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Understanding Filtered Right Turn Through Crashes Occurring at Traffic Signals Intersections

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Executive Summary

Filter right-turn crashes at signalised intersections are one of the most dangerous intersection conflicts on the network. The reasons for this are complex and involve critical decision-making by drivers to identify and select an appropriate gap in traffic across multiple lanes. This involves the judging of speed and proximity of approaching traffic, monitoring changes in traffic signal phases, and having awareness of the presence of other road users potentially crossing side roads that drivers are entering.

Right-turn type crashes are also some of the most severe types of crashes, particularly for side impact collisions involving passengers as noted in Austroads Guide to Road Safety Part 2 (Austroads, 2024), since the level of protection from side-impacts is less than frontal and rear-end type collisions and the passenger side is more exposed to through moving vehicles.

For this reason, Main Roads identified the need to better understand the nature and timing of thru-right crashes at signalised intersections and how to potentially manage filtered traffic signals to minimise the risk of this crash type occurring.

This project involved the collection of video survey data of filtered right-turn traffic movements at eight signalised intersections located across metropolitan Perth and then the application of video analytics software to identify filter right-turn crashes and near-miss incidents. While no real-world crashes were captured by the video surveys, 977 instances of filter right-turn manoeuvres were identified as meeting the near-miss definition established by adopting two surrogate safety/traffic conflict measures, post-encroachment time (PET) and time-to-collision (TTC).

To assist understanding the level of risk associated with filter-right-turn crashes, the potential severity of the identified near-miss incidents was estimated via estimates of delta-v and the kinetic energy involved if a collision were to occur. A review of crash data for the eight intersections included in the study showed that right-turn collisions accounted for approximately 45% (n=177) of all crashes reported over a five-year period, representing 5% of FSI collisions at these sites.

A key question for the study was when in the signal phase the near-miss incidents occurred; analysis found that almost 98% occurred during the green phase and just under 3% occurred during the yellow phase; no near-miss incidents were recorded occurring during the red phase of the signal cycle.

Other key results of the analysis were as follows:

- While the speed of turning vehicles tended to be in the low to moderate range, almost 68% of vehicles in the opposing movement exceeded the accepted Safe System speed threshold of 50 km/h for this type of crash.
- On average 8.27% of near-miss incidents fell into the 'higher likelihood of a collision' range for PET/TTC¹ combination.

In addition to analysis of the surrogate safety/traffic conflict metrics, a selection of video of the recorded near-miss incidents was reviewed to gain an understanding of potential 'other' factors, including driver behaviour. A key conclusion of this review was the influence of dynamic visual obstruction as a contributing causal factor in near-miss incidents. It was observed that obstructions and interruptions of a right-turning driver's line of sight to opposing traffic flows increased the potential for error in selecting suitable gaps in

¹ PET is 'post encroachment time', which refers to the time gap between the departure of the encroaching vehicle from the conflict point and the arrival of the second vehicle with the right-of-way at the conflict point. PET can predict the probability of crashes without assessing their severity. A PET value of zero indicates a crash, while non-zero PET values indicate crash proximity.

TTC is 'Time to collision', which is the delay remaining between the instant considered and the time of the collision between the subject vehicle and the target vehicle.

traffic to execute the right-turn manoeuvre. It was noted this is primarily, but not exclusively, a feature at sites where right-turns were required to be made from right/through traffic lanes.

Drawing from the data and observations from the analysis undertaken for this study, a limited number of measures to mitigate the risk of thru-right type crashes are suggested. These include:

1. Eliminating filter right-turn manoeuvres through re-phasing traffic signals. The approach might involve prioritising sites based on crash risk with consideration of:
 - a. available lines of sight
 - b. demand for the right-turn and viable alternative locations
 - c. approach speed to the intersection for through traffic movements.
2. Altering traffic arrangements at priority intersections. This might include:
 - a. providing dedicated right-turn lanes, improving storage and reducing conflict with following through traffic
 - b. facilitating right-turns by allocating more green time to right-turn movements to reduce the need for filter right-turn movements.
3. Measures to improve lines of sight for drivers in stacked right-turn traffic. This might include:
 - a. increasing the offset of opposing traffic lanes
 - b. technology solutions to provide warning to drivers of the potential conflict or when suitable gaps are available. This may involve dynamic signing in the short-term and infrastructure-to-vehicle connectivity solutions in the longer-term.
4. Reducing speed in the through traffic stream. This could be delivered by:
 - a. reducing speed limits on approach
 - b. only permitting filter right-turns at sites where the sign speed limit is 50 km/h or lower (aligning with the Safe System speed thresholds)
 - c. introducing the vertical deflection approaching and through the intersections where filter right-turns are permitted (note: raised intersections are effectively applied in other jurisdictions with safety improvements and minimal impact on intersection efficiency).

