# *SYDNEY SOUTHEAST LIGHT RAIL*

Traffic Impact Statement – *Report 2*

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# 1. Introduction

## 1.1 Background and Study Area

The CBD and South East Light Rail (CSELR) project was orchestrated by the government to combat infrastructure issues in Sydney, highlighting the benefits of this project. The route will extend over 12 kilometers with 19 stops from Circular Quay along George street to Central, through to Surry hills, Kensington and Kingsford via Anzac Parade and Randwick via Alison Road and High street.

Compared to our current bus system, CSELR will provide a modern, reliable and sustainable service that will connect business, tourist, commuters and communities along the route. Easier access to facilities such as sporting and entertainment events in Moore Park and Randwick, TAFE, the University of New South Wales and health precincts in Randwick are also provided by the light rails.

Through implementing the light rail, approximately 220 fewer buses will operate during peak hour resulting in less congestion on the road. Light rails are more reliable than buses where up to 34% of buses arrive on time in the CBD and 97% for light rails. Light rail services are more frequent with the waiting time between each service is 4 minutes and a capacity of up to 13,500 passengers per hour. The light rail estimates the capacity of 450 people per tram. Realistically, only 80% of the capacity, approximately 380 people, is met before operating trams will be over crowded resulting in people willing to wait on the platform for the next service.

In addition, CSELR helps combat other infrastructural issues. The rise in climate change is an increasing concern and any resolutions that reduce the emission of pollution will benefit humanity. By reducing the amount of buses on the road, a decrease in greenhouse gas is achieved by reducing fuel consumption. Light rails are operated by electricity that may come from renewable energy which can improve sustainability in the environment.

**Figure 1.1.1** Focus Network and Study Area with Labelled Centroids

## 1.2 Project Objective

This report aims to detail a possible plan for a light rail network in the South-Eastern suburbs of Sydney from the CBD. It will discuss the proposed plans for the location of stops and the frequency of trains to and from these suburbs. There will be many impacts to the current road network with infrastructure needed to be built to accommodate this new project. Comparisons to the current network and use of statistical data will be the major driving factor in assessing the viability and environmental impacts the new proposed public transport system will have on this region. The use of modelling software will be crucial in giving indications of what effect large-scale changes will have on a wide area of land. For this project, AIMSUN will be used to gather data on the implementation of the LRT.

Model development is crucial as it represents a reflection of the real-world traffic to ensure expectations are being satisfied. The model will accurately verify, calibrate and validate the model parameters set out by the client as well as provide an appropriate simulation of future performance and a benchmark to measure the effectiveness of the proposed design.

The base model of the Sydney South-East region developed on AIMSUN will be used to predict the impacts the project will have on this neighbourhood. The model will only consider buses and cars for simplicity and will run during the peak hours of 8:00 AM and 9:00AM with a 15-minute warm-up period. Traffic signals and public transport lines as well as the O-D matrix representing an estimation of the movement of vehicles in the system have already been coded into the base model. The implementation of tracks and stations for the LRT system were coded into the AIMSUN file. In addition, subsequent changes to the network's road geometry were also carried out to accommodate the trains running throughout the network. Analysis of these simulations and their outputs are outlined in this report.

## 1.3 Report Outline

This report contains 10 chapters:

- This chapter (chapter one) highlights the project proposed by the government and the objective of this report include:
– The government's project plans to extend the Inner West Light Rail to CSELR;
– A proposed model of the implementation of the light rail compared to real-world traffic;
– And other infrastructural issues that can be resolved.
- Chapter two accounts for any assumptions and considerations made through engineering judgements
- Chapter three highlights any data obtained and the usage of each information.
- Chapter four addresses the option testing, coding and refinement of the network. This includes any changes to:
– Light rail network geometry (e.g. positions of the proposed stops)
– Road geometry refinement;
– Traffic signals and phasing;
– Bus route alterations;
– And any innovations that could assist in future growth.
- Chapter 5 provides operational results obtained through the base model. This includes:
– Critical intersections where they are considered critical as congestion is caused which disrupts traffic flow resulting in large delay times and queue lengths;
– Pinch points where congestions likely occur;

- Speed Profiles and Total System Travel Time which relates to the density and flow of the system.
- Chapter 6 display the future demand for Light Rails including:
- Future land use;
- And a future Origin-Destination Matrix (O-D matrix) estimation.
- Chapter 7 utilises outputs from AIMSUN scenario testing of the implemented Light Rail Transits and explores operational results such as:
- Critical intersections;
- Pinch points;
- And Speed profile and Total system travel time.
- Chapter 8 provides a stability analysis of the model after it has been calibrated and validated to ensure the model remains justifiable and reliable.
- A larger amount of simulations will result in a more accurate and reliable interpretation of the results.
- Chapter 9 discuss and compares the base model and light rail model's outputs. This is done by comparing the:
- Total system travel time savings
- Changes in location of the congested areas
- Emission assessments;
- And cost benefit analysis.
- Chapter 10 will conclude the report providing a recommendation through the engineering judgements.

## 2. Accounting for LRT: Considerations and Assumptions

One obvious limitation of the model would be the lack of pedestrian and cycling traffic in the network. With around 1200 cyclist a day on Anzac Parade (*Roads and Maritime Services, 2019).* Furthermore, the model cannot account for adverse weather conditions, which could affect the traffic conditions experience. With the introduction of the LRT, bus services are bound to change due to the similarity of purposes. Frequency and the routes of the bus network will be altered and affect traffic conditions. Therefore, in combination with changes to the population demographic in the area, changes to the demand matrix will be necessary. As certain stops will be closer to major destinations, there will be an uneven distribution of trips across the network. However, we will assume there is no variance in dwell times on the network for simplicity.

The geometry of the road network will also need to be modified to accommodate the construction of tracks for the LRT. The Allison road busway will simply be converted into the tracks for the Randwick line of the LRT, with little change to the already constructed section. Focus will be made on intersections where the light rail will need to cross. While priority signaling could be used in the construction of the LRT, this model will not utilise this feature as the AIMSUN software has difficulty implementing this complex system. The interaction of the LRT to intersections will greatly affect the general traffic conditions of the surrounding environment as well as affecting the perception of the usefulness of the public transport system in the minds of potential users of the new LRT.

Furthermore, the frequent stops at traffic lights introduces some problems with the speed of the light rail. As the trains would need to start and stop at each red light, it would result in a higher than usual travel time when compared to the system which uses priority signaling.

## 3. Datasets and Usage

**Table 3.1** Light Rail Metrics *(Transport for NSW, 2013 & 2017)*

| **Frequency (min)** | | | |
|---|---|---|---|
| **Randwick** | | **Kingsford** | |
| **Peak** | **Off Peak** | **Peak** | **Off Peak** |
| 6 | 8 | 6 | 8 |
| **Length (m)** | **Width (m)** | **Carriages** | **Max speed (km/hr)** |
| 67 | 2.65 | 10 | 30 |

**Table 3.2** Benchmark ODM (Base Model):

| O\D | 1 | 2 | 3 | 4 | 5 | 6 | 7 | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 250 | 200 | 1000 | 600 | 600 | 200 | 2850 |
| 2 | 50 | 0 | 50 | 1300 | 500 | 250 | 75 | 2225 |
| 3 | 20 | 20 | 0 | 40 | 20 | 20 | 20 | 140 |
| 4 | 700 | 1000 | 400 | 0 | 500 | 250 | 200 | 3050 |
| 5 | 400 | 400 | 200 | 600 | 0 | 150 | 125 | 1875 |
| 6 | 400 | 300 | 100 | 800 | 200 | 0 | 100 | 1900 |
| 7 | 75 | 100 | 75 | 275 | 100 | 100 | 0 | 725 |
| TOTAL | 1645 | 2070 | 1025 | 4015 | 1920 | 1370 | 720 | 12765 |

**Table 3.3** Adjusted ODM (LRT implemented)

| O\D | 1 | 2 | 3 | 4 | 5 | 6 | 7 | TOTAL |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 225 | 180 | 860 | 540 | 540 | 180 | 2525 |
| 2 | 45 | 0 | 45 | 1117 | 450 | 225 | 68 | 1950 |
| 3 | 18 | 18 | 0 | 35 | 18 | 18 | 18 | 125 |
| 4 | 630 | 900 | 360 | 0 | 450 | 225 | 180 | 2745 |
| 5 | 360 | 360 | 180 | 516 | 0 | 135 | 113 | 1664 |
| 6 | 360 | 270 | 90 | 688 | 180 | 0 | 90 | 1678 |
| 7 | 68 | 90 | 68 | 237 | 90 | 90 | 0 | 643 |
| TOTAL | 1481 | 1863 | 923 | 3453 | 1728 | 1233 | 649 | 11330 |

**Table 3.4 Fuel Consumption Model Parameters**

| **Parameters** | **Car** | **Bus** | **Parameters** | **Car** | **Bus** |
|---|---|---|---|---|---|
| **Engine Size*** | 1.6 litres* | 9.0 litres* | **Engine Size Ratio** | 1 | 5.625 |
| **Fi (ml/s)** | 0.330 | 1.856 | **C1 (ml/s)** | 0.420 | 2.363 |
| **F1 (1/100km)** | 4.700 | 26.438 | **C2 (ml/s)** | 0.260 | 1.463 |
| **F2 (l/100km)** | 6.500 | 36.563 | **Fd (ml/s)** | 0.530 | 2.981 |

* *Researched specifications from 'cars.com' for the 2015 Ford Fiesta and Scania K280UB.*

AIMSUN Manual bases the fuel consumption model for cars off the Ford Fiesta- thus when interpolating the parameters for buses, values are based off the ratio of engine size for the bus to car, considering the Scania K280UB as the most popular bus model in the Sydney city.

**Table 3.5 Unit Values of Emissions** *(Austroads Ltd, 2012)*

| **Pollutant** | **Value of emissions in $/tonne** |
|---|---|
| Carbon Dioxide (CO2) | 52.4 |
| Carbon Monoxide (CO) | 3.3 |
| Oxides of Nitrogen (Nox) | 2,089.2 |
| Particulate Matter (PM10) | 332,505.9 |
| Total Hydrocarbons (THC) | 1,046.8 |

# 4. Option Testing & Coding/ Network Refinement

## 4.1 Light Rail Network Geometry

The trains to be used for the Sydney light rail network have been decided to be the Citadis X05 series. The trains running along the Randwick line and the Kingsford lines will be 67m long and 2.65m wide. The fleet will consist of two 33m trains connected in a 10-carriage configuration and Appendix 1 visually compares the light rail to similar objects. It will have a passenger capacity of 450 *(Transport for NSW, 2017)*. There will be 120 seats in each train and the doors will be double doors to allow quick and easy entry and exit from the train carriages.

