rail case study**

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## **Abstract**

Patronage on the Inner West Light Rail is exceeding the forecasts developed for the design of the Dulwich Hill extension. UTS has been working with students, Transdev and TfNSW to examine options to increase service delivery using the existing assets to cope with this increased demand.

In 2018, UTS completed a research program to determine how saving four minutes and reducing running time variability could reduce the current deployed fleet size by one vehicle. This saving could then be reinvested to decrease the vehicle-headway for no additional cost.

This paper provides a background on the inner west light rail then outlines the research program examining the impact of dwell-times and signalised intersections on light rail operations; and suggestions for reducing that impact. Then this paper examines why running time and running time variability impact the headway adherence and the operating costs.

## **1 Introduction**

In May 2016, the author (Mr Mathew Hounsell) undertook a study using Opal records into passenger usage of Inner West Light Rail (IWLRL) for the Institute for Sustainable Futures at the University of Technology Sydney (UTS). This started an IWLRL research programme focusing on how to improve customer satisfaction and operations efficiency. Dr Michelle Zeibots led the supervision of engineering capstone students and the author co-supervised.

This paper examines why the IWLRL optimisation programme was undertaken, the driving principles, and some of the key findings of that programme.

The research programme was begun using the principles of least cost planning, our objective was to determine ways to improve service quality with the least investment in capital and operating expenditure. Ideally the programme would find ways to improve services and also reduce costs. Initial investigations determined that there may be many ways to improve the operations of the IWLRL. It was determined that saving four minutes from the end-to-end runtime on the Inner West Light Rail could reduce the size of the deployed fleet. Those saving could then be used to improve the farebox-recovery-ratio or reinvested as lower vehicle-headways. The key approaches identified were operating speeds, dwell times, intersection delays and targeted service delivery.

A new crop of engineering students arrived seeking capstone topics. Initially three students were each shepherded into assessing one of the key approaches listed above. Those students worked closely with Transdev and TfNSW in assessing specific and achievable low-cost improvements. After the written components of the projects were completed the students worked with Dr Zeibots and Mr Hounsell to deliver a forum to communicate the findings to the partners. The partners were impressed with the initial results of the program and were impressed with the approach, key findings, and the cohesive nature of the results. The partners committed to actioning some of the suggestions and investigating others.

The process demonstrated that a focussed student research programme could provide both useful practical experience for the students and useful research results to industry partners.

#### Inner West Light Rail research team



Additionally, this programme demonstrated that the principles used are not widely understood. There is a need for andragogic materials and approaches to provide both students and industry persons with a grounding in these principles. There is a need for these principles to be disseminated throughout the cluster including to roles as diverse as land use planning and contract managers. This paper aims to demonstrate how we communicated to lay persons that reducing runtimes and runtime variability can be used to reduce cost or improve services.

First, a background on the IWLR is provided for readers. Next, an outline of pertinent results from the original study are outlined to explain why the programme was started. Then, the engineering capstone projects are discussed. Finally, the paper examines the principles as we communicated them in detail. The paper takes a different approach to other texts due to the practical experience communicating these materials to lay-persons.

In addition, there are several nuances that were codified during this program that are covered throughout the paper.

### 1.1 The operator

Transport for NSW (TfNSW) is the department overseeing the NSW transport cluster. TfNSW oversee the IWLR operator (Transdev), the roads operator (RMS), the traffic signal operator (RMS), the Transport Management Centre, the Asset Standards Authority and the Customer Experience group. TfNSW determines the number of trams required and purchases

them. TfNSW determines the number of services that are deployed at any time. TfNSW also controls the ticketing, stops, wayfinding, track, operating speeds, operating rules, etc. TfNSW determines if additional vehicles are deployed to cope with crowding or variability. RMS determines how the signalised intersections are programmed.

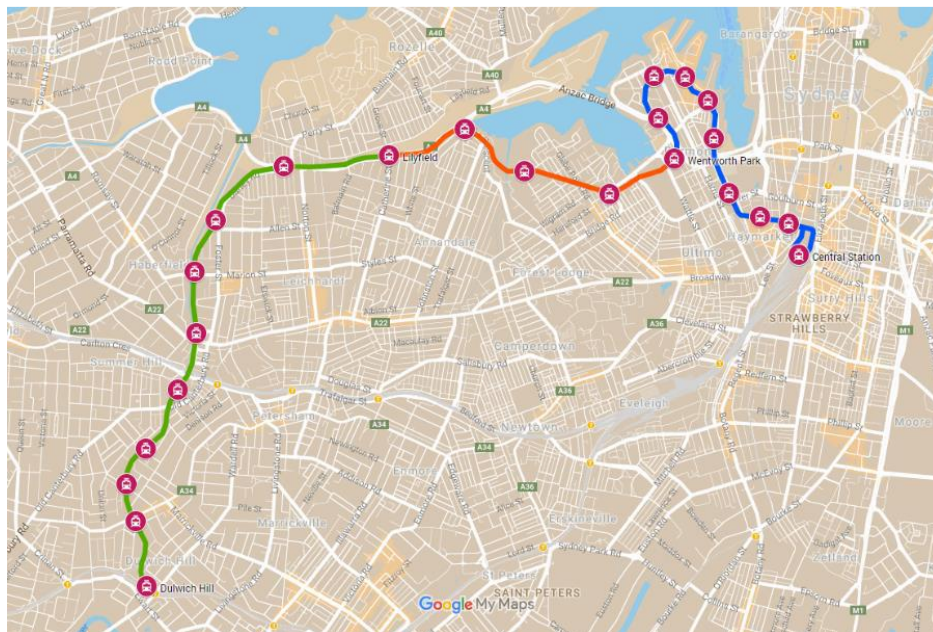
This paper uses the phrase **operator** to refer to the harmonious combination of department, agencies, and corporations working together to deliver the IWLR services.

This research programme aimed to demonstrate to TfNSW several ways to reduce IWLR end-to-end running times in order to deliver a reduced vehicle-headway using the same number of crewed vehicles. The reduced vehicle-headway would reduce the passenger's average and maximum waiting times. In turn that would improve the attractiveness of the service and improve the Farebox Recovery Ratio. Delivering reducing running times would lead to direct fiscal benefits and wider societal, economic and environmental benefits.

Sydney has grown to 4.6 million persons and is expected to continue growing by 100,000 persons a year. The IWLR has become a major transport line. In Australia's two most important cities the previous *laissez-faire* approach of providing reasonable transport service with reasonable reliability is no longer sufficient. For Australia's economy to keep growing and our environmental footprint to reduce Australia must provide excellent public transport.

This paper uses the Inner West Light Rail (IWLR) in Sydney as a case-study. Our research suggests that the principles in this paper are generically applicable to other locations and forms of public transport such as heavy rail, metros, ferries, and buses.