The analysis reported through this study highlighted areas of risk and provided a level of evidence of the factors contributing to crashes across the right-turn crash codes. Additional insights could be obtained through a similar analysis of real-world crashes, which could be facilitated via the Main Roads CCTV network. The process would then apply the Safe System Crash Review process to gain insights to driver decision-making processes and where breakdowns in the road transport system, as a whole, occurred, permitting FSI collisions to occur. Additional insights as to how vehicle design and technology might assist in crash avoidance and to reduce injury severity outcomes could be gained from such an approach.

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1 Introduction

1.1 Background and Context

One of the most dangerous conflicts at signalised intersections are vehicles turning right when the opposing approach has a green signal.

In a right-turn filter arrangement, drivers select gaps in the opposing vehicle flow in order to turn right. At some intersections a leading green turn arrow is presented, which drops off to a filtered right-turn arrangement. Other signalised intersections have a filtered arrangement whenever through vehicles are provided with a green light.

Filtered right-turn movements are used for several key reasons, including:

1. Improving intersection efficiency and capacity – permitting right-turns during the green phase (without a dedicated arrow) means intersections can handle more vehicles and reduce overall delays, especially where right-turn volumes are relatively low.
2. Road design and policy considerations – the decision to allow filtered right-turns is guided by road safety policies and risk assessments. Site constraints and cost may preclude the provision of right-turn storage and dedicated right-turn phasing in the signal cycle.

While the use of a right-turn filter arrangement at signalised intersections is common in Australia and in other parts of the world, it is associated with a known higher risk of through right-turn (hereafter presented as thru-right) crashes, which are considered some of the highest severity crashes on the network.

It is hypothesised that a major cause of thru-right crashes and near misses at signalised intersections in Western Australia that operate filtered right-turns may be the lack of driver understanding of how to negotiate this type of traffic signal. It is believed that most of the crashes and near misses are likely to occur at the late amber stage of the signals. At that stage of the signal phasing, the right-turning vehicle will likely be propped within the intersection and most drivers believe they need to clear the intersection prior to the signals turning red. Legally, however, a single right-turning vehicle, which has crossed the stop line during the green interval, may legally complete the turn during the inter-green, or all red, phase.

In developing this project, Main Roads is interested in understanding the nature and timing of thru-right crashes at signalised intersections and how to potentially manage filtered traffic signals to minimise the risk of this crash type occurring.

1.2 Project Scope and Purpose

The study was developed to: (1) examine nominated traffic control signals (TCS) sites to observe driver behaviour and response to thru-right conflict, (2) review how other jurisdictions manage these risks, and (3) recommend ways of managing thru-right crashes at filtered intersections.

Through a greater understanding of the factors contributing to right-turn crashes at TCS, Main Roads will be able to inform improved policy, design, and operation of TCS to reduce the likelihood and severity of right-turn crashes on the WA network.

1.3 Objectives

The study sought to examine thru-right crashes and near-miss incidents at signalised intersections under right-turn filter control, with a view to improving the understanding of factors contributing to crashes, particularly at what time in the signal phasing they are most likely to occur.

1.4 Limitations

The study was conducted through an analysis of observations recorded over specific periods at eight nominated signalised intersections where right-turns are permitted. While the nominated sites may be considered typical of the traffic arrangements and representative of these types of signalised intersections, there will be site-specific conditions that may influence a driver's gap selection decisions.

The collection of site observations and the subsequent identification of crash and near-miss incidents involving right-turn and through traffic is by video survey and the application of incident detection software applying defined parameters for determining what is a recordable incident.

The study did not involve a reconstruction and detailed analysis of individual crashes or near-miss incidents; nor did it involve interviews with vehicle controllers or other witnesses to crashes or near-miss incidents at the nominated study sites.

As a result of these limitations, the analysis and discussion to understand factors contributing to driver decisions and near-miss incidents is a sampling only.

2 Literature Review

Jurisdictions across Australia approach the application of filtered and controlled right-turn arrangements at traffic signals arrangements differently; they generally provide their own guidance on traffic signal phasing design, with reference to Austroads for common technical guidance.

The following jurisdictions were examined as part of this literature review:

- Australian Capital Territory – Transport Canberra and City Service (TCCS)
- New South Wales – Transport for New South Wales (TfNSW)
- Northern Territory – Department of Infrastructure, Planning and Logistics (DIPL)
- Queensland – Department of Transport and Main Roads (TMR)
- South Australia – Department of Infrastructure and Transport's (DIT)
- Victoria – VicRoads (Department of Transport)
- Tasmania – Department of State Growth's (DSG)
- Western Australia – Main Roads Western Australia (Main Roads).

In addition to jurisdictional guidance, consideration was also given to the University of Western Australia's *Understanding right-turn through crashes occurring at filtered traffic signals in Western Australia* (Legge & Goodsell 2022) (the UWA report). The UWA report provides the following recommendations in relation to signal phasing and managing filter right-turn related crashes.

It is recommended that fully-controlled right-turn signal phasing should be considered as the preferred signal phasing option. Partially-controlled right-turn phasing with a leading right-turn phase be considered as the next preferred signal phasing option, followed by partially-controlled right-turn phasing with a lagging right-turn phase and then filter turn phasing.