Figure 4.1.1 *Proposed Stops for the Light Rail Lines*

In accordance with the proposed plan from Transport NSW there will be 4 stops on the Randwick branch and 5 stops along the Kingsford line. Table 4.1.1 summarises the position of the stops and Figure 4.1.1 gives a physical representation of the positions of the proposed stops within the model area. However, only the first three stops will be implemented on the Kingsford line while all four on the Randwick line will be implemented. Services on the Randwick and Kingsford lines will be scheduled to run every 6 and 4 minutes respectively during peak times. These lines will go on and continue through the city where the NSW government have proposed that trains will run every 2-3 minutes during peak hour (Transport for NSW, 2012). This means that commuters will be able to turn-up-and-go without needing to consult a timetable, resulting in a less stressful commute. With the proposal, outlined in a later section, to convert all bus routes to the city into feeder routes, ridership will be high. Furthermore, as ridership increases with frequency (Gao et. al, 2016), the high frequency will help move large numbers of commuters through to the city as well as possibly encouraging new commuters to switch from car travel to using the light rail network. However, Gao et al. goes on to suggest that once past a certain threshold, the number of riders per fleet will start decreasing and therefore increase the cost per ride. With almost 5300 commuters (ABS, 2016) travelling to work from Randwick alone using public transport, a 4 to 6-minute frequency would be an ideal range to provide adequate level of transport without over supplying and risking empty rides. The dwell times for the light rail at stations will be similar to the dwell times of busses. The use of large doors as well as the fleet having more doors allows for quicker entry and exit of a larger capacity of passengers, ensuring a short wait time at each stop. This therefore reduces the chance of bottlenecks of passengers at stations and thus allows for the light rail to remain on schedule.

**Table 4.1.1.** Proposed stops for the Light Rail, based off *(NSW Government ,2019)*

| Line | Stop Number | Location | Landmarks |
|---|---|---|---|
| Randwick | 1 | Allison Road near corner with Darley Road | Randwick TAFE & Randwick Racecourse |
| | 2 | Allison Road near corner of Cowper St | Randwick Racecourse (lower) |
| | 3 | High Street at the corner of Wansey St | UNSW (upper campus) |
| | 4 | High Street at the corner of Belmore Road | Prince of Wales Hospital & Sydney Children's Hospital |
| Kingsford | 1 | Corner of Anzac Parade & Carlton St | E.S. Marks Athletics Field |
| | 2 | Anzac Parade near Todman Avenue | Kensington Public School |
| | 3 | Anzac Parade near High St | UNSW (lower campus) |
| | 4 | Anzac Parade near Strachan St | Kensington Oval |
| | 5 | Anzac Parade & Gardners Road Intersection | The Juniors Kingsford |

## 4.2 Road Geometry Refinement

Implementation of both the Kingsford and Randwick Light Rail lines will mostly run along Anzac Parade and Allison road respectively. In the outbound direction, both routes will run along the existing busway with the Randwick line continuing along the bus way while the Kingsford line will run along Anzac Parade. A summary of the changes to the base model can be seen in Table 4.2.1.
Figure 4.2.1 outlines the proposed routes for the two lines going to Randwick and Kingsford.

**Figure 4.2.1.** *Planned Light Rail Routes*

As seen in Figure 4.2.2, the Randwick line continues along the busway along Allison Road. The busway will no longer be connected to Doncaster Avenue and will continue to Darley Road. The tracks will then cross the intersection and switch to the Racecourse side of Allison Road as seen in Figure 4.2.3 and continue to Wansey Road. The train will go up along Wansey Road and make one final turn at the intersection of Wansey and High St, where it will continue up High St towards Randwick Junction. The section of High Street which the light rail runs along has been converted into a one-way street to accommodate the new tram lines along the narrow street section. Vehicles will only be able to travel along this section of High St from the Randwick Junction direction.

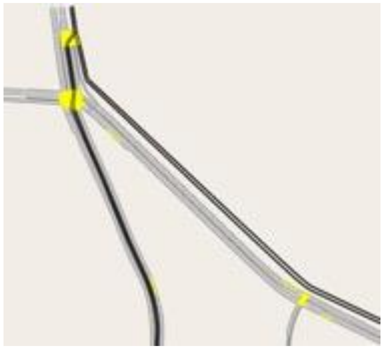

**Figure 4.2.2.** (Left) *Closer plan of the corner of Anzac Parade and Allison Road*
**Figure 4.2.3.** (Right) *Randwick Line Continued*

The Kingsford line will run all along Anzac Parade through the whole model. Figure 4.2.2 illustrates the proposed deviation from the busway. A new intersection will be put in place before the large Anzac x Allison intersection to reduce the impact the light rail may have on traffic at the intersection. The outbound lanes on Anzac Parade will increase from 3 lanes prior to the new intersection to 5 lanes post the intersection. Two of these lanes will be right-turn only lanes. The next two lanes will be for traffic continuing along Anzac parade and then final lane will be for vehicles planning to turn onto Allison Road. Figure 4.2.2 also shows the plan for the Kingsford light rail line to run in between the two opposing vehicular traffic sections of Anzac Parade. To accommodate the new light rail tracks, a lane from either direction has been taken and converted into the tracks the light rail will run along. The dedicated public transport lane has also been converted into a normal lane to compensate for the reduction in capacity. Vehicles will also no longer be able to make a right turn from Anzac Parade to Doncaster Avenue as it would be a safety hazard with the light rail running and a lack of space to construct extra room for a dedicated right turn lane.

Sydney light rail team has also collaborated with Ausgrid to remove any existing overhead networks as underground electrical and communication networks is being completed. In zone 28, Anzac Parade between Tay Lane and Abbotford Street, 56 hours of intensive work has resulted in most wooden poles being removed where the remaining is left for street lighting. Work such as 160 meters of new footpaths, roadways including pram ramps, curbs, driveway laybacks, road trenching and road installment have been completed to restore the construction.

**Table 4.2.1** *Summary of changes to the model*

| Location | Modelled Change |
|---|---|
| Anzac Parade/Allison Road busway | Implementation of tracks along the busway |
| Allison Road busway x Doncaster Avenue | Busway no longer connected at this intersection as busway was converted to light rail tracks. Busway no longer used by busses |
| Anzac Parade | Implementation of light rail tracks on the middle two lanes of Anzac Pde all the way to Kingsford |
| Anzac Parade Near the intersection with Allison road | New intersection added for the light rail to cross onto Anzac Parade from the busway |
| Wansey Road | Converted into a one-way street to accommodate the light rail. Traffic only from Allison road to Arthur St. Two-way in between Arthur St and High St. |
| High St | One-way between Wansey Rd and Avoca St to accommodate light rail |
| Anzac Parade | Reduction by one lane in each direction |
| Anzac Parade | Conversion of bus lane to a normal traffic lane |
| Anzac Parade & Doncaster Avenue | Right turns no longer allowed due to light rail posing a potential safety hazard |

## 4.3 Traffic Signals and Phasing

With the introduction of the light rail network, traffic signals will need to be changed. Most of the network will have little change observed, with changes only occurring along the Light rail lines. Table 4.3.1 summarises all the signal changes made in the system. The Randwick line will need to cross 3 intersections along its' route. Actuated signals have been put in place at signals such that when detectors receive the signal of a light rail tram the signal plan will activate the phase for the light rail tracks to go green. Figure 4.3.1 summarises the phases present in the intersection between Allison Road and Darley Road. Phase 4 has been modified so that it will only be called when the detector is triggered, thus reducing the need for traffic to wait through the whole signal phase if there is no light rail present. Similar modifications have been made along the rest of the Randwick line at the two intersections on High Street. The traffic phases likewise have been changed to accommodate the light rail. However, along Anzac

Parade, the track signals have just been added to the existing phase where traffic running parallel to the trains were set to green. This bypasses the need for a dedicated light rail-only traffic phase, reducing the chances of congestion from an extra phase of red for the other directions. The consequence of this is that the light rail system may see delays to the schedule due to frequent stopping and starting at lights. Combined with the frequent number of stops along Anzac Parade can reduce the time-saving benefits of using the light rail as cars would experience similar, if not faster travel times. Priority at lights may be a possible solution to this problem however, this may cause congestion to the rest of the network, especially on Anzac Parade where there are many intersections. Furthermore, the group had encountered difficulty coding in the priority into each control plan for intersections. The group planned to originally utilise the 'Priority' feature in the control plan though, the implementation of priority requests seemed to have no effect. Thus, a potential improvement to the system could be the implementation of priority to light rail along sections such as on the Randwick line, where the light rail would only cross one major intersection.

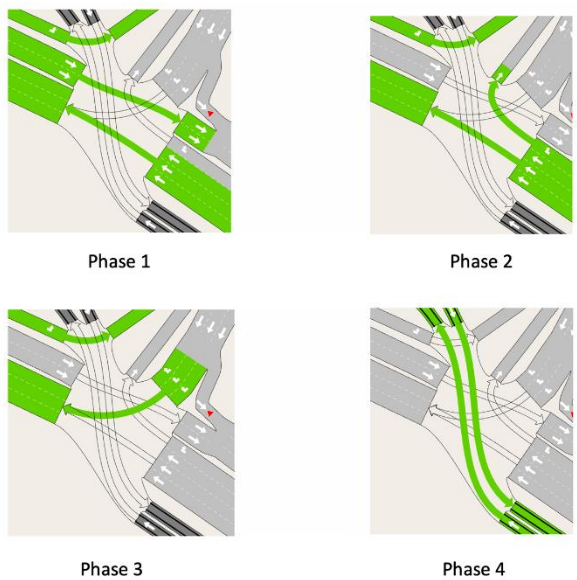


**Figure 4.3.1** *Allison Road and Darley Street Intersection Phases*

**Table 4.3.1** *Summary of Traffic Signal Changes*

| **Intersection** | **Implemented Change** |
|---|---|
| Former busway to Anzac Parade | Implementation of new traffic light and the use of an actuated system where detection of the Kingsford line will automatically change the light for the light rail to travel through |
| Anzac Pde & Allison Rd | Added the Kingsford line to control plan inside the phase for traffic running along Anzac Pde |
| Anzac Pde & Todman Ave | Added the Kingsford line to control plan inside the phase for traffic running along Anzac Pde |
| Anzac Pde & Doncaster Ave | Added the Kingsford line to control plan inside the phase for traffic running along Anzac Pde |
| Anzac Pde & High St | Added the Kingsford line to control plan inside the phase for traffic running along Anzac Pde |

| | |
|---|---|
| Anzac Pde & Barker St | Added the Kingsford line to control plan inside the phase for traffic running along Anzac Pde |
| Allison Rd & Darley Rd | Modified previous plan to an actuated control plan with the new Randwick line activating with trigger detection |
| Wansey St & High St | Added an actuated control plan with the new Randwick line activating with trigger detection |
| High St & Botany St | Added the Randwick line to control plan inside phase for traffic running along High St. Phases slightly modified to reflect the removal of the eastbound High St lane and addition of the Light rail line. |

## 4.4 Bus Routes

Bus routes will be heavily impacted from the introduction of the light rail. With the primary goal of reducing congestion along the roads, the aim is to eliminate overlapping of bus routes and the light rail.

Table 4.4.1, details the proposed changes to the bus routes within the system. As the LRT Kingsford line will take the same route as most of the buses that travel along Anzac Parade, they will either be abolished or be terminated along Anzac Parade, where commuters will then be able to get on the light rail service towards the city. Similar actions are proposed for buses that go along Allison road from suburbs such as Randwick, Clovelly and Coogee. Most of these routes will continue to operate but will terminate as they enter Allison road. Commuters will then need to transfer to the Randwick light rail service in order to travel to the city. Express services have all been proposed to be demolished as they will become redundant once the light rail is in place. As the only differences between the express routes such as the X39 or the X73 and the normal routes was that the express routes had skipped the stops along Allison road and Anzac Parade, these routes were deemed redundant as the routes were running the same routes from the terminus to Allison road.