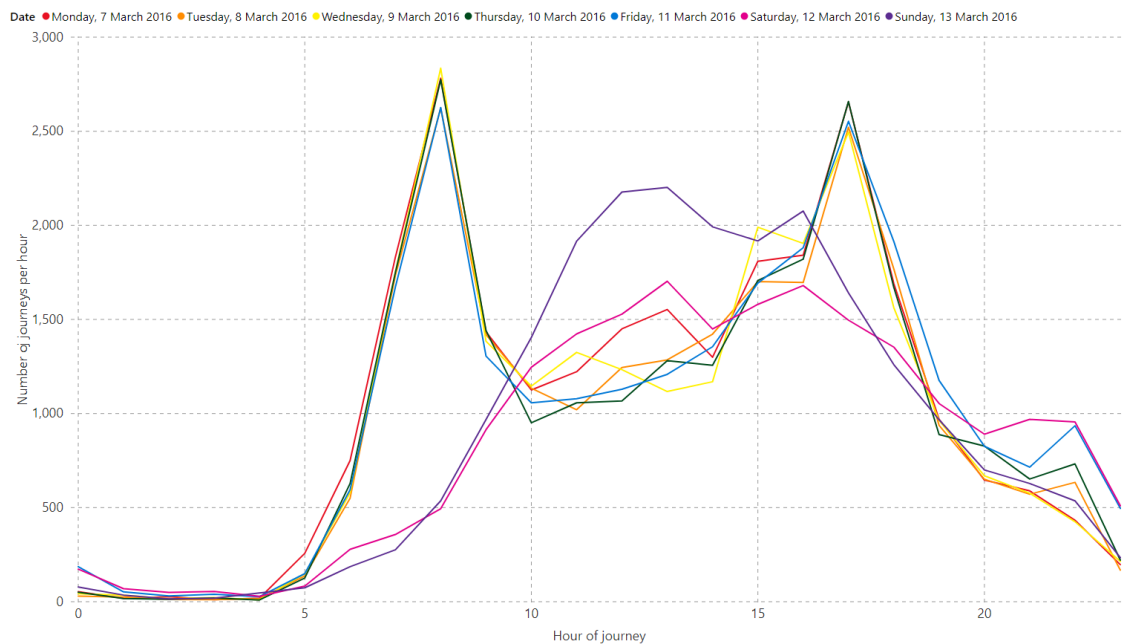
**Figure 1: Inner West Light Rail Map with stages of implementation. Source: Samra (2017)**



## 2 Using data to understand & improve the Inner West Light Rail

The authors 2017 analysis of the Opal ticketing records shows that the number of workday peak hour patronage on the IWLR back in March 2016 was at least 2,600 persons per hour, with some days exceeding over 2,800 persons per hour (see Figure 2 below). In addition, the **Sunday** 'off-peak' patronage was observed as around 2,000 persons per hour for the five hours between 11:00 and 16:00; **almost as high as the weakly peak**. Media reports and detailed analysis show significant passenger crowding on the IWLR; as described in *Hounsell (2017)*, *Mileusnic (2017)*, *Samra (2017)*, and *Smalley (2017)*.

**Figure 2: IWLR journeys by date per hour (excluding Fare Minimization). Source: Hounsell (2017)**



Examining the Opal ticketing records showed the number of tap-ons per minute at each stop were a random pattern not a peaking pattern. The random arrival pattern indicates passengers are not aiming to arrive for the timetable departure times, indicating passengers are treating the IWLR as a turn-up-and-go service. As such, during the morning peak hours the average passenger wait duration will be 4 minutes (maximum of 8 min). During the off-peak hours the average wait duration will be 7 ½ minutes (maximum of 15 min).

## 2.1 Why optimising the Inner West Light Rail is important

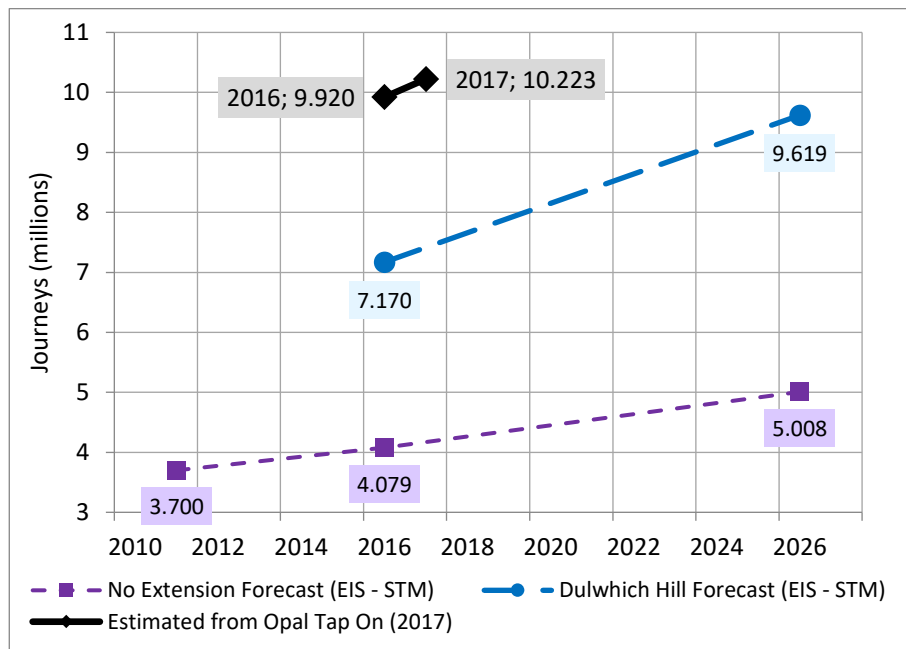
Patronage modelling was commissioned for the Stage 3 extension to Dulwich Hill to guide the infrastructure and operations designs; *GHD (2010)*. The infrastructure was designed, and the vehicle fleet purchased with the assumption that there would be 10 years of operation before patronage reached 10 million passengers.

The IWLR extension to Dulwich Hill opened in 2014. The Opal electronic ticketing system was rolled out on the line in 2015. Complaints about crowding on the line began to be received and were reported in the media. *O'Sullivan (2017)*. From *TPA (2018)* the 2016 patronage was estimated at 9.9 million annual journeys<sup>1</sup>, exceeding the design for 2026 of 9.6 million annual journeys in *GHD (2010)*. The FY 2016-17 numbers were calculated after the Opal rules changed to eliminate the fare minimisation practice reported on the IWLR.

In 2017, the estimated annual patronage was 10.2 million journeys which exceeds the IWLR design constraints expected in 2026. With the construction of two other transport infrastructure projects - the Sydney Metro rail line and Westconnex motorway - there are few resources available for upgrading a light rail opened three years before. UTS began examining ways to optimise operations on the IWLR to determine what service improvements could be wrung out of the existing infrastructure.

<sup>1</sup> Transport for NSW audits passengers on the IWLR for fare compliance. *TPA (2017)* show a 93.2% compliance rate for the IWLR. The journeys reported in *TFNSW (2018)* were adjusted to include both compliant and non-compliant trips.

**Figure 3: Annual Inner West Light Rail System patronage observed and forecast for different scenarios**



**Table 1: Patronage over twelve-month period on IWLR; note January closures for construction**

Jul 16 to Jun 17	Aug 16 to Jul 17	Sep 16 to Aug 17	Oct 16 to Sep 17	Nov 16 to Oct 17	Dec 16 to Nov 17	Jan 17 to Dec 17	Feb 17 to Jan 18	Mar 17 to Feb 18	Apr 17 to Mar 18	May 17 to Apr 18	Jun 17 to May 18	Jul 17 to Jun 18
9.84	9.85	9.78	9.79	9.87	10.05	10.22	9.97	9.99	9.95	9.97	9.99	9.99

*Note: during January 2017 & January 2018 there were significant long IWLR shutdowns.*

UTS presented a group of engineering capstone students with the above data and asked them to consider the literature on best practice and identify operational adjustments that would optimise IWLR operations without building new infrastructure.

## 2.2 Inner West Light Rail – specifications and operations

The Inner West Light Rail (IWLR) is an overhead electrified tramway running in a dedicated separate carriageway from a single-track stub terminus at Dulwich Hill station. At Darling Dr in Haymarket, the carriageway moves to a semi-mixed running section on Hay St then to a separated balloon loop around Belmore Park to the colonnade at Central Station. The mixed running section has five intersections and is controlled by four SCATS traffic light groups.

While the vehicles are in-service they would be run from the first stop at Dulwich Hill to the last stop at Central Station and then returned to Dulwich Hill before being turned around for repeat return runs between Dulwich Hill and Central Station. The (simplified) convention in NSW is that services running towards Central Station are inbound and services running from Central Station are outbound. There are 23 passenger stops on the IWLR, including Dulwich Hill and Central Station. The timetable shows a passenger travel time of 37 minutes from Dulwich Hill to Central Station.

