University of Southern Queensland

Faculty of Engineering and Surveying

# Evaluation of the operational characteristics of heavy vehicles at signalised intersections in Queensland

A dissertation submitted by

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**Courses ENG4111 and 4112 Research Project**

towards the degree of

**Bachelor of Engineering (Civil)**

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# Abstract

Heavy vehicles are known to have a negative impact on roadway capacity. This can be attributed to the size of the vehicle and the operational characteristics such as acceleration, deceleration, and manoeuvrability. The impact on roadway capacity is exaggerated at intersections where the heavy vehicles are forced to stop and accelerate back up to operating speed.

Traditional traffic modelling often relies on an assumption of having a homogenous traffic flow. Effects of non-standard vehicles, such as trucks and buses or even bicycles are accounted for by assuming they are equivalent to a fixed number of 'standard' passenger cars. A factor known as a passenger car equivalent is applied to the number of heavy vehicles in the traffic stream to convert the mixed traffic volume to an equivalent flow of cars. The equivalent flow of cars can then be used to undertake roadway capacity analysis.

This project has developed passenger car equivalent values at signalised intersections for the types of heavy vehicles in use on Queensland roads. The values derived for each of the vehicle types analysed have been developed using a MATLAB model that simulates traffic flow through a signalised intersection. The values obtained have been determined for varying roadway and traffic conditions to provide a reference when undertaking traffic modelling at signalised intersections.

Recommendations for areas of future research have also been given. This project has been shown to lead to a number of areas where more in-depth analysis could provide greater insight into the behaviour of heavy vehicles on the roadway.

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# ENG4111 Research Project Part 1 & ENG4112 Research Project Part 2

## Limitations of Use



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# CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature

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Date

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# Table of Contents

# List of Figures

# List of Tables

# 1.0 Introduction

## *1.1 Background*

In Queensland there is approximately 33400km of state controlled roads which are owned and maintained by the Queensland government. It is the responsibility of the 73 local government areas to maintain the remainder of the road network.

Roads have an important role in contributing to the local and national economy by allowing passenger and freight movements over large distances. Queensland's growing population and economy have seen large increases in the number of vehicles that use the roadway. The increase in traffic has led to congestion on major road links with effects such as slower travelling speeds, longer trip times and increased queuing and delays experienced by motorists. It is predicted that by 2020 the avoidable congestion in Australian cities will cost in excess of $20 billion (BTRE, 2007).

Traffic on Queensland roads (both urban and rural) consists of a variety of vehicles ranging in size from bicycles to articulated trucks. These vehicles have widely different performance characteristics which will impact on the capacity of the roadway. Despite being a small proportion of the overall traffic flow heavy vehicles are known to cause significant impacts on the traffic flow. This impact is exaggerated at interrupted flow facilities such as traffic signals where the heavy vehicles have to stop and accelerate back up to the operating speed.

The capacity of a segment of roadway is expressed in passenger cars per hour. This is the maximum number of vehicles that can pass a point on the road based on the roadway and traffic conditions. The effect of vehicles on roadway capacity can be described using a factor known as a passenger car equivalent. Passenger car equivalents are used to convert the mixed traffic volume to an equivalent flow of cars which can then be used in roadway capacity analysis. To ensure the roadway operates efficiently it is important that the effect each vehicle has on capacity is accurately accounted for.

## *1.2 Project Aim*

The aim of this project is to investigate the impact heavy vehicles have on signalised intersection capacity.

To achieve this, the following objectives have been developed:

a. Investigate the operational characteristics of heavy vehicles in use on Queensland roads.
b. Investigate the operation of traffic signals and the impact that they have on the roadway capacity.
c. Using the research conducted into heavy vehicle operation and traffic signal capacity develop a MATLAB model that calculates the effect of heavy vehicles on intersection capacity.
d. Develop a set of passenger car equivalent values that can be used as a reference when undertaking intersection capacity analysis
e. Verify the values derived from the MATLAB model from observations of traffic flow at signalised intersections.

# 2.0 Literature Review

## *2.1 Heavy Vehicles in Queensland*

Improvements in road transport productivity and road infrastructure quality have resulted in the road network being increasingly used to transport freight between towns over more traditional methods such as rail transport.

The population and economic growth currently being experienced within South-East Queensland (SEQ) is expected to increase freight movements significantly. The forecast freight movements in South-East Queensland are shown in Table 2.1.

Table 2.1: Forecast Freight Movements in South-East Queensland

| Economic Activity | SEQ Freight Flows (Mt) | |
|---|---|---|
| | 2003 | 2026 (base case) |
| SEQ Production | 45 | 80 |
| SEQ Household Consumption | 15 | 41 |
| Locally-sourced SEQ Household Consumption | 7 | 12 |
| Non-SEQ-sourced SEQ Household Consumption | 8 | 29 |
| SEQ Industrial Consumption | 33 | 66 |
| Locally-sourced SEQ Industrial Consumption | 18 | 36 |
| Non-SEQ-sourced SEQ Industrial Consumption | 15 | 30 |
| Surplus SEQ production to outside SEQ | 20 | 32 |
| Outside SEQ production to SEQ consumption | 23 | 59 |
| Transit Freight Flows | 6 | 14 |

Source: Queensland Transport, 2009

The forecast freight movements show that over the 23 year period analysed freight movements are expected to increase between 60% for surplus SEQ production and 173% for SEQ household consumption. This would result in a 110% overall increase in freight movements within South East Queensland.

### 2.1.1 Heavy Vehicle Classification

The vehicles allowed on Australian roads are restricted to ensure safety to road users and preservation of the road asset. To ensure that vehicles maintain performance and safety standards government regulations are imposed. "The characteristics of the current heavy vehicle fleet are regulated by a set of mass and dimensional regulations, Australian Design Rules (ADRs) and Australian Vehicle Standards Regulations (AVSR)" (Austroads, 2002).

Vehicle classification allows road authorities to restrict access to roads based on mass, dimensional limits and the suitability of the road to safely carry the vehicle. The vehicles in use on Australian roads have been categorised into 12 vehicle classes based on axle configuration and spacing by Austroads. Table 2.2 defines each of the 12 Austroads vehicle classes.

Table 2.2: Austroads Vehicle Classification

| Level 1 | Level 2 | | Level 3 | Austroads classification | |
|---|---|---|---|---|---|
| Length (indicative) | Axles and axle groups | | Vehicle type | | |
| Type | Axles | Groups | Description | Class | Parameters |
| | LIGHT VEHICLES | | | | |
| Short<br>Up to 5.5 m | 2 | 1 or 2 | Short<br>Sedan, wagon, 4WD, utility, light van, bicycle, motorcycle, etc. | 1 | $d_1 \leq 3.2$ m<br>and axles = 2 |
| Medium<br>5.5 m to 14.5 m | 3, 4 or 5 | 3 | Short – towing<br>trailer, caravan, boat, etc. | 2 | groups = 3,<br>$2.1 \text{ m} \leq d_1 \leq 3.2$ m<br>$d_2 \geq 2.1$ m,<br>and axles = 3, 4 or 5 |
| | HEAVY VEHICLES | | | | |
| | 2 | 2 | Two axle truck or bus | 3 | $d_1 > 3.2$ m<br>and axles = 2 |
| | 3 | 2 | Three axle truck or bus | 4 | axles = 3<br>and groups = 2 |
| | > 3 | 2 | Four axle truck | 5 | axles > 3<br>and groups = 2 |
| Long<br>11.5 m to 19.0 m | 3 | 3 | Three axle articulated or rigid vehicle and trailer | 6 | $d_1 > 3.2$ m,<br>axles = 3 and groups = 3 |
| | 4 | > 2 | Four axle articulated or rigid vehicle and trailer | 7 | $d_2 < 2.1$ m,<br>or $d_1 < 2.1$ or $d_1 > 3.2$ m<br>axles = 4 and groups > 2 |
| | 5 | > 2 | Five axle articulated or rigid vehicle and trailer | 8 | $d_2 < 2.1$ m,<br>or $d_1 < 2.1$ or $d_1 > 3.2$ m<br>axles = 5 and groups > 2 |
| | 6<br>> 6 | > 2<br>3 | Six axle (or more) articulated or rigid vehicle and trailer | 9 | axles = 6 and groups > 2; or<br>axles > 6 and groups = 3 |
| Medium combination<br>17.5 m to 36.5 m | > 6 | 4 | B Double or<br>heavy truck and trailer | 10 | axles > 6<br>and groups = 4 |
| | > 6 | 5 or 6 | Double road train or<br>heavy truck and two trailers | 11 | axles > 6<br>and groups = 5 or 6 |
| Long combination<br>over 33 m | > 6 | > 6 | Triple road train or<br>heavy truck and three trailers | 12 | axles > 6<br>and groups > 6 |

Source: Austroads, 2009

To determine the operational characteristics of heavy vehicles at signalised intersections the vehicle classifications developed by Austroads will be grouped into vehicles with similar size, mass, trailer configuration and performance characteristics. The groupings determined for this project are as follows:

- Austroads Classes 6 – 9
- Austroads Class 10
- Austroads Class 11
- Austroads Class 12

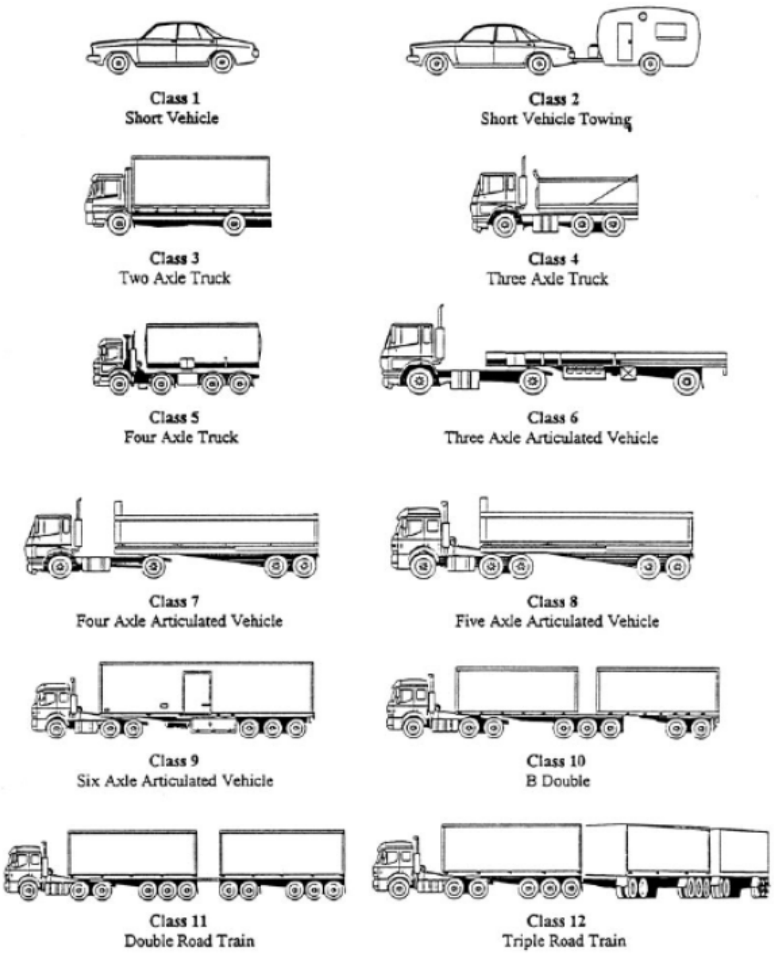



Figure 2.1: Austroads Representative Vehicles
(Source: Austroads, 2009)

### 2.1.2 Heavy Vehicle Performance

The heavy vehicle performance characteristics that will influence capacity at traffic signals are as follows:

Heavy vehicle length

The length of heavy vehicles is considerably larger than that of passenger cars. The length of each vehicle will have a negative impact on the queue length at the intersection and vehicle headway. The vehicle lengths of the representative Austroads classes chosen for this project are defined by QDMR (2004) as follows:

- Austroads Classes 6 – 9 (19m)
- Austroads Class 10 (25m)
- Austroads Class 11 (36m)
- Austroads Class 12 (53m)

Heavy vehicle acceleration

The acceleration of heavy vehicles will impact on the time it takes for the individual vehicle to clear the intersection. Slow intersection clearance times will significantly reduce the signalised intersection capacity. There are many different models for heavy vehicle acceleration developed based on empirical data and mechanistic relationships. These models range in complexity from simple relationships based on observed data to models that have been developed for individual engine and transmission configurations. As this project determines the average impact on roadway capacity for each vehicle classification, a model representative of all the vehicles in each class has been chosen.

The following models based on empirical data (Bunker and Haldane, 2003) and mechanistic relationships (McLean, 1989) have been determined to be representative of vehicles in each classification.

Bunker and Haldane (2003) define the acceleration of multi-combination vehicles by the following equation:

$$a = Ct + a_0 \qquad [2.1]$$

Where:

$a$ = Acceleration of the multi combination vehicle at time (m/s$^2$)

$a_0$ = Initial acceleration rate of the vehicle (m/s$^2$)

$C$ = A constant derived from field tests

The values for C and $a_0$ that have been derived by Bunker and Haldane (2003) for each of the vehicle types analysed is shown in Table 2.3.

Table 2.3: Empirical Heavy Vehicle Acceleration Data

| Vehicle | C | $a_0$ |
|---|---|---|
| -5% Grade | | |
| B-Double | -0.0373 | 1.06 |
| A-Double | -0.0252 | 0.93 |
| A-Triple | -0.0263 | 0.894 |
| AAB-Quad | -0.0228 | 0.798 |
| -2% Grade | | |
| B-Double | -0.0285 | 0.817 |
| A-Double | -0.0257 | 0.809 |
| A-Triple | -0.0127 | 0.621 |
| AAB-Quad | -0.0152 | 0.573 |
| 0% Grade | | |
| B-Double | -0.0227 | 0.741 |
| A-Double | -0.0238 | 0.719 |
| A-Triple | -0.0175 | 0.587 |
| AAB-Quad | -0.0144 | 0.45 |
| 2% Grade | | |
| B-Double | -0.0214 | 0.668 |
| A-Double | -0.0167 | 0.588 |
| A-Triple | -0.015 | 0.478 |
| AAB-Quad | -0.0086 | 0.332 |
| 5% Grade | | |
| B-Double | -0.0154 | 0.471 |
| A-Double | -0.0116 | 0.394 |
| A-Triple | -0.0053 | 0.242 |
| AAB-Quad | -0.0044 | 0.192 |

Source: Bunker and Haldane, 2003

The mechanistic relationship derived by McLean (1989) to calculate heavy vehicle acceleration is as follows:

$$a = \frac{P_{DR}}{Mv} - \frac{0.5\rho C_D A v^2}{M} - \frac{C_R + \theta}{g} \qquad [2.2]$$

Where:

$v$ = Vehicle velocity (m/s)

$P_{DR}$ = Power delivered to the drive wheels (W)

$M$ = Mass of the vehicle (kg)

$\rho$ = Density of air (1.22kg/m$^3$)

$C_D$ = Aerodynamic drag coefficient (0.65)

$A$ = Projected frontal area (8.5m$^2$ for articulated vehicles)

$C_R$ = Rolling resistance coefficient (0.010)

$\theta$ = Gradient (m/m)

$g$ = Acceleration due to gravity (9.81m/s$^2$)

To calculate the heavy vehicle acceleration based on the roadway and vehicle parameters the mechanistic relationship developed by McLean (1989) has been used in this project.

Heavy vehicle braking

As heavy vehicles are much larger and weigh more than passenger cars they require a longer distance to decelerate to rest. This will impact on when the heavy vehicle needs to start decelerating to stop at the traffic signals. The stopping sight distance defined by QDMR (2002a) is as follows:

$$SSD = \frac{R_T V}{3.6} + \frac{V^2}{254(d + 0.01a)} \qquad [2.3]$$

Where:

$V$ = Vehicle velocity (m/s)

$R_T$ = Driver reaction time (2.0s)

$d$ = Coefficient of deceleration

$a$ = Longitudinal grade (%)

The values of the coefficient of deceleration (d) for trucks defined by QDMR (2002a) are shown in Table 2.4.

Table 2.4: Coefficient of Deceleration for trucks on Level Grade

| Design Speed (km/h) | Coefficient of Longitudinal Deceleration |
|---|---|
| 50 | 0.29 |
| 60 | 0.29 |
| 70 | 0.29 |
| 80 | 0.29 |
| 90 | 0.29 |
| 100 | 0.28 |
| 110 | 0.26 |

Source: QDMR, 2002a

Heavy vehicle speed

Trucks generally travel at slower operating speeds than passenger cars. "Observed differences in mean speed for the two vehicle classes are typically in the range of 3 to 15km/h for level terrain. The speed differences are more pronounced on up-grades" (McLean, 1989). The differences between the operating speed of trucks and cars have decreased over time due to the improvements in heavy vehicle design. At lower speeds such as those experienced at traffic signals this difference is negligible.

### 2.1.3 Performance Based Standards

Currently the National Transport Commission (NTC) is creating a set of performance based vehicle standards to regulate heavy vehicles allowed on the roads. Performance based standards classify vehicles on key performance indicators such as acceleration, braking and turning radius rather than size and trailer configuration. With the introduction of performance based standards the freight industry will no longer be required to conform to standard vehicle types and can design a vehicle to suit a particular transport need. Trucks conforming to the performance based standards have been called SMART trucks.

"SMART trucks carry more freight and are safer on the road than the 'off-the-shelf' one-size-fits-all vehicles they replace. The end result is fewer trucks on the road for the same freight task, improved road safety, less transport emissions and a more competitive domestic economy" (National Transport Commission, 2010)

As the performance based standards are still being introduced this project will assess the impact of heavy vehicles at signalised intersections based on the current Austroads vehicle classification system.

## *2.2 Passenger Car Equivalent*

Heavy vehicles that travel slower and have poorer performance than passenger cars can have a detrimental impact on the roadway capacity. This can be seen on Australian highways where there are high percentages of heavy vehicles. "Large trucks, buses, and recreational vehicles have performance characteristics (slow acceleration and inferior braking) and dimensions (length, height, and width) that have an adverse effect on roadway capacity" (Mannering et al., 2005)

Passenger car equivalents (PCE) allow for the effect of heavy vehicles on the traffic stream due to their larger size and poorer vehicle performance. Passenger car equivalents are used in determining the reduction in roadway capacity due to the different vehicle types in the traffic stream. The US Highway Capacity Manual (Transportation Research Board, 2000) defines passenger car equivalents as "the number of passenger cars that are displaced by a single heavy vehicle under prevailing roadway, traffic, and control conditions". Using PCE values a non-homogeneous traffic flow can be expressed in a terms of an equivalent number of passenger cars.

The calculation of passenger car equivalents can be separated into two categories based on the traffic flow conditions expected on the roadway. The first is where the traffic is in free flow conditions (highways, freeways etc.). The impact of a heavy vehicle on a traffic stream in free flow conditions can be attributed to the size and speed of the vehicle. This is generally because the size of the heavy vehicle and the gap between the vehicle in front and behind is much larger than those of passenger cars. Second is where the traffic flow is congested or there is queuing in the traffic stream. The heavy vehicle size and operational characteristics become more significant when determining passenger car equivalents for congested flow.

### 2.2.1 US Highway Capacity Manual

The US Highway Capacity Manual (TRB, 2000) incorporates the use of PCE through a heavy-vehicle factor ($f_{HV}$) to adjust the saturation flow rate of the traffic stream. Equation 2.4 and 2.5 show the saturation flow rate adjustment. The US Highway Capacity Manual classifies heavy vehicles into trucks, buses and recreational vehicles (RVs). "Adjustment for heavy vehicles in the traffic stream applies to three types of vehicles: trucks, RVs, and buses. No evidence indicates any distinct differences in the performance characteristics of trucks and buses on multilane highways; therefore, buses are considered (as) trucks in this method" (TRB, 2000).

$$S = S_0 \times f_{HV} \qquad [2.4]$$

$$f_{HV} = \frac{1}{1 + (P_T \times (E_T - 1) + P_R \times (E_R - 1))} \qquad [2.5]$$

Where:

$S$ = Saturation flow rate (veh/h)

$S_0$ = Base saturation flow rate (veh/h)

$P_T$ = Percentage of trucks in the traffic stream

$E_T$ = Passenger car equivalency factor for trucks

$P_R$ = Percentage of RVs in the traffic stream

$E_R$ = Passenger car equivalency factor for RVs

The passenger car equivalents can be determined by either the general type of terrain as shown in Table 2.5, or based on a specific length of grade and proportion of trucks.

Table 2.5: Passenger Car Equivalents on Extended General Highway Segments

| Factor | Type of Terrain | | |
|---|---|---|---|
| | Level | Rolling | Mountainous |
| $E_T$ (trucks and buses) | 1.5 | 2.5 | 4.5 |
| $E_R$ (RVs) | 1.2 | 2 | 4 |

Source: TRB, 2000

For the installation of traffic signals the Highway Capacity Manual (TRB, 2000) recommends adopting a passenger car equivalent value of 2.0 for all types of heavy vehicle.

### 2.2.2 Walker Method

The Walker method defines PCE in terms of the overtaking rate of cars around a single heavy vehicle relative to the overtaking rate of a stream of cars (McLean, 1989). Figure 2.2 shows that the gap in opposing traffic at which cars can overtake a heavy vehicle is significantly larger than the gap required overtaking another car.

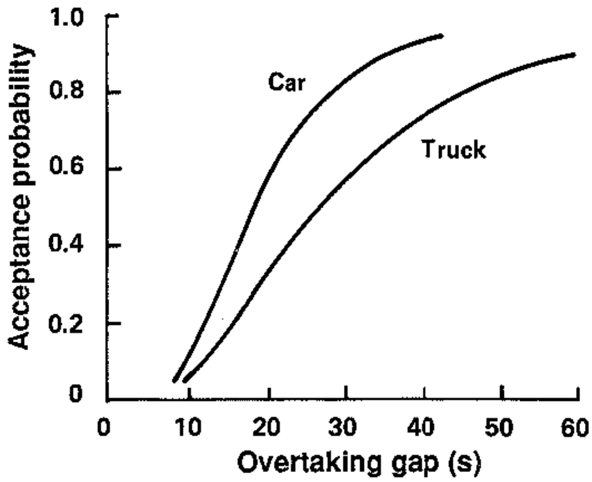



Figure 2.2: Overtaking Gap Acceptance
(Source: McLean, 1989)

The PCE values derived from the Walker method are dependent on the opposing traffic flow rate and the amount of overtaking opportunities on the road. On roads where there is a low opposing flow rate cars can overtake the heavy vehicle easily resulting in a low PCE value. Where there is a high opposing flow rate there are fewer opportunities to overtake resulting in a much higher PCE value. The Walker method is derived from free flow conditions where the overtaking rate of vehicles can be measured.