With the new planned bus network, there will also be some changes to the time schedules of some bus routes. Table 4.4.1 outlines the proposed changes to the timetables for the bus routes that will be changing. The frequency for bus routes such as the 374 and 377 will increase to meet the excess demand created from the abolishment of the express routes that were covering the same routes. As Tirachini (2010) suggests, dwell times are dependent on commuter demand and the layout of the bus itself. With no significant change to the bus design and increased demand to be offset by the new proposed timetable changes, there should be little effect on the amount of time buses wait at each stop compared to the times set out in the base model. Most buses will have a dwell time of around 20 seconds with deviation set to 10 seconds for all stops.

**Table 4.4.1** *Proposed Bus Route Changes*

| Bus Route | Proposed Change | Frequency Changes |
|---|---|---|
| 391, 392, 393, 394, 399 | Continue operation from outer suburbs and terminate routes at Todman Avenue | Frequency will not be changed |
| M10, M50 | Abolish the eastern suburbs section of routes | N/A |

| | | |
|---|---|---|
| 374, 377 | Continue operation from Coogee/Maroubra beach and terminate route at corner of Allison Rd and Cowper St | Frequency will be increased to accommodate the removal of similar routes as well as new commuters |
| 338, 373, 376, 395, 396, X73, X74, X77, X39, X40, 891 | Abolish routes | N/A |
| 339 | Continue operation from Clovelly terminate route at Randwick TAFE | Frequency will be increased to accommodate the removal of the 338 as well as new commuters |
| 375 (376 replacement) | New route: Maroubra Beach – Sydney University | Will operate at a similar frequency to the 376 that it is replacing |

## 4.5 Innovations

## Bicycles

The rise in bicycles usage in European countries and Japan has seen an increase in travel efficiency and a reduction in pollutions. They are mobile and do not require segregated lanes – although dedicated bicycle paths are a factor of bike usage. Its versatility on roads allows it to be an efficient way of travel, which minimises individual vehicles on roads and congestions.

Australia has a low bicycle usage, relative to other countries due to many policies and factors. The most impactful policy is the *1991 Mandatory Helmet Act.* This policy makes wearing a helmet compulsory for all ages and has repelled potential bike riders and decreased the amount of bicycle users over the years, due to the discomfort of wearing a helmet. Countries such as Japan and Paris have stopped the demand for helmets for over of the ages of 17 and has seen an improvement in usages of bikes. This has enabled them to manage their congestions as well as improving quality of life and health for their citizens.

The Australian government should reconsider the *1991 Mandatory Helmet Act* to increase bicycle usages to work. This may reduce the needs for parking spaces near light rail platform and stations. For stops without parking spaces, commuters will be inclined to park on residential streets, which could deteriorate the living quality or be an inconvenience to residence. For example, the light rail stop located on High Street may attract more commuters to park their car on that street. This will be problematic to staffs working at UNSW as they are unable to find parking spots. By relaxing the mandatory helmet act, it will allow commuters to increase their options of travelling to work.

Apart from abolishing compulsory helmets, foreign countries have also implemented road infrastructures to aid cyclists which took into consideration safety and security for the cyclists. These implementations included segregated lanes at pedestrian crossing to reduce potential collisions with pedestrians; this has been demonstrated in Figure 4.5.1. They have also increased bicycle racks for cyclists at platforms and the security around these racks by installing cameras. Furthermore, a heavy fine should be considered to mitigate vandalism and theft at these racks.

**Figure 4.5.1** (https://i.ytimg.com/vi/FlApbxLz6pA/maxresdefault.jpg) - *green paths demonstrates cyclist path*

To further increase bicycle use as a mode of transportation, foreign governments have introduced bike sharing. Bike sharing allows the rider to rent a bike for a period of time and enables them to rack at a different location where ever there is a racking station. The bikes can be rented via Opal card – and instead of using QR codes/email like existing bike sharing services provided by private companies. In foreign countries, this service has been seen to improve the three pillars of sustainability;

- Social: Improve health and living quality of the community, reduces congestions, reduces crash risks, the cheap implementation allows the government to increase expenditure in other sectors, increases work opportunities.
- Environmental: Reduces amounts of cars on roads which subsequently reduces pollution emitted, decreased air and noise pollutions, lower carbon footprint compared to other transport modes.
- Economic: Cheaper to implement, reduces congestions which subsequently increases economic activity.

The government can implement bike sharing services throughout the Sydney CBD to improve efficiency between travel modes. These services can also be placed near light rail platforms to provide a more efficiency in travelling to facilities close to the light-rail without the need of busses. For example, stops near Moore Park can implement these services, can improve travel time for commuters who are travelling to sporting precincts. These sporting precincts will also have racking station where they are able to place after their renting. However, with all services, there are risks and mitigations.

**Table 4.5.1**: *Risks and Mitigation of bike sharing services*

| Risks | Mitigation |
|---|---|
| Bikes being rented longer | Implementing a renting system can reduce long borrowings (inspired by foreign countries)<br>1. Free rental for the first 15-30 minutes |

| | |
|---|---|
| than allowed period | 2. After this time, the user will be charged $0.5 to their Opal account<br>3. Until the 2nd hour of borrowing, the rider will be heavily penalised. |
| Theft and Vandalism | Bikes can only be borrowed through Opal cards with banking statement or credit card. This will reduce the amount of theft as the user can be easily traced. |
| Bikes not returning to underused stations | This can be combated by providing incentives that credits riders 15 minutes of additional ride by returning their bike to a specific racking station.<br>There will also be riders who would drive to these locations to remove or fill the bikes, which improves job opportunities. |

This innovative idea can only be implemented in certain countries, suggested by (Midgley, 2009). It was suggested that this country required; a strong commitment towards sustainability, sufficient resources and bicycle infrastructures, in which Sydney has. Implementing this strategy will allow improvements in the assigned network and increase the usage of public transport. It will also allow Sydney to increase amenity and reputation.

**SMART ROAD**

Smart Road is a strategy that gives priority to different transport modes at different times of day. It has been implemented in many cities (e.g. Melbourne) and has been seen to reduce congestions and pollutions, improve public transport, improve safety and improve the total travel time for commuters who drives cars.


**Figure 4.5.2**: Smart road plan (*VicRoads, 2019*)

The priority system given to different transport mode is based on the time;

- Busses and Trams: Given priority during morning and afternoon peak hours. This will ensure no delays in public transport which may be caused by accidents, and improves reliability in public transport. By implementing this strategy, it will guarantee that the light rail will come every 4 minutes during peak hours as promised by the government.
- Walking: Walking is encouraged by providing pedestrians with friendly paths and increasing the space in high activity zones.
- Trucks and Cars: Alternative routes are given, where there will be signs to detour the driver.
- Cycling: On-road and off-road cycling paths for cyclists to avoid other transport modes. This will tie in nicely with the innovations to increase bike usage that were aforementioned.

Smart traffic light technology will be used in these areas to a give priority to different traffic modes. The Australian government should implement this strategy to ensure the promised frequent time of 4 minutes during peak hour.


**Figure 4.5.3**: Smart Road plan of Melbourne (*VicRoads, 2019)*

**STADTBAHN**

Stadtbahn is a German invention that integrates the light railway into the heavy rail tracks. This may improve the efficiency in changing transport modes as it provides commuters less travel to the next transport mode. Besides the transition efficiency, Stadtbahn can allow light rails to be decentralised. For example, implementing Stadtbahn from Sydney to Parramatta, can allow the depot at Randwick to provide light rail carriages to Parramatta during times that are unexpected; e.g. a sudden rise in demands for light rail service in Parramatta where Parramatta cannot provide. Since depot requires a large land and ideally somewhere away from the CBD and residency, the Stadtbahn allows areas to develop light rails. This innovation allows the government to provide a back-up plan for the Parramatta light rail service that will commence in the future, as part of the Western Sydney Infrastructure Plan.

**MOBILITY AS A SERVICE (MaaS)**

MaaS is a platform that integrates all transportation modes – public and private transports into one, to provide seamless experience for the user. This service is still an ongoing development in many countries. The software utilises AI technology, urban mobility analytics and real time information to improve efficiency on the road. For phone users, it will provide the most optimal travel options tailoring the user based on their preferences and will display the cost of each option. For car users, it will provide the driver with live data of the roads, providing information about; congested roads, accidents or road maintenance.

MaaS primary purpose is to reduce the use of personally-owned modes of transportation and reducing the main public transport from overcrowding during peak times. This software will also benefit the economy;

- As the future grows, there will be a rise in autonomous taxi companies. These companies will utilise MaaS to find the most optimal route with live data. The growing industry will also their manufacturers, AI expertise and partnership.

- An increase in convivence of travel allows for a reduction in cars on the road, which subsequently reduces congestions, decrease CO2 emissions, increase public health and quality of life.

As more commuters swap to public transportation in the future, it is necessary that they are provided with all the information to optimise their trip, hence MaaS is a perfect solution to improve their travel.

### LIGHT RAIL INTERSECTION PRIORITY

An option to make the light rail an even more attractive option, that we have tried to implement, is to adjust signals to give the Light Rail priority at intersections for a decreased LRT delay time to close to 0. This could be implemented by the signal phases to sync with the LRT - with detectors to adjust for slight deviations in the light rail arrival timings such that the signal is always green for the LRT. This makes the LRT network consistent and reliable while also being a definitive faster mode of transport than cars and buses. As more commuters shift towards this new attractive option, the roads would in-turn be even less congested than before.

### TRIGGER DETECTORS AND ADJUSTABLE SIGNAL PHASES

Whilst running AIMSUN, it has been seen that cars will queue onto the path of the light rail, portrayed in Figure 4.5.4. To prevent further vehicles from adding into the queueing length, a detector that counts the flow of cars should be implemented to avoid this incident. Once the detector is triggered, it will alter the traffic signals to prevent the cars from interfering with the path of the light rail. On top of this, adjustable signal phases allow signal lights to adapt to the current vehicle flow. It will utilise AI technology, live flow count and External Traffic Control and Management System (ETCMS) to determine the amount of green time a lane should have.

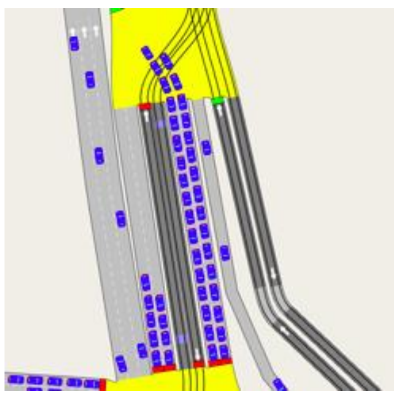

**Figure 4.5.4:** AIMSUN simulation showing cars obstructing the light rail's path

# 5.0 2015 Base Model Operational Results

## 5.1 Critical intersections

The intersections tabulated in Appendix 8 have been deemed the most critical in the system. They have been considered as critical for one of the two reasons:

- The delay time and queue length associated with this intersection is tremendously large, compared to other intersections in the system.

- The intersection has caused some kind of traffic wave or disturbance in the traffic flow system, which has caused additional delay times and queue lengths for other parts of the network.