One advantage of an overhead electrified tramway is the IWLR requires no additional refuelling or recharging time to re-energise the vehicle. Crew changes are accomplished by a driver swap while in-service at one of the stops near a depot. Two vehicles are kept in reserve and vehicles are taken out of service and returned to the depot for cleaning, maintenance, etc.

During the case study the IWLR operated with two service patterns: a standard all-stops Dulwich Hill to Central, and a late night short-run from ‘The Star’ to Central Station. During the case study the standard all-stops service operated to a peak hour 8-minute headway using 10 crewed vehicles, an intermediate 10-minute headway using 8 crewed vehicles, or an off-peak 15-minute headway using 6 crewed vehicles.

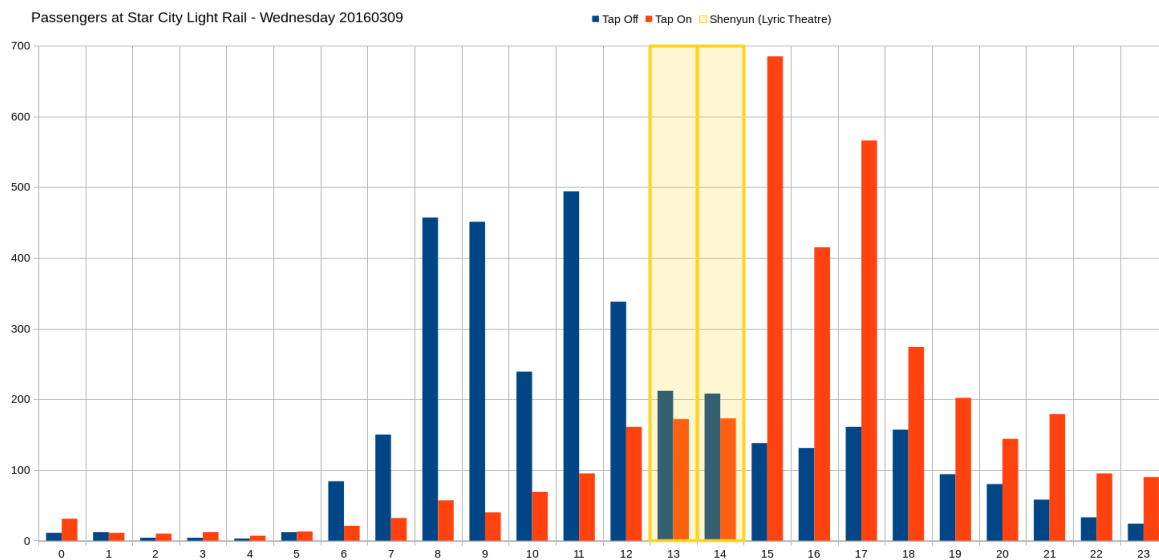
## 2.1 Options for reducing end to end running times

This section outlines the projects undertaken by the students with the goal of reducing the end-to-end runtime by 4 minutes and reducing runtime variability. The following section outlines the analysis that demonstrated why reducing the mean IWLR end-to-end running time by 3.5 minutes from 36 minutes to 32.5 minutes would allow the operator to save one vehicle. The following section also demonstrates that reducing the variability of the IWLR end-to-end running time could help the operator reduce the overhead built into the timetable.

The Inner West Light Rail has a significant level of passengers on the service. During the many peak periods the number of passengers leads to vehicle crowding, stop crowding, and increases in dwell-times. Controlling variability in dwell-times from passenger crowding were the focus of investigation for *Mileusnic (2017)*.

Analysis of the Opal ticketing records in *Hounsell (2017)* showed that the Inner West Light Rail experiences many peak periods. Some of these peaks are due to the large event crowds travelling to and from The Star. Figure 4 below shows that there is a surge of passengers travelling to The Star in the mid-morning. In the afternoon at about 15:45 the data shows that there was a surge of passengers leaving The Star. Discussions with the operators of the 2,000 seat Lyric Theatre indicate that the Wednesday matinee performance of the Shenyun dances had just finished at that time. Our analysis of the data convinced the department to investigate further and lead to a decrease in vehicle headways to cater to the Wednesday matinee crowd.

**Figure 4: Passengers at Star City Light Rail on Wednesday 9<sup>th</sup> March 2016.**



### 2.1.1 Engineer Capstones Programme

In 2017, three students completed capstone theses investigating methods to improve the end-to-end runtime on the Inner West Light Rail. The student theses provided useful information to the operators and other researchers. The theses allowed the operators to conduct an initial feasibility assessment of the options considered. The theses also provided data to support further research including the conclusions in this paper.

*Mileusnic (2017)* investigated the dwell times at stops along the IWLRL using direct observation and CCTV demonstrated that usually the dwell-times were within expected operating ranges. However, certain locations such as The Star and Pymont Bay experienced longer than average dwell times, with occurrences of significant dwell events.

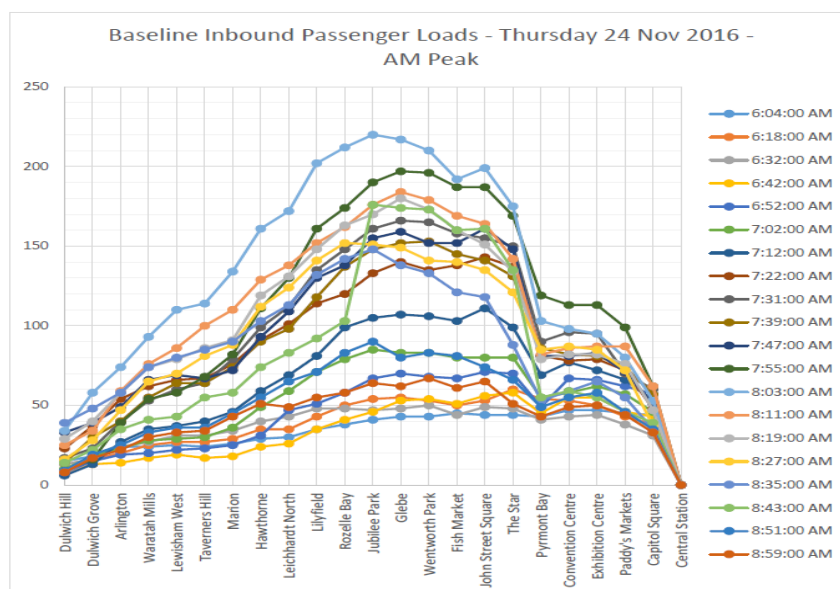
**Figure 5: Summary of dwell times at The Star Light Rail from *Mileusnic (2017)***

Station	Eastbound AM			Westbound AM		
	Average Dwell Time	Min Dwell Time	Max Dwell Time	Average Dwell Time	Min Dwell time	Max Dwell Time
The Star	00:00:34	00:00:23	00:00:57	0:00:36	0:00:25	0:01:30
	Eastbound PM			Westbound PM		
The Star	00:00:48	00:00:28	00:02:27*	0:00:37	0:00:25	0:01:11

Mr Mileusnic analysis showed that there were several stops where structural issues increased dwell-times and recommended operational changes to revert those increase. After examining the introduction of the Sydney Trains Passenger Guidance program, he considered opportunities for a similar program on the IWLRL. Also, passenger crowding was again demonstrated to increase running times. The recommendations were noted by the department and the operator and are under consideration.

*Samra (2017)* examined the system and notes the significant operation constraints imposed by the design of the IWLRL extension. His thesis also notes the impact of track speed limits; and the previous improvements to track speeds in 2015 after a review by Parsons Brinckerhoff. Also noted was the stop entry speeds of 20km/h in the dedicated right of way; these entry speeds are lower than most other jurisdictions. *Samra (2017)* examined the impact of a short running service using Opal ticketing records to assess patronage. Short running was deemed unviable with the current fleet due to the variability of the on-street running.