### 2.2.3 Headway Method

The headway method of calculating PCE values is defined as the ratio of the average headway for trucks to the average headway for passenger cars in the traffic stream (McLean, 1989). This relationship is shown in equation 2.6.

$$E_T = \frac{h_T}{h_C} \qquad [2.6]$$

Where:

$h_T$ = Average headway of trucks in the traffic stream

$h_C$ = Average headway of cars in the traffic stream

$E_T$ = Passenger car equivalent of trucks in the traffic stream

The headway method requires the vehicle headway to be measured from the rear of the first vehicle to the rear of the second vehicle. This allows for the size of the vehicle to be included in the PCE calculations (McLean, 1989).

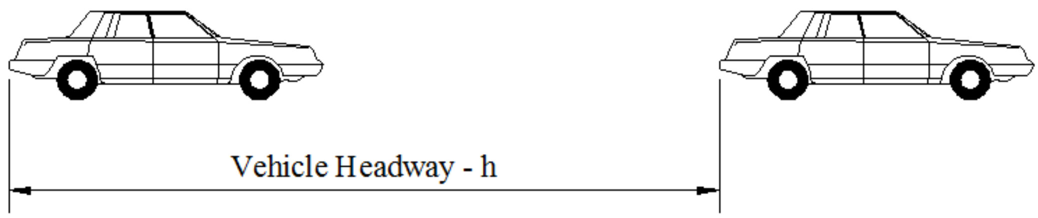



Figure 2.3: Vehicle Headway

On two-lane highways where there are limited overtaking opportunities the heavy vehicle is likely going to be a platoon leader due to the heavy vehicle’s slower overall speed and hence will have a large headway to the next vehicle. This will result in overestimation of the PCE value.

### 2.2.4 Capacity Method

The capacity method of deriving PCE values is directly related to flow performance. The PCE value is calculated by the ratio of the flow of a stream of cars to the mixed flow of cars and heavy vehicles (McLean, 1989). Using the capacity method the equivalent flow of passenger cars can be derived from equation 2.7.

$$q_C = (1 - P_T)q_M + P_T q_M E_T \qquad [2.7]$$

Where:

$q_C$ = Equivalent flow in passenger cars (veh/h)

$q_M$ = Mixed traffic flow (veh/h)

$P_T$ = Percentage of trucks in the traffic stream

$E_T$ = Passenger car equivalency factor for trucks

The PCE value for the heavy vehicles can be determined from equation 2.8.

$$E_T = 1 + \frac{(q_C / q_M - 1)}{P_T} \qquad [2.8]$$

As the capacity method can be applied to both free flow and congested flow it will be used in determining PCE values in this project.

## *2.3 Signalised Intersections*

Traffic signals are used to control conflicts between opposing vehicles or pedestrians at an intersection. Signals are usually provided at intersections with congestion and safety problems or to provide access from local streets to the arterial road system.

The use of traffic signals is governed by a series of warrants which are used to determine if the installation of signals is appropriate at a particular intersection. Traffic signal warrants have been developed by road authorities around the world based on the local traffic conditions. The warrants outlined by the Queensland Department of Main Roads (QDMR, 2003) are as follows:

a) Traffic Volume – Traffic volumes of 600 vehicles per hour exist on the major road and 200 vehicles per hour on the higher volume approach of the minor road for any 4 hours of an average day.
b) Continuous Traffic - Traffic volumes of 900 vehicles per hour exist on the major road and 100 vehicles per hour on the higher volume approach of the minor road for any 4 hours of an average day. Provided that the installation would not disrupt progressive traffic flow and there is no alternative and reasonably accessible signalised intersections present on the major road.
c) Accidents - If there is a 3-year average of 3 or more reported casualty accidents per year of a type which can be eliminated or reduced by traffic control and the traffic volumes is at least 0.8 times the volume warrants given in (a) and (b). Signals should only be considered if simpler devices will not effectively reduce the accident rate.
d) Combined Factors – In exceptional cases, signals occasionally may be justified where no single warrant specified above is satisfied but where two or more of the guidelines above are satisfied to the extent of 0.8 times or more of the stated values.

While traffic signals are designed to improve safety and intersection capacity they can also have certain disadvantages (Rogers, 2003):

- Traffic signals must be frequently maintained and monitored to ensure maximum effectiveness.
- There can be inefficiencies during off peak times leading to increased delays.
- Rear end accidents can increase.
- Signal breakdown due to mechanical/electrical failure can cause disruption to the traffic flow.

Table 2.6 can be used as a guide as to whether the installation of traffic signals at an intersection will be appropriate for a particular traffic problem.

Table 2.6: Appropriateness of Traffic Signals

| Symptom | Cause | Signal Control |
|---|---|---|
| Congestion | Excessive delays at STOP or GIVE WAY signs | Appropriate |
| | Excessive delays to turning traffic | Appropriate |
| | Volume greater than capacity, i.e. Substitute for poor road design | Inappropriate |
| Accidents | Angle collisions and pedestrian accidents | Appropriate |
| | Rear-end accidents | Inappropriate |
| | Right turn accidents | Inappropriate * |
| Access Control | Flow on to freeways | Appropriate |
| | Insufficient flow to traffic on surface street system | Appropriate |

* - Unless separate turn phase is provided

Source: QDMR, 2003

### 2.3.1 Phasing

Traffic at an intersection can be categorised by the trajectory the vehicle takes through the intersection. These trajectories are known as the movements of the intersection. A traffic signal phase is the condition of the traffic signals where one or more movements are given right of way. "Signal phasing is the basic control mechanism by which the operational efficiency and safety of a signalised intersection is determined" (Akçelik, 1998).

"A phase is identified by at least one movement gaining right of way at the start of it and at least one movement losing right of way at the end of it" (Austroads, 2007). If a movement has right of way during more than one phase it is known as an overlapping movement. Increases in the complexity of the phasing system will result in more overlapping movements.

Each phase is assigned a letter to distinguish it from the other phases which is shown in Figure 2.5. The complete sequence of phases at a signalised intersection is known as the signal cycle.

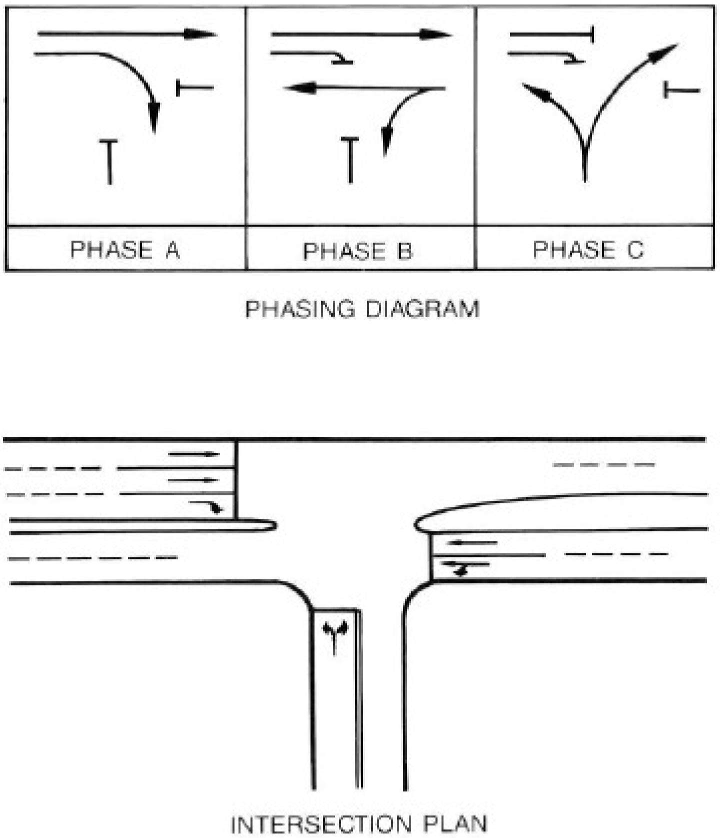



Figure 2.4: Traffic Signal Phasing Diagram
(Source: Akçelik, 1998)

The Queensland Department of Main Roads (2002b) defines the most common forms of intersection phasing as follows:

- Protected Right Turn – The right turn movement on one approach is protected by being on a separate phase to the opposing through movement. If the right turn movement precedes the opposing phase it is known as a "leading right turn" and if it is following it is known as a "lagging right turn".
- Diamond Turn – Where the opposing right turns are on a phase of their own.
- Diamond Overlap Turn – Where both right turns start at the same time but one terminates and the opposing through movement is started.
- Lead-Lag Turn – Where there is the combination of a protected leading right turn in one direction followed by the through movements and then the lagging right turn in the opposing direction.
- Split Phase – Where the movements of opposing flows are in totally separate phases. The right turn and through movements flow at the same time while all opposing movements are stopped.

### 2.3.2 Signal Timing

Traffic signals can be set to three different types of control, fixed time, semi actuated and fully actuated. The method of timing used at a particular intersection is allocated using the traffic signal controller. The signal controller regulates the sequence and timing of phases (QDMR, 2002).

Fixed time signals are where the green time is determined for each phase based on the traffic volumes at each leg of the intersection. The timing allocated to each phase remains the same regardless of the presence of vehicles on the opposing intersection legs. Different timing can be allocated to different hours during the day as traffic volumes change.

Semi actuated signals are where the green time allocated to each phase is affected by the presence of vehicles on some approaches of the intersection. Semi-actuated signals are usually installed where a low volume road intersects a high volume road. This allows the high volume road to continue to have a green light until a vehicle is detected on the low volume road.

Fully actuated signals are where the green time allocated to each phase is determined by the detection of vehicles on all of the approaches. Fully actuated signals are generally used at the intersection of two high volume roads where the traffic volume varies during the day.

### 2.3.3 Co-ordination of Traffic Signals

The co-ordination of traffic signals is used to avoid frequent stopping and delays to the traffic stream at closely spaced intersections. Traffic signal co-ordination is achieved by determining the expected traffic arrival time of the traffic platoons from the previous set of traffic signals. "Signal co-ordination is accomplished essentially by operating all signals in the area with a common cycle time and by staggering the green periods" (Akçelik, 1998). "The closer the traffic control signals are spaced the less random the arrival patterns become and the greater the opportunities are for improved efficiency afforded by co-ordination" (QDMR, 2002b). Figure 2.6 shows how the staggering of the green periods achieves co-ordination for the signals.

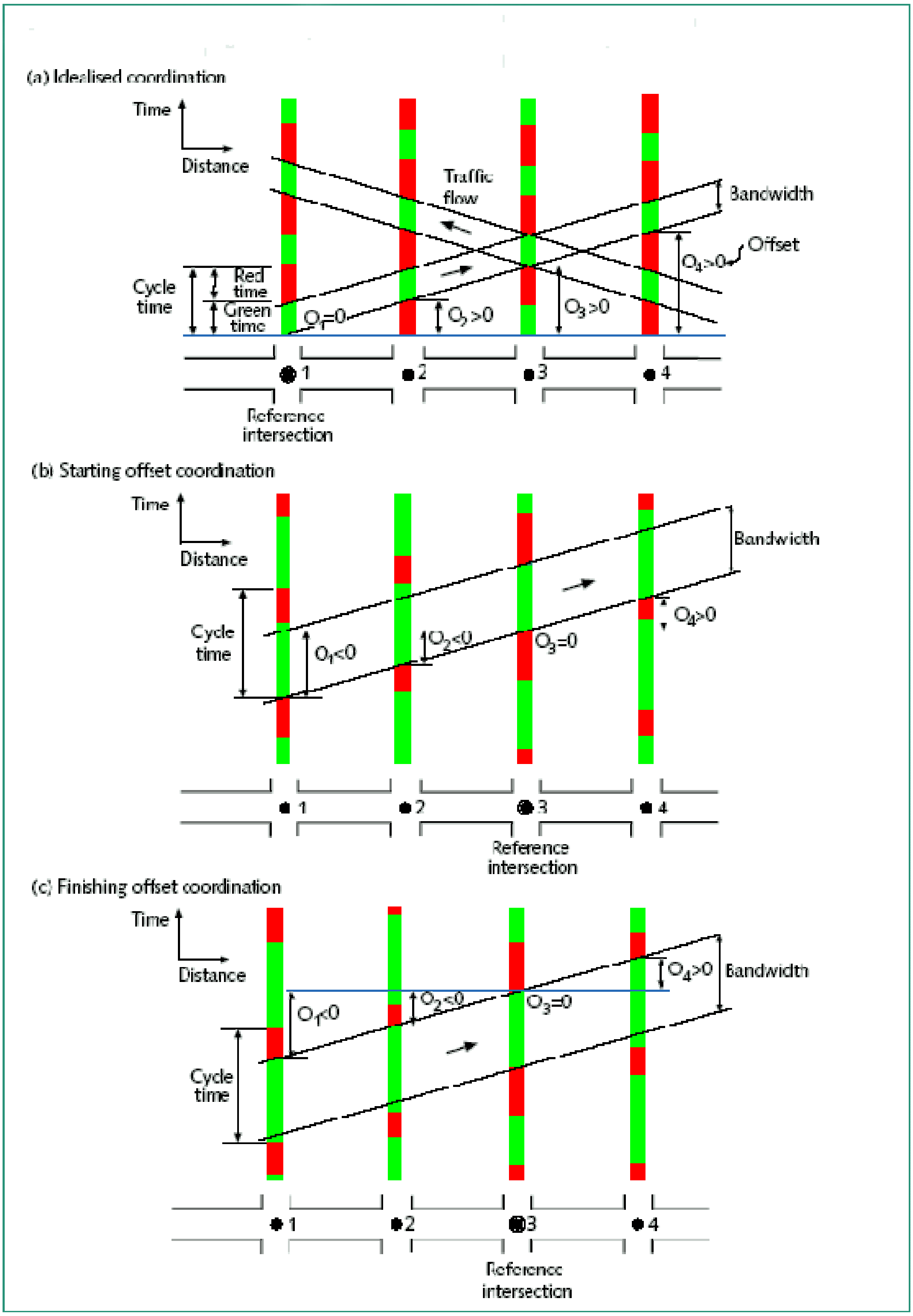



Figure 2.5: Co-ordination of Traffic Signals

(Source: Austroads, 2009)

### 2.3.4 Capacity

The capacity of each movement at a set of traffic signals is based on the maximum rate at which traffic can depart and the proportion of the signal cycle that is green for the relevant phase. Equation 2.9 calculates the capacity for the movement.

$$Q = S \times \left( \frac{g}{c} \right) \qquad [2.9]$$

Where:

$Q$ = Capacity for the movement (veh/h)

$S$ = Saturation flow rate of the intersection (veh/h)

$g$ = Effective green time for the phase (s)

$c$ = Cycle time for the intersection (s)

"The saturation flow rate may be defined as the maximum rate of flow that can pass through a given traffic movement (or intersection approach) under the prevailing roadway and traffic conditions" (Austroads, 2009)

The effective green time is equivalent green time at saturation flow accounting for the departure rate being lower at the start of the green period while the vehicles accelerate to the operating speed and at the end of the green period as some vehicles will stop and others will not. This is known as start loss and end lag. "The basic model assumes that when the signal changes to green, the flow across the stop line increases rapidly to a rate called the saturation flow, $S$, which remains constant until either the queue is exhausted or the green period ends" (Akçelik, 1998). Figure 2.7 shows the movement capacity for the effective green period.

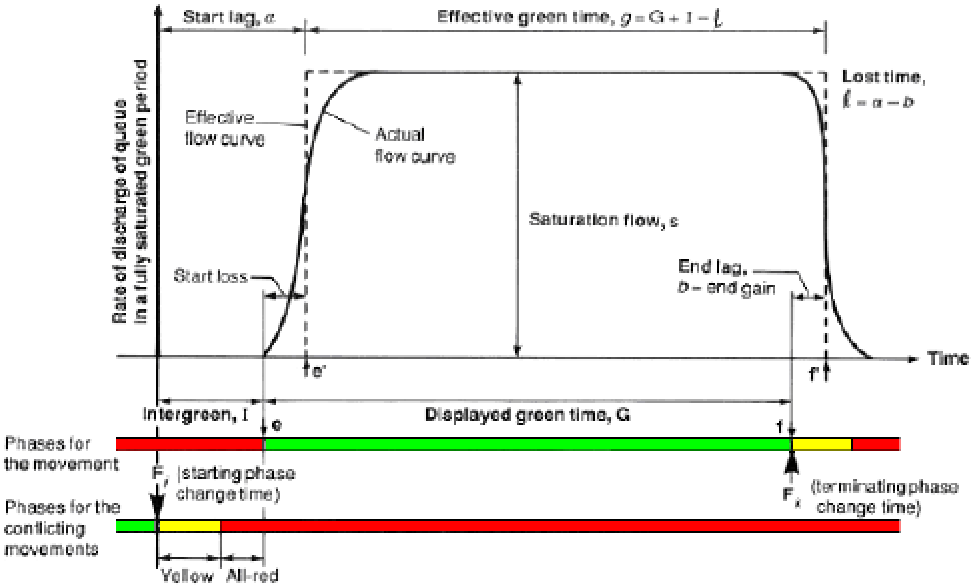



Figure 2.6: Traffic Signal Capacity

(Source: Akçelik, 1998)

Austroads (2009) calculates the saturation flow rate, S, as follows:

$$S = \frac{f_w f_g S_b}{f_c} \qquad [2.10]$$

Where:

$f_w$ = Lane width factor

$f_g$ = Gradient factor

$S_b$ = The base saturation flow rate (veh/h)

$f_c$ = The traffic composition factor

Austroads (2009) defines the lane width factor as follows:

- 0.55+0.14w for lane widths between 2.4 and 3.0 m
- for lane widths between 3.0m and 3.7 m
- 0.83+0.05w for lane widths between 3.7 and 4.6 m.

The gradient factor is given by:

$$f_g = 1 \pm \frac{0.5 \times (percent\ gradient)}{100} \qquad [2.11]$$

The base saturation flow rates at signalised intersections are shown in Table 2.7.

Table 2.7: Base Saturation Flows at Intersections

| Environment class | Lane Type | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| A | 1850 | 1810 | 1700 |
| B | 1700 | 1670 | 1570 |
| C | 1580 | 1550 | 1270 |

(Source: Austroads, 2009)

Austroads (2009) defines the environment classes as follows:

- Class A – ideal or nearly ideal conditions for the free movement of vehicles on both approach and exit sides, including good visibility, very few pedestrians, and almost no interference due to loading and unloading of goods vehicles or parking turn over (typically, but not necessarily, on a suburban residential or parkland area).
- Class B – average conditions, including adequate intersection geometry, small to moderate numbers of pedestrians, some interference by loading and unloading of goods vehicles or parking turn over and vehicles entering and leaving premises (typically, but not necessarily, in an industrial or shopping area).
- Class C – poor conditions, including large numbers of pedestrians, poor visibility, interference from standing vehicles, loading and unloading of goods vehicles, taxis and buses, and high parking turn over (typically, but not necessarily, in a central city area).

Austroads (2009) defines the lane types as follows:

- Type 1 – through lane – a lane containing through vehicles only.
- Type 2 – turning lane – a lane that contains any type of turning traffic, such as an exclusive left-turn lane, an exclusive right-turn lane, or a shared lane from

which vehicles may turn left or right or continue straight through. There should be an adequate turning radius, and negligible pedestrian interference to turning vehicles.

- Type 3 – restricted turning lane – a lane similar to a type 2 lane, but with turning vehicles subject to a small turning radius and some pedestrian interference.

Austroads (2009) defines the traffic composition factor as:

$$f_c = \frac{\sum e_i Q_i}{Q} \qquad [2.12]$$

Where:

$Q_i$ = Flow in vehicles per hour per vehicle type and movement i

$Q$ = Total movement flow in vehicles per hour

$e_i$ = Through car equivalent of vehicular traffic and movement from table 2.8

Table 2.8: Through car equivalent for different types of vehicle and movement

| Vehicle | Through | Opposed turn | |
|---|---|---|---|
| | | Normal | Restricted |
| Car | 1 | 1 | 1.25 |
| Heavy vehicles | 2 | 2 | 2.5 |

(Source: Austroads, 2009)

# 3.0 Methodology

The objective of this research project is to obtain a set of passenger car equivalent values that can be used when undertaking signalised intersection capacity investigations. A MATLAB model has been produced that simulates traffic flow through an intersection. The simulated traffic flow is then used to develop passenger car equivalent values using the capacity method.

Each simulated vehicle in the traffic stream is assigned a number of parameters relating to the vehicle's operating characteristics and driver behaviour. The parameters will determine the appropriate driver behaviour given different roadway and traffic conditions within the simulation. Some parameters will be random and independent of the vehicle type such as the arrival pattern at the intersection. Other parameters such as acceleration capability of each vehicle will be assigned according to the vehicle type in the simulation.

To develop the simulation model some parameters have been adopted from the literature review while others have been collected from data on site.

## *3.1 Data Collection*

Data was collected from the following intersections in Toowoomba:

- James Street and Ruthven Street
- James Street and Anzac Avenue
- Tor Street and Taylor Street

These intersections form part of the Warrego Highway which is a major road in the transportation of freight from the Darling Downs region to Brisbane. This section of the Warrego highway has an AADT of 23600 vehicles per day with 14 % heavy vehicles.

The data that was collected consists of traffic camera videos and traffic detector loop data obtained from the Queensland Department of Transport and Main Roads. Data has also been collected from observations at the intersection sites. The traffic camera videos were taken over three days which were 7/3/2011, 9/3/2011 and 11/3/2011. The videos were taken between the hours of 9:00 and 11:00 AM and 3:00 and 5:00 PM on each day. These were known to be times of high traffic flows for the three intersections.

Figure 3.1: Data collection from the James St and Ruthven St intersection

### 3.1.1 Vehicle Performance

Vehicle acceleration

Heavy vehicle acceleration is calculated using the mechanistic relationship outlined in section 2.1.2 which was derived by McLean (1989). The acceleration capability of each vehicle in the traffic flow is calculated at each time interval. The parameters used for each type of heavy vehicle are outlined in Table 3.1.

Table 3.1: Heavy Vehicle Acceleration Parameters

| Vehicle Type | Semi-Trailer | B-Double | Type 1 Road Train | Type 2 Road Train |
|---|---|---|---|---|
| Vehicle Power (1) | 225 kW | 269.6 kW | 273 kW | 347.2 kW |
| Vehicle Mass (1) | 42.5 t | 62.4 t | 89.8 t | 140 t |
| Drag Coefficient (2) | 0.65 | 0.65 | 0.65 | 0.65 |
| Frontal Area (2) | 8.5 $m^2$ | 8.5 $m^2$ | 8.5 $m^2$ | 8.5 $m^2$ |
| Rolling Resistance (2) | 0.010 | 0.010 | 0.010 | 0.010 |

(1) – Source: Austroads, 2010

(2) – Source – Austroads, 2002

The acceleration of cars in the MATLAB simulation has been incorporated using a model that decreases linearly with speed.

$$a = a_0 \times \left(1 - \frac{v}{v_m}\right) - g \times \theta \qquad [3.1]$$

Where:

$a$ = Acceleration capability (m/s$^2$)

$v$ = Vehicle speed (m/s)

$a_0$ = Maximum acceleration capability at $v = 0$ (m/s$^2$)

$v_m$ = Maximum vehicle speed attainable (m/s)

$\theta$ = Gradient (m/m)

$g$ = Acceleration due to gravity (9.81m/s$^2$)

For an average passenger car McLean (1989) recommends the following parameters:

- $a_0$ = 2.82 m/s$^2$
- $v_m$ = 32 m/s

<u>Vehicle deceleration</u>

Vehicle deceleration in the simulation is calculated using the sight distance formula shown in equation 2.3. The simulation checks if the vehicle can stop before the intersection. If the vehicle can stop it decelerates at the recommended rate otherwise the vehicle continues to travel through the intersection. As recommended in section

2.1.2 the deceleration coefficient adopted for heavy vehicles is 0.29. For passenger cars Austroads (2010) recommends a value of 0.36 be adopted. This represents a 90th percentile value for braking on wet sealed pavements.