### 5.2 Pinch points

The rate and degree of congestion throughout most parts of the network worsened with time as the inactive, quieter streets remained static. The worst levels of congestion were recorded on Anzac Parade and Alison Road. This is not surprising as both are main roads and is used for majority of the grips generated in the network (4000-5000 vehicles) for both roads near the end of the simulation). Even though both roads were heavily congested, the delay time and queue lengths associated with Anzac Parade appeared to be fluctuating (more so decreasing) with time. However, the opposite can be said for Alison Road as delay times and queue lengths began to increase exponentially with time. This may have been caused by the traffic jam which occurred at High Street approximately halfway through the traffic simulation.

At approximately 8.35am, a large number of buses began turning into High Street from Anzac Parade (most belonged to the 891 route) which led to massive amounts of congestion and delays for the surrounding streets. This occurred because High Street is a single lane road and hence, other vehicles could not overtake the buses whilst they were loading/unloading their passengers. This became even more problematic as High Street contained two bus stops which lead to increased queueing and reduced vehicle flow rates (Figure 5.2.1).

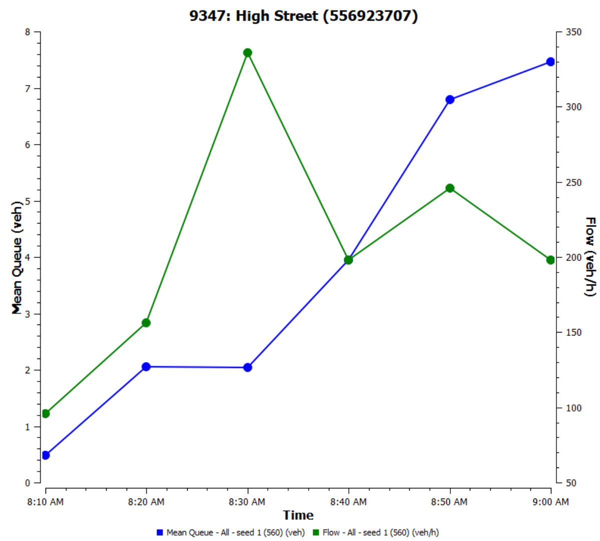


**Figure 5.2.1:** *Graph illustrating increased Queue lengths and reduces Vehicle flow rates*

The traffic congestion developed on High Street had detrimental effects on neighbouring streets. See Figure 5.2.2 and 5.2.3 which illustrate the drastic change in characteristics for Wansey Road.

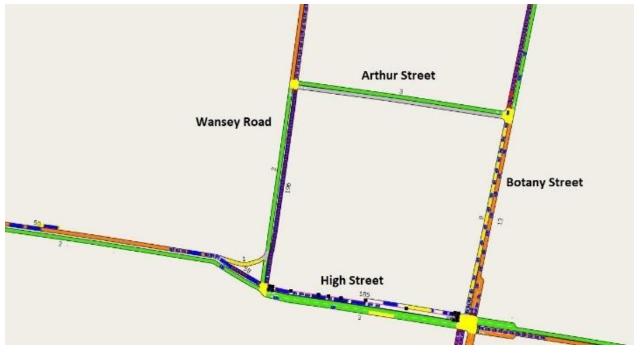


**Figure 5.2.2:** *Graph illustrating the effects of congestion on neighbouring roads*

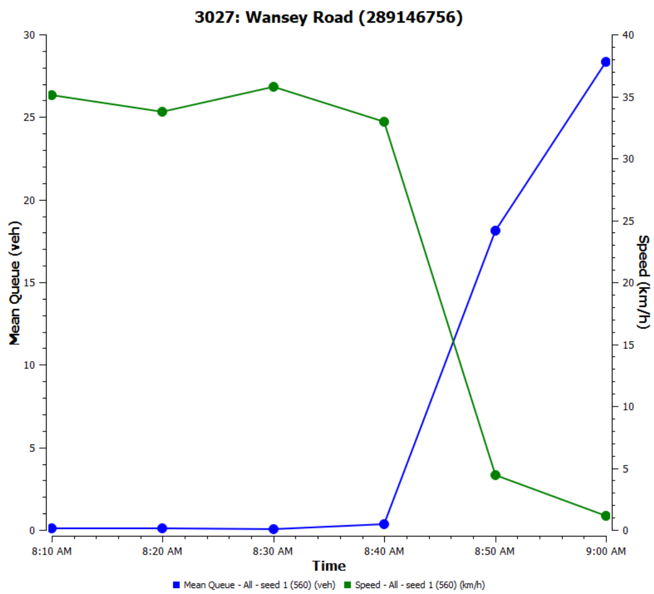


**Figure 5.2.3:** *Graph illustrating the change in traffic flow qualities of Wansley Road*

A good way to verify the time at which an intersection was the most congested, is to compare the two durations correlated to the maximum delay time and queue length (Appendix 5). Since these two parameters are closely related to one another (Figure 5.2.4), both times should be roughly the same or close to one another (to account for queue accumulation lag).

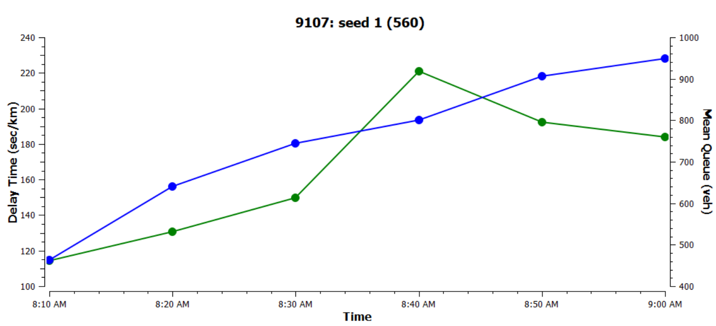


**Figure 5.2.4:** *Graph illustrating the relationship between Delay time and Queue length*

At approximately 8.35am, a large number of buses began turning into High Street from Anzac Parade (most belonged to the 891 route) which led to massive amounts of congestion and delays for the surrounding streets. This occurred because High Street is a single lane road and hence, other vehicles could not overtake the buses whilst they were loading/unloading passengers. This became even more problematic as High Street contained two bus stops as shown in (Figure 5.2.2), which lead to further increased delay times.

A peculiar detail to notice is that no matter how congested High Street and Wansey Street were, no cars decided to take a detour onto Arthur Street (which was completely congestion-free). This would have been the optimal route choice as both different routes would have led to intersection 5 (Botany/High Street).

### 5.3 Speed profile and total system travel time

The speed of vehicles throughout the system is related to both the density and flow of the system. Since delay times and queue lengths can be used to establish a relationship between a system's flow rate, the same two parameters should theoretically be able to predict the trend of the system's vehicle speed profile. Figure 5.3.1 shows the relationship between the mean speed profile and flow of the system. It is also important to realise that the figure represents the average values obtained throughout the whole network. Although the system vehicle speed is shown to be decreasing, you cannot assume that all parts of the network follow this the same trend. A more in-depth analysis using AMISUN will be required to find the speed profile for specific parts of the network (identical concept for delay time, queue length and other output parameters).

The total system travel time calculated through AMISUN is 1145.82 hours.

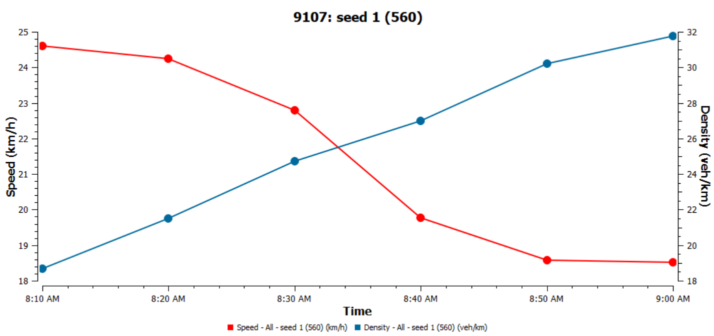


**Figure 5.3.1:** *Graph illustrating the relationship between Traffic flow and Vehicle speed profile*

## 6. 2020 Light Rail Future Year Demand

### 6.1 Future Land Use

The development of an LRT network can bring gentrification to the city, (Cavers and Patterson, 2014) evident through previous studies in Canadian cities Toronto and Montreal- where "improvements to average monthly rent, the proportion of people in professional occupations, the percentage of owner-occupied dwellings, average family income, and number of degrees per capita". Property value also appreciates with proximity to Light Rail Stations resulting in increasing economic value for both present, and future buildings.

Along with the construction of the LRT network, the construction of more parking spaces and pickup-drop-off zones must be considered to accommodate for commuters to arrive to their local light rail stations via car.

The increased convenience and accessibility due to the new transit facility promotes higher density development in areas of LRT construction, which, in turn, can alter travel patterns and mode choices over time within the greater urban system. Investment in LRT can spur urban growth, revitalize declining areas, and promote more transit-oriented development in a city's downtown core, inner suburbs, and outlying areas *(D Higgins and Ferguson, 2014)* - which can be reflected in not only in the eastern suburbs of Randwick and Kingsford, but also for suburbs in between our focus network and the CBD. Businesses along this line would benefit from greater exposure when in close proximity to new LRT stations as there is now greater accessibility for Students and Staff of UNSW whom would normally take an express bus service to and from UNSW and Central Station *(NSW Government, 2012)*. The LRT's improved transport capacity and accessibility will also facilitate the expansion of UNSW and future increased enrolment of students.

## 6.2 Future Origin-Destination Matrix Estimation

The introduction of LRT may induce a reduction in the number of car trips, and hence adjustment of the O-D Matrix may be necessary.
*(Please see **appx 7** and excel file, "ODM Reduction sheet" for visualisation of the following procedure)*

A case study on Portland, Oregon revealed that "up to *70%* of new rail ridership is diverted from bus", and results were reproduced in Sydney *(Hensher and Waters, 1994)*.
Furthermore, assuming all current bus passengers switch to the LRT system, in Sydney, *20.9%* of trips for work are accounted by public transport in 2016 *(O'Sullivan, 2017)*.
And thus, 79.1% trips are taken by cars. (assume cyclists and walkers are negligible)

From the Project Brief Addendum, there were originally 12,765 total trips in the ODM. Applying the previous statistics then produces 3373 passengers converting to LRT, 1446 of whom were formerly using cars.

However, parking is more scarce in the CBD, hence it is more likely for commuters who work in firms or businesses with an office setting in the CBD to switch from their cars to the LRT- ***(see appenxdix 3*** for data from ABS for population professions around the focus network).
Meanwhile, traffic outbound from the city would be more likely to remain the same as 1) the other centroids have much lesser attraction compared to the CBD during the morning peak hour, and hence all outbound traffic is lesser. 2) parking is more convenient for both big and small businesses outside the CBD, as they are in less densely populated areas with greater freedom of land use.
From the ABS statistics, an increased weighting of 40% shall be applied to column 4 of the ODM's trip subtractions, which represents inbound traffic to the city. This means more of the 1446 car commuters whom convert to using the LRT come from column 4 of the ODM.