**Figure 6: Baseline Inbound Passenger Loads (Thursday 24 Nov 2016) AM Peak. Source: *Samra (2017)***

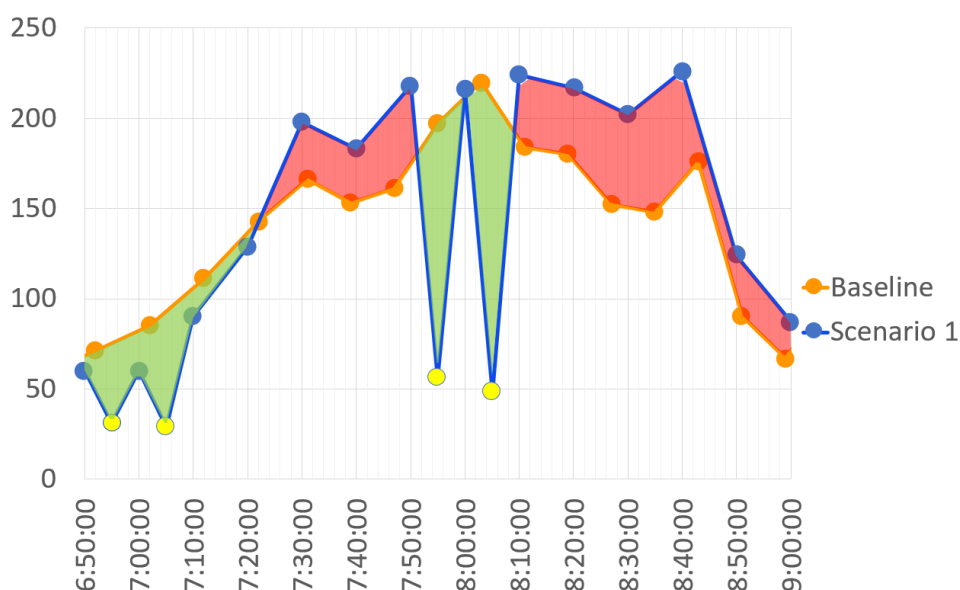


Mr Samra and Mr Hounsell developed a method using Excel to take the passenger records from the Opal dataset and assign those to timetabled services to determine the expected crowding levels on each service. Since the passengers had previously been proven to arrive at

random times we can assume that any normal weekday would provide a comparable random sample for analysis. Passengers were assigned to the next service scheduled to arrive at their stop after they had tapped on at-stop Opal reader.

In the baseline all services run all stops the full line from Central Station to Dulwich Hill during the AM Peak. In Scenario 1 Mr Samra used the above passenger load estimation methodology to test the crowding on services when two services an hour are cut short only to Lilyfield. Figure 7 below shows that scenario results in significant increases in passenger loading all long running services (red shading); whereas the short running services get very few passengers. Mr Samra tested with the then fleet size and notes that purchase of additional vehicles would allow the addition of short running vehicles without cutting any full runs.

**Figure 7: Maximum inbound passenger load per service (Thur 24 Nov 2016) AM. Source: Samra (2017)**



The industry partners were impressed with the thoroughness of the analysis and were interested to see results indicating short running would prove unsuccessful. They also expressed interesting in examining this option in the future, especially with new vehicles.

*Smalley (2017)* examined the impact of the signalised intersections on running times of a subsection from Exhibition through the Central Station terminal loop and returning to Exhibition. Smalley, with assistance, computed the actual patronage on the light rail through each signalised section using the Opal ticketing records. *Smalley (2017)* then examined three scenarios of signal programming changes to determine their impact on light rail passengers, bus passengers and motorists.

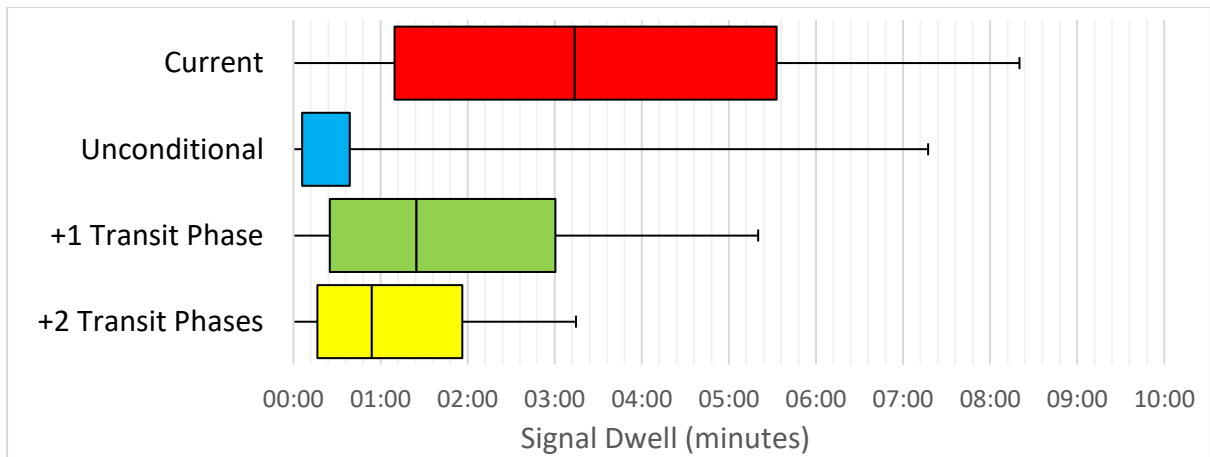
Smalley recommended the introduction of an optional transit phase between each road phase and determined that control program may reduce the waiting time for light rail passengers and reduce end-to-end running times. With the change it is estimated that intersection wait times for the fourth quartile would be reduced from 5.5 minutes to under 2 minutes; and the maximum reduced from 8.25 minutes to under 3.25 minutes. Note that signal phasing is entirely controlled by the roads agencies and not the light rail operator.

The current SCATS configuration uses the C phase to check if a tram has been detected and if so the tram is given a green light. Smalley suggests the addition of two extra identical optional which he calls X & Y as shown in Table 2 below. Note that proposal will still often result in the tram having to come to a complete stop.

**Table 2: Indicative SCATS program for IWLR intersection.**

Original	+2 Transit Phases
<ul style="list-style-type: none"> <li>• A (road)</li> <li>• B (road)</li> <li>• C (optional IWLR)</li> <li>• D (road)</li> <li>• E (Road)</li> </ul>	<ul style="list-style-type: none"> <li>• A (road)</li> <li>• X (optional IWLR)</li> <li>• B (road)</li> <li>• C (optional IWLR)</li> <li>• D (road)</li> <li>• Y (optional IWLR)</li> <li>• E (Road)</li> </ul>

**Figure 8: Smalley (2017) Signal Dwell Times for Proposed LRV Priority**



The department provided very positive feedback on this recommendation because of the ability to easily implement it without additional infrastructure and because of its integration with the existing traffic control approach.

The industry partners were pleased with the results of our research programme and found the workshop to communicate the results extremely useful. They were also heartened that we took extra care to explain to the lay-persons that reducing end-to-end-runtimes could reduce the number of deployed vehicles and lead to cost savings. They were also impressed by the common theme demonstrating that eliminating runtime variability caused by signalised intersections etc would also ensure those savings could be realised. The department was also quite happy to see that the research focused on delivering low-cost high impact changes.

### 3 Vehicle headways and running times

Vuchic (2005) describes the rules relating return runtime or cycle-time ( $r$ ), vehicle headway ( $h$ ), and the number of whole vehicles ( $V$ ).