Vehicle maximum speed

Traffic signals can be installed on roads with speed limits up to 80km/h as long as unprotected right turning traffic is not turning across more than two lanes. However the majority of traffic signal installations occur in urban areas where the speed limit is 50 – 60km/h. The speed limit of the simulation is set to 60km/h; this is the maximum speed attainable for all the vehicles in the simulation.

### 3.1.2 Vehicle Headway

To determine the vehicle headway parameters to be adopted for the simulation, data has been collected from the traffic camera videos at the three signalised intersection in Toowoomba.


Figure 3.2: Headway Determined form Traffic Camera Videos

The headway data was collected in periods of high traffic flows. This was chosen to give a better representation of the interaction of vehicles as the intersection approaches capacity. The vehicle headway was determined by recording the time at which the vehicles passed linemarking features on the road surface. At each intersection the time that each vehicle passed the first linemarking feature was recorded. The time difference between the leading and trailing vehicle was then used to calculate the headway of the trailing vehicle. The calculated headways have been taken from the rear of each vehicle as recommended by McLean (1989). The time that the leading vehicle passed a second linemarking feature was recorded so that the leading vehicle speed was able to be calculated. This was completed to determine if vehicle speed had an effect on the headway calculated.

A sample calculation of the vehicle headway at the James Street and Anzac Avenue intersection is as follows:

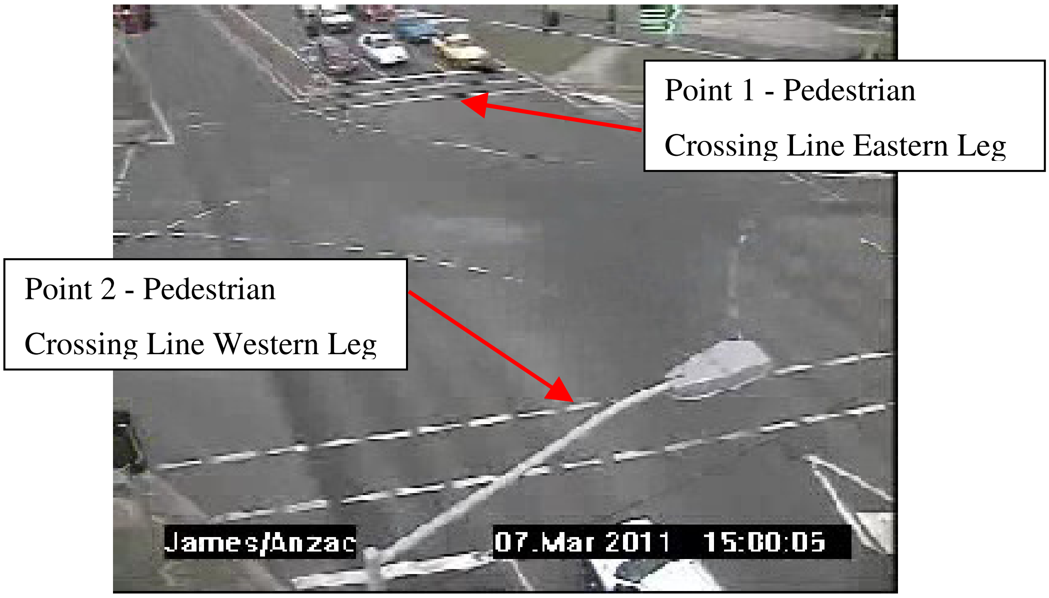



Figure 3.3: Linemarking Reference Points – James St and Anzac Ave Intersection

Table 3.2: Headway Example Data

| Vehicle Type | Time Point 1 (s) | Time Point 2 (s) |
|---|---|---|
| Car | 56.82 | 59.36 |
| Car | 58.36 | - |

<u>Vehicle Headway</u>

$$headway = 58.36 - 56.82$$
$$headway = 1.54s$$

Vehicle Speed

The measured distance between Point 1 and Point 2 for the James St and Anzac Ave intersection is 26.3m

$$speed = \frac{26.3}{(59.36 - 56.82)} \times \frac{3600}{1000}$$
$$speed = 37.3 km/h$$

The results of the observed vehicle headway have been split into passenger cars and heavy vehicles and are shown in Figure 3.4.

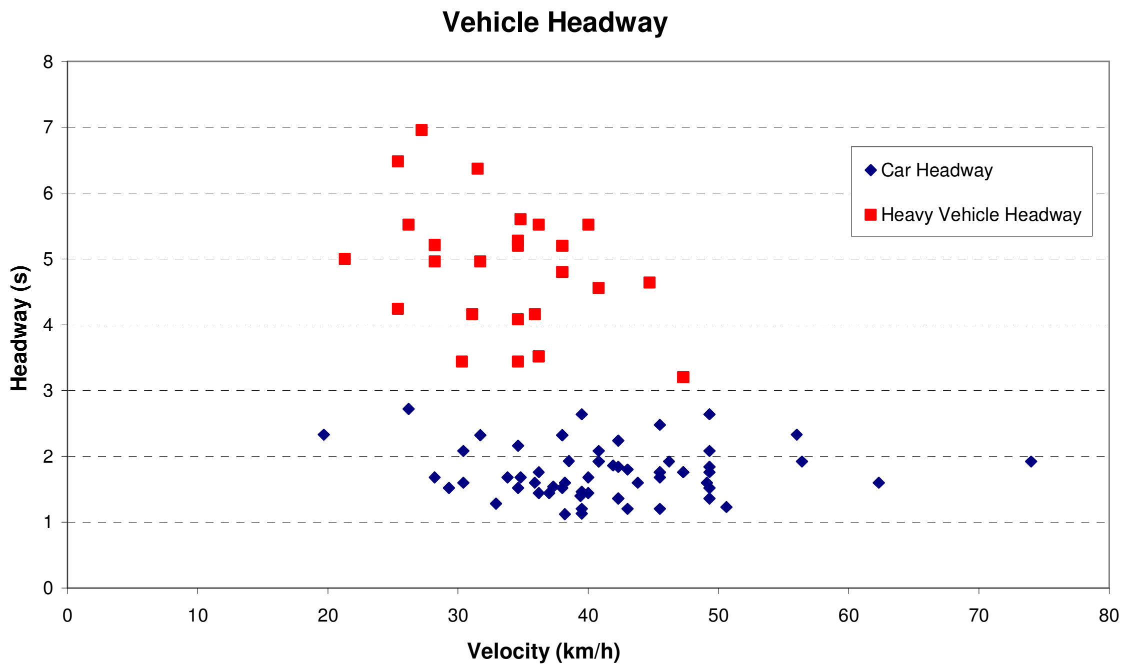



Figure 3.4: Headway Data Collected

The headway data was collected for 88 vehicles, of which 62 were passenger cars and 26 were heavy vehicles ranging in size from Semi Trailers to B-Doubles. May (1990) suggests that vehicle headway can be approximated by applying the normal distribution. This requires the average headway and the standard deviation to be calculated. As the headway data was collected during times of uninterrupted flow (traffic volume ($Q$) is 2200 veh/h) the average headway ($\bar{t}$) is calculated as follows:

$$\bar{t} = \frac{3600}{Q}$$
$$\bar{t} = \frac{3600}{2200}$$
$$\bar{t} = 1.64s$$

The standard deviation can be calculated from the minimum expected headway ($\alpha$) which is assumed to be 2 standard deviations from the mean headway. The minimum expected headway is calculated based on a 0.5s gap between vehicles. As the headway data measured is measured between the rear of each vehicle the adjusted minimum headway is calculated as follows:

$$\alpha = 0.5 + \frac{5.5}{60/3.6}$$
$$\alpha = 0.83s$$

The standard deviation ($s$) of the headway is then calculated as follows:

$$s = \frac{\bar{t} - \alpha}{2}$$
$$s = 0.405s$$

The histogram in Figure 3.5 shows the comparison of the headway data collected with the normal distribution calculated.

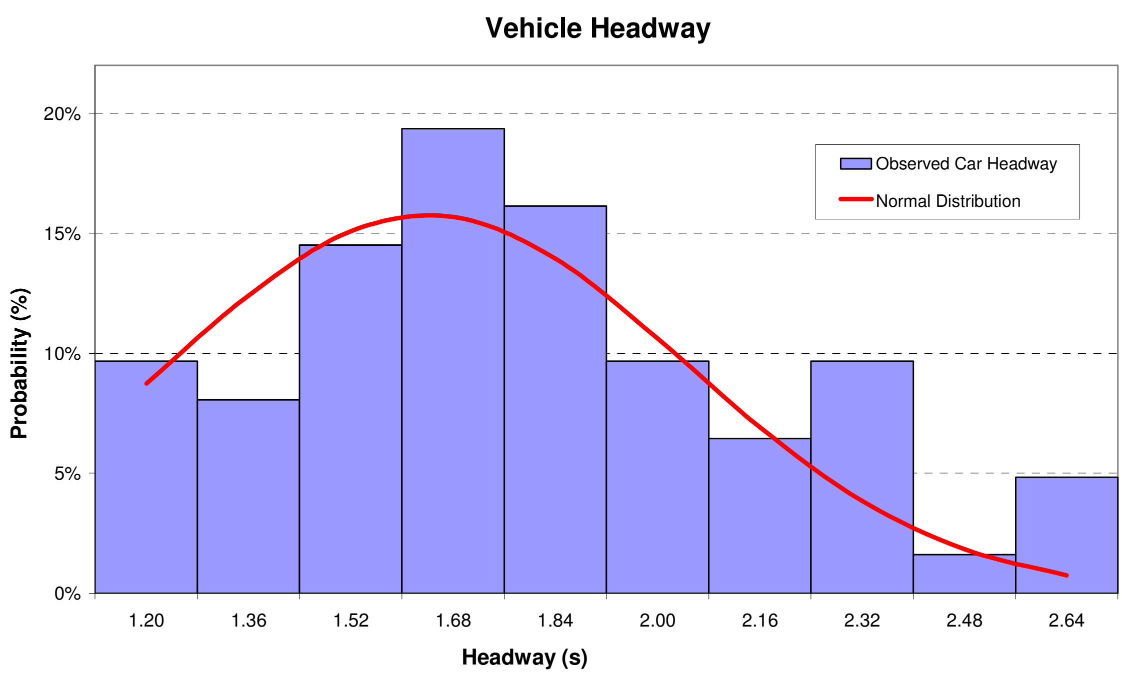



Figure 3.5: Histogram of Passenger Car Headway Data

To be able to use the headway results in the simulation the length of the length of each vehicle would need to be considered. Accounting for the length of each vehicle the data collected had an average headway of 1.3s for passenger cars and 2.4s for heavy vehicles. These figures have been adopted in the MATLAB simulation. The speed of the vehicle was found to have little effect on the headway measured.

### 3.1.3 Traffic Volumes

The traffic volumes at each site were calculated from traffic detector loop data supplied by the Queensland Department of Transport and Main Roads. This data was used to ensure that the vehicle headway data was calculated based on times of high traffic volumes. Figures 3.6, 3.7 and 3.8 show the traffic volumes at each of the intersection sites on the 9th of March 2011.

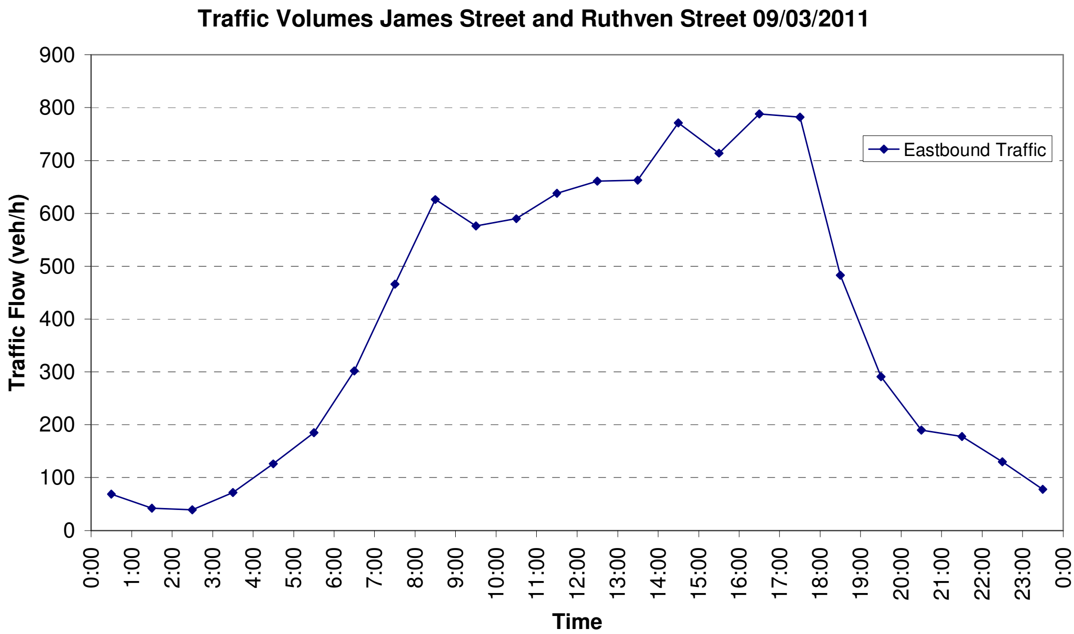



Figure 3.6: Traffic Volumes at James Street and Ruthven Street

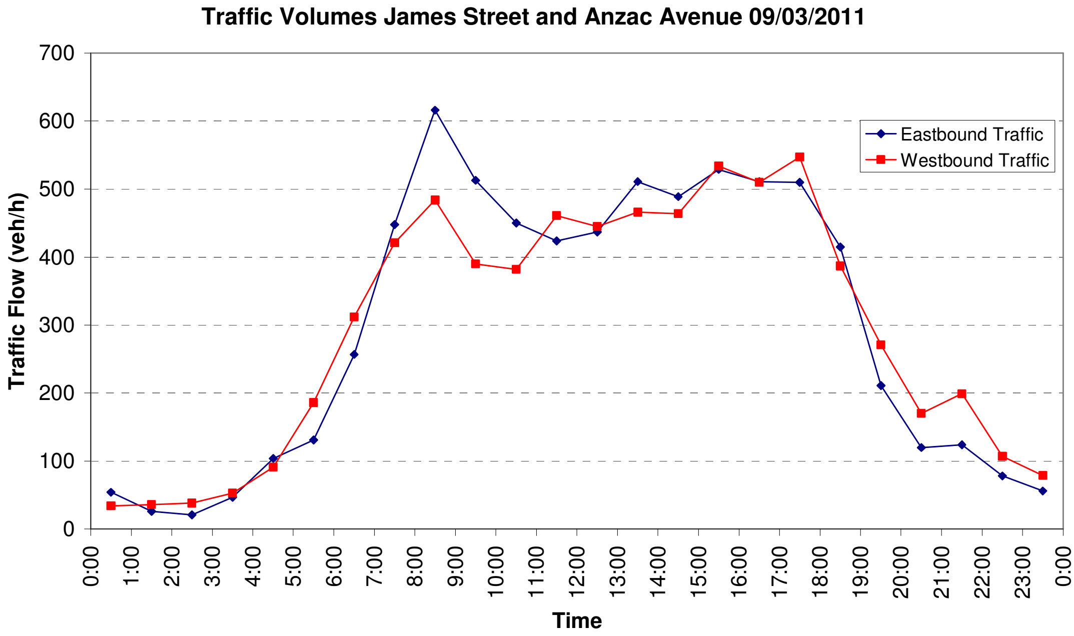



Figure 3.7: Traffic Volumes at James Street and Anzac Avenue

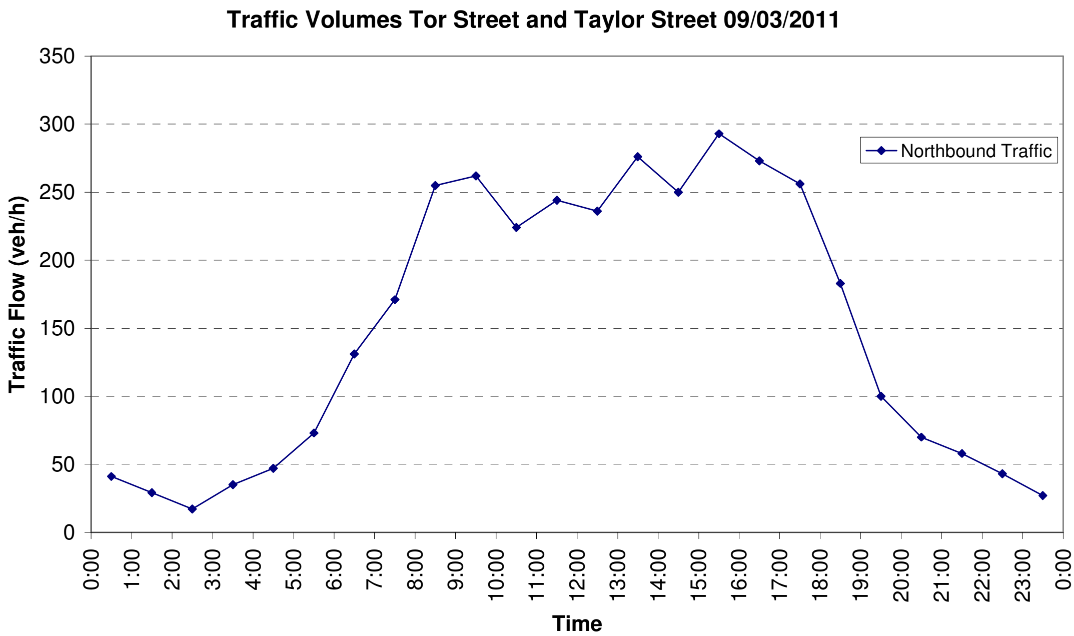



Figure 3.8: Traffic Volumes at Tor Street and Taylor Street

The traffic volumes show that for the time periods covered by the intersection traffic camera videos both the Ruthven Street and Anzac Avenue intersections experience traffic flows between 400 and 800 vehicles per hour for the eastbound and westbound movements. The intersection of Tor Street and Taylor Street has shown lower traffic volumes during these times and has been excluded from data collection purposes.

### *3.2 Model Development*

To determine the passenger car equivalent values at signalised intersections for the heavy vehicles in use on Queensland roads a simulation model has been developed using MATLAB. The simulation calculates the PCE value for each vehicle based on a single through lane traffic movement.

The position of each vehicle within the extents of the intersection is calculated at each time interval. Once the simulation has completed the number of vehicles that have past the extents of the intersection are counted to calculate the passenger car equivalent value using the capacity method.

The MATLAB model determines driver and vehicle behaviour based on the flow chart shown in Figure 3.9.

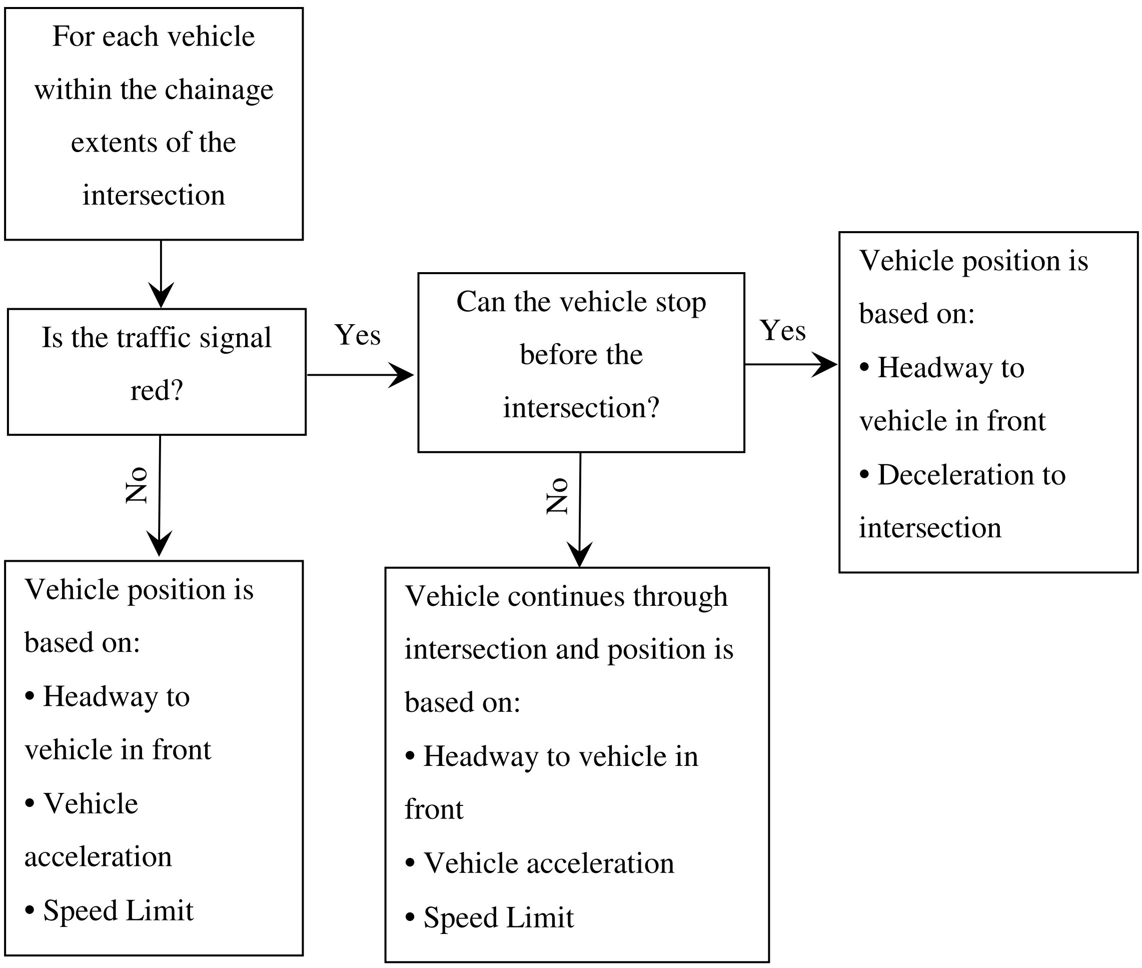



Figure 3.9: MATLAB Model Flow Chart

### 3.2.1 Vehicle Arrival Pattern

To determine the probability of a vehicle arriving at the intersection at a particular point in time the Poisson arrival distribution has been used. The Poisson arrival distribution calculates the probability of a vehicle arriving in a specified length of time. This probability can be calculated as follows:

$$P_n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \qquad [3.1]$$

Where:

$P_n(t)$ = The probability of n vehicles arriving during the time interval t

$\lambda$ = The average number of arrivals per unit time

The Poisson arrival distribution assumes that the arrival rate is completely random, i.e. it is not influenced by factors upstream such as other traffic signals. The simulation does not take into account the effects of coordinated traffic signals. Traffic signal coordination would result in a lower passenger car equivalent value due to less heavy vehicles having to stop at the intersection.