The resulting subtraction ODM is then normalised for the total to be back to 1446 total car travelers being subtracted. Finally, subtracting the Base Model ODM to this matrix yields the final adjusted ODM in Figure 6.2.1:

| **O\D** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|
| **1** | **0** | **225** | **180** | **860** | **540** | **540** | **180** | **2525** |
| **2** | **45** | **0** | **45** | **1117** | **450** | **225** | **68** | **1950** |
| **3** | **18** | **18** | **0** | **35** | **18** | **18** | **18** | **125** |
| **4** | **630** | **900** | **360** | **0** | **450** | **225** | **180** | **2745** |
| **5** | **360** | **360** | **180** | **516** | **0** | **135** | **113** | **1664** |
| **6** | **360** | **270** | **90** | **688** | **180** | **0** | **90** | **1678** |
| **7** | **68** | **90** | **68** | **237** | **90** | **90** | **0** | **643** |
| **TOTAL** | **1481** | **1863** | **923** | **3453** | **1728** | **1233** | **649** | **11330** |

**Figure 6.2.1** *Final adjusted ODM:*

# 7. 2020 Light Rail Model Operational Results

### 7.1 Critical intersections

Similar so section 5.1. Refer to Appendix 9

### 7.2 Pinch points

A large majority of the street segments that are connected to a centroid (roads for entering the system) have small queue lengths. This is purely a misconception which does not truly represent the queue lengths for these streets in reality. The given queue lengths are misleading because these segments do not represent the entirety of the road length itself and hence, the maximum queue lengths for these roads will simply be the maximum (physically) number of cars that can fit into the road geometry modelled in Amisun.

The rate and degree of congestion throughout most parts of the network worsened with time as the inactive, quieter streets remained static. The worst levels of congestion were recorded on Anzac Parade and Alison Road. This is not surprising as both are main roads and is used for majority of the grips generated in the network (3000-4000 vehicles) for both roads near the end of the simulation).

A good way to verify the time at which an intersection was the most congested, is to compare the two durations correlated to the maximum delay time and queue length (Appendix 9). Since these two parameters are closely related to one another (Figure 7.2.1), both times should be roughly the same or close to one another (to account for queue accumulation lag).

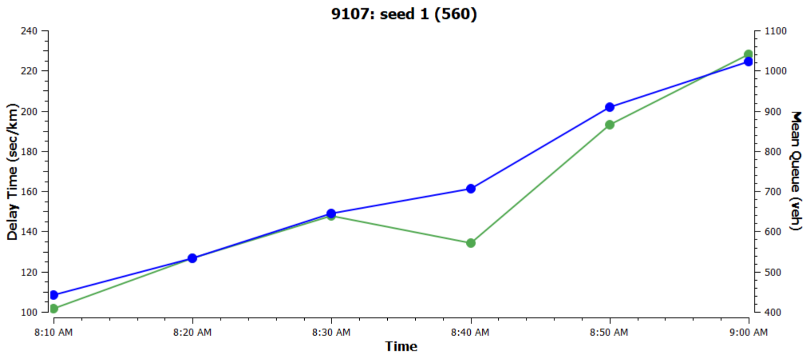


**Figure 7.2.1:** *Graph illustrating the relationship between Delay time and Queue length*

For the first half of the simulation, the traffic flow on Alison Road appeared to be functioning normally. However, at approximately 8:33am, large numbers of cars travelling outbound on Alison Road began to take a detour (Alison Road -> Cowper Street -> Prince Street -> Alison Road) only to end up travelling back onto Alison Road (outbound). The two roads that used for the detour were both single lane and connected through a roundabout. They reached their capacities only 10 minutes later at 8:43am. This did not make much sense and most definitely affected the simulation results associated with Alison Road.

### 7.3 Speed profile and Total System Travel Time

The speed of vehicles throughout the system is related to both the density and flow of the system. Since delay times and queue lengths can be used to establish a relationship between a system's flow rate, the same two parameters should theoretically be able to predict the trend of the system's vehicle speed profile. Figure 7.3.1 shows the relationship between the mean speed profile and flow of the system. It is also important to realise that the figure represents the average values obtained throughout the whole network. Although the system vehicle speed is shown to be decreasing, you cannot assume that all parts of the network follow this the same trend. A more in-depth analysis using AMISUN will be required to find the speed profile for specific parts of the network (identical concept for delay time, queue length and other output parameters).

The total system travel time calculated through AMISUN is 1011.49 hours.

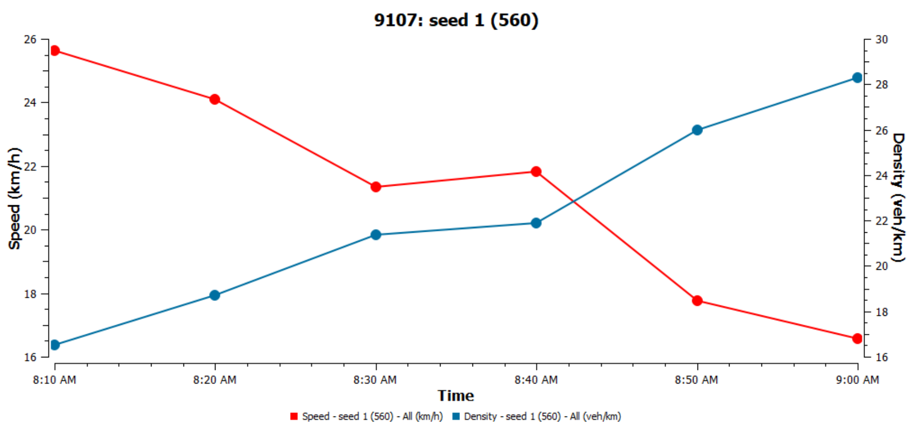


**Figure 7.3.1**: *Graph illustrating the relationship between Traffic flow and Vehicle speed profile*

## 8. Stability Analysis

After the model has been calibrated and validated, it was then simulated under 5 different seed values. The total travel time (TTT) was extracted from the output of AIMSUN with its standard deviation. These values were used to conduct a stability analysis which is to find the amount of repetition necessary to be within the chosen confidence interval.

$$N = \left(\frac{Z_{\frac{\alpha}{2}} * \sigma}{\Delta}\right)^2$$

Where :

- Zalpha/2 : The z-score for a two-tailed confidence interval (CI) with normal distribution (1.96 for a 95% CI). A higher value of CI will require more repetition of a model

- Sigma: The average standard deviation of TTT (specified as the average of 5 replications, obtained from AMISUN). A larger standard deviation indicates a higher degree of uncertainty and hence, will require more simulations, increasing the value of N
- Δ: The acceptable level of precision/inaccuracy tolerance, in decimal form (specified as 5%) multiplied by the mean TTT. Assuming that the average TTT remains static, an increase in precision will also require a higher amount of accuracy, increasing the value of N.

From the output:

TTT = 1027.2, Std = sigma = 26.55

- For 5% TTT mean:

  N = 1.02 ~ 2 repetitions required

- For a tighter inaccuracy tolerance. Δ=3% x (TTT mean) may be taken to be conservative:

  N = 2.85 ~ 3 repetitions required

# 9. Discussion of Model Outputs and Comparisons

## 9.1 Comparisons of Network Performance

### 9.1.1 Total System Travel Time

**Table 9.1.1**: *Key output parameters used for comparison (rounded where necessary)*

| Comparison of outputs | Base Model | | Scenario testing | |
|---|---|---|---|---|
| | Value | Standard deviation | Value | Standard deviation |
| Total trips - All | 12765 | N/A | 11330 | N/A |
| Delay time – All (sec/km) | 166.38 | 171.92 | 156.36 | 125.59 |
| Density – All (veh/km) | 26 | N/A | 23.03 | N/A |
| Flow – All (veh/hr) | 11127 | N/A | 9615 | N/A |
| Mean queue – All (veh) | 751 | N/A | 763 | N/A |
| Speed – All (km/hr) | 21.31 | 10.37 | 21.29 | 10.57 |
| Total system travel time (TSTT) (hr) | 1145.82 | N/A | 1011.49 | N/A |
| Vehicles outside – All (veh) | 11127 | N/A | 9615 | N/A |
| Vehicles waiting to enter – All (veh) | 1349 | N/A | 822 | N/A |

The tabulated parameters discuss and explain important characteristics of a transport network. They are all linked to one another and are essential when attempting to simulate an optimally functioning transport system. From the tabulated outputs, the implementation of the LRT system has proved advantageous by reducing the total system travel time. However, the TSTT of a network is not a decisive factor that can distinguish better transport systems from one another. This is because different transport systems deal with mostly non-homogenous amounts of users and vehicles as well as different trip lengths and distances.

Consequently, a better parameter than can be used to measure the efficiency and optimality of a system is the delay time of vehicles. Users may experience a high delay time due to different reasons such as:

- overcrowding of roads (numerous amounts of cars or heavy vehicles)
- road blockages (car accidents or double parking)
- Poorly optimised traffic signals (giving roads at an intersection excessive green time)

The alterations from our base model to our scenario testing model ultimately asked the question, will the user delay time be more affected by a reduction in the number of O-D trips in a network or by the removal of road lanes in a network?

In addition, it is important to pay attention to the parameter "vehicles waiting to enter –All" as it can also be used to estimate the operating capacity of a network. Clearly, as network congestion levels rise, the numerical value of this parameter will also increase, indicating that a network is reaching at its maximum capacity. Ultimately, the implementation of the LRT resulted in a reduction in the TSTT and the average delay time experienced by vehicles.

### 9.1.2 Changes in the location of congested areas in the network.

The congestion levels associated with Anzac Parade and Alison Road were critical for both scenarios (before and after the LRT implementation) and became worse with respect to time. The congested road segments were often characterised by their traffic shock waves and their ability to cumulatively cause successive congestion chain reactions in the network.

Subtle alterations in a transport network can lead to drastic and unexpected changes in the system's behaviour. One of the major congested areas in the base model involved the issue with a large number of buses arriving in High Street (1-2 lane road) at approximately 8:35am. Though, since the LRT has been implemented, that bus route (891) no longer exists. This has proved to be very advantageous as now there is an increased vehicle flor rate through High Street itself and other neighbouring roads (Wansey Road and Botany Street).

With reference to Tables 5.1.1 and 7.11, it is also evident the upper part of Anzac Parade (after Todman Avenue) became more congested after the implementation of the LRT system, while the lower part of Anzac Parade (after Todman Avenue) became less congested. The decrease in congestion was due the insufficient green time at the intersection between Anzac Parade and Barker Street. This meant that instead of a steady flow of vehicles entering the lower half of Anzac Parade, they arrived in batches and were able to transverse the network at almost free flow speed.

Conversely, the increase in congestion in the upper half of Anzac Parade was due to the reduction in road lanes (from 3 to 2) at the intersection between Anzac Parade and Doncaster Avenue, illustrated in Figures 9.1.2.