**Equation 1: Key fleet equations <sup>2</sup>**

$$V = \lceil r/h \rceil$$

$$r = v \times h$$

$$h = r/v$$

<sup>2</sup> Return runtime ( $r$ ), vehicle headway ( $h$ ), and number of vehicles ( $v$ ) are positive rational numbers:  $\{r \in \mathbb{Q} \mid 0 < r < \infty\}$ ,  $\{h \in \mathbb{Q} \mid 0 < h < \infty\}$ , and  $\{v \in \mathbb{Q} \mid 0 < v < \infty\}$ .

The ceiling operation finds the smallest integer greater than or equal to the given rational number:  $\lceil v \rceil = \min\{V \in \mathbb{Z} \mid V \geq v\}$ . Ceiling is written in Vuchic (2005) as  $\lceil \cdot \rceil^+$ . Integral number of vehicles ( $V$ ) is a positive integer  $\{V \in \mathbb{N} \mid 0 < V < \infty\}$ .

In the real-world there can only be a whole number of vehicles. Running half a bus is only possible in cartoons & comedies. As such, the whole number of vehicles is a discrete integer.

This paper aims to demonstrate that considering the number of vehicles ( $v$ ) as a continuous rational variable allows operators to more easily perceive opportunities for savings. That is why section 2.3 is titled ‘Saving 0.2 of a vehicle’.

Equation 2: Continuous **rational** form of key fleet <sup>2</sup>

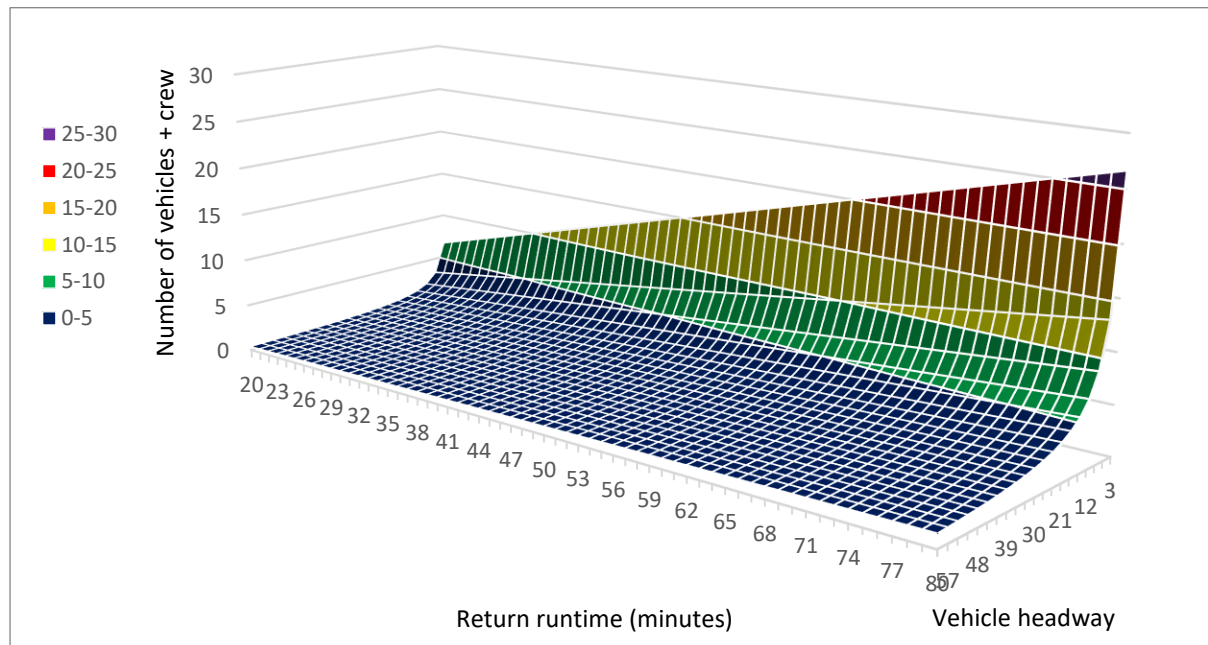
$$v = r/h$$

$$r = v \times h$$

$$h = r/v$$

The three rational equations form a smooth three-dimensional curve as in Figure 9 below. As the vehicle headway increases the shape of the curve transitions from steep to a flatter plane. Transport professional are used to considering this curve as a stepped discrete shape. The aim of the research programme was to demonstrate that treating the curve as continuous would allow student engineers to focus on what small changes were needed to decrease fleet size.

Figure 9: Number of vehicles per runtime per headway – three dimensional



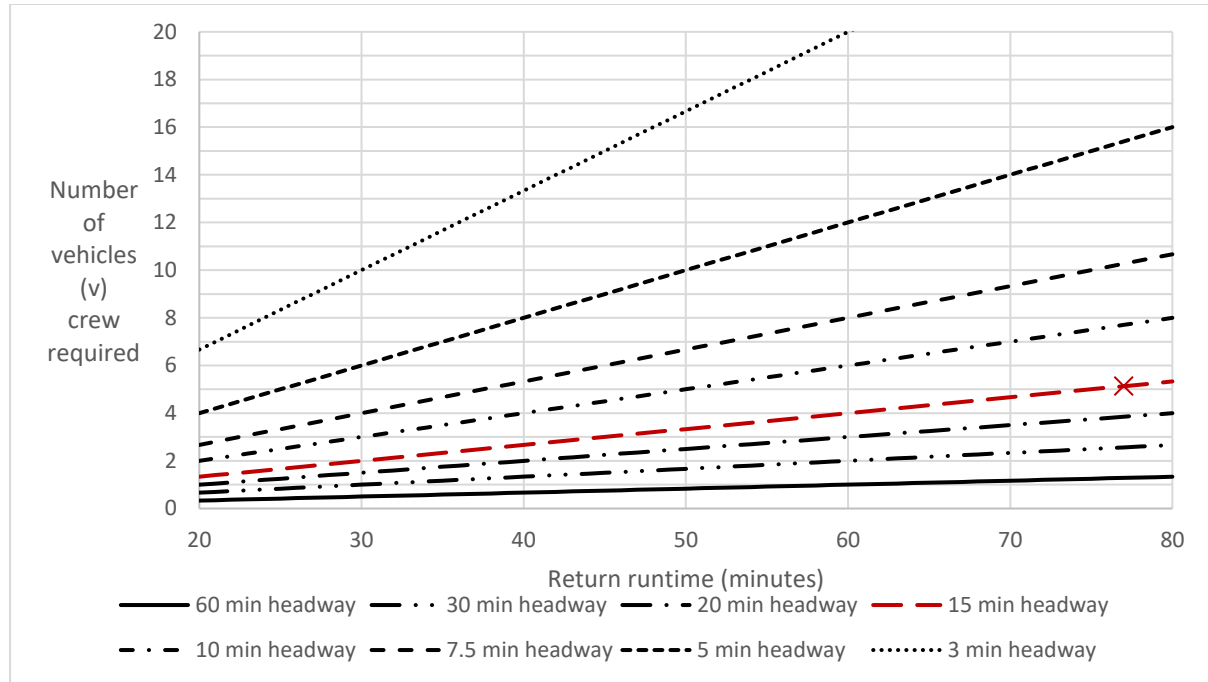
The three-dimensional curve shows the inter-relationship between all the variables above and that change to any one variable will change the values of the other variables. Although it is convenient to consider transport systems as derived from discrete values, the continuous curve shows us that there are benefits from shorter running times and cost from allowing variability to cause longer running times. The continuous curve also shows the opportunities for more frequent service with the same number of vehicles by using vehicle headways that are not clock-face (integer factors of sixty). There is a complacency in public transport delivery in Australia, by changing our perspective there are opportunities to deliver a more attractive service for the same or even lower cost; or at least improving cost-recovery.