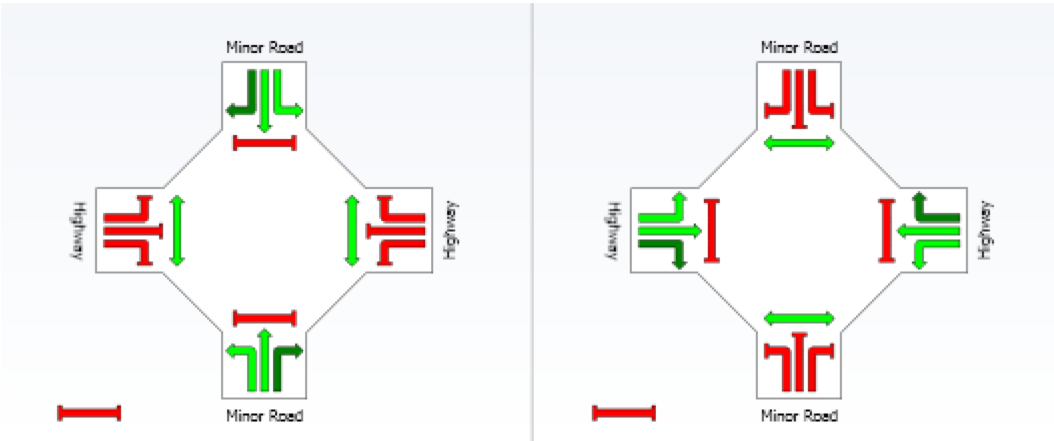
In the MATLAB simulation the arrival probability is calculated from the traffic flow rate entered by the user. The probability is calculated for a single vehicle arriving within the calculation time interval of the simulation. A random number generator is then used at each time interval to determine if a vehicle arrives at that point in time. To ensure that the equivalent flow of cars is calculated correctly the same arrival pattern is used for the mixed traffic flow and the flow of equivalent cars.

### 3.2.2 Position of Heavy Vehicles in the Traffic Queue

The type of vehicle for each position in the traffic queue is determined from the proportion of heavy vehicles entered by the user. A random number generator is used to determine the vehicle type based on the percentage of heavy vehicles in the traffic flow.

### 3.2.3 Traffic Signal Phasing

The traffic signal phasing that has been incorporated into the model has been based on a two phase system with both the highway and minor road having similar traffic volumes.




Phase A

Phase B

Figure 3.10: MATLAB Simulation Phasing Diagram

The MATLAB simulation simulates traffic flow for a single through movement of the intersection. The default timing values for the movement used in the simulation are as follows:

- Green time of movement – 56s
- Yellow time of movement – 4s
- Cycle length – 120s

These timings have been used to determine the passenger car equivalent values provided in Appendix C. These values can be changed to more accurately reflect the passenger car equivalent value at a particular intersection.

### 3.2.4 Traffic Flow through the Intersection

The simulation runs for a number of cycles to provide an average passenger car equivalent value for vehicles that have to stop at the traffic signals and vehicles that are able to continue through the intersection uninterrupted. The position of each vehicle within the extents of the intersection is calculated at each time interval during the simulation.

Figure 3.11 shows the position of each vehicle within the simulation. The blue lines represent the rear of each vehicle in the simulation while the red, yellow and green lines at the zero chainage represent the phase of the traffic signal at each point in time. The heavy vehicles in the simulation can be seen as they require more space in the traffic queue and have lower acceleration than cars.

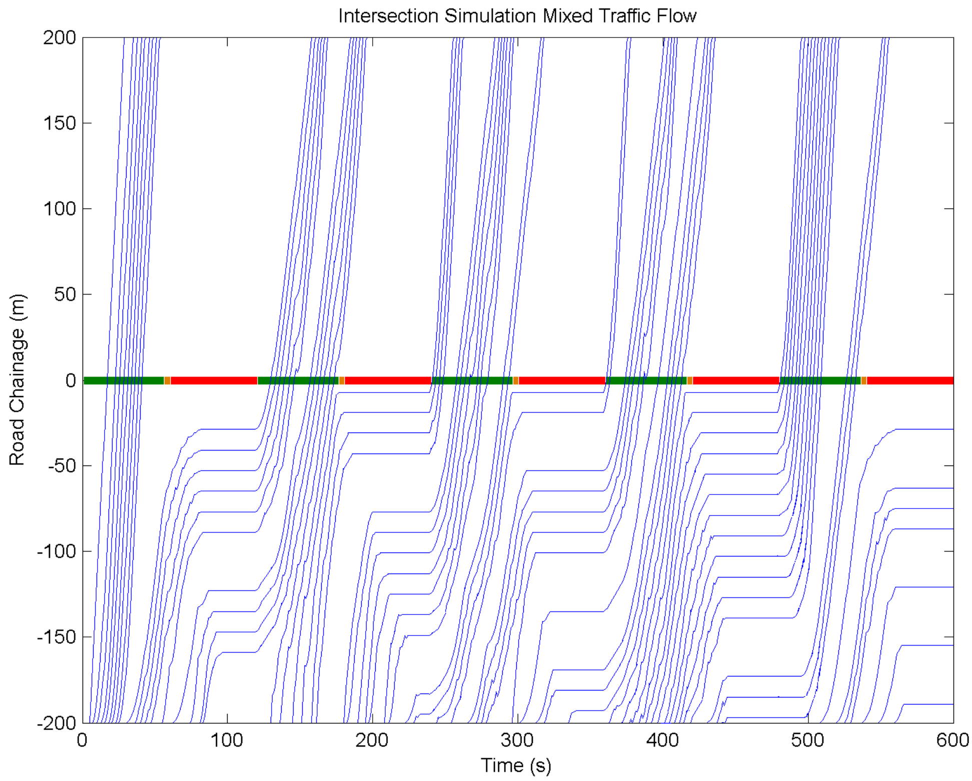



Figure 3.11: Simulation Output of Vehicle Position

Once the simulation is completed for the required number of cycles the number of vehicles that has passed the end chainage is counted. This is completed for the mixed traffic flow and the equivalent flow of cars. The number of heavy vehicles is also counted to determine the percentage of heavy vehicles in the traffic stream.

### 3.2.5 Equivalent Flow of Cars

The capacity method for determining passenger car equivalent values requires the calculation of an equivalent flow of cars for the intersection. To determine this, the simulation is run a second time with the same traffic volume, roadway grade and vehicle arrival pattern. In this simulation each heavy vehicle in the traffic queue is changed to a passenger car and the total flow throughout the simulation is measured.

The simulation calculates the passenger car equivalent value for the prevailing traffic and roadway conditions using the capacity method. The simulation is then run 50 times to calculate an average passenger car equivalent value for the roadway and traffic conditions. A histogram showing the results of a sample simulation is shown in Figure 3.12.

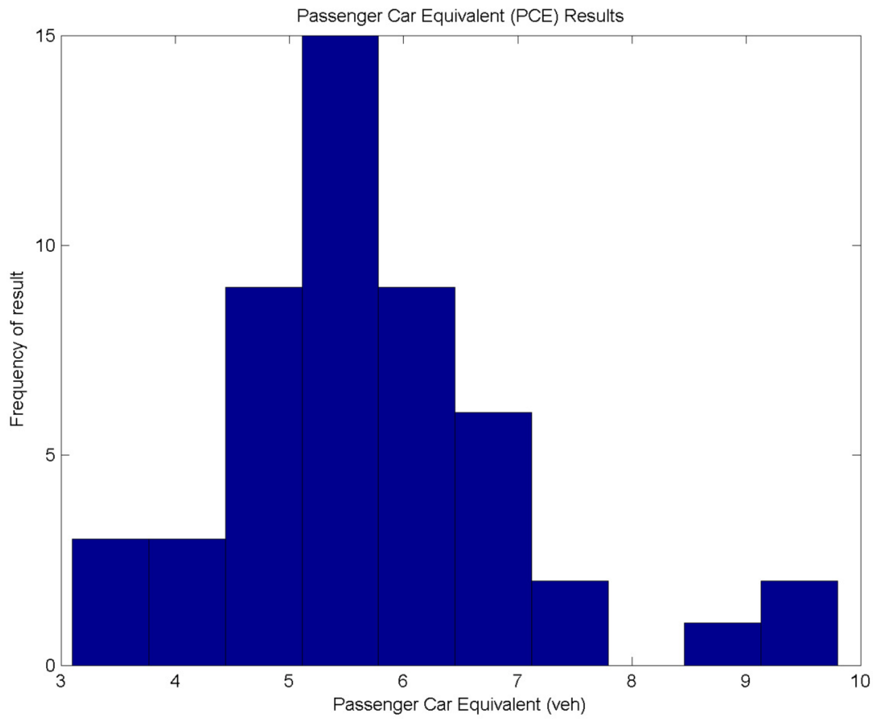



Figure 3.12: Histogram of Simulation Results

# 4.0 Simulation Results

## *4.1 Passenger Car Equivalents for the Vehicle Types Analysed*

The MATLAB simulation has been used to determine a set of passenger car equivalent values for each vehicle type analysed. These values have been determined by varying the roadway and traffic input parameters to produce a set of tables that can be used as a reference for undertaking intersection capacity analysis. The tables for each vehicle type are outlined in Appendix C.

Table 4.1 summarises the passenger car equivalent results outlined in Appendix C based on typical roadway and traffic conditions experienced at traffic signal sites. These values have been based on the roadway being level and a traffic volume of 900veh/h with 11% heavy vehicles.

Table 4.1: Simulation Results for Typical Conditions

| Vehicle | PCE Value |
|---|---|
| Semi-Trailer | 2.6 |
| B-Double | 3.1 |
| Type 1 Road Train | 3.1 |
| Type 2 Road Train | 4.7 |

For intersections with different roadway and traffic conditions to those used in Table 4.1 the results in Appendix C should be used to give an accurate representation of the impact each heavy vehicle will have on the intersection capacity.

The results generated by the simulation show differences in passenger car equivalent values for the heavy vehicle types analysed. As expected the results have shown the larger vehicles have greater passenger car equivalent values due to their larger size and poorer performance characteristics. The larger vehicles have also shown to have a greater variation in the results generated. The variation in results generated for each vehicle type is shown in Figure 4.1.

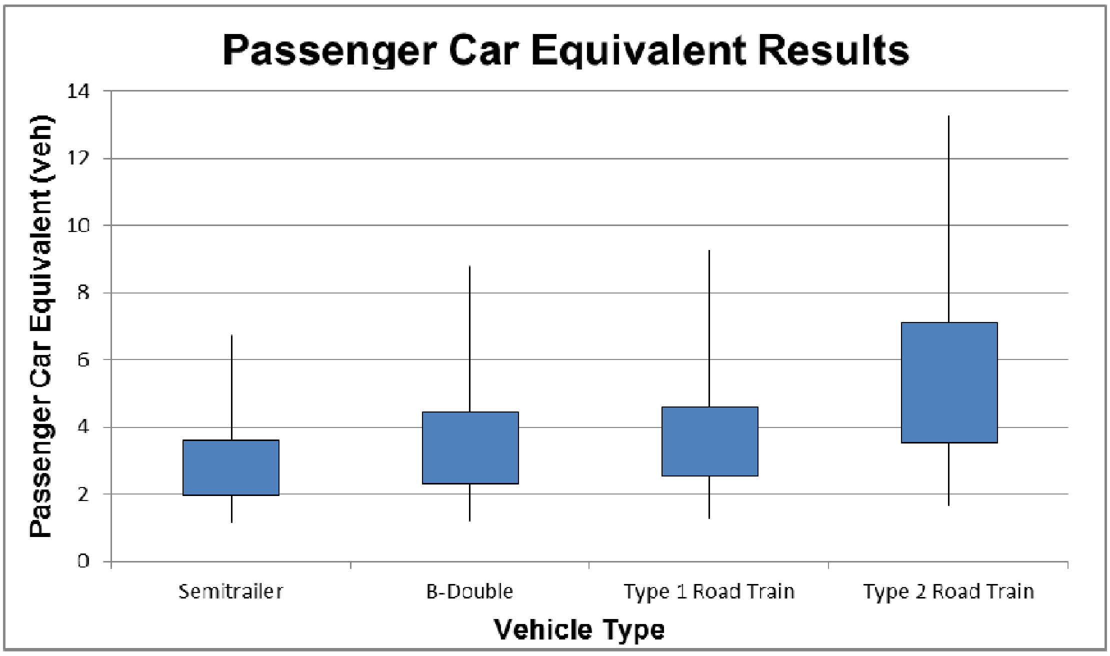


Figure 4.1 Box Plots of Simulation Results

The results generated for each of the vehicle types range from the following:

- Semi Trailers – Passenger car equivalents range from 1.2 to 6.7 vehicles
- B-Doubles – Passenger car equivalents range from 1.2 to 8.8 vehicles
- Type 1 Road Trains – Passenger car equivalents range from 1.3 to 9.3 vehicles
- Type 2 Road Trains – Passenger car equivalents range from 1.7 to 13.3 vehicles

## *4.2 The Effect of Grade on Passenger Car Equivalent Results*

Small grades have been shown to have a significant influence on performance for vehicles with low power to weight ratios such as the vehicles analysed in this project. Upgrades have been shown to cause significant increases in the passenger car equivalent values obtained from the simulation. This shows that the acceleration capability of the heavy vehicle has a large influence on its impact on the roadway capacity.

Figure 4.2 shows the impact the roadway grade has on the passenger car equivalent values derived for each of the vehicle types analysed in this project.

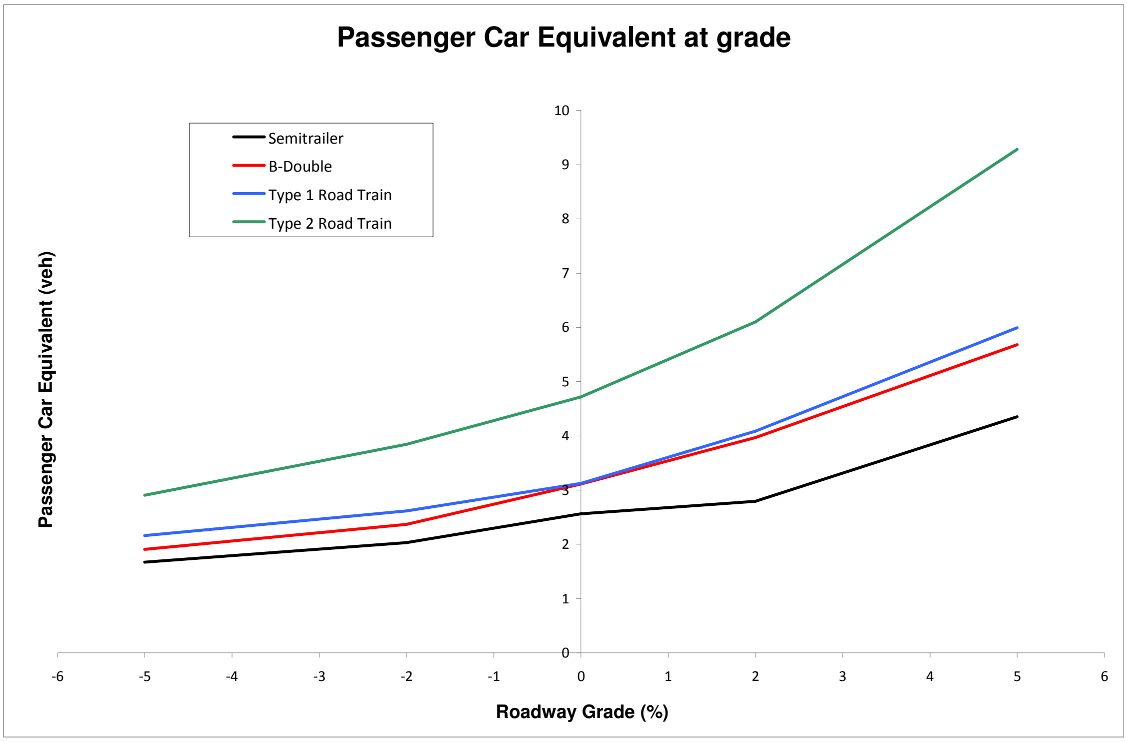



Figure 4.2: Impact of Grade on Passenger Car Equivalent Values

## *4.3 The Effect of traffic Volume on Passenger Car Equivalent Results*

As traffic volumes increase the results have shown that effect of each heavy vehicle also increases. Once the roadway reaches capacity the queue of vehicles waiting to arrive at the intersection grows, but the same number of vehicles pass through the intersection. This will result in the mixed flow and the flow of cars being similar in the each of the simulations. The Passenger car equivalent values for the intersection remain relatively constant once this flow is reached. This has been shown typical for all the vehicle types analysed.

Based on the traffic signal phasing used during the simulation the capacity of the intersection is 864 passenger cars per hour. This has been calculated from the method outlined by Austroads (2009) which is shown in section 2.3.4. Figure 4.3 shows the effect that the traffic volume has on the passenger car equivalent values developed.

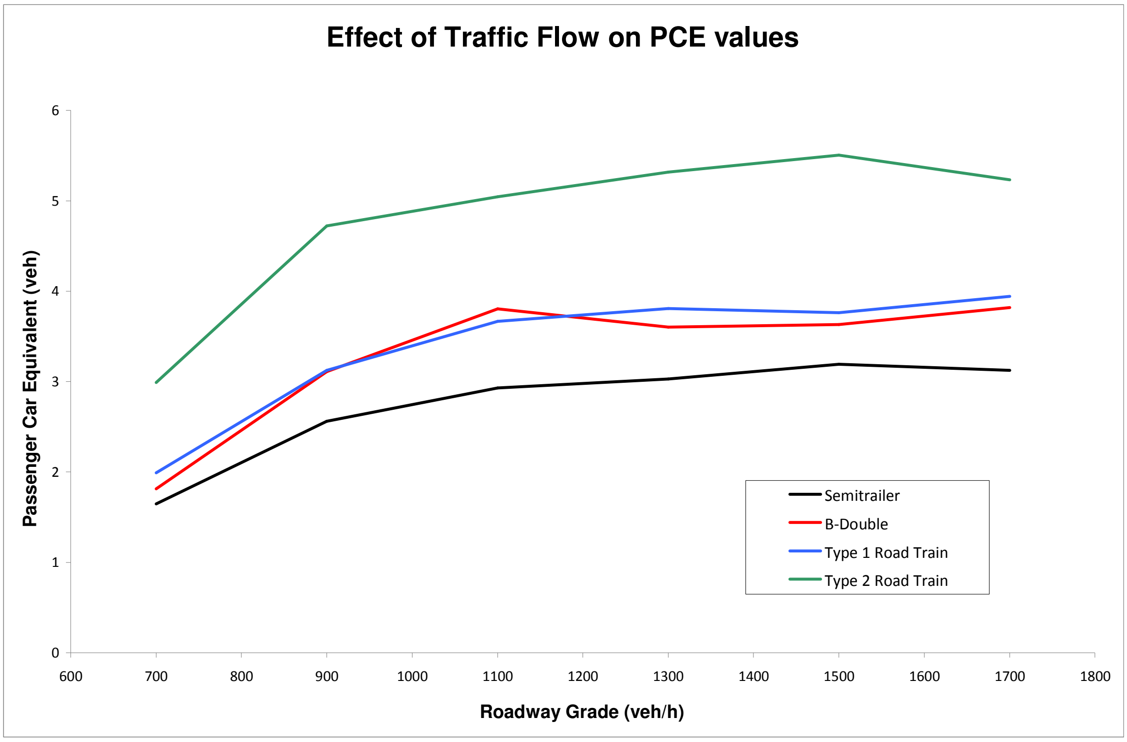



Figure 4.3: Impact of Traffic Volume on Passenger Car Equivalent Values

## *4.4 The Effect of Traffic Composition on Passenger Car Equivalent Results*

The results of the simulation show that as the percentage of heavy vehicles increases the passenger car equivalent value reduces for each heavy vehicle. This is due to the proportion of heavy vehicles increasing at a faster rate than the reduction in intersection capacity. This has resulted in a lower passenger car equivalent value for each heavy vehicle but as there are more heavy vehicles on the roadway the effect of the heavy vehicles on the intersection capacity still increases overall.

Figure 4.4 shows the impact the proportion of heavy vehicles in the traffic stream has on the passenger car equivalent values derived in this project.

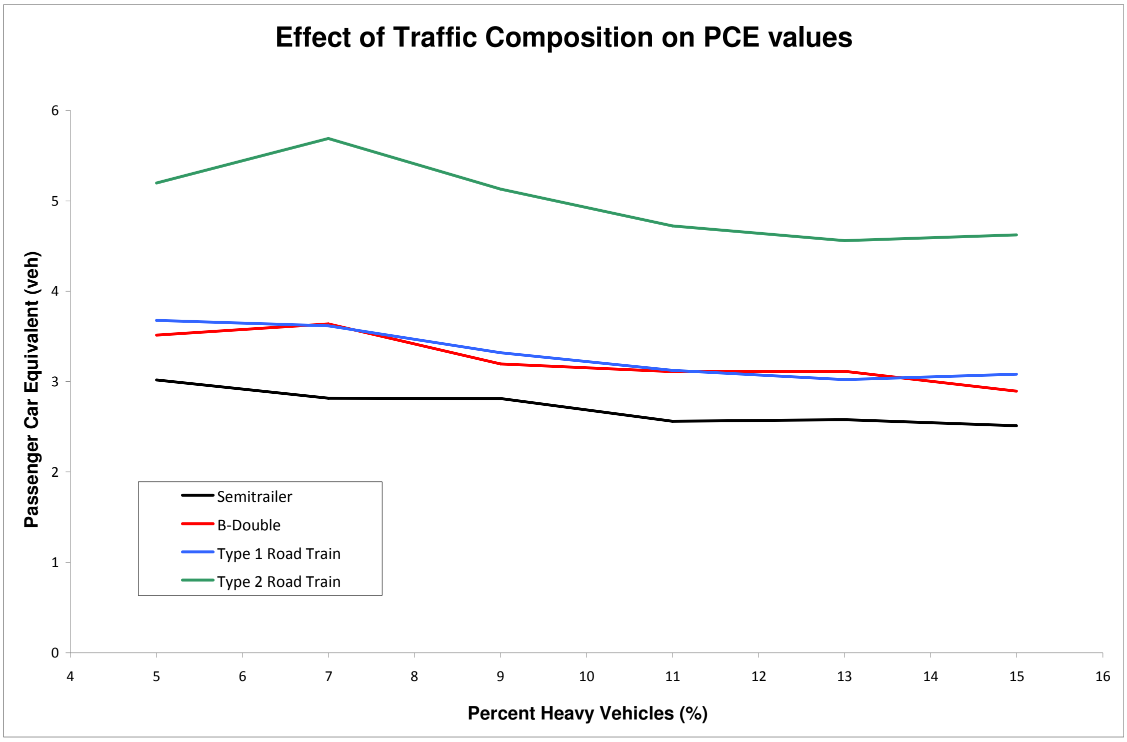



Figure 4.4: Impact of Traffic Composition on Passenger Car Equivalent Values

## *4.5 Incorporation of Results into SIDRA Analysis*

To determine the impact that the results of this project would have on a typical signalised intersection the traffic signal timing and capacity software SIDRA INTERSECTION has been used to undertake a comparison the results generated by this project with results generated using the current practice for adopting a passenger car equivalent value of 2.0 for all heavy vehicle types.