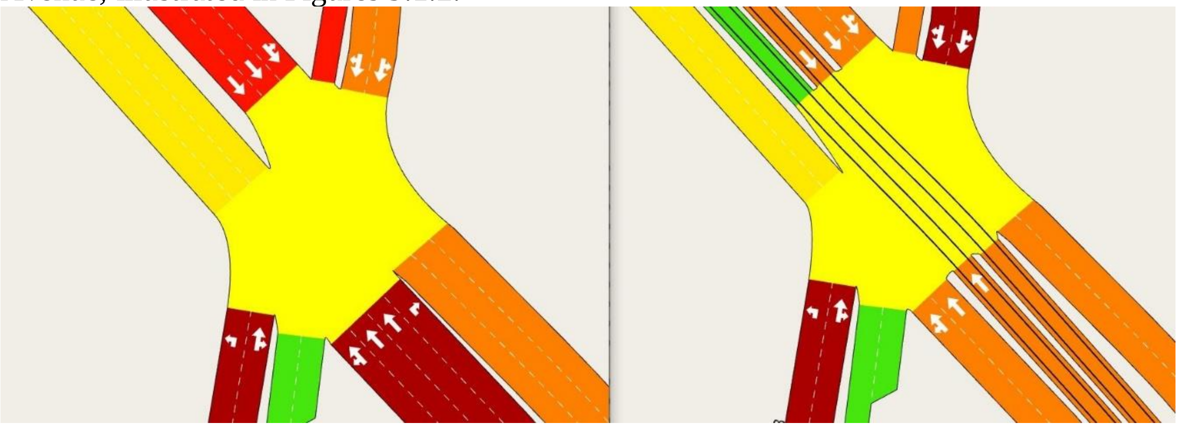

**Figure 9.1.2:** *Before the implantation of the LRT (left) and after (right)*

Unsurprisingly, other nearby roads (Todman Avenue and Doncaster Avenue) have also become more congested when compared to the prior road adjustments before the implementation of the LRT system. This was likely to happen as congestion through a network can travel very quickly and create traffic shocks.

Surprisingly, despite the LRT system being implemented near Alison Road, it does not have much effect on the increased delay times and congested as we saw in Anzac Parade. This is simply because the tracks of LRT system minimally interfered with the traffic flow throughout Alison Road (unlike Anzac Parade where road lanes were removed). An important limitation to note is that although AMISUN projects the congestion level of the road network, it does not project or reveal anything about the congestion levels situated around LRT stops.

## 9.2 Travel Time Savings

**Table 9.2.1** D*etails AIMSUN outputs regarding Travel Time in the models.*

| Outputs | Base Model | | LRT implemented | | Units |
|---|---|---|---|---|---|
| Time Series | Value | Standard Deviation | Value | Standard Deviation | |
| Total Travel Time - All | 1145.82 | N/A | 1011.49 | N/A | h |
| Total Travel Time - Car | 1111.52 | N/A | 985.03 | N/A | h |
| Total Travel Time - Bus | 34.3 | N/A | 21.23 | N/A | h |
| Total Travel Time - Light Rail | | | 5.23 | N/A | h |
| Travel Time - All | 229.57 | 170.63 | 220.34 | 124.21 | sec/km |
| Travel Time - Car | 229.65 | 172.21 | 218.77 | 123.49 | sec/km |
| Travel Time - Bus | 226.18 | 70.4 | 330.04 | 129.05 | sec/km |
| Travel Time - Light Rail | | | 154.45 | 17.75 | sec/km |

Total Travel Time for all vehicles decreased from 1145.82 hours to 1011.49 hours, a net saving of 134.33 hours. Considering the new minimum wage of $19.49 an hour, this improved productivity time translates to $2,618 saved in our focus network for the hour.

Travel Time savings can be further analysed by subtracting the TTT Matrix (from Path Assignment Outputs) of the Base model, with the TTT of the new light rail model shown by Figure 9.2.2

**Figure 9.2.2** *Travel Time Savings Matrix (units unspecified by AIMSUN's manual)*

| O/D | 1 | 2 | 3 | 4 | 5 | 6 | 7 | total |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | -19 | -4 | -164 | -205 | -316 | 17 | -691 |
| 2 | -25 | 0 | -125 | -50 | -41 | -177 | -60 | -478 |
| 3 | 10 | -31 | 0 | -141 | 44 | -33 | -29 | -180 |
| 4 | -196 | 63 | -65 | 0 | 10 | -157 | 92 | -253 |
| 5 | -23 | 281 | 158 | -212 | 0 | 10 | 341 | 555 |
| 6 | -1 | -101 | -95 | -52 | -93 | 0 | -81 | -423 |
| 7 | -165 | -110 | -43 | -198 | -127 | -217 | 0 | -860 |
| total | -400 | 83 | -174 | -817 | -412 | -890 | 280 | -2330 |

*(negative means improvements, while positive values indicate increased travel times)*

There is a total 2330 units of Travel Time improvement across the entire network, indicating that the implementation of the LRT has indeed improved traffic conditions overall.
Most notably, there are savings in travel times across all trips towards Centroid 4, indicating great effectiveness in improving traffic conditions for commuters travelling to the CBD through Anzac Parade and Allison Road for a total of 817 saved units from all other Centroids. A surprising result was trips originating from Centroid 2 having much less improvements than those that originate from Centroid 7 (-50 vs –198), despite both centroids being right next to each other. This indicates that there was previous trouble for commuters from Centroid 7, trying to turn left into Anzac Parade which has now been helped with the new road conditions and traffic signal changes.
The areas with the most increased travel times were trips which originated from Centroid 5, travelling to Centroids 2, 3, and 7. This may be due to difficulty in turning right onto Anzac Parade. This is reflected in an increase in Simulated Delay Time in Todman Avenue from 249 to 395 units.

It is definitive that there are overall huge savings in Travel Time with the implementation of the LRT, however some traffic intersection signals may be better optimised to avoid huge increases in travel times in some areas.

## 9.3 Emissions Assessment

Subtracting the emissions outputs of the LRT implemented model to the base model yields:

**Table 9.3.1:** *Comparison of output emissions.*

| Time Series | Base Model | LRT Implemented | Difference | Units |
|---|---|---|---|---|
| | Value | Value | | |
| **Fuel Consumption - All** | 3807.77 | 3095.42 | -712.35 | l |
| **Fuel Consumption - Car** | 3410.32 | 2873.96 | -536.36 | l |
| **Fuel Consumption - Bus** | 397.45 | 221.46 | -175.99 | l |
| **Fuel Consumption - Light Rail** | N/A | 0 | | l |
| **IEM Emission - CO2 - All** | 8,229,742.82 | 6,993,881.39 | -1,235,861.43 | g |
| **IEM Emission - CO2 - Interurban - All** | 299,617.33 | 194,535.75 | -105,081.58 | g/km |
| **IEM Emission - NOx - All** | 19,486.17 | 14,276.75 | -5,209.42 | g |
| **IEM Emission - NOx - Interurban - All** | 709.43 | 397.11 | -312.32 | g/km |
| **IEM Emission - PM - All** | 2,132.44 | 1,771.75 | -360.69 | g |
| **IEM Emission - PM - Interurban - All** | 77.64 | 49.28 | -28.36 | g/km |
| **IEM Emission - VOC - All** | 14,428.95 | 13,236.03 | -1,192.92 | g |
| **IEM Emission - VOC - Interurban - All** | 525.31 | 368.16 | -157.15 | g/km |
| **IEM Emission - CO2 - Car** | 7,378,621.51 | 6,555,454.93 | -823,166.58 | g |
| **IEM Emission - CO2 - Interurban - Car** | 268,630.86 | 182,340.86 | -86,290.00 | g/km |
| **IEM Emission - NOx - Car** | 12,029.82 | 10,539.97 | -1,489.85 | g |
| **IEM Emission - NOx - Interurban - Car** | 437.97 | 293.17 | -144.80 | g/km |
| **IEM Emission - PM - Car** | 1,907.11 | 1,643.61 | -263.50 | g |
| **IEM Emission - PM - Interurban - Car** | 69.43 | 45.72 | -23.71 | g/km |
| **IEM Emission - VOC - Car** | 13,864.99 | 12,907.72 | -957.27 | g |

| | | | | |
|---|---|---|---|---|
| **IEM Emission - VOC - Interurban - Car** | 504.78 | 359.03 | -145.75 | g/km |
| **IEM Emission - CO2 - Bus** | 851,121.31 | 407,336.51 | -443,784.80 | g |
| **IEM Emission - CO2 - Interurban - Bus** | 30,986.47 | 11,330.12 | -19,656.35 | g/km |
| **IEM Emission - NOx - Bus** | 7,456.35 | 3,682.82 | -3,773.53 | g |
| **IEM Emission - NOx - Interurban - Bus** | 271.46 | 102.44 | -169.02 | g/km |
| **IEM Emission - PM - Bus** | 225.33 | 120.04 | -105.29 | g |
| **IEM Emission - PM - Interurban - Bus** | 8.20 | 3.34 | -4.86 | g/km |
| **IEM Emission - VOC - Bus** | 563.96 | 271.85 | -292.11 | g |
| **IEM Emission - VOC - Interurban - Bus** | 20.53 | 7.56 | -12.97 | g/km |
| **IEM Emission - Light Rail - CO2** | | 31089.95 | | g |

(LRT emissions should be 0 due to the use of electric motors- however there was an error in the AIMSUN model which had the LRT produce emissions, however these do not greatly impact the overall differences.)

Over the hour, there is an overall in all categories of emissions, most notably:
decrease in total fuel consumption by 712.35 litres and decrease in total CO2 emissions of 1.236 tonnes. The monetary benefits of which, will be further discussed in Costs and Benefits.

## 9.4 Costs and Benefits

Light rails deliver an appropriate option to increase mobility in the CBD as it provides an alternative between bus routes and trains. It is powered by electricity and provides a more sustainable mode of transport which in response will decrease the amount of pollution released into the environment. The shift to construct and operate the light rail were determined through multiple factors which include economic, financial, social and environmental impacts, that provide a positive outcome to justify the investment.

*Capital and operational cost*

The operating cost is considers all construction cost, delivery, project management, property acquisition, risk and contingency and escalation costs. It is expected the construction of CSELR will cost $1.6 billion where some funds were provided from the government and some private sector investors.

To determine the future usage of the light rail, a Public Transport Project Model was preformed which considered the employment, land-use patterns, parking availability, transport plans and forecast population. It was predicted that 17,900 customers will board during morning peak hour and 31.4 million trips annually in 2021 will grow to 39.6 million trips annually in 2036. With this demand expecting to increase it will attract 17% of car users which will reduce the amount of vehicles on the road and help with the reduction of congestion.

*Economic benefits*

With the project costing approximately $1.6 billion, it is expected that over 30 years there will be $4 billion worth in benefits. This equates to $2.50 worth of benefits per dollar invested. The benefits result in a faster, comfortable and reliable journey. The light rail is expected to provide

$264 million operational savings through decongestion, $333 million for pedestrians in journey time savings and amenity, $707 million in public transport operational savings through reduced bus operating costs and $308 million worth in environmental savings through the reduction of air and noise pollution.

*Social benefits*

Light rails will improve the connection between individuals and recreational locations. It will increase livability and amenity by attracting business to grow along the routes. Through this an increase in healthy behaviours such as walking by lowering car usage could result in a reduction in obesity. Light rails could also be a key aspect to attract tourists as well as commuters and residents. Light rails are perceived to be more reliable and easier to navigate as it follows a fixed path that is highly visible compared to buses that could follow multiple routes. By improving the city's public transportation a higher consumer satisfaction can be made enhancing the city reputation amongst travelers. For example, Melbourne is known for their tram system where tourists travel to experience this form of public transportation.