Comparing two slices of the curve show there are different operational outcomes depending on the cycle time that can be maintained. Figure 9 above shows that the shorter cycle times of 20-30 minutes will need few vehicles to satisfy a short vehicle-headways. In contrast examining a slice of longer return runtimes (70-80 minutes) in Figure 9 above, shows that the number of vehicles and crew requires rises slowly until a transition around vehicle-headways 15 minutes where lower headways quickly require significantly more vehicles to deliver.

In *Mazloumi (2008)* and *Mazloumi (2009)* the authors demonstrate that runtime-variability and travel time variability are related to the length of the route. Combined with the shape of the continuous curve, operators can demonstrate that more vehicles will be required to maintain headway-adherence the longer a route becomes.

The three-dimensional curve in Figure 9 can be simplified and graphed as a collection of lines in two dimensions as shown in Figure 10 below. The lines in this plot are straight because they plot the continuous rational number of vehicles ( $\nu$ ) variable.

**Figure 10: Number of vehicles per runtime per headway – two dimensional**

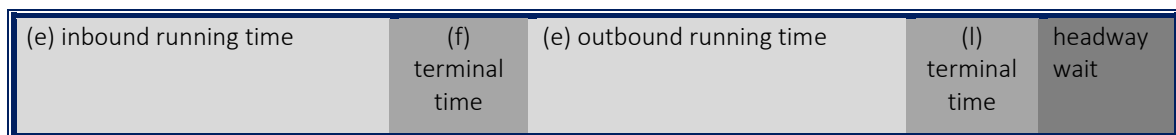


The plot and equations show that off-peak 15-minute vehicle headway for the IWLR's 78-minute cycle time requires 5.2 vehicles. The continuous plot clearly shows that only minor reduction in runtime are required to reduce fleet size. From a conventional stepped integer plot, that outcome must be inferred from understanding the nature of fleet allocation. In presentations and meetings, both students and policy makers understood the interactions between runtime and fleet size more quickly from the straight continuous rational chart of partial vehicles ( $\nu$ ) than from the stepped discrete integer chart of whole vehicles ( $V$ ).

### 3.1 Limits of one-way running time

As stated above the IWLR was operated off-peak as a 15-minute headway using 6 crewed vehicles ( $V$ ) because the timetable required 5.2 crewed vehicles ( $\nu$ ). The IWLR timetable is constantly under review and may have changed since this study.

**Figure 11: Components of cycle time (r)**



Assume a constant terminal time of 1 minutes at Central Station ( $l$ ) and a 3-minute terminal time at Dulwich Hill ( $f$ ). As such the maximum viable end to end running time ( $e$ ) for a 15-minute headway using 6 crewed vehicles is 43 minutes as follows:

$$r = 2 \times e + f + l$$

$$r = V \times h$$

$$\therefore r = 6 \times 15 = 90$$

$$\therefore 90 = 2 \times e + 2 + 0$$

$$\therefore e = 86/2 = 43$$

For a given integral number of vehicles ( $V$ ) at a given vehicle headway ( $h$ ) and the terminal times ( $f$  &  $l$ ), it is possible to calculate the end-to-end running time ( $e$ ) that service must not exceed. If the delivered end-to-end running time exceeds that value for a significant number of runs, then the promised timetable cannot be achieved.

**Equation 3: Upper limit for the end-to-end runtime for a given number of vehicles at a given headway**

$$e_{limit} = \frac{V \times h - f - l}{2}$$

The IWLR is operated with a single route and stopping pattern on an electrified right-of-way with crew changes while in-service. As such the vehicles can maintain a vehicle-headway based timetable by running repeating return services for the entire day. Table 3 below contains the upper limit for end-to-end runtimes ( $e_{limit}$ ). If the end to end running time regularly exceeds the values listed, then the operator would be unable to maintain the given headway with the listed number of vehicles.

**Table 3: Upper limit for the end-to-end runtime for service patterns on the IWLR**

	Near-peak	Peak
	8 vehicles	10 vehicles
	10-min headway	8-min headway
Maximum cycle time	80	80
$e_{limit}$ when $f = 3, l = 1$	38	38

Consider the IWLR running 8 vehicles at a 10-minute headway. In this case  $e_{limit} = (8 \times 10 - 3 - 1)/2 = (80 - 4)/2 = 38$ . The 37-minute end-to-end runtime for the IWLR only has room for less than a 1-minute of variation before the number of vehicles would need to be increased (assuming a constant 4-minute terminal time).

Table 4 below compares the limit for the end-to-end runtime on the IWLR running at a 15-minute vehicle-headway for a fleet of 6 to a fleet of 5 vehicles. The table shows that a end-to-end runtime of 35.5 minutes (compared to the current 37 minutes) would allow a 15-minute headway to be operated using one less vehicle and crew.

**Table 4: Comparing upper limit for the end-to-end runtime for off-peak service with different fleet-sizes**

Off-peak; 15-min headway	6 vehicles	5 vehicles
Maximum cycle time	90	75
$e_{limit}$ when $f = 3, l = 1$	43	35.5

### 3.2 Schedule limits with a variable runtime

If the end-to-end runtimes are stable and controlled, then they should conform to a normal distribution. As a normal distribution, 68% of the end-to-end-runtimes would fall with  $\pm 1$  standard deviations ( $\sigma_e$ ) from the mean end-to-end runtime ( $\bar{e}$ ), and 95% would fall with  $\pm 2$  standard deviations from the mean. The IWLR is primarily grade separated; it should have

controlled and stable end-to-end runtime with minimal skew. Scheduled end-to-end running time should contain an allowance of four standard deviations of the observed end-to-end runtimes to be achievable in 95% of cases under stable operating conditions, see *Hounsell (2018)*. An allowance of four end-to-end standard deviations is required because the number of vehicles is based on total cycle time which is comprised of two end-to-end-runtimes.

**Equation 4: Upper limit for the end-to-end runtime using number of vehicles, headway, & variability**

$$e_{limit} = \bar{e} + 2 \times \sigma_e$$

$$V \times h = 2 \times e_{limit} + f + l$$

$$V \times h = 2 \times \bar{e} + 4 \times \sigma_e + f + l$$

A summary of observed runtimes for the IWLR is included in Table 5 below. This summary shows that the IWLR has a mean end-to-end runtime ( $\bar{e}$ ) of 36.0 ( $\pm 0.04$ ) minutes, with a standard deviation of 2.0 minutes.

**Table 5: Observed runtimes on the IWLR on Tuesday, Wednesday or Thursday by direction**

Day	Mean ( $\bar{e}$ )	95% C.I.	Standard Deviation ( $\sigma_e$ )	Variance	Samples	Coefficient of Variation
Mon	35.7	$\pm 0.09$	1.8	3.4	1,629	0.050
Tue	35.7	$\pm 0.08$	1.5	2.3	1,644	0.042
Wed	36.3	$\pm 0.10$	2.0	4.2	1,684	0.055
Thu	36.1	$\pm 0.09$	1.8	3.2	1,652	0.050
Fri	36.3	$\pm 0.10$	2.0	4.1	1,659	0.055
Sat	35.8	$\pm 0.11$	2.0	3.9	1,332	0.056
Sun	36.1	$\pm 0.14$	2.6	6.6	1,340	0.072
All Days	36.0	$\pm 0.04$	2.0	3.9	10,940	0.056

Table 5 above shows that the mean end-to-end runtime for the IWLR is less than the scheduled 37 minutes, as such the service will often be on-time. However, the standard deviation of 2-minutes means that the service has a significant change of being 3-minutes late. Worse still there is a high chance of the service exceeding the 38-minute limit from Table 3 above required to maintain the 8-minute vehicle-headway with 10 vehicles.