SIDRA INETERSECTION estimates intersection capacity, level of service and performance at signalised intersections. As the intersection level of service and performance characteristics are a direct indication of the impact of vehicles on traffic signal operation these are the SIDRA outputs that will be compared.

The intersection that will be analysed is the set of potential future traffic signals at the intersection of the Warrego Highway and Gowrie Junction Road. This site has been chosen as it has high traffic volumes and is on a grade of approximately 2% in the eastbound direction and -2% in the westbound direction. The intersection layout entered into SIDRA matches the existing intersection layout and is shown in Figure 4.5.

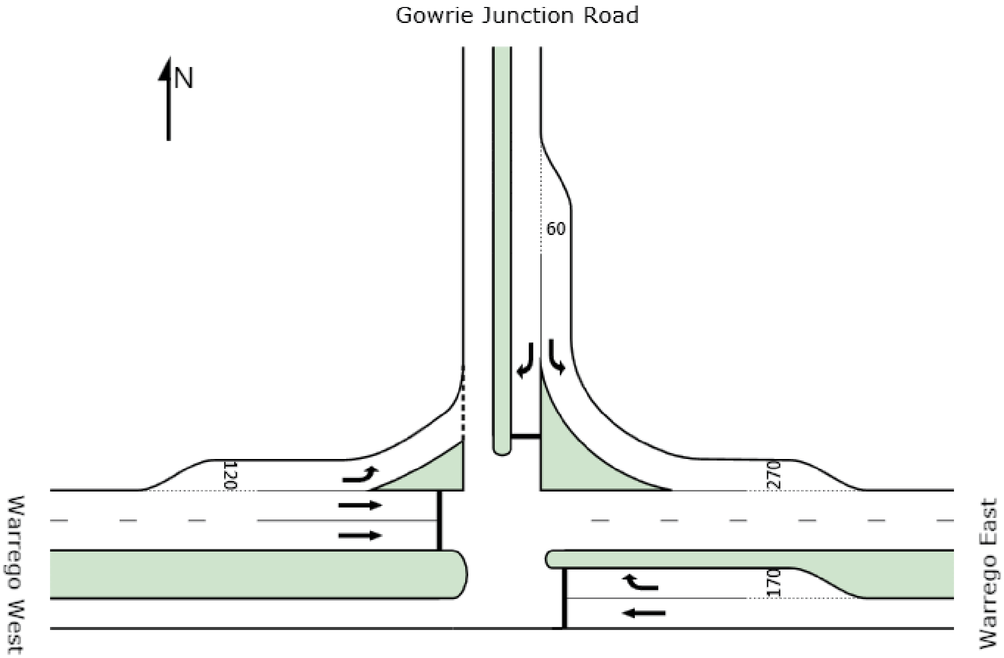



Figure 4.5: SIDRA Intersection Layout

The existing AM and PM peak hour traffic volumes for the intersection have been supplied by the Queensland Department of Transport and Main Roads and are shown in Table 4.2 and 4.3.

Table 4.2: Gowrie Junction Road AM Peak Hour Traffic Volumes

| Intersection Leg | Warrego Highway East | | Warrego Highway West | | Gowrie Junction Road | |
|---|---|---|---|---|---|---|
| Movement | Through | Right Turn | Through | Left Turn | Left Turn | Right Turn |
| Vehicle Type | | | | | | |
| Passenger Car | 293 | 30 | 401 | 14 | 309 | 35 |
| Semi Trailer | 14 | 2 | 19 | 2 | 16 | 6 |
| B-Double | 16 | - | 21 | - | - | - |
| Type 1 Road Trains | 4 | - | 6 | - | - | - |

Table 4.3: Gowrie Junction Road PM Peak Hour Traffic Volumes

| Intersection Leg | Warrego Highway East | | Warrego Highway West | | Gowrie Junction Road | |
|---|---|---|---|---|---|---|
| Movement | Through | Right Turn | Through | Left Turn | Left Turn | Right Turn |
| Vehicle Type | | | | | | |
| Passenger Car | 393 | 316 | 399 | 34 | 89 | 13 |
| Semi Trailer | 19 | 18 | 18 | 5 | 4 | 2 |
| B-Double | 21 | - | 20 | - | - | - |
| Type 1 Road Trains | 6 | - | 6 | - | - | - |

### 4.5.1 SIDRA Output Using Current PCE Values

The current traffic data has been incorporated into a SIDRA simulation of the intersection. This simulation has been developed adopting the current practice outlined in the Austroads Guide to Traffic Management: Part 3. This involves assigning a passenger car equivalent value of 2.0 to each of the heavy vehicles in the vehicles in the queue. Figure 4.6 and 4.7 show the graphical output of the AM and PM peak traffic volumes entered into SIDRA.

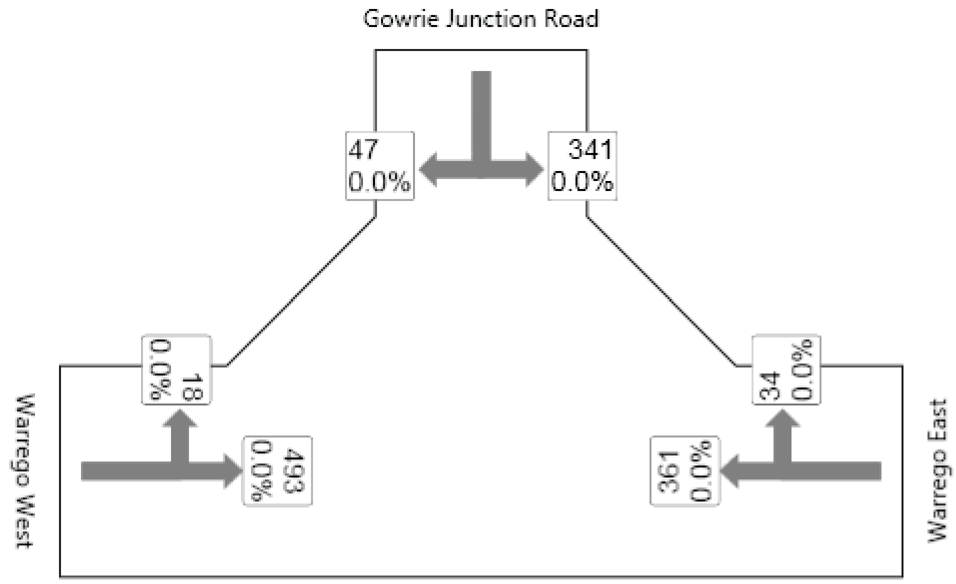



Figure 4.6: AM Peak Traffic Volumes Adopting a PCE of 2.0 for all Heavy Vehicles

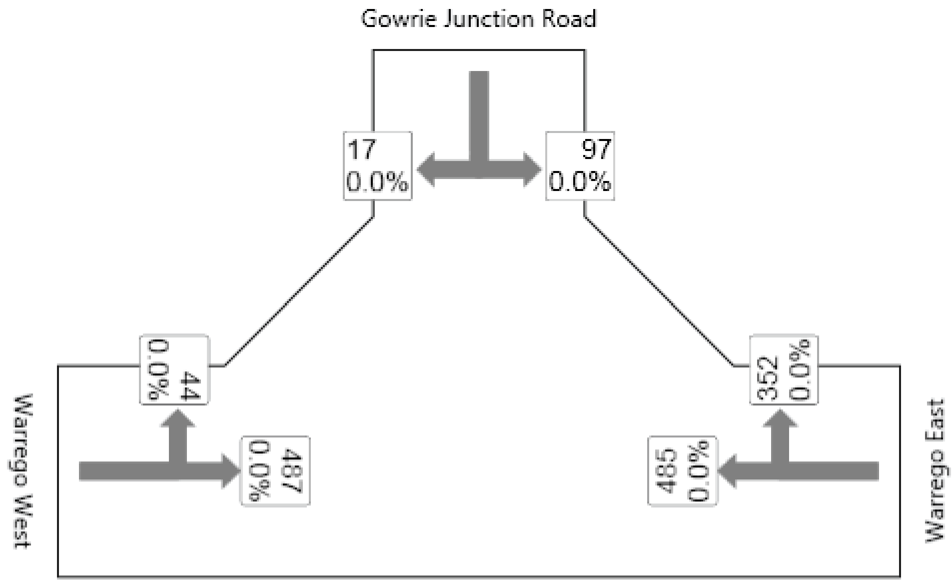



Figure 4.7: PM Peak Traffic Volumes Adopting a PCE of 2.0 for all Heavy Vehicles

Tables 4.4 and 4.5 provide a tabulation of the results of the intersection capacity analysis based on a 20 year design life of the intersection. SIDRA has determined a cycle time of 40s should be adopted for the AM peak hour traffic flow and 130s for the PM peak hour. SIDRA has determined that the intersection does not reach capacity within the 20 year design life for the AM peak hour but reaches capacity within 8 years for the PM peak hour.

Table 4.4: AM Peak SIDRA Intersection Results Adopting a PCE of 2.0 for all Heavy Vehicles

Intersection ID: 1
Fixed-Time Signals, Cycle Time = 40 sec (Practical Cycle Time)

| Lane No. | Effective Red and Green Times (sec) R1 | G1 | R2 | G2 | Dem Flow veh/h | Cap veh/h | Deg. Satn x | Aver. Delay sec | Eff. Stop Rate | Queue 95% Back veh | m | Lane Length m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **East: Warrego East** | | | | | | | | | | | | |
| 1 T | 18 | 22 | 0 | 0 | 760 | 1084 | 0.701 | 7.9 | 0.72 | 11.6 | 81.4 | 500.0 |
| 2 R | 24 | 16 | 0 | 0 | 72 | 325 | 0.220 | 19.1 | 0.76 | 1.0 | 7.0 | 170.0T |
| **North: Gowrie Junction Road** | | | | | | | | | | | | |
| 1 L | 0 | 40 | 0 | 0 | 718 | 1876 | 0.383 | 7.6 | 0.60 | | | 60.0T |
| 2 R | 34 | 6 | 0 | 0 | 99 | 281 | 0.352 | 27.0 | 0.76 | 1.9 | 13.2 | 500.0 |
| **West: Warrego West** | | | | | | | | | | | | |
| 1 L | 6 | 6 | 6 | 22 | 38 | 1226 | 0.031 | 10.8 | 0.69 | 0.1 | 0.8 | 120.0T |
| 2 T | 18 | 22 | 0 | 0 | 519 | 1073 | 0.484 | 6.1 | 0.57 | 6.4 | 44.5 | 500.0 |
| 3 T | 18 | 22 | 0 | 0 | 519 | 1073 | 0.484 | 6.1 | 0.57 | 6.4 | 44.5 | 500.0 |

T Short lane due to specification of Turn Bay

Table 4.5: AM Peak SIDRA Intersection Results Adopting a PCE of 2.0 for all Heavy Vehicles

Intersection ID: 1
Fixed-Time Signals, Cycle Time = 130 sec (User-given Cycle Time)

| Lane No. | Effective Red and Green Times (sec) R1 | G1 | R2 | G2 | Dem Flow veh/h | Cap veh/h | Deg. Satn x | Aver. Delay sec | Eff. Stop Rate | Queue 95% Back veh | m | Lane Length m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **East: Warrego East** | | | | | | | | | | | | |
| 1 T | 18 | 112 | 0 | 0 | 715 | 1697 | 0.421 | 2.0 | 0.22 | 9.6 | 67.0 | 500.0 |
| 2 R | 22 | 108 | 0 | 0 | 519 | 578 | 0.898 | 48.0 | 0.95 | 33.3* | 233.4 | 170.0T |
| **North: Gowrie Junction Road** | | | | | | | | | | | | |
| 1 L | 0 | 130 | 0 | 0 | 143 | 1876 | 0.076 | 7.6 | 0.60 | | | 60.0T |
| 2 R | 124 | 6 | 0 | 0 | 25 | 87 | 0.289 | 77.9 | 0.71 | 1.6 | 11.5 | 500.0 |
| **West: Warrego West** | | | | | | | | | | | | |
| 1 L | 6 | 6 | 10 | 108 | 65 | 852 | 0.076 | 10.4 | 0.68 | 0.3 | 2.3 | 120.0T |
| 2 T | 18 | 112 | 0 | 0 | 359 | 1680 | 0.214 | 1.6 | 0.16 | 3.7 | 26.2 | 500.0 |
| 3 T | 18 | 112 | 0 | 0 | 359 | 1680 | 0.214 | 1.6 | 0.16 | 3.7 | 26.2 | 500.0 |

* Percentile Queue length exceeds short lane length.
For calculation of this statistic, you may specify the lane with full length.
T Short lane due to specification of Turn Bay

### 4.5.2 SIDRA Output Using Project Results

The current traffic flows at the intersection have also been entered into SIDRA using the passenger car equivalent values derived in this project. As this project has only developed passenger car equivalent values for through traffic movements the current practice of adopting a PCE value of 2.0 will be used for all turning movements.

The passenger car equivalent values required for each of the through movements have been based on the following:

- Warrego Highway East
  - Roadway Grade = -2%
  - AM Traffic flow in lane (based on 20 year design life) = 777veh/h
  - PM Traffic flow in lane (based on 20 year design life) = 1043 veh/h
  - Proportion of heavy vehicles = 11%
- Warrego Highway West
  - Roadway Grade = 2%
  - AM Traffic flow in each lane (based on 20 year design life) = 532veh/h

- PM Traffic flow in each lane (based on 20 year design life) = 530 veh/h
- Proportion of heavy vehicles = 11%

From Appendix C the passenger car equivalent values that have been adopted for each movement are as follows:

- Warrego Highway East
    - AM Peak
        - Semi Trailer = 1.4 veh
        - B-Double = 1.5 veh
        - Type 1 Road Train = 1.7 veh
    - PM Peak
        - Semi Trailer = 2.5 veh
        - B-Double = 2.9 veh
        - Type 1 Road Train = 2.9 veh
- Warrego Highway West
    - AM Peak
        - Semi Trailer = 1.6 veh
        - B-Double = 2.4 veh
        - Type 1 Road Train = 2.7 veh
    - PM Peak
        - Semi Trailer = 1.6 veh
        - B-Double = 2.4 veh
        - Type 1 Road Train = 2.7 veh

The equivalent flow of passenger cars for each of the movements for the AM and PM peak is shown in Figure 4.8 and 4.9.

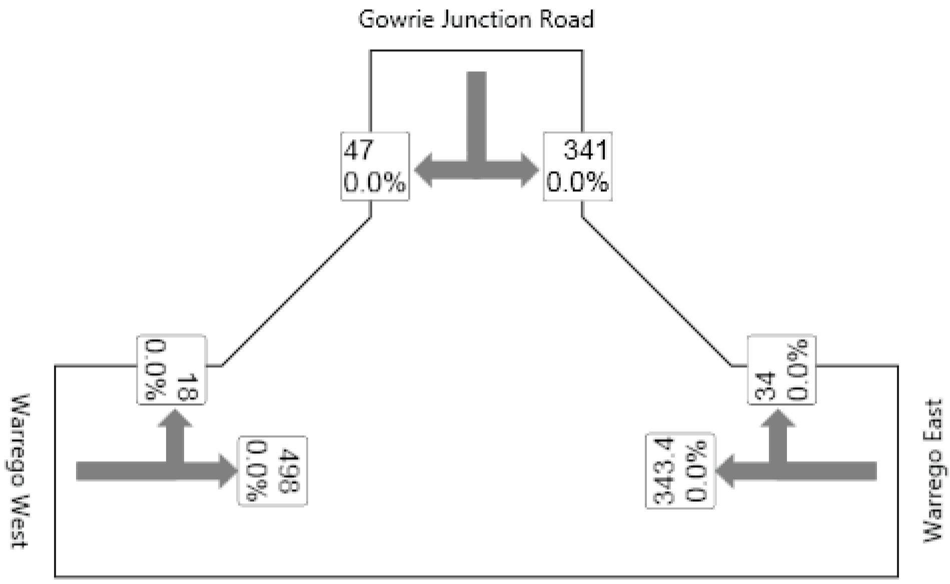



Figure 4.8: AM Peak Traffic Volumes Adopting Project Results

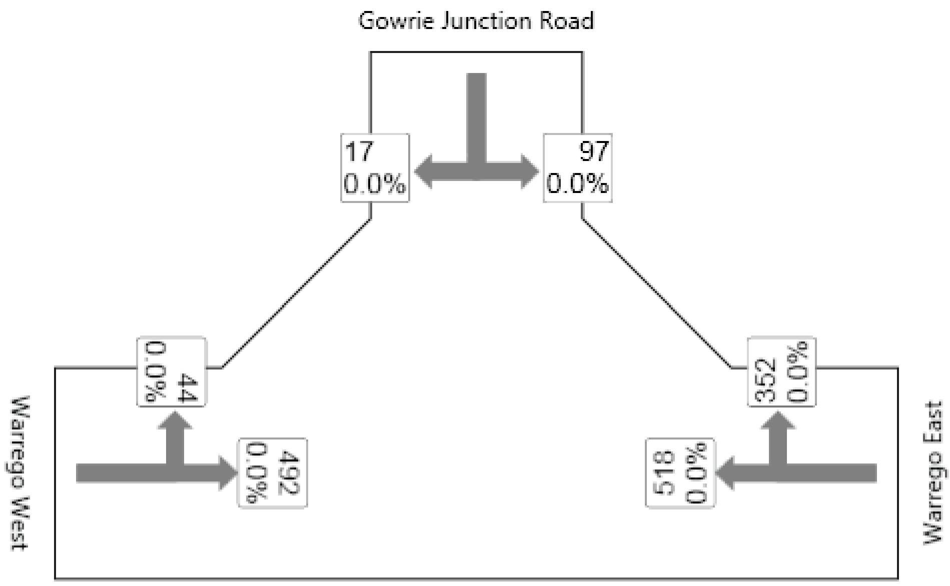



Figure 4.9: PM Peak Traffic Volumes Adopting Project Results

Tables 4.6 and 4.7 provide a tabulation of the results of the intersection capacity analysis based on a 20 year design life of the intersection. SIDRA has determined a cycle time of 40s should be adopted for the AM peak hour traffic flow and 140s for the PM peak hour. To maintain consistency with the results using the current practice a peak hour cycle time of 130 seconds was adopted for the PM peak. SIDRA has determined that the intersection does not reach capacity within the 20 year design life for the AM peak hour but reaches capacity within 8 years for the PM peak hour.

Table 4.6: AM Peak SIDRA Intersection Results Adopting Project Results

Intersection ID: 1
Fixed-Time Signals, Cycle Time = 40 sec (Practical Cycle Time)

| Lane No. | Effective Red and Green Times (sec) R1 | G1 | R2 | G2 | Dem Flow veh/h | Cap veh/h | Deg. Satn x | Aver. Delay sec | Eff. Stop Rate | Queue 95% Back veh | m | Lane Length m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| East: Warrego East | | | | | | | | | | | | |
| 1 T | 18 | 22 | 0 | 0 | 723 | 1084 | 0.667 | 7.2 | 0.68 | 12.0 | 84.0 | 500.0 |
| 2 R | 24 | 16 | 0 | 0 | 72 | 322 | 0.222 | 19.2 | 0.76 | 1.5 | 10.7 | 170.0T |
| North: Gowrie Junction Road | | | | | | | | | | | | |
| 1 L | 0 | 40 | 0 | 0 | 718 | 1876 | 0.383 | 7.6 | 0.60 | | | 60.0T |
| 2 R | 34 | 6 | 0 | 0 | 99 | 281 | 0.352 | 27.0 | 0.76 | 2.8 | 19.4 | 500.0 |
| West: Warrego West | | | | | | | | | | | | |
| 1 L | 6 | 6 | 6 | 22 | 38 | 1226 | 0.031 | 10.8 | 0.69 | 0.2 | 1.4 | 120.0T |
| 2 T | 18 | 22 | 0 | 0 | 524 | 1073 | 0.489 | 6.1 | 0.57 | 8.1 | 56.9 | 500.0 |
| 3 T | 18 | 22 | 0 | 0 | 524 | 1073 | 0.489 | 6.1 | 0.57 | 8.1 | 56.9 | 500.0 |

T Short lane due to specification of Turn Bay

Table 4.7: PM Peak SIDRA Intersection Results Adopting Project Results

Intersection ID: 1
Fixed-Time Signals, Cycle Time = 130 sec (User-given Cycle Time)

| Lane No. | Effective Red and Green Times (sec) R1 | G1 | R2 | G2 | Dem Flow veh/h | Cap veh/h | Deg. Satn x | Aver. Delay sec | Eff. Stop Rate | Queue 95% Back veh | m | Lane Length m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| East: Warrego East | | | | | | | | | | | | |
| 1 T | 18 | 112 | 0 | 0 | 736 | 1697 | 0.434 | 2.1 | 0.22 | 10.0 | 70.2 | 500.0 |
| 2 R | 21 | 109 | 0 | 0 | 500 | 591 | 0.847 | 31.4 | 0.88 | 23.9 | 167.2 | 170.0T |
| North: Gowrie Junction Road | | | | | | | | | | | | |
| 1 L | 0 | 130 | 0 | 0 | 138 | 1876 | 0.073 | 7.6 | 0.60 | | | 60.0T |
| 2 R | 124 | 6 | 0 | 0 | 24 | 87 | 0.279 | 77.8 | 0.71 | 1.6 | 11.0 | 500.0 |
| West: Warrego West | | | | | | | | | | | | |
| 1 L | 6 | 6 | 10 | 108 | 63 | 861 | 0.073 | 10.4 | 0.68 | 0.3 | 2.2 | 120.0T |
| 2 T | 18 | 112 | 0 | 0 | 350 | 1680 | 0.208 | 1.6 | 0.16 | 3.6 | 25.4 | 500.0 |
| 3 T | 18 | 112 | 0 | 0 | 350 | 1680 | 0.208 | 1.6 | 0.16 | 3.6 | 25.4 | 500.0 |

T Short lane due to specification of Turn Bay

### 4.5.3 Impact on Signalised Intersection Capacity

The traffic volumes that were derived for each of the methods analysed have been shown to remain similar for the western leg of the intersection with an increase of 1% for both the AM and PM peak hour volumes using the PCE values derived in this project. The traffic volumes derived for the eastern leg of the intersection resulted in a decrease of 4.9% in the AM peak and an increase of 6.8% in the PM peak hour.