*Environmental benefits*

Light rails are an energy-efficient and sustainable form of transportation. Since electricity is generated at a location further away, at more efficient power plants, there is a decrease of greenhouse gas emission in the city, increasing its overall sustainability. The reduction of greenhouse gases over 30 years is estimated to be 700,000 tonnes of $CO_2$.

From table 9.3.1, there is total 1.2 million grams reduction in $CO_2$ emission after the light rail was implemented in our model. Approximately 77% of this reduction is due to the decrease in cars and 23% due to buses. The total number of $CO_2$ emission for cars in the base model is 7.4 million grams but once the light rail transit is implemented it will reduce by 820,000 to 6.6million grams of emission. Bus emission will be smaller compared to the car emission of $CO_2$, where 850,000g will decrease to 410,000g after the light rail. The social cost of carbon pollution was estimated as $37 per ton of CO2 by the Obama administration in 2013- however, the global economic cost of carbon emissions is researched to be closer to $200 per tonne, due to global warming slowing economic growth (Nuccitelli, 2018). Thus, for the morning peak hour, our model produced a monetary benefit of $247 in social costs.

However, referring to **Table 3.5** (in Datasets and Usage) an alternative cost may be calculated:

**Table 9.4.1**: *Cost of Emissions, referring to* **Table 3.5 & Table 9.3.1**

| **Pollutant** | **Amount Reduced in Model (tonnes)** | **Value of emissions $/tonne** | **Reduced Emissions Costs ($)** |
|---|---|---|---|
| Carbon Dioxide (CO2) | 1.236 | 52.40 | 64.77 |
| Oxides of Nitrogen (Nox) | 0.005209 | 2,089.20 | 10.88 |
| Particulate Matter (PM10) | 0.000361 | 332,505.90 | 120.03 |

| | | | |
|---|---|---|---|
| | | Total: | 195.68 |

Fuel consumption for both bus and cars will also decline by 712 litres. Assuming an average fuel price of ~$1.50/litre *(NRMA, 2019*)- this is a monetary benefit of $1,068 regarding petrol consumption. Electricity can be generated from renewable sources; hence no fossil fuels will be used to power the light rail transit in the future, which will benefit the overall carbon footprint

*Operational cost of Light rail and Bus*

When measuring between the light rail and busses, it is essential to compare the cost of running both transport mode over the next few years. To obtain the cost, many assumptions and considerations were accounted for. General assumptions were that the supply and demand of both travel modes remained constant, the inflation rate is assumed to be 3% - as it has been the average of the past 10 years and that data has been collected only for peak hours of the assigned area.

To find the monetary cost of running busses during peak hour, the amount of fuel per liter consumed was obtained by running a simulation via AIMSUN. The results shown that busses in the network uses roughly 400 liters of fuel during peak hour. This data was multiplied by the average price of diesel per dollar for 2018. To find the cost for the next few years, diesel prices were extrapolated by considering inflation of 3% as assumed. However, due to the scarcity nature of diesel, 1.5% was added on to the inflation rate – the value is low to be conservative.

Likewise, the monetary value of light rail was found via similar approach; however, due the confidentiality, the energy required for Alstom Citadis X05 was calculated using information provided by Alstom. It was stated that their model uses ten times less energy than a car per KWh per seated passenger. By considering that an average car uses 17.4 KWh/100km, simple calculation was used to find the energy of the model travelling in the assigned area. It was first converted to per kilometers then divided by ten (converting efficiency of car to light rail), then multiplied by 450 (the number of passengers that Alstom Citadis X05 can carry). This value is then multiplied by 5.4km (the length of the light rail in the system), giving a value of 42KWh/5.4km. As stated, the frequency of light rail during peak hour is every 4 minutes, hence there will be 15 light rails per line (Randwick line and Kingsford line), making it 30 light rails in the system; giving us a total of 1266KWh/5.4km. This value is then multiplied by the cost of electricity in 2018 with a 3% inflation. It is assumed that the cost of electricity per KWh will remain the same due to improvements of electricity generation.

As a result, the light rail is better in terms of operation cost the difference against bus operation will increase due to the scarcity of diesels. This demonstrated in Table 9.1.2.1 and Appendix 4.

**Table 9.1.2.1**: A snapshot of the operational cost during peak hour

| Cost during morning peak hour | 2018 | 2025 | 2035 |
|---|---|---|---|
| Bus | $534 | $726 | $1,128 |

| | | | |
|---|---|---|---|
| Light Rail | $196 | $240 | $323 |

## Conclusion and Recommendations

Comparison of the AIMSUN LRT model with the base model has successfully evaluated the impact of the proposed light rail network that runs through Anzac Parade and Allison Road.

The change upgraded the existing network by increasing the flow capacity of both roads while improving the community's access to public transport which resulted in overall increased flow and less congestion, as intended. This is reflected in the output matrices such as the Total Travel Time and Emissions where there were vast improvements to the system throughout.
These then led to overall economic improvements which may offset the initial cost of the rather expensive implementation of the LRT.

Overall, this report highly recommends and supports the NSW Government's plans for the construction of the LRT on not only the focus network around Randwick and Kinsgord, but encourage it throughout Sydney as well when feasible.

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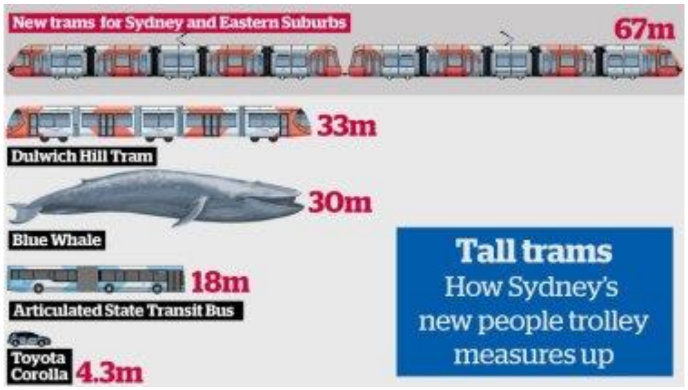
## Appendix:

**Appendix 1:** *Light rail visualisation*



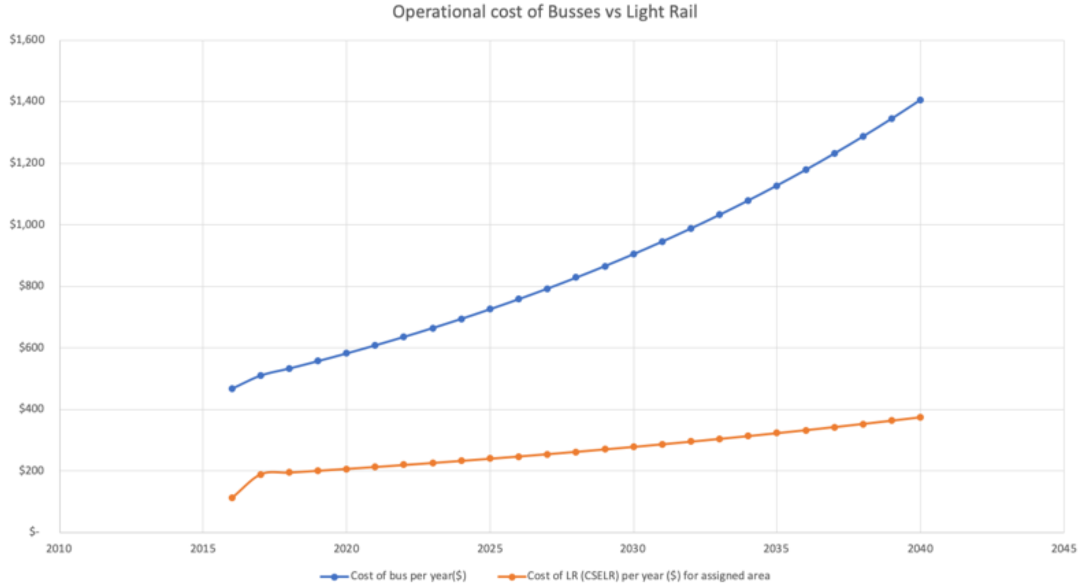

**Appendix 2:** Official proposed changes to bus routes (Transport for NSW, 2013)

| Route Number | Old Route | New Route |
|---|---|---|
| **372** | Coogee-Railway Square via Cleveland Street | Coogee-Railway Square via Cleveland Street, through-routed with 412/413 to align with the city centre bus network redesign |
| **373** | Coogee-Circular Quay via Oxford Street | Route cancelled |
| **374** | Coogee-Circular Quay via Foveaux Street | Operates existing route to Anzac Parade, then travels to Edgecliff via Darlinghurst Road and William Street (subject to detailed implementation planning on routing) |
| **375** | N/A | New service operating Maroubra Beach-Sydney University via Randwick Junction, High Street and Todman Avenue |
| **376** | Maroubra Beach-Circular Quay via Marine Parade, Alison Road and Foveaux Street | Route cancelled, replaced with 375 |
| **377** | Maroubra Beach-Circular Quay via Marine Parade, Alison Road and Oxford Street | Operates existing route to Alison Road via Belmore Road and terminates |
| **395/396** | Maroubra Beach-City via Maroubra Junction and Anzac Parade | Routes cancelled, to be replaced with extended Route 343 |
| **343** | Kingsford-City via Gardeners Road and Elizabeth Street | Route extended to operate to/from Maroubra Beach along old 395/396 alignment |
| **397** | South Maroubra-City via Anzac Parade | Operates existing route to Kingsford interchange, then Gardeners Road to Sydenham via Mascot/Sydney Airport |
| **M10** | Metrobus route between Maroubra Junction and Leichhardt | No longer operates in the eastern suburbs to align with the city centre bus network redesign |
| **M50** | Metrobus route between Drummoyne and Coogee | No longer operates in the eastern suburbs to align with the city centre bus network redesign |
| **391** | La Perouse-City via Bunnerong Road and Anzac Parade | Operates existing route to Todman Avenue, Kensington and terminates |
| **392** | Little Bay-City via Anzac Parade | Operates existing route to Todman Avenue, Kensington and terminates |
| **393** | La Perouse-City via Bunnerong Road and Anzac Parade | Operates existing route to Todman Avenue, Kensington and terminates |
| **394** | La Perouse-City via Bunnerong Road and Anzac Parade | Operates existing route to Todman Avenue, Kensington and terminates |
| **399** | Little Bay-City via Anzac Parade | Operates existing route to Todman Avenue, Kensington and terminates |
| **L94** | La Perouse-City via Bunnerong Road and Anzac Parade | Operates existing route to Anzac Parade, then travels to Edgecliff via Darlinghurst Road and William Street (subject to detailed implementation planning on routing) |

**Appendix 3:** Population and occupation data in the surrounding suburbs from the 2016 census (Australian Bureau of Statistics, 2019)

| Suburb | Population | Occupation Proportion (%) | | |
|---|---|---|---|---|
| | | Professionals | Managers | Clerical and Admin |
| Sydney | 17,252 | 27.1 | 14.4 | 8.9 |
| Darlinghurst | 11,320 | 42.3 | 19.5 | 10.6 |
| Kensington | 15,004 | 15.2 | 12.4 | 13 |
| Zetland | 10,076 | 36.1 | 18.5 | 12.6 |
| Waterloo | 14,616 | 36.8 | 17.3 | 11.5 |
| Randwick | 29,986 | 39.2 | 16.1 | 12.6 |
| Bronte | 6,733 | 40.3 | 21.2 | 11.5 |
| Coogee | 15,212 | 40.5 | 17.5 | 12.1 |
| Kingsford | 15,482 | 33.8 | 11.4 | 13.6 |
| Pagewood - Hillsdate - Daceyville | 11,373 | 20.8 | 11.8 | 15 |
| Rosebery | 10,117 | 14.5 | 14.5 | 15.1 |

**Appendix 4:** A graph displaying operation cost of light rail against bus




**Appx 7: Calculations for ODM adjustment**
Former Cars/ Former Bus = 30/70.

Assuming all current bus passengers switch to the LRT system, in Sydney, *20.9%* of trips for work are accounted by public transport in 2016 *(O'Sullivan, 2017)*.
*100-20.9 = 79.1%* trips are taken by cars. (assume cyclists and walkers are negligible)

From the Project Brief Addendum, there were originally 12,765 total trips in the ODM.
(Total Trips taken by bus) / (Total Trips taken by cars) = Tb /12,765 = 20.9%/79.1%

Therefore: Tb = Trips taken by bus = 3372.8 = 3373 trips
Assume all 3373 passengers transfer to LRT.