Combined terminal time at Central Station and Dulwich Hill embeds at least two minutes of runtime variability allowance. In further calculations we explicitly address runtime variability using ( $\sigma_e$ ). As such more accurate values for terminal time are needed; we will use 0 minutes at Central Station ( $f'$ ) and a 2-minutes at Dulwich Hill ( $f$ ); see 'Figure 11: Components of cycle time (r) above'

It is possible to calculate what the maximum mean end-to-end runtime ( $\bar{e}_{limit}$ ) can be to maintain the given vehicle-headway with the given number of vehicles using the above equations and can be expressed as below.

**Equation 5: Example limit for mean end-to-end runtime for number of vehicles, headway, and variability**

$$\bar{e}_{limit} = \frac{V \times h - f - l - 4 \times \sigma_e}{2}$$

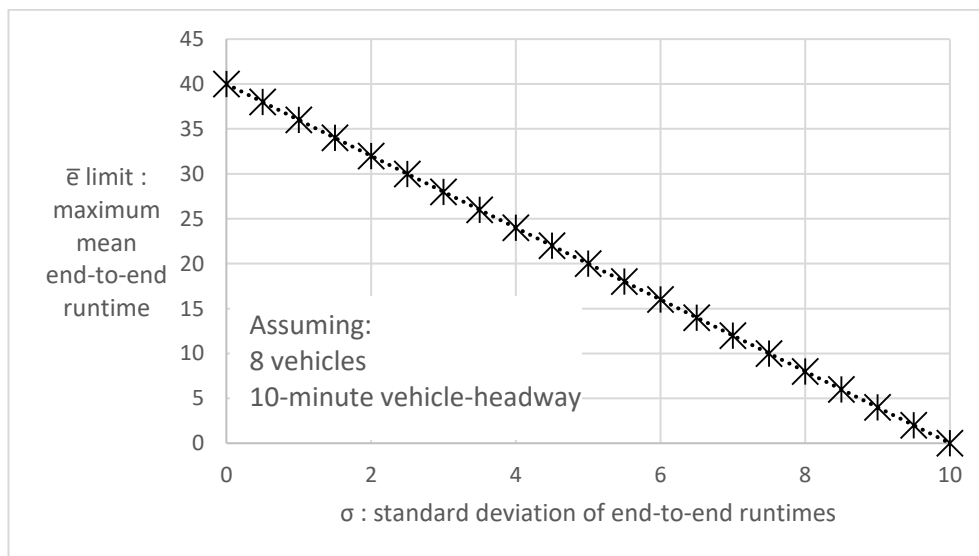
$$\bar{e}_{limit} = \begin{cases} \frac{V \times h - 2 - 0 - 8}{2} = \frac{V \times h}{2} - 5, & \sigma_e = 2, f' = 2, l' = 0 \\ \frac{V \times h - 2 - 0 - 4}{2} = \frac{V \times h}{2} - 3, & \sigma_e = 1 \\ \frac{V \times h - 2 - 0 - 2}{2} = \frac{V \times h}{2} - 2, & \sigma_e = 0.5 \end{cases}$$

**Table 6: Upper limit for the end-to-end runtime for service patterns on the IWLR with variability**

$\bar{e}_{limit}$ when $f = 2, l = 0$	Near-peak	Peak	Off-peak	Off-peak
	10 vehicles 8-min headway	8 vehicles 10-min headway	6 vehicles 15-min headway	5 vehicles 15-min headway
Maximum return runtime	80	80	90	75
$\sigma_e = 2$ (current variability)	35	35	40	32.5
$\sigma_e = 1$ (½ current variability)	37	37	42	34.5
$\sigma_e = 0.5$ (¼ current variability)	38	38	43	35.5

As shown in Equation 5 above and Table 6 above the larger the variability of the end-to-end runtimes the lower the mean end-to-end runtime must be in order to achieve a given vehicle-headway using a given number of vehicles. As such reducing variability allows the same service to be operated with the same fleet but longer end-to-end runtimes.

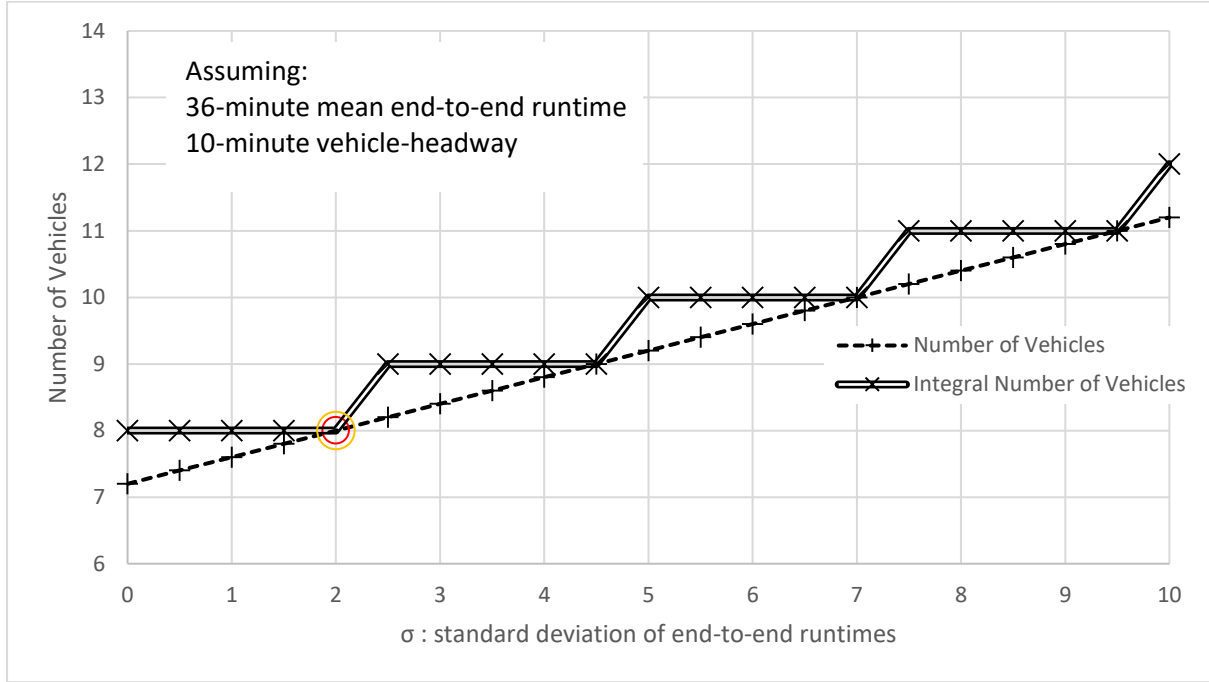
In Figure 12 below the maximum mean end-to-end running time (x-axis) allowed by eight vehicles running at a 10-minute vehicle headway is plotted against the possible standard deviation in end-to-end runtime (x-axis). This graph shows that as the variability increases the upper limit on the mean end-to-end running time decreases.

**Figure 12: Upper limit for the end-to-end runtime for 8 vehicles at 10-min headway per variability**


In other words, increased variability increases the number of vehicles required to maintain a given vehicle-headway; as plotted in the example Figure 13 below. Correspondingly reducing variability on highly variable services can reduce the deployed fleet size.

The current standard deviation of end-to-end runtime ( $\sigma_e$ ) is 2 minutes. The plot in Figure 13 shows that an increase in the standard deviation to 2.5 minutes would increase the deployed fleet requirement from 8 vehicles to 9 vehicles. If the deployed fleet was not increased a standard-deviation of 2.5 min would prevent the IWLR from delivering its promised vehicle-headway. This plot also shows that the IWLR is at the upper limit of variability tolerance and that reducing variability would reduce risk of missing service targets and contractual KPIs.