The impact of each method analysed in SIDRA has been determined by comparing the following performance criteria from the SIDRA results:

- Degree of Saturation
- Average Delay

The degree of saturation of the intersection is the ration of the traffic flow to the movement capacity. The degree of saturation indicates the proportion of the capacity used by each movement. The SIDRA results generated show the following changes in capacity by adopting the passenger car equivalent values derived using this project:

- AM Peak
  - 3.4% increase in available capacity for traffic on the Warrego East leg of the intersection.
  - 0.5% decrease in available capacity for traffic on the Warrego West leg of the intersection.
- PM Peak
  - 1.3% decrease in available capacity for traffic on the Warrego East leg of the intersection.
  - 0.6% increase in available capacity for traffic on the Warrego West leg of the intersection.

The average delay is the average delay of all the vehicles undertaking the movement. The average delay includes both vehicles that form part of a queue and those that travel through the intersection without delay. The SIDRA results generated show the following changes in the average delay experienced for each movement:

- AM Peak
  - 8.9% decrease in average delay for traffic on the Warrego East leg of the intersection.
  - No change in average delay for traffic on the Warrego West leg of the intersection.
- PM Peak
  - 5.0% increase in average delay for traffic on the Warrego East leg of the intersection.

- No Change in average delay for traffic on the Warrego West leg of the intersection.

The results have shown that the passenger car equivalent values derived in this project have had both a positive and negative influence on the performance criteria analysed. This will bring about differences in the optimum cycle times calculated by SIDRA as was shown with the PM peak cycle time increasing from 130s to 140s. The change in cycle time will be more representative of the traffic conditions experienced and will reduce the overall delay experienced by the motorist at the intersection.

# 5.0 Simulation Verification

## *5.1 Data collected from Site Observations*

To verify the data that has been produced by the simulation passenger car equivalent values have been calculated manually using the traffic camera videos obtained from the Queensland Department of Transport and Main Roads. This has been undertaken at the following intersection sites:

- James Street and Ruthven Street
- James Street and Anzac Avenue

These intersection sites were selected as they provided the best observations for the through traffic movements.

The data collected was required to meet conditions to ensure that it would be suitable for the model verification purpose. The requirements for the site are as follows:

- At each site being investigated a traffic stream containing only passenger cars was required for use with the capacity method for determining passenger car equivalent values.
- The mixed traffic flow in the observation is to contain only one type of heavy vehicle. The capacity method calculates passenger car equivalent values for one type of heavy vehicle at a time.
- The time measured between the first and last vehicle in the flow of cars is required to be equal to or greater than that of the mixed traffic flow.

To determine the flow of vehicles for the results verification the time that each vehicle crossed a linemarking feature at each site was recorded. This has been used to calculate the flow rate of the traffic stream for both the flow of cars and the mixed traffic flow.

### 5.1.1 Verification at James Street and Ruthven Street

The traffic flow at the intersection of James Street and Ruthven was observed with equivalent flow of cars and the mixed traffic flow recorded. The data in Table 5.1 was collected on the eastbound traffic lane on James Street which is on an upgrade of approximately 0.4%.

Table 5.1: James Street and Ruthven Street Observations

| James Street and Ruthven | | | | | |
|---|---|---|---|---|---|
| Vehicle | Flow of Cars | Mixed Traffic Flow 1 | | Mixed Traffic Flow 2 | |
| | Time (s) | Time (s) | Vehicle Type | Time (s) | Vehicle Type |
| 1 | 0 | 0 | Car | 0 | Car |
| 2 | 1.28 | 1.44 | Car | 2.08 | Car |
| 3 | 2.72 | 3.28 | Car | 9.92 | B-Double |
| 4 | 4.4 | 5.28 | Car | 12.24 | Car |
| 5 | 6.96 | 7.12 | Car | 13.64 | Car |
| 6 | 8.48 | 14.96 | B-Double | 15.04 | Car |
| 7 | 10.24 | 17.6 | Car | 17.36 | Car |
| 8 | 12.16 | - | - | - | - |
| 9 | 13.84 | - | - | - | - |
| 10 | 16.24 | - | - | - | - |
| 11 | 17.92 | - | - | - | - |
| 12 | 20.72 | - | - | - | - |
| 13 | 23.04 | - | - | - | - |
| 14 | 25.44 | - | - | - | - |

<u>Observed Mixed Traffic Flow 1</u>

Calculating the equivalent flow of cars based on the number of cars passing through the intersection before the last vehicle in the mixed traffic flow:

$$q_C = \frac{10}{16.24} \times 3600$$
$$q_C = 2217 \; veh / hour$$

Calculating the mixed traffic flow:

$$q_M = \frac{7}{17.6} \times 3600$$
$$q_M = 1432 \; veh / hour$$

Calculating the proportion of heavy vehicles:

$$P_T = \frac{1}{7}$$
$$P_T = 0.143$$
$$P_T = 14.3\%$$

From Equation 2.8 the passenger car equivalent

$$E_T = 1 + \frac{(q_C / q_M - 1)}{P_T}$$
$$E_T = 1 + \frac{(2217/1432 - 1)}{0.143}$$
$$E_T = 4.83\, veh$$

By interpolating the Semi-Trailer results obtained from the simulation for 0% and 2% upgrades the passenger car equivalent value predicted for the mixed traffic volume is 3.74 vehicles.

<u>Observed Mixed Traffic Flow 2</u>

Calculating the equivalent flow of cars based on the number of cars passing through the intersection before the last vehicle in the mixed traffic flow:

$$q_C = \frac{10}{16.24} \times 3600$$
$$q_C = 2217\ veh/hour$$

Calculating the mixed traffic flow:

$$q_M = \frac{7}{17.36} \times 3600$$
$$q_M = 1452\ veh/hour$$

Calculating the proportion of heavy vehicles:

$$P_T = \frac{1}{7}$$
$$P_T = 0.143$$
$$P_T = 14.3\%$$

From Equation 2.8 the passenger car equivalent

$$E_T = 1 + \frac{(q_C / q_M - 1)}{P_T}$$
$$E_T = 1 + \frac{(2217/1452 - 1)}{0.143}$$
$$E_T = 4.68\, veh$$

By interpolating the Semi-Trailer results obtained from the simulation for 0% and 2% upgrades the passenger car equivalent value predicted for the mixed traffic volume is 3.74 vehicles.

### 5.1.2 Verification at James Street and Anzac Avenue

The traffic flow at the intersection of James Street and Anzac Avenue was observed with equivalent flow of cars and the mixed traffic flow recorded. The data in Table 5.2 was collected on the westbound traffic lane on James Street which is on an upgrade of approximately 2.6%.

Table 5.2: James Street and Anzac Avenue Observations

| James Street and Anzac Avenue | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Flow of Cars | Mixed Traffic Flow 1 | | Mixed Traffic Flow 2 | | Mixed Traffic Flow 3 | |
| Vehicle | Time (s) | Time (s) | Vehicle Type | Time (s) | Vehicle Type | Time (s) | Vehicle Type |
| 1 | 0 | 0 | Car | 0 | Car | 0 | Car |
| 2 | 1.84 | 5.12 | Semi Trailer | 5.52 | Semi Trailer | 1.84 | Car |
| 3 | 2.96 | 7.36 | Car | 7.68 | Car | 3.68 | Car |
| 4 | 4.56 | 9.34 | Car | 9.52 | Car | 4.88 | Car |
| 5 | 6.08 | 11.04 | Car | 11.04 | Car | 12.56 | Semi Trailer |
| 6 | 8.32 | 14.65 | Semi Trailer | 12.4 | Car | 14.32 | Car |
| 7 | 10.16 | 18.49 | Car | 13.92 | Car | 15.68 | Car |
| 8 | 11.52 | 21.85 | Car | 16.32 | Car | 17.12 | Car |
| 9 | 13.76 | 23.72 | Car | 18.4 | Car | - | - |
| 10 | 16 | - | - | - | - | - | - |
| 11 | 17.12 | - | - | - | - | - | - |
| 12 | 18.8 | - | - | - | - | - | - |
| 13 | 21.52 | - | - | - | - | - | - |
| 14 | 23.6 | - | - | - | - | - | - |
| 15 | 26 | - | - | - | - | - | - |

Observed Mixed Traffic Flow 1

Calculating the equivalent flow of cars based on the number of cars passing through the intersection before the last vehicle in the mixed traffic flow:

$$q_C = \frac{14}{23.6} \times 3600$$
$$q_C = 2136 \; veh / hour$$

Calculating the mixed traffic flow:

$$q_M = \frac{9}{23.72} \times 3600$$
$$q_M = 1366 \; veh / hour$$

Calculating the proportion of heavy vehicles:

$$P_T = \frac{2}{9}$$
$$P_T = 0.222$$
$$P_T = 22\%$$

From Equation 2.8 the passenger car equivalent

$$E_T = 1 + \frac{(q_C / q_M - 1)}{P_T}$$
$$E_T = 1 + \frac{(2136/1366 - 1)}{0.222}$$
$$E_T = 3.54 \; veh$$

By interpolating the Semi-Trailer results obtained from the simulation for 2% and 5% upgrades the passenger car equivalent value predicted for the mixed traffic volume is 3.46 vehicles.

Observed Mixed Traffic Flow 2

Calculating the equivalent flow of cars based on the number of cars passing through the intersection before the last vehicle in the mixed traffic flow:

$$q_C = \frac{11}{17.12} \times 3600$$
$$q_C = 2313 \; veh / hour$$

Calculating the mixed traffic flow:

$$q_M = \frac{9}{18.4} \times 3600$$
$$q_M = 1761 \, veh/hour$$

Calculating the proportion of heavy vehicles:

$$P_T = \frac{1}{9}$$
$$P_T = 0.111$$
$$P_T = 11\%$$

From Equation 2.8 the passenger car equivalent

$$E_T = 1 + \frac{(q_C / q_M - 1)}{P_T}$$
$$E_T = 1 + \frac{(2313/1761 - 1)}{0.111}$$
$$E_T = 3.83 \, veh$$

By interpolating the Semi-Trailer results obtained from the simulation for 2% and 5% upgrades the passenger car equivalent value predicted for the mixed traffic volume is 3.76 vehicles.

<u>Observed Mixed Traffic Flow 3</u>

Calculating the equivalent flow of cars based on the number of cars passing through the intersection before the last vehicle in the mixed traffic flow:

$$q_C = \frac{11}{17.12} \times 3600$$
$$q_C = 2313 \, veh/hour$$

Calculating the mixed traffic flow:

$$q_M = \frac{8}{17.12} \times 3600$$
$$q_M = 1682 \, veh/hour$$

Calculating the proportion of heavy vehicles:

$$P_T = \frac{1}{8}$$
$$P_T = 0.125$$
$$P_T = 12.5\%$$

From Equation 2.8 the passenger car equivalent

$$E_T = 1 + \frac{(q_C / q_M - 1)}{P_T}$$
$$E_T = 1 + \frac{(2313/1682 - 1)}{0.125}$$
$$E_T = 4.0\ veh$$

By interpolating the Semi-Trailer results obtained from the simulation for 2% and 5% upgrades the passenger car equivalent value predicted for the mixed traffic volume is 3.76 vehicles.

## *5.2 Results of Simulation Verification*

The results that have been developed from the observations at existing traffic signal installations have been compared to those obtained from the MATLAB simulation. The comparison has shown a difference in results of between 1.9 and 6.4% for the Semi-Trailer and 23.8 and 29.1% for the B-Double observations.

The results generated from the site observations are limited however as they only calculate the passenger car equivalent value for a single queue of vehicles discharging at the signalised intersection. This is not representative of conditions where the heavy vehicles can travel through the intersection without stopping which would reduce the passenger car equivalent value derived. However these values can be used as a guide to confirm the values derived by the simulation are in the same vicinity.

# 6.0 Conclusion

This dissertation set out to develop a set of passenger car equivalent values for heavy vehicles at signalised intersections. Passenger car equivalent values for traffic signals vary from those derived for free flow conditions because the heavy vehicles are required to stop and then accelerate back up to speed. The passenger car equivalent values in this project have been derived for the heavy vehicle types in use on Queensland roads.

A MATLAB simulation was developed to simulate the traffic flow of a through lane of a signalised intersection. The model was developed using data collected on driver behaviour and vehicle operating characteristics. The MATLAB simulation compares the mixed traffic flow with a traffic flow of only cars to determine the passenger car equivalent values for each vehicle type using the capacity method.

The results developed as part of this project have shown that the vehicle type, roadway and traffic conditions all influence the impact each heavy vehicle has on intersection capacity. Using the MATLAB simulation a set of tables for each vehicle type have been derived that can be used as a reference when undertaking traffic signal capacity analysis.

It has been shown that the current practice of adopting a single passenger car equivalent value for the heavy vehicle types at signalised intersections does not accurately reflect the conditions experienced on the roadway. As shown in the SIDRA analysis the results of this project can have both a positive and negative impact on the intersection capacity when compared to existing methods. This can result in either an increase or a reduction in the design life of the intersection depending on the roadway and traffic conditions experienced.

Without accurately accounting for the traffic conditions intersections can reach their design life before they are expected to do so. This can result in large delays experienced and in extreme cases may require costly remedial treatment to the intersection to ensure the traffic flows with an appropriate level of service.

## *6.1 Further Research and Recommendations*

The simulation developed in this project has been based on through traffic movements at signalised intersections. The result of this research has shown that the current practice does not accurately reflect the impact of heavy vehicles in determining signalised intersection capacity.

While at the majority of intersection sites the heavy vehicles analysed in this project are restricted to travelling in the through movements there are cases such as the intersection of two highways where turning movements are able to be undertaken. The results that have been obtained do not reflect these situations and further research into heavy vehicle turning manoeuvres is required. This research could also be expanded to include intersection treatments other than traffic signal control such as roundabouts and give way situations.

The results generated from the MATLAB simulation have been developed using only a two phase traffic signal cycle. The phasing system adopted in this project results in the through lane movement having a capacity of 864 passenger cars per hour. Other phasing systems such as diamond turns and split phases would have an influence on the intersection capacity and need to be analysed to determine their impact on the passenger car equivalent values for each heavy vehicle.

As my results have shown adopting a single passenger car equivalent value for heavy vehicles at signalised intersections does not reflect actual roadway conditions. My recommendations from this project are as follows:

- Use the set of tables showing passenger car equivalent values for different vehicle types, traffic and roadway conditions in Appendix C as a reference when undertaking traffic signal capacity analysis.
- Incorporate the ability to assign different passenger car equivalent values for each vehicle type in traffic signal timing and capacity software such as SIDRA which has been used in this project. This is less critical however as it is felt that the manual calculation of the equivalent number of passenger cars as shown in section 4.5.1 will provide reasonable results.

### 6.4 Summary

As traffic volumes and the number of heavy vehicles on Australia's highways increase the delays experienced by the motorist also increase. This is exaggerated at interrupted flow facilities such as signalised intersections.

This project is intended to introduce a more thorough approach to handling heavy vehicles in the analysis of signalized intersection capacity. By placing greater emphasis on the vehicle operating characteristics and roadway conditions than had previously been done so, it is felt that a more accurate representation of the effect of heavy vehicles can be obtained. It is anticipated that the use of the passenger car equivalent values developed in this project when undertaking intersection capacity analysis will result in improved traffic signal efficiency and reduce delays experienced by the motorist.

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# Appendix A – Project Specification

University of Southern Queensland

Faculty of Engineering and Surveying

# ENG4111/ENG4112 Research Project

# Project Specification

**FOR:** **Karl ZELLER**

**TOPIC:** Evaluation of operational characteristics of heavy vehicles at signalised intersections on highways in Queensland

**SUPERVISOR:** Soma Kathirgamalingam

**PROJECT AIM:** The project aims to develop a model to predict Passenger Car Equivalents (PCE) at signalised intersections for different classes of heavy vehicles in use on Queensland roads.

**PROGRAMME:** Issue A, 21 March 2011

1. Review literature relating to passenger car equivalents and Australian vehicle classification
2. Establish intersections for data collection
3. Collect data from intersections and collate
4. Investigate operating characteristics for heavy vehicles such as vehicle headway, length , gap acceptance and acceleration
5. Develop a model to determine discharge and speed for each heavy vehicle classification
6. Compare model results with that of passenger cars to determine PCE for each vehicle classification

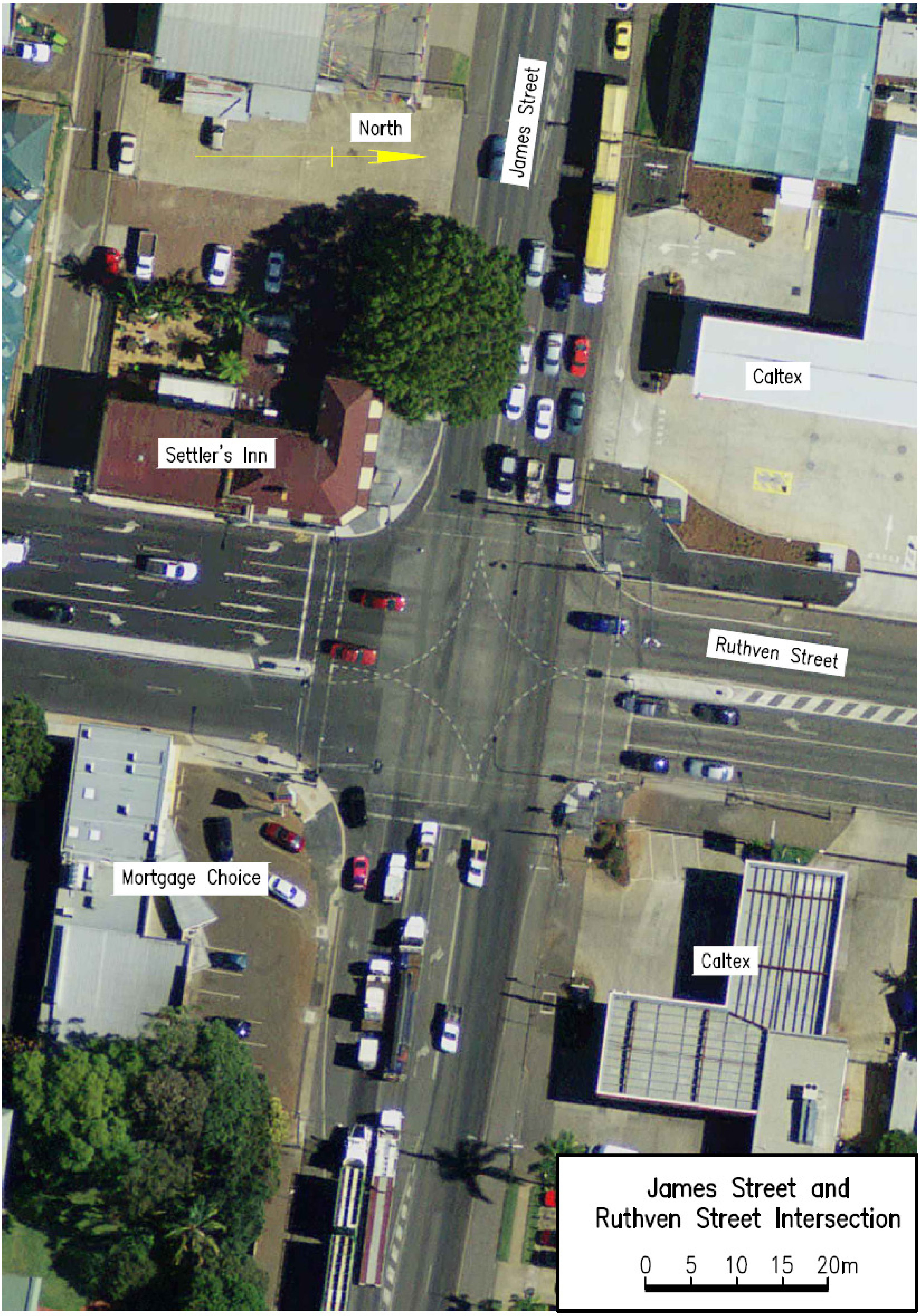
**AGREED:**

_____________________ (Student) _____________________ (Supervisor)

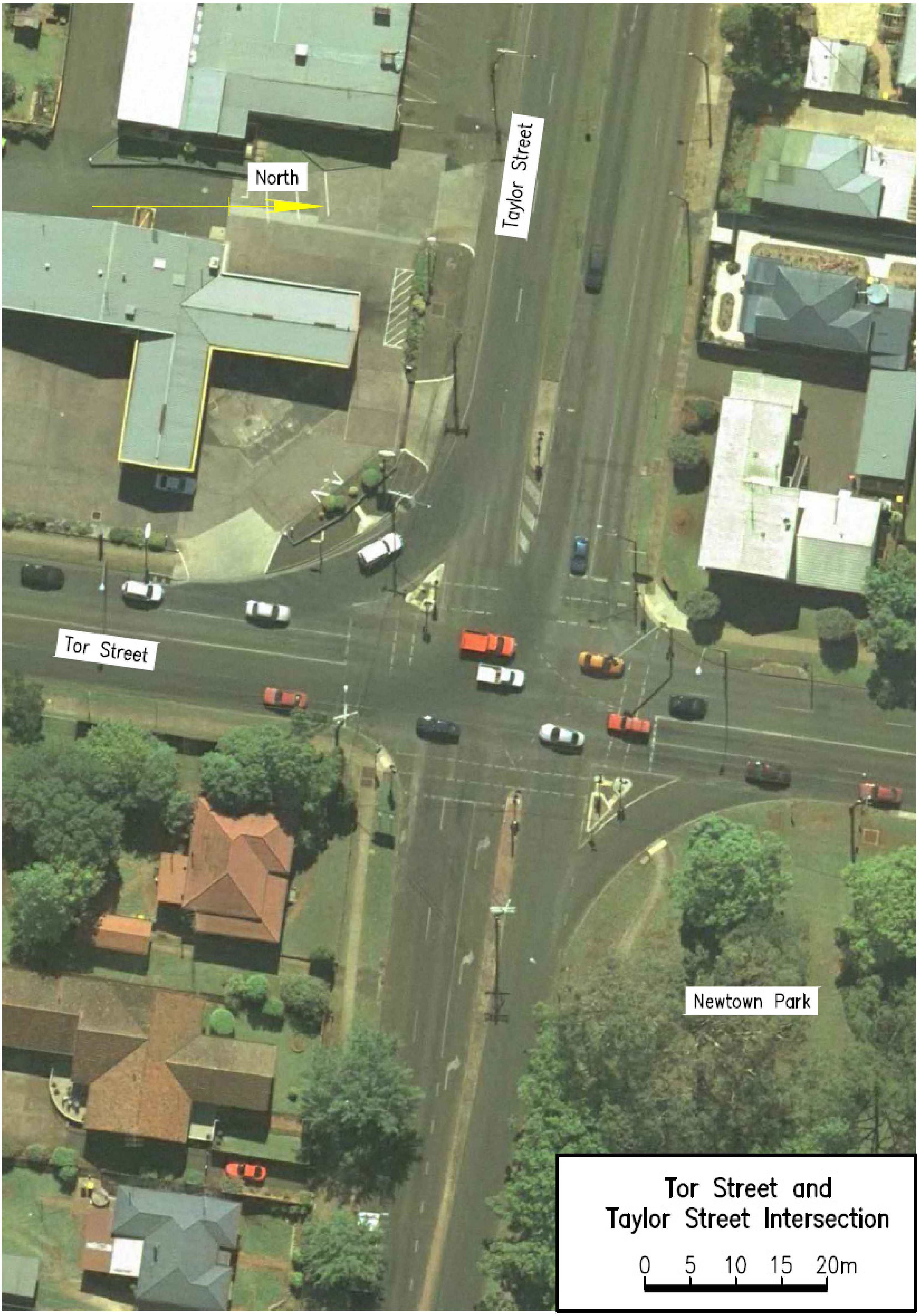
Date___/___/_____ Date___/___/_____

Examiner/Co-examiner _______________

# Appendix B – Intersection Layouts


North
James Street
Caltex
Settler's Inn
Ruthven Street
Mortgage Choice
Caltex
James Street and
Ruthven Street Intersection
0 5 10 15 20m