LRT 30:70 split yields: Pc/Pb = 30/70 (P are converted LRT passengers from cars or buses)
Passengers converted from cars = Pc = 3373*30 /70 = 1445.57 = **1446** trips converted from cars.
Percentage of converted passengers to total trips: 1446/12765 = 11.328%

From the ABS statistics, an increased weighting of 40% shall be applied to column 4 of the ODM's trip subtractions, which represents inbound traffic to the city. This means more of the 1446 car commuters whom convert to using the LRT come from column 4 of the ODM.

The resulting subtraction ODM is then multiplied by 1446/1627.93 to normalise the total back to 1446 total car travelers being subtracted. Finally, subtracting the Base Model ODM to this matrix yields the final adjusted ODM in Figure 6.2.1.

**Appx 8:** *Outputs generated from AMISUN for **base model** testing*

| Intersection | Intersecting roads | Average delay time (sec/km) | Maximum delay time (sec/km) | Average queue length (vehicles) | Maximum queue length (vehicles) |
|---|---|---|---|---|---|
| 1 | Anzac Parade (A), Dacey Avenue (B), Alison Road (C) | A (Outbound): 28<br>A (Inbound): 45<br>B to C (Outbound): 101<br>C to B (Inbound): 119 | A (Outbound): 31 (8-8:10am)<br>A (Inbound): 71 (8-8:10am)<br>B - C (Outbound): 207 (8:10-8:20am)<br>C - B (Inbound): 115 (8:50-9am) | A (Outbound): 8<br>A (Inbound): 7<br>B - C (Outbound): 12<br>C - B (Inbound): 34 | A (Outbound): 9 (8-8:10am)<br>A (Inbound): 12 (8-8:10am)<br>B - C (Outbound): 17 (8:10-8:20am)<br>C - B (Inbound): 46 (8:50-9am) |
| 2 | Anzac Parade (A), Todman Avenue (D) | A (Outbound): 21<br>A (Inbound): 40<br>D (Outbound): 148<br>D (Inbound): 28 | A (Outbound): 23 (8:50-9am)<br>A (Inbound): 70 (8:00-8:10am)<br>D (Outbound): 249 (8:50-9am)<br>D (Inbound): 33 (8:50-9am) | A (Outbound): 10<br>A (Inbound): 12<br>D (Outbound): 15<br>D (Inbound): 2 | A (Outbound): 11 (8:20-8:30am)<br>A (Inbound): 23 (8:00-8:10am)<br>D (Outbound): 22 (8:50-9am)<br>D (Inbound): 2 (8:50-9am) |
| 3 | Anzac Parade (A), Doncaster Avenue (E) | A (Outbound): 55<br>A (Inbound): 122<br>E (Outbound): 46<br>E (Inbound): 568 | A (Outbound): 65 (8:20-8:30am)<br>A (Inbound): 190 (8:10-8:20am)<br>E (Outbound): 55 (8:50-9am)<br>E (Inbound): 779 (8:40-8:50am) | A (Outbound): 19<br>A (Inbound): 18<br>E (Outbound): 10<br>E (Inbound): 44 | A (Outbound): 20 (8:20-8:30am)<br>A (Inbound): 18 (8:10-8:20am)<br>E (Outbound): 15 (8:50-9am)<br>E (Inbound): 50 (8:40-8:50am) |
| 4 | Anzac Parade (A), Barker Street (F) | A (Outbound): 40<br>A (Inbound): 149<br>F (Outbound): 100<br>F (Inbound): 56 | A (Outbound): 51 (8:00-8:10am)<br>A (Inbound): 223 (8:30-8:40am)<br>F (Outbound): 198 (8:50-9am)<br>F (Inbound): 69 (8:50-9am) | A (Outbound): 15<br>A (Inbound): 21<br>F (Outbound): 26<br>F (Inbound): 9 | A (Outbound): 16 (8-8:10am)<br>A (Inbound): 22 (8:30-8:40am)<br>F (Outbound): 35 (8:50-9am)<br>F (Inbound): 11 (8:50-9am) |
| 5 | Botany Street (G), High Street (H) | G (Outbound): 20<br>G (Inbound): 27<br>H (Outbound): 98<br>H (Inbound): 42 | G (Outbound): 30 (8:50-9am)<br>G (Inbound): 40 (8:40-8:50am)<br>H (Outbound): 239 (8:50-9am)<br>H (Inbound): 117 (8:50-9am) | G (Outbound): 4<br>G (Inbound): 7<br>H (Outbound): 8<br>H (Inbound): 4 | G (Outbound): 7 (8:50-9am)<br>G (Inbound): 12 (8:40-8:50am)<br>H (Outbound): 12 (8:50-9am)<br>H (Inbound): 8 (8:50-9am) |
| 6 | Alison Road (C), Botany Street (G) | C (Outbound): 25<br>C (Inbound): 20 | C (Outbound): 52 (8:10-8:20am) | C (Outbound): 10<br>C (Inbound): 6 | C (Outbound): 16 (8:10-8:20am) |

| | | | | | |
|---|---|---|---|---|---|
| | | G (In/Outbound): 85 | C (Inbound): 32 (8:30-8:40am)<br>G (Outbound): 229 (8:50-9am) | G (Outbound): 13 | C (Inbound): 6 (8-9am)<br>G (Outbound): 26 (8:50-9am) |

**Appx 9:** *Outputs generated from AMISUN for* ***scenario*** *testing*

| Intersection | Intersecting roads | Average delay time (sec/km) | Maximum delay time (sec/km) | Average queue length (vehicles) | Maximum queue length (vehicles) |
|---|---|---|---|---|---|
| 1 | Anzac Parade (A), Dacey Avenue (B), Alison Road (C) | A (Outbound): 53<br>A (Inbound): 41<br>B to C (Outbound): 78<br>C to B (Inbound): 154 | A (Outbound): 62 (8:00-8:10am)<br>A (Inbound): 51 (8:00-8:10am)<br>B - C (Outbound): 104 (8:20-8:30am)<br>C - B (Inbound): 273 (8:50-9am) | A (Outbound): 12<br>A (Inbound): 10<br>B - C (Outbound): 13<br>C - B (Inbound): 36 | A (Outbound): 14 (8-8:10am)<br>A (Inbound): 12 (8:20-8:30am)<br>B - C (Outbound): 19 (8:20-8:30am)<br>C - B (Inbound): 50 (8:40-8:50am) |
| 2 | Anzac Parade (A), Todman Avenue (D) | A (Outbound): 114<br>A (Inbound): 72<br>D (Outbound): 234<br>D (Inbound): 29 | A (Outbound): 187 (8:40-8:50am)<br>A (Inbound): 126 (8:00-8:10am)<br>D (Outbound): 491 (8:50-9am)<br>D (Inbound): 33 (8:50-9am) | A (Outbound): 21<br>A (Inbound): 23<br>D (Outbound): 12<br>D (Inbound): 1 | A (Outbound): 24 (8:40-8:50am)<br>A (Inbound): 35 (8:00-8:10am)<br>D (Outbound): 23 (8:50-9am)<br>D (Inbound): 3 (8:50-9am) |
| 3 | Todman Avenue (D), Doncaster Avenue (E) | D (Outbound): 143<br>E (Outbound): 69<br>E (Inbound): 14 | D (Outbound): 285 (8:40-8:50am)<br>E (Outbound): 167 (8:50-9am)<br>E (Inbound): 25 (8:30-8:40am) | D(Outbound): 21<br>E (Outbound): 9<br>E (Inbound): 3 | D (Outbound): 31 (8:40-8:50am)<br>E (Outbound): 21 (8:50-9am)<br>E (Inbound): 4 (8:40-8:50am) |
| 4 | Anzac Parade (A), Doncaster Avenue (E) | A (Outbound): 46<br>A (Inbound): 46<br>E (Outbound): 129<br>E (Inbound): 346 | A (Outbound): 81 (8:10-8:20am)<br>A (Inbound): 108 (8:10-8:20am)<br>E (Outbound): 204 (8:40-8:50am)<br>E (Inbound): 1061 (8:50-9am) | A (Outbound): 118<br>A (Inbound): 21<br>E (Outbound): 20<br>E (Inbound): 27 | A (Outbound): 27 (8:00-8:10am)<br>A (Inbound): 34 (8:10-8:20am)<br>E (Outbound): 29 (8:30-8:40am)<br>E (Inbound): 49 (8:50-9am) |
| 5 | Anzac Parade (A), Barker Street (F) | A (Outbound): 37<br>A (Inbound): 180<br>F (Outbound): 52<br>F (Inbound): 89 | A (Outbound): 49 (8:00-8:10am)<br>A (Inbound): 240 (8:30-8:40am)<br>F (Outbound): 62 (8:20-8:30am)<br>F (Inbound): 310 (8:50-9am) | A (Outbound): 15<br>A (Inbound): 28<br>F (Outbound): 7<br>F (Inbound): 21 | A (Outbound): 21 (8-8:10am)<br>A (Inbound): 29 (8:50-9am)<br>F (Outbound): 8 (8:30-8:40am)<br>F (Inbound): 57 (8:50-9am) |
| 6 | Alison Road (C), Botany Street (G) | C (Outbound): 69<br>C (Inbound): 15<br>G (In/Outbound): 46 | C (Outbound): 130 (8:40-8:50am)<br>C (Inbound): 17 (8-8:10am) | C (Outbound): 13<br>C (Inbound): 6<br>G (Outbound): 10 | C (Outbound): 18 (8:40-8:50am)<br>C (Inbound): 6 (8-9am) |

| | | | | | |
|---|---|---|---|---|---|
| | | | G (Outbound): 63 (8:30-8:40am) | | G (Outbound): 13 (8:40-8:50am) |

The intersections tabulated in Appendix 8 have been deemed the most critical in the system. They have been considered as critical for one of the two reasons:

- The delay time and queue length associated with this intersection is tremendously large, compared to other intersections in the system.
- The intersection has caused some kind of traffic wave or disturbance in the traffic flow system, which has caused additional delay times and queue lengths for other parts of the network.