**Figure 13: Number of vehicles as impacted by end-to-end runtime variability.**



### 3.3 Saving 0.2 of a vehicle

With a 15-minute headway the IWLR requires the deployment of 5.2 vehicles. To reduce the integral number of vehicles deployed ( $N$ ) by one the operator needs only reduce the number of vehicles ( $n$ ) by 0.2. By recalculating the maximum allowable runtime for a 15-minute headway with one less vehicle we can calculate the maximum end-to-end runtimes to ensure only 5 trams of the vehicles fleet need to be deployed.

**Equation 6: Upper limit for the end-to-end runtime for a reduced number of vehicles at a given headway**

$$e_{save} = \frac{(V - 1) \times h - f - l}{2} \quad \Bigg| \quad \therefore e_{save} = \frac{(6 - 1) \times 15 - 3 - 1}{2} = 71/2 = 35.5$$

The timetabled end-to-end runtime for the IWLR was 37 minutes. As shown in Table 3 above, if the running time could be reduced by more than 1.5 minutes each way then one less crewed vehicle would be required to provide the same vehicle-headway. If the operator could save 20 seconds at or between each stop that would be over a total saving of over 7 minutes.

There is a catch, if the running time was regularly 36 minutes the service would need 6 vehicles to reliably achieve its vehicle headway. As such the operator must achieve savings greater than 1.5 minutes to leave an allowance for running time variability.

$$v = \frac{2 \times e + f + l}{h} = \frac{2 \times 36 + 3 + 1}{10} = 5.06 \quad \therefore V = \lceil 5.06 \rceil = 6$$

To counter the runtime variability, we can use the limit formula with embed standard deviations to compensate for the observed variation. The observed variability on the IWLR was 2 minutes indicating that the range of one way running times, if in a normal distribution, was 8 minutes and that runtimes were regularly over 4 minutes slow or 4 minutes fast. The below calculations move the runtime compensation from the terminal time to ( $\delta_e$ ).

**Equation 7: Upper limit for the end-to-end runtime for a reduced number of vehicles with variability**

$$\bar{e}_{save} = \frac{(V - 1) \times h - f - l - 4 \times \sigma_{e_{save}}}{2} \quad \left| \quad \bar{e}_{save} = \frac{(6 - 1) \times 15 - 2 - 0 - 4 \times 2}{2} = 32.5$$

**That calculation shows that reducing the mean end-to-end running time by 3.5 minutes from 36 minutes to 32.5 minutes would allow the operator to save one vehicle.**

From these results we can determine that by minimising end to end runtime variability and reducing end-to-end runtimes the operators would be able to deliver the same service with less vehicles. Alternatively, the operator could redeploy the vehicles to deliver a shorter vehicle headway, thus increasing customer satisfaction and likely inducing demand.

### 3.4 Implications of the variability in intersection waits on running times

It is a simplification to assume that end-to-end running time only depends on the time between stops ( $r_i$ ) and the dwell times ( $d_i$ ). There are additional causes for additional waiting time and those pseudo-random causes will contribute to runtime variability. For instance, the cycle times of on-street bus and tram services depend on the time waiting for traffic lights. Additional waits can be combined as the right-of-way delay ( $w$ ). The right-of-way delay can be considered as a component of running times or of the cycle time.

**Equation 8: Runtime with right-of-way delay**

$$e = \sum_{i=1..n-1} r_i + \sum_{i=1..n} d_i + w \quad r = 2 \times e + f + l + w$$

While running the loop from the Exhibition stop, the Inner West Light Rail will pass through the signalised intersection at Darling Dr, George St, and Pitt St twice and the signalised intersection at Castlereagh St once. On a return run from/to Dulwich Hill the IWLR will pass through 9 signalised intersections. Half of the return runtime right-of-way delays observed in *Smalley (2017)* exceeded three minutes in duration, with 25% over 5.5 minutes in duration.

The IWLR has a compulsory stop inbound at Darling Drive; due to the sharp corner and significantly reduced visibility due to a recently constructed tower. There is another compulsory stop outbound at Pitt Street; due to many conflict points in the design of the intersection and the lack of traffic light priority for the light rail.

As noted in *Smalley (2017)* the IWLR does not have priority in the current SCATS phases and may have to wait a full cycle for right-of-way. In addition, the sensors may not detect the trams. The control program occasionally enters a state where a detected tram will never get right-of-way. Manual intervention is regularly required from the Transport Management Centre to give a trapped tram the right-of-way.

The one-way running time for 10 vehicles at an 8-minute headway with a bare minimum of 2 minutes in terminal time must be completed in 39 minutes. If the mean end-to-end running time is 36 minutes, then there is only six minutes of variability that can be absorbed before

operations are impacted. If 25% of total signal wait times on a return run are over 5.5 minutes, then the signalised intersections will ensure the operations will be unstable.

The variability in cycle times will be determined by the variability in between stops running time, dwell time variability, and right-of-way variability. To deliver the promised vehicle-headway with the minimal vehicle fleet requires the cooperation of stakeholders to stabilise and reduce the running times, dwell-times, and right-of-way delays especially at signalised intersections.

## 4 Conclusion

IWLR has observed mean end-to-end runtime ( $\bar{e}$ ) of 36.0 ( $\pm 0.04$ ) minutes, with a standard deviation ( $\sigma_e$ ) of 2.0 minutes. This variation already exceeds the upper threshold of 36-minutes + 1.5 minutes variability for operations using 10 vehicles for an 8-minute headway.

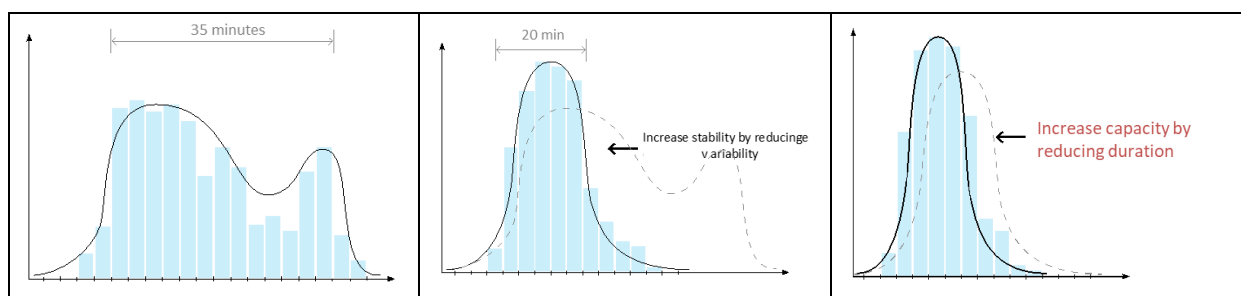
To deliver reliable operations running times must be stabilised and minimised. If improvements to the IWLR were able to reduce the one-way running times by 3.5 minutes or reduce the variability in running times, then the operator could decrease costs or decrease the vehicle headway.

UTS was able to develop this IWLR research programme because the author's continuing research using the Opal dataset aims to understand customers actual behaviour 24 hours a day, 7 days a week. The authors initial analysis proved significant off-peak congestion and that helped bring the industry partners onboard to actively support the programme.

UTS and its students investigated several mechanisms to improve operations and determined that there were viable options for reducing variability and then further reducing running times. These options would reduce operating costs while also improving customer service. Thereafter there exists an option for the state to reinvest the savings into better services.

Optimisation of the Inner West Light Rail and on-street running provides the opportunity to deliver more services using the existing asset. Optimisation is required to service patronage growth. The number of journeys on the IWLR in 2017 and 2018 already exceeds the 2026 patronage forecasts developed for the design of the extension.

**Figure 14: Run time variability impacts what services are promised & delivered**



## 5 Acknowledgements

UTS and ISF would like to thank the students for embracing the spirit of a capstone thesis and working hard investigating real world problems. UTS, ISF and the students would like to thank Transport for NSW, the IWLR operator Transdev, and those professionals who assisted the students in researching their theses.

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