James Street and
Anzac Avenue Intersection


North
Taylor Street
Tor Street
Newtown Park
Tor Street and
Taylor Street Intersection
0 5 10 15 20m

# Appendix C – Passenger Car Equivalent Results

## *C.1 Passenger Car Equivalent Results for Semi Trailers*

### C.1.1 Roadway Grade -5%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.2 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 |
| 7% | 1.2 | 1.7 | 1.9 | 2.0 | 2.0 | 1.9 |
| 9% | 1.2 | 1.6 | 1.9 | 2.0 | 1.9 | 2.0 |
| 11% | 1.2 | 1.7 | 1.9 | 1.9 | 2.0 | 2.0 |
| 13% | 1.2 | 1.7 | 1.9 | 1.9 | 1.9 | 1.9 |
| 15% | 1.2 | 1.6 | 1.8 | 1.9 | 1.9 | 1.9 |

### C.1.2 Roadway Grade -2%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.3 | 2.2 | 2.7 | 2.8 | 2.8 | 2.8 |
| 7% | 1.3 | 2.1 | 2.6 | 2.6 | 2.8 | 2.7 |
| 9% | 1.3 | 2.2 | 2.4 | 2.5 | 2.5 | 2.5 |
| 11% | 1.4 | 2.0 | 2.5 | 2.5 | 2.6 | 2.6 |
| 13% | 1.4 | 2.1 | 2.4 | 2.4 | 2.4 | 2.5 |
| 15% | 1.6 | 2.2 | 2.3 | 2.4 | 2.4 | 2.4 |

### C.1.3 Roadway Grade 0%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.7 | 3.0 | 3.6 | 3.6 | 3.7 | 3.7 |
| 7% | 1.7 | 2.8 | 3.6 | 3.4 | 3.5 | 3.3 |
| 9% | 1.7 | 2.8 | 3.1 | 3.2 | 3.2 | 3.3 |
| 11% | 1.6 | 2.6 | 2.9 | 3.0 | 3.2 | 3.1 |
| 13% | 1.7 | 2.6 | 2.8 | 2.9 | 2.9 | 3.0 |
| 15% | 1.7 | 2.5 | 2.7 | 2.8 | 2.9 | 2.9 |

### C.1.4 Roadway Grade 2%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.8 | 3.5 | 4.4 | 4.6 | 4.3 | 4.5 |
| 7% | 2.0 | 3.4 | 4.0 | 4.0 | 4.0 | 4.0 |
| 9% | 1.9 | 3.2 | 3.6 | 3.7 | 3.7 | 3.8 |
| 11% | 1.6 | 2.8 | 3.4 | 3.5 | 3.5 | 3.6 |
| 13% | 1.8 | 2.9 | 3.3 | 3.2 | 3.3 | 3.5 |
| 15% | 1.8 | 2.6 | 3.1 | 3.0 | 3.2 | 3.2 |

### C.1.5 Roadway Grade 5%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 3.7 | 5.6 | 6.3 | 6.3 | 6.7 | 6.2 |
| 7% | 3.1 | 4.9 | 5.7 | 6.2 | 6.0 | 5.5 |
| 9% | 3.2 | 4.6 | 5.1 | 5.4 | 5.3 | 5.6 |
| 11% | 3.1 | 4.4 | 4.9 | 5.1 | 5.0 | 5.3 |
| 13% | 2.8 | 3.9 | 4.5 | 4.5 | 4.9 | 4.8 |
| 15% | 2.8 | 3.8 | 4.3 | 4.4 | 4.5 | 4.5 |

## *C.2 Passenger Car Equivalent Results for B-Doubles*

### C.2.1 Roadway Grade -5%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.3 | 1.7 | 2.2 | 2.2 | 2.3 | 2.5 |
| 7% | 1.3 | 1.8 | 2.1 | 2.2 | 2.3 | 2.5 |
| 9% | 1.3 | 1.8 | 2.3 | 2.2 | 2.2 | 2.3 |
| 11% | 1.2 | 1.9 | 2.2 | 2.2 | 2.2 | 2.2 |
| 13% | 1.3 | 1.9 | 2.2 | 2.2 | 2.2 | 2.2 |
| 15% | 1.2 | 1.9 | 2.1 | 2.2 | 2.2 | 2.2 |

### C.2.2 Roadway Grade -2%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.5 | 2.7 | 3.1 | 3.4 | 3.1 | 3.5 |
| 7% | 1.5 | 2.8 | 3.2 | 3.1 | 3.2 | 3.1 |
| 9% | 1.6 | 2.5 | 2.9 | 3.1 | 2.9 | 3.0 |
| 11% | 1.5 | 2.4 | 2.9 | 2.9 | 3.1 | 2.9 |
| 13% | 1.6 | 2.5 | 2.7 | 2.9 | 2.9 | 2.8 |
| 15% | 1.8 | 2.5 | 2.8 | 2.9 | 2.9 | 2.8 |

### C.2.3 Roadway Grade 0%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.9 | 3.5 | 4.2 | 4.3 | 4.4 | 4.4 |
| 7% | 2.0 | 3.6 | 3.8 | 3.9 | 4.0 | 4.1 |
| 9% | 1.7 | 3.2 | 3.8 | 3.9 | 3.8 | 3.9 |
| 11% | 1.8 | 3.1 | 3.8 | 3.6 | 3.6 | 3.8 |
| 13% | 1.9 | 3.1 | 3.4 | 3.3 | 3.5 | 3.6 |
| 15% | 2.0 | 2.9 | 3.3 | 3.3 | 3.5 | 3.3 |

### C.2.4 Roadway Grade 2%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 2.4 | 4.4 | 5.4 | 5.4 | 5.4 | 5.5 |
| 7% | 2.7 | 4.0 | 4.7 | 4.9 | 5.2 | 5.3 |
| 9% | 2.5 | 4.0 | 4.6 | 4.7 | 5.2 | 4.8 |
| 11% | 2.4 | 4.0 | 4.2 | 4.3 | 4.3 | 4.6 |
| 13% | 2.6 | 3.6 | 4.3 | 4.1 | 4.2 | 4.2 |
| 15% | 2.5 | 3.5 | 3.8 | 4.0 | 4.1 | 4.0 |

### C.2.5 Roadway Grade 5%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 4.8 | 7.3 | 7.9 | 8.7 | 8.8 | 8.6 |
| 7% | 5.1 | 6.5 | 8.2 | 7.3 | 7.0 | 7.4 |
| 9% | 4.1 | 6.1 | 6.6 | 6.8 | 6.8 | 7.2 |
| 11% | 3.9 | 5.7 | 6.4 | 6.4 | 6.8 | 6.7 |
| 13% | 3.5 | 5.3 | 5.7 | 5.9 | 6.1 | 5.7 |
| 15% | 3.5 | 5.3 | 5.4 | 5.6 | 5.8 | 5.9 |

## *C.3 Passenger Car Equivalent Results for Type 1 Road Trains*

### C.3.1 Roadway Grade -5%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.4 | 2.2 | 2.4 | 2.6 | 2.6 | 2.5 |
| 7% | 1.3 | 2.1 | 2.6 | 2.4 | 2.5 | 2.6 |
| 9% | 1.3 | 2.1 | 2.4 | 2.5 | 2.5 | 2.6 |
| 11% | 1.3 | 2.2 | 2.4 | 2.4 | 2.5 | 2.5 |
| 13% | 1.5 | 2.0 | 2.4 | 2.4 | 2.5 | 2.4 |
| 15% | 1.5 | 2.2 | 2.4 | 2.4 | 2.3 | 2.4 |

### C.3.2 Roadway Grade -2%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.6 | 2.6 | 3.1 | 3.2 | 3.3 | 3.1 |
| 7% | 1.4 | 2.5 | 3.1 | 2.9 | 3.1 | 3.2 |
| 9% | 1.5 | 2.6 | 2.9 | 3.0 | 3.1 | 3.2 |
| 11% | 1.7 | 2.6 | 2.9 | 3.0 | 3.2 | 3.0 |
| 13% | 1.6 | 2.5 | 2.8 | 3.0 | 2.9 | 3.0 |
| 15% | 1.7 | 2.6 | 2.7 | 2.8 | 2.9 | 2.9 |

### C.3.3 Roadway Grade 0%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 2.0 | 3.7 | 4.3 | 4.3 | 4.6 | 4.2 |
| 7% | 2.0 | 3.6 | 4.4 | 4.2 | 4.0 | 4.2 |
| 9% | 2.0 | 3.3 | 3.9 | 4.1 | 4.0 | 4.1 |
| 11% | 2.0 | 3.1 | 3.7 | 3.8 | 3.8 | 3.9 |
| 13% | 2.1 | 3.0 | 3.5 | 3.5 | 3.6 | 3.4 |
| 15% | 2.2 | 3.1 | 3.5 | 3.4 | 3.5 | 3.6 |

### C.3.4 Roadway Grade 2%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 2.6 | 4.5 | 5.5 | 5.7 | 5.5 | 6.0 |
| 7% | 2.6 | 4.2 | 5.0 | 5.5 | 5.5 | 5.3 |
| 9% | 2.7 | 4.4 | 4.7 | 4.9 | 4.7 | 4.9 |
| 11% | 2.7 | 4.1 | 4.4 | 4.6 | 4.6 | 4.6 |
| 13% | 2.6 | 3.8 | 4.3 | 4.5 | 4.4 | 4.4 |
| 15% | 2.6 | 3.7 | 4.0 | 4.1 | 4.3 | 4.2 |

### C.3.5 Roadway Grade 5%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 4.7 | 7.6 | 8.0 | 8.3 | 9.3 | 8.3 |
| 7% | 4.4 | 7.0 | 7.4 | 8.2 | 7.7 | 7.7 |
| 9% | 4.3 | 6.1 | 6.8 | 7.3 | 6.9 | 7.4 |
| 11% | 4.0 | 6.0 | 6.5 | 6.7 | 6.7 | 6.6 |
| 13% | 4.1 | 5.5 | 6.2 | 6.1 | 6.4 | 6.4 |
| 15% | 3.7 | 5.1 | 5.6 | 5.7 | 5.9 | 6.0 |

## *C.4 Passenger Car Equivalent Results for Type 2 Road Trains*

### C.4.1 Roadway Grade -5%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 1.7 | 2.9 | 3.7 | 3.5 | 3.8 | 3.4 |
| 7% | 1.7 | 2.7 | 3.3 | 3.4 | 3.5 | 3.5 |
| 9% | 1.9 | 2.8 | 3.4 | 3.3 | 3.5 | 3.4 |
| 11% | 1.9 | 2.9 | 3.3 | 3.2 | 3.4 | 3.4 |
| 13% | 1.8 | 2.9 | 3.2 | 3.1 | 3.2 | 3.3 |
| 15% | 1.9 | 2.7 | 3.2 | 3.1 | 3.2 | 3.4 |

### C.4.2 Roadway Grade -2%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 2.1 | 4.1 | 4.8 | 4.7 | 4.7 | 4.9 |
| 7% | 2.4 | 4.1 | 4.5 | 4.6 | 4.8 | 5.0 |
| 9% | 2.6 | 4.2 | 4.3 | 4.7 | 4.5 | 4.7 |
| 11% | 2.6 | 3.8 | 4.2 | 4.5 | 4.5 | 4.4 |
| 13% | 2.6 | 3.7 | 4.4 | 4.3 | 4.3 | 4.4 |
| 15% | 2.7 | 3.9 | 4.0 | 4.3 | 4.1 | 4.2 |

### C.4.3 Roadway Grade 0%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 3.2 | 5.2 | 6.7 | 6.0 | 6.4 | 7.1 |
| 7% | 2.9 | 5.7 | 5.6 | 6.3 | 5.8 | 6.1 |
| 9% | 3.1 | 5.1 | 5.4 | 5.5 | 5.4 | 6.3 |
| 11% | 3.0 | 4.7 | 5.0 | 5.3 | 5.5 | 5.2 |
| 13% | 3.2 | 4.6 | 4.8 | 4.9 | 5.3 | 5.3 |
| 15% | 3.1 | 4.6 | 4.8 | 4.8 | 4.8 | 5.0 |

### C.4.4 Roadway Grade 2%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 4.5 | 7.2 | 8.2 | 7.6 | 8.5 | 8.4 |
| 7% | 4.2 | 6.5 | 7.2 | 7.7 | 7.6 | 7.9 |
| 9% | 4.3 | 6.8 | 7.4 | 7.4 | 7.1 | 7.4 |
| 11% | 4.5 | 6.1 | 6.5 | 7.0 | 6.9 | 6.8 |
| 13% | 4.5 | 5.8 | 6.0 | 6.3 | 6.6 | 6.7 |
| 15% | 4.1 | 5.5 | 5.9 | 6.0 | 6.5 | 6.3 |

### C.4.5 Roadway Grade 5%

| Proportion of Heavy Vehicles | Traffic Flow (Veh/hour) | | | | | |
|---|---|---|---|---|---|---|
| | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
| 5% | 8.2 | 12.1 | 13.3 | 13.0 | 13.3 | 12.4 |
| 7% | 7.4 | 11.2 | 12.0 | 13.2 | 12.7 | 11.3 |
| 9% | 8.2 | 10.3 | 11.4 | 11.6 | 10.4 | 11.4 |
| 11% | 7.0 | 9.3 | 10.1 | 11.0 | 10.7 | 11.1 |
| 13% | 7.1 | 9.1 | 9.4 | 9.9 | 10.3 | 10.2 |
| 15% | 6.6 | 8.5 | 8.6 | 9.1 | 9.8 | 9.6 |

# Appendix D – Headway Data

| | Vehicle 1 | | | Vehicle 2 | | | |
|---|---|---|---|---|---|---|---|
| Intersection | Type | Time Point 1 | Time Point 2 | Type | Time Point 1 | Speed (km/h) | Headway (s) |
| James St & Anzac Ave | Car | 33.87 | 36.27 | Car | 35.27 | 39.4 | 1.4 |
| James St & Anzac Ave | Car | 40.43 | 42.36 | Car | 42.03 | 49.1 | 1.6 |
| James St & Anzac Ave | Car | 38.95 | 41.35 | Car | 40.41 | 39.5 | 1.46 |
| James St & Anzac Ave | Car | 56.82 | 59.36 | Car | 58.36 | 37.3 | 1.54 |
| James St & Anzac Ave | Car | 1.49 | 3.89 | Car | 2.62 | 39.5 | 1.13 |
| James St & Anzac Ave | Car | 3.65 | 6.11 | Car | 5.58 | 38.5 | 1.93 |
| James St & Anzac Ave | Semi Trailer | 21.53 | 23.73 | Car | 22.73 | 43 | 1.2 |
| James St & Anzac Ave | Car | 22.73 | 27.53 | Car | 25.06 | 19.7 | 2.33 |
| James St & Anzac Ave | Car | 5.30 | 7.56 | Car | 7.16 | 41.9 | 1.86 |
| James St & Anzac Ave | Car | 17.13 | 19.33 | Car | 18.93 | 43 | 1.8 |
| James St & Anzac Ave | Car | 9.70 | 11.39 | Car | 12.03 | 56 | 2.33 |
| James St & Anzac Ave | Car | 12.03 | 13.95 | Car | 13.79 | 49.3 | 1.76 |
| James St & Anzac Ave | Car | 13.79 | 15.87 | Car | 16.27 | 45.5 | 2.48 |
| James St & Anzac Ave | Car | 55.75 | 58.87 | Semi Trailer | 59.19 | 30.3 | 3.44 |
| James St & Anzac Ave | Car | 35.99 | 38.71 | Car | 37.67 | 34.8 | 1.68 |
| James St & Anzac Ave | Car | 37.67 | 40.55 | Car | 38.95 | 32.9 | 1.28 |
| James St & Anzac Ave | Car | 38.95 | 41.75 | Car | 40.63 | 33.8 | 1.68 |
| James St & Anzac Ave | Car | 55.86 | 57.94 | Car | 57.62 | 45.5 | 1.76 |
| James St & Anzac Ave | Car | 57.62 | 59.70 | Car | 59.38 | 45.5 | 1.76 |
| James St & Anzac Ave | Semi Trailer | 1.22 | 3.14 | Car | 2.58 | 49.3 | 1.36 |
| James St & Anzac Ave | Semi Trailer | 54.00 | 56.64 | Semi Trailer | 58.16 | 35.9 | 4.16 |
| James St & Anzac Ave | Car | 59.40 | 62.12 | B-Double | 65.00 | 34.8 | 5.6 |
| James St & Anzac Ave | Car | 56.42 | 59.43 | B-Double | 62.79 | 31.5 | 6.37 |
| James St & Anzac Ave | Car | 51.84 | 56.28 | Semi Trailer | 56.84 | 21.3 | 5 |
| James St & Anzac Ave | B-Double | 45.38 | 48.42 | Semi Trailer | 49.54 | 31.1 | 4.16 |
| James St & Anzac Ave | Semi Trailer | 9.13 | 10.65 | Car | 10.73 | 62.3 | 1.6 |
| James St & Ruthven St | Semi Trailer | 43.21 | 45.37 | Semi Trailer | 48.42 | 28.2 | 5.21 |
| James St & Ruthven St | Semi Trailer | 49.34 | 51.74 | Semi Trailer | 53.58 | 25.4 | 4.24 |
| James St & Ruthven St | Car | 55.80 | 58.12 | Car | 58.52 | 26.2 | 2.72 |
| James St & Ruthven St | Car | 2.58 | 4.26 | Car | 4.02 | 36.2 | 1.44 |
| James St & Ruthven St | Car | 6.53 | 8.29 | Car | 8.05 | 34.6 | 1.52 |
| James St & Ruthven St | Car | 57.48 | 59.24 | Semi Trailer | 60.92 | 34.6 | 3.44 |
| James St & Ruthven St | Car | 9.38 | 11.06 | Semi Trailer | 12.90 | 36.2 | 3.52 |
| James St & Ruthven St | Semi Trailer | 12.90 | 14.42 | B-Double | 18.42 | 40 | 5.52 |
| James St & Ruthven St | Car | 7.61 | 9.05 | Car | 8.97 | 42.3 | 1.36 |
| James St & Ruthven St | Car | 23.89 | 25.57 | Semi Trailer | 27.41 | 36.2 | 3.52 |
| James St & Ruthven St | Car | 24.70 | 26.38 | B-Double | 30.22 | 36.2 | 5.52 |
| James St & Ruthven St | Car | 21.00 | 22.36 | B-Double | 25.64 | 44.7 | 4.64 |
| James St & Ruthven St | Car | 39.72 | 41.48 | Semi Trailer | 45.00 | 34.6 | 5.28 |
| James St & Ruthven St | Car | 19.47 | 21.23 | Semi Trailer | 23.55 | 34.6 | 4.08 |
| James St & Ruthven St | B-Double | 55.14 | 57.46 | B-Double | 60.66 | 26.2 | 5.52 |
| James St & Ruthven St | Car | 4.04 | 6.44 | B-Double | 10.52 | 25.4 | 6.48 |
| James St & Ruthven St | Car | 29.72 | 31.32 | B-Double | 34.52 | 38 | 4.8 |
| James St & Ruthven St | Car | 22.19 | 23.63 | Car | 24.03 | 42.3 | 1.84 |
| James St & Ruthven St | Car | 30.76 | 32.28 | Car | 32.20 | 40 | 1.44 |
| James St & Ruthven St | Car | 32.20 | 33.72 | Car | 33.88 | 40 | 1.68 |
| James St & Ruthven St | Car | 33.88 | 35.80 | Car | 36.20 | 31.7 | 2.32 |
| James St & Ruthven St | Car | 36.20 | 38.12 | Semi Trailer | 41.16 | 31.7 | 4.96 |
| James St & Ruthven St | Car | 40.49 | 42.09 | Car | 42.01 | 38 | 1.52 |
| James St & Ruthven St | Semi Trailer | 48.17 | 49.77 | Car | 50.49 | 38 | 2.32 |

| Intersection | Vehicle 1 | | | Vehicle 2 | | Speed (km/h) | Headway (s) |
|---|---|---|---|---|---|---|---|
| | Type | Time Point 1 | Time Point 2 | Type | Time Point 1 | | |
| James St & Ruthven St | Car | 29.13 | 30.81 | Car | 30.89 | 36.2 | 1.76 |
| James St & Ruthven St | Car | 30.89 | 32.49 | Car | 33.21 | 38 | 2.32 |
| James St & Ruthven St | B-Double | 46.33 | 48.57 | B-Double | 53.29 | 27.2 | 6.96 |
| James St & Ruthven St | B-Double | 53.29 | 55.45 | B-Double | 58.25 | 28.2 | 4.96 |
| James St & Ruthven St | Car | 38.71 | 40.79 | Car | 40.23 | 29.3 | 1.52 |
| James St & Ruthven St | Car | 42.95 | 44.95 | Car | 45.03 | 30.4 | 2.08 |
| James St & Ruthven St | Car | 47.03 | 49.03 | Car | 48.63 | 30.4 | 1.6 |
| James St & Ruthven St | B-Double | 6.75 | 8.51 | Car | 8.91 | 34.6 | 2.16 |
| James St & Ruthven St | Car | 8.91 | 10.51 | B-Double | 14.11 | 38 | 5.2 |
| James St & Ruthven St | Car | 58.43 | 59.87 | Car | 59.79 | 42.3 | 1.36 |
| James St & Ruthven St | Car | 6.80 | 8.96 | Car | 8.48 | 28.2 | 1.68 |
| James St & Ruthven St | B-Double | 39.76 | 41.52 | Semi Trailer | 44.96 | 34.6 | 5.2 |
| James St & Anzac Ave | Car | 4.22 | 6.22 | B-Double | 7.42 | 47.3 | 3.2 |
| James St & Anzac Ave | Car | 14.48 | 16.64 | Car | 16.08 | 43.8 | 1.6 |
| James St & Anzac Ave | Car | 18.24 | 20.56 | Car | 20.32 | 40.8 | 2.08 |
| James St & Anzac Ave | Car | 20.32 | 22.19 | Car | 21.55 | 50.6 | 1.23 |
| James St & Anzac Ave | Car | 21.55 | 22.83 | Car | 23.47 | 74 | 1.92 |
| James St & Anzac Ave | Car | 8.35 | 10.27 | Car | 10.43 | 49.3 | 2.08 |
| James St & Anzac Ave | Car | 12.51 | 14.43 | Car | 14.35 | 49.3 | 1.84 |
| James St & Anzac Ave | Car | 14.35 | 16.40 | Car | 16.27 | 46.2 | 1.92 |
| James St & Anzac Ave | Car | 19.48 | 21.56 | Car | 21.16 | 45.5 | 1.68 |
| James St & Anzac Ave | Car | 21.96 | 23.96 | Car | 23.72 | 47.3 | 1.76 |
| James St & Anzac Ave | Car | 44.17 | 46.65 | Car | 45.29 | 38.2 | 1.12 |
| James St & Anzac Ave | Car | 45.29 | 47.61 | Car | 47.21 | 40.8 | 1.92 |
| James St & Anzac Ave | Car | 47.21 | 49.29 | Car | 48.41 | 45.5 | 1.2 |
| James St & Anzac Ave | Semi Trailer | 18.70 | 20.94 | Car | 20.94 | 42.3 | 2.24 |
| James St & Anzac Ave | Car | 20.94 | 22.62 | Car | 22.86 | 56.4 | 1.92 |
| James St & Anzac Ave | Car | 59.46 | 61.94 | Car | 61.06 | 38.2 | 1.6 |
| James St & Anzac Ave | Car | 1.06 | 3.70 | Car | 2.66 | 35.9 | 1.6 |
| James St & Anzac Ave | Car | 2.66 | 5.14 | Car | 4.26 | 38.2 | 1.6 |
| James St & Anzac Ave | Car | 4.26 | 6.58 | Car | 6.18 | 40.8 | 1.92 |
| James St & Anzac Ave | B-Double | 36.01 | 38.33 | Semi Trailer | 40.57 | 40.8 | 4.56 |
| James St & Anzac Ave | Car | 22.43 | 24.83 | Car | 23.63 | 39.5 | 1.2 |
| James St & Anzac Ave | Car | 23.63 | 26.19 | Car | 25.07 | 37 | 1.44 |
| James St & Anzac Ave | Car | 25.07 | 27.47 | Car | 27.71 | 39.5 | 2.64 |
| James St & Anzac Ave | Car | 27.71 | 29.71 | Car | 29.47 | 47.3 | 1.76 |
| James St & Anzac Ave | Car | 29.47 | 31.39 | Car | 32.11 | 49.3 | 2.64 |
| James St & Anzac Ave | Car | 32.11 | 34.03 | Car | 33.63 | 49.3 | 1.52 |

# Appendix E – Program Listing

The MATLAB simulation has been developed with a number of scripts, each of which perform a specific function and are used in the simulation at different times. To run the simulation the open the Main.m script in MATLAB. The Main.m script runs all the other scripts in turn and generates the passenger car equivalent results. A full listing of all the scripts required to run the simulation is shown below.

## *E.1 Main.m*

```
% Undergraduate Project for Karl Zeller - Q11219325
% EVALUATION OF THE OPERATIONAL CHARACTERISTICS OF HEAVY VEHICLES
% AT SIGNALISED INTERSECTIONS IN QUEENSLAND

% The aim of this project is to determine the effect of heavy vehicles on
% signalised intersection capacity.  This MATLAB file simulates traffic
% flow at a signalised intersection to determine PCE values for the
% types of heavy vehicles on Queensland Roads.

clc         % Clearing screen and variables
clear all

% Input of variables
Inputs

% Determining the traffic signal cycle times
Cycletimes

% Running the simulation



for x = 1:1:50; %Running simulation
  qv = 0;
  hvcount = 0;
  qc = 0;
  Arrival
  Mixedflow
  for y = 1:1:noofveh;
    if vehdisp(y,itterations)==200;
      qv = qv + 1;
    end
    if veh(y) == 2;
      hvcount = hvcount + 1;
```

```
        end
    end
    pt = hvcount/noofveh;
    Carflow
    for y = 1:1:noofveh;
        if vehdispcar(y,itterations)==200;
            qc = qc + 1;
        end
    end
    Et(x)=roundn(1+((qc/qv-1)/pt),-1);
end

%%% Plotting Data
%% Create figure
figure1 = figure(...
  'Color',[1 1 1],...
  'Name','Intersection Simulation Mixed Traffic Flow',...
  'PaperPosition',[0.6345 6.345 20.3 15.23],...
  'PaperSize',[20.98 29.68],...
  'PaperType','a4letter');

%% Create axes
axes1 = axes('Parent',figure1);
title(axes1,'Intersection Simulation Mixed Traffic Flow');
xlabel(axes1,'Time (s)');
ylabel(axes1,'Road Chainage (m)');
hold(axes1,'all');
box on

for a=1:1:noofcycles;
    plot(greenplotx(a,:),greenploty(1,:),'Color',[0 0.498 0],'LineWidth',4)
    plot(orangeplotx(a,:),orangeploty(1,:),'Color',[0.8706 0.4902 0],'LineWidth',4)
    plot(redplotx(a,:),redploty(1,:),'Color',[1 0 0],'LineWidth',4)
end

plot(T,vehdisp(1,:),'b')
for i=2:1:noofveh;
    plot(T,vehdisp(i,:),'b')
end

print -dtiff -r200 Output_Capacity.tiff

pause
```

```
close all

%%% Plotting Data
%% Create figure
figure2 = figure(...
  'Color',[1 1 1],...
  'Name','Passenger Car Equivalent Results',...
  'PaperPosition',[0.6345 6.345 20.3 15.23],...
  'PaperSize',[20.98 29.68],...
  'PaperType','a4letter');

%% Create axes
%axes1 = axes('Parent',figure1);

% Create xlabel
xlabel('Passenger Car Equivalent (veh)');

% Create ylabel
ylabel('Frequency of result');

% Create title
title('Passenger Car Equivalent (PCE) Results');
%hold(axes1,'all');
box on

hist(Et)

print -dtiff -r200 Output_Et.tiff

fprintf('The simulated PCE value is %3.1f \n',mean(Et))
```

## *E.2 Inputs.m*

```
% User input for intersection characteristics

trafficvolume = input('Traffic volume in lane (Vehicles/Hour) '); %Assigning Traffic Volume
fprintf('\n')
fprintf('Types of Heavy Vehicle \n')
fprintf('        1. Semi Trailer \n')
fprintf('        2. B-Double \n')
```

```
fprintf('         3. Type 1 Road Train \n')
fprintf('         4. Type 2 Road Train \n')
vehtype = input('Enter the number corresponding to the type of heavy vehicle ');
fprintf('\n')
hvpercent =  input('Heavy vehicle percentage lane (%) '); %Assigning Heavy Vehicle %
grade =  input('Traffic lane grade (%) '); %Assigning Grade %
grade = grade/100;
g = 9.81; % Gravitational acceleration
speedlimit=60/3.6; % Setting maximum vehicle speed for the simulation

% Start and end chainages of simulation
startch=-200;
endch=200;

% Assigning traffic signal phasing times
cycletime = 120; % Seconds
green = 56; % Seconds
orange = 4; % Seconds
red = cycletime-(green+orange); % Seconds

% Assigning simulation length
noofcycles = 5; % Number of signal cycles in simulation
dt = 1; % Assigning simulation time interval

% Assigning Car Performance Characteristics
% Vehicle Characteristics from McLean, 1989 (Medium performance)

a0 = 2.82;
vm = 32;

% Assigning Heavy Vehicle Performance Characteristics
% Vehicle Characteristics from Austroads

if vehtype == 1 % Semi Trailer Characteristics
   Pdr = 260000*.8; %W
   v(1) = 0.01; %m/s
   M = 42500; %kg
   rho = 1.22; %kg/m3
   Cd = 0.65;
   Area = 8.5; %m2
   Cr = 0.01;
   x=[-5,-2,0,2,5];
   y=[1.060,0.817,0.741,0.668,0.471];
   maxacc = interp1(x,y,grade*100);
```

```
    vehlength=19;
elseif vehtype == 2 % B-Double Characteristics
    Pdr = 300000*.8; %W
    M = 62500; %kg
    rho = 1.22; %kg/m3
    Cd = 0.65;
    Area = 8.5; %m2
    Cr = 0.01;
    x=[-5,-2,0,2,5];
    y=[1.060,0.817,0.741,0.668,0.471];
    maxacc = interp1(x,y,grade*100);
    vehlength=25;
elseif vehtype == 3 % Type 1 Road Train Characteristics
    Pdr = 405000*.8; %W
    M = 79000; %kg
    rho = 1.22; %kg/m3
    Cd = 0.65;
    Area = 8.5; %m2
    Cr = 0.01;
    x=[-5,-2,0,2,5];
    y=[0.930,0.809,0.719,0.588,0.394];
    maxacc = interp1(x,y,grade*100);
    vehlength=28;
elseif vehtype == 4 % Type 2 Road Train Characteristics
    Pdr = 421000*.8; %W
    M = 119000; %kg
    rho = 1.22; %kg/m3
    Cd = 0.65;
    Area = 8.5; %m2
    Cr = 0.01;
    x=[-5,-2,0,2,5];
    y=[0.894,0.621,0.587,0.478,0.242];
    maxacc = interp1(x,y,grade*100);
    vehlength=42;
end
```

## *E.3 Arrival.m*

```
% Calculating the vehicle arrival pattern and traffic signal phasing

% Vehicle arrival rate
```

```
lamda = trafficvolume/3600; % Converting traffic volume to vehicles/second
noofveh=0; % Setting the vehicle count to 0

% Determining vehicle arrival pattern based on Poisson model
for h =1:1:itterations;
   T(h)=(h-1)*dt;
   if rand<((lamda*dt)^1*exp(-1*lamda*dt))/factorial(1);
      arrival(h)=1;
      noofveh=noofveh+1;
      vehdepart(noofveh)=h*dt;
   else
      arrival(h)=0;
   end
end
```

## *E.4 Mixedflow.m*

```
% Running Simulation for mixed traffic flow.

% Determining vehicle arrival type

for i = 1:1:noofveh;
   if rand*100<hvpercent
      veh(i)=2;
   else
      veh(i)=1;
   end
end

% Setting the No. of vehicles that have reached the intersection to 0
veharrived = 0;

for i = 1:1:itterations;
   for j = 1:1:noofveh; % Assigning default values for vehicles yet to arrive at intersection
      vehacc(j,i)=0;
      vehvel(j,i)=60/3.6; % Setting vehicle approach velocity to 60km/h (in m/s)
      vehdisp(j,i)=startch;
   end
   if arrival(i) == 1 % Checking if a vehicle arrives at the intersection at the point in time
      veharrived = veharrived + 1; % Counting the vehicles arrived at the intersection
   end
   if veharrived > 0 % Running simulation for the vehicles that have arrived at the intersection
     if i > 1;
```

```
    if tc(i)==1 %If the traffic light is green
      for k = 1:1:veharrived;
        if k == 1
          if veh(k) == 1 % Checking if vehicle is a car and calculating acceleration and displacement
            vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
            vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
            vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,endch);
          else % acceleration and displacement for heavy vehicles
            vehmaxacc(k,i)=min((Pdr/(M*vehvel(k,i-1))-0.5*rho*Cd*Area*vehvel(k,i-1)^2/M-
(Cr+grade)*g),maxacc);
            vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
            vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,endch);
          end
        else
          if veh(k) == 1 % Checking if vehicle is a car and calculating acceleration and displacement
            vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
            vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
            headway = max(1.3*vehvel(k,i-1)+6,12);
            if vehdisp(k-1,i)==endch
              vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,endch);
            else
              vehdisp(k,i)=max(min(vehdisp(k,i-1)+vehvel(k,i)*dt,min(vehdisp(k-1,i)-
headway,endch)),startch);
            end
            vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
          else % acceleration and displacement for heavy vehicles
            vehmaxacc(k,i)=min((Pdr/(M*vehvel(k,i-1))-0.5*rho*Cd*Area*vehvel(k,i-1)^2/M-
(Cr+grade)*g),maxacc);
            vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
            headway = max(2.4*vehvel(k,i-1)+vehlength,vehlength+6);
            if vehdisp(k-1,i)==endch
              vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,endch);
            else
              vehdisp(k,i)=max(min(vehdisp(k,i-1)+vehvel(k,i)*dt,min(vehdisp(k-1,i)-
headway,endch)),startch);
            end
            vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
          end
        end
      end
    else  % If traffic signal is orange or red simulation stops any vehicles before the stop line
      for k = 1:1:veharrived;
        if k == 1
          if veh(k) == 1 % Checking if vehicle is a car and calculating acceleration and displacement
```

```
            d = 0.36; % Deceleration coefficient for cars
            if vehdisp(k,i-1)<(0-(vehvel(k,i-1)^2/(2*d))-6)
                vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
                vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
                vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,-6-1);
                vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
            elseif vehdisp(k,i-1)<0
                vehmaxacc(k,i)=-9.81*d;
                vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
                vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,-6-1);
            else
                vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
                vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
                vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,endch);
            end
        else % acceleration and displacement for heavy vehicles
            d = 0.29; % Deceleration coefficient for heavy vehicles
            if vehdisp(k,i-1)<(0-(vehvel(k,i-1)^2/(2*d))-1*vehlength)
                vehmaxacc(k,i)=min((Pdr/(M*vehvel(k,i-1))-0.5*rho*Cd*Area*vehvel(k,i-1)^2/M-
(Cr+grade)*g),maxacc);
                vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
                vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,-1*vehlength-1);
                vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
            elseif vehdisp(k,i-1)<0
                vehmaxacc(k,i)=-9.81*d;
                vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
                vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,-1*vehlength-1);
            else
                vehmaxacc(k,i)=min((Pdr/(M*vehvel(k,i-1))-0.5*rho*Cd*Area*vehvel(k,i-1)^2/M-
(Cr+grade)*g),maxacc);
                vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
                vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,endch);
            end
        end
    else
        if veh(k) == 1 % Checking if vehicle is a car and calculating acceleration and displacement
            d = 0.36; % Deceleration coefficient for cars
            if vehdisp(k,i-1)<(0-(vehvel(k,i-1)^2/(2*d))-6)
                vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
                vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
                headway = max(1.3*vehvel(k,i-1)+6,12);
                if vehdisp(k-1,i)==endch
                    vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,-6-1);
                else
```

```
          vehdisp(k,i)=max(min(vehdisp(k,i-1)+vehvel(k,i)*dt,min(vehdisp(k-1,i)-headway,-6-1)),startch);
        end
        vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
      elseif vehdisp(k,i-1)<-6
        vehmaxacc(k,i)=-9.81*d;
        vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
        headway = max(1.3*vehvel(k,i-1)+6,12);
        if vehdisp(k-1,i)==endch
          vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,-6-1);
        else
          vehdisp(k,i)=max(min(vehdisp(k,i-1)+vehvel(k,i)*dt,min(vehdisp(k-1,i)-headway,-6-1)),startch);
        end
        vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
      else
        vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
        vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
        headway = max(1.3*vehvel(k,i-1)+6,12);
        if vehdisp(k-1,i)==endch
          vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,endch);
        else
          vehdisp(k,i)=max(min(vehdisp(k,i-1)+vehvel(k,i)*dt,min(vehdisp(k-1,i)-headway,endch)),startch);
        end
        vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
      end
    else % acceleration and displacement for heavy vehicles
      d = 0.29; % Deceleration coefficient for trucks
      if vehdisp(k,i-1)<(0-(vehvel(k,i-1)^2/(2*d))-1*vehlength)
        vehmaxacc(k,i)=min((Pdr/(M*vehvel(k,i-1))-0.5*rho*Cd*Area*vehvel(k,i-1)^2/M-(Cr+grade)*g),maxacc);
        vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
        headway = max(2.4*vehvel(k,i-1)+vehlength,vehlength+6);
        if vehdisp(k-1,i)==endch
          vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,-1*vehlength-1);
        else
          vehdisp(k,i)=max(min(vehdisp(k,i-1)+vehvel(k,i)*dt,min(vehdisp(k-1,i)-headway,-1*vehlength-1)),startch);
        end
        vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
      elseif vehdisp(k,i-1)<-1*vehlength
        vehmaxacc(k,i)=-9.81*d;
        vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
```

```
                headway = max(2.4*vehvel(k,i-1)+vehlength,vehlength+6);
                if vehdisp(k-1,i)==endch
                    vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,-1*vehlength-1);
                else
                    vehdisp(k,i)=max(min(vehdisp(k,i-1)+vehvel(k,i)*dt,min(vehdisp(k-1,i)-headway,-
1*vehlength-1)),startch);
                end
                vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
            else
                vehmaxacc(k,i)=min((Pdr/(M*vehvel(k,i-1))-0.5*rho*Cd*Area*vehvel(k,i-1)^2/M-
(Cr+grade)*g),maxacc);
                vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
                headway = max(2.4*vehvel(k,i-1)+vehlength,vehlength+6);
                if vehdisp(k-1,i)==endch
                    vehdisp(k,i)=min(vehdisp(k,i-1)+vehvel(k,i)*dt,endch);
                else
                    vehdisp(k,i)=max(min(vehdisp(k,i-1)+vehvel(k,i)*dt,min(vehdisp(k-1,i)-
headway,endch)),startch);
                end
                vehvel(k,i)=max((vehdisp(k,i)-vehdisp(k,i-1))/dt,.001);
            end
          end
        end
      end
     end
    end
  end
end
```

## E.5 Carflow.m

```
% Running simulation for a constant flow of cars

% Setting the No. of vehicles that have reached the intersection to 0
veharrived = 0;

for i = 1:1:itterations;
  for j = 1:1:noofveh; % Assigning default values for vehicles yet to arrive at intersection
    vehacc(j,i)=0;
    vehvel(j,i)=60/3.6; % Setting vehicle approach velocity to 60km/h (in m/s)
    vehdispcar(j,i)=startch;
  end
```

```
if arrival(i) == 1 % Checking if a vehicle arrives at the intersection at the point in time
    veharrived = veharrived + 1; % Counting the vehicles arrived at the intersection
end
if veharrived > 0 % Running simulation for the vehicles that have arrived at the intersection
    if i > 1
    if tc(i)==1 %If the traffic light is green
        for k = 1:1:veharrived;
            if k == 1
                vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
                vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
                vehdispcar(k,i)=min(vehdispcar(k,i-1)+vehvel(k,i)*dt,endch);
            else
                vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
                vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
                headway = max(1.3*vehvel(k,i-1)+6,12);
                if vehdispcar(k-1,i)==endch
                    vehdispcar(k,i)=min(vehdispcar(k,i-1)+vehvel(k,i)*dt,endch);
                else
                    vehdispcar(k,i)=max(min(vehdispcar(k,i-1)+vehvel(k,i)*dt,min(vehdispcar(k-1,i)-
headway,endch)),startch);
                end
                vehvel(k,i)=max((vehdispcar(k,i)-vehdispcar(k,i-1))/dt,.001);
            end
        end
    else  % If traffic signal is orange or red simulation stops any vehicles before the stop line
        for k = 1:1:veharrived;
            if k == 1
                d = 0.36; % Deceleration coefficient for cars
                if vehdispcar(k,i-1)<(0-(vehvel(k,i-1)^2/(2*d))-6)
                    vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
                    vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
                    vehdispcar(k,i)=min(vehdispcar(k,i-1)+vehvel(k,i)*dt,-6-1);
                    vehvel(k,i)=max((vehdispcar(k,i)-vehdispcar(k,i-1))/dt,.001);
                elseif vehdispcar(k,i-1)<0
                    vehmaxacc(k,i)=-9.81*d;
                    vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
                    vehdispcar(k,i)=min(vehdispcar(k,i-1)+vehvel(k,i)*dt,-6-1);
                else
                    vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
                    vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
                    vehdispcar(k,i)=min(vehdispcar(k,i-1)+vehvel(k,i)*dt,endch);
                end
            else
                d = 0.36; % Deceleration coefficient for cars
```

```
          if vehdispcar(k,i-1)<(0-(vehvel(k,i-1)^2/(2*d))-6)
            vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
            vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
            headway = max(1.3*vehvel(k,i-1)+6,12);
            if vehdispcar(k-1,i)==endch
              vehdispcar(k,i)=min(vehdispcar(k,i-1)+vehvel(k,i)*dt,-6-1);
            else
              vehdispcar(k,i)=max(min(vehdispcar(k,i-1)+vehvel(k,i)*dt,min(vehdispcar(k-1,i)-headway,-6-1)),startch);
            end
            vehvel(k,i)=max((vehdispcar(k,i)-vehdispcar(k,i-1))/dt,.001);
          elseif vehdispcar(k,i-1)<-6
            vehmaxacc(k,i)=-9.81*d;
            vehvel(k,i)=max(min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit),0.001);
            headway = max(1.3*vehvel(k,i-1)+6,12);
            if vehdispcar(k-1,i)==endch
              vehdispcar(k,i)=min(vehdispcar(k,i-1)+vehvel(k,i)*dt,-6-1);
            else
              vehdispcar(k,i)=max(min(vehdispcar(k,i-1)+vehvel(k,i)*dt,min(vehdispcar(k-1,i)-headway,-6-1)),startch);
            end
            vehvel(k,i)=max((vehdispcar(k,i)-vehdispcar(k,i-1))/dt,.001);
          else
            vehmaxacc(k,i)=a0*(1-vehvel(k,i-1)/vm)-g*grade;
            vehvel(k,i)=min(vehvel(k,i-1)+vehmaxacc(k,i)*dt,speedlimit);
            headway = max(1.3*vehvel(k,i-1)+6,12);
            if vehdispcar(k-1,i)==endch
              vehdispcar(k,i)=min(vehdispcar(k,i-1)+vehvel(k,i)*dt,endch);
            else
              vehdispcar(k,i)=max(min(vehdispcar(k,i-1)+vehvel(k,i)*dt,min(vehdispcar(k-1,i)-headway,endch)),startch);
            end
            vehvel(k,i)=max((vehdispcar(k,i)-vehdispcar(k,i-1))/dt,.001);
          end
        end
      end
    end
    end
  end
end
```