Also:

It is recommended that the use of flashing yellow arrows or other signal options be investigated as a filter right-turn indicator.

Austroads (2023) identifies that there is a significant road safety risk at signalised intersections where the most prevalent crash type causing fatal and serious injuries is collisions involving right-turning and opposing through traffic. The preferred countermeasure is full signal control of right-turn movements; filter right-turns should only be used following an assessment that demonstrates the road safety risk is low.

Within a Safe System, Austroads (2018) suggests intersection crashes need to be considered from a system failure perspective rather than as road user performance failure. Conventional signal control varies from unprotected to protected turns where the efficiency of an intersection may be favoured over safety. In lieu of complete separation, a Safe System approach to signal control would have fully controlled right-turns as a default arrangement on the major road.

Austroads (2017) emphasises that improving intersection safety requires a shift from traditional crash mitigation approaches to a Safe System perspective, where intersections are designed to accommodate human error without resulting in fatal or serious injury. Austroads recommends fully controlled right-turn phasing as a preferred treatment to reduce conflict between turning and through movements.

Reasons for considering the installation of a fully controlled right-turn phase are outlined in Austroads (2020b):

- when new signals are being installed
- when a high number of through-right casualty crashes have occurred over several consecutive years
- where there are two or more lanes turning right at one approach (double right-turn)
- where there are two or more right-turn lanes on the opposite approach

- when right-turning traffic is opposed by two or more through lanes of traffic
- when there are high operating speeds in two or more opposing through traffic lanes
- when a service road adjacent to the opposing approach continues through the intersection (i.e. not truncated).

The Austroads Guide to Traffic Management Part 9 (Austroads, 2022) provides guidance on the design and operation of transport control systems, including traffic signal phasing strategies. It reinforces the Safe System approach by advocating for fully controlled right-turn phases at intersections where crash risk is elevated due to high speeds, multiple opposing lanes, or poor sight distance. The Austroads framework recommends that safety should take precedence over efficiency in signal design, especially where vulnerable road users or high-speed conflicts are present.

This literature review has sourced technical publications from all Australian states and territories to identify relevant information. These include traffic signal phasing design guidelines, policy frameworks and road user guidance literature.

In relation to right-turn filter and fully controlled right-turn arrangements, the discussion of relevant literature considered in this review is presented in the following sections:

Section 2.1 Guidance from each state and territorial jurisdiction on when and where to provide these traffic arrangements.

Section 2.2 Current practice by jurisdictions to advocate and implement these treatments. These may be in the form of road safety policy, supporting guidelines or information for road users.

Section 0 Crash reduction factors for treatments to address opposing turn crashes at signalised intersections. The increase or reduction in crashes is demonstrated for filtered right-turns and fully controlled right-turns.

2.1 Jurisdictional Guidance

Jurisdictional guidance for right-turn control movements in relation to right-turn filter and fully-controlled right-turn arrangements is summarised in Table 2.1.

Table 2.1: Jurisdictional guidance

Jurisdiction	Guidance on right-turn movements
Australian Capital Territory	<i>Traffic control devices municipal infrastructure standards</i> (TCCS 2019)– does not provide specific information about right-turn filter arrangements.
New South Wales	<i>Traffic signal design section 7 phasing and signal group display sequence</i> (RMS 2016)– provides the most comprehensive information about the design of right-turn phasing. This includes guidance on right-turn phases with or without right-turn filters and conflicts associated with right-turn filters.
Northern Territory	The <i>Road safety treatments</i> web page (DIPL 2025) provides guidance on not providing right-turn filter arrangements at new signalised intersections.
Queensland	Two local guides are available. The <i>Guideline systems and procedures for arterial traffic control – traffic signals in Queensland</i> (TMR 2021) and <i>Traffic and road use management (TRUM) Volume 1 – Guide to traffic management part 9: traffic operations / transport control systems – strategies and operations (2016) / (2020)</i> (TMR 2020). Both provide guidance on right control turn movements, with emphasis on not allowing filter right-turns.
South Australia	The <i>Manual of legal responsibilities and technical requirements for traffic control devices part 2 – code of technical requirements</i> (DIT 2025) provide design standards for right-turn movements, with emphasis on not allowing filter right-turns.
Tasmania	The <i>T3 – Road design guidelines and standards</i> (DSG 2020) has an interim update and references Austroads. There are no specific guidelines on right-turn control movements.
Victoria	The Supplement to <i>Austroads guide to traffic management part 9: transport control systems – strategies and operations</i> (Austroads 2020b) provides guidance and criteria on methods of right-turn control movements, including filter right-turns and fully controlled right-turns.

Jurisdiction	Guidance on right-turn movements
Western Australia	The on-line guideline <i>Vehicular signals</i> (MRWA 2022) provides guidance on right-turn control movements and supports Austroads' guidance on right-turns being prevented from filtering.

2.1.1 Australian Capital Territory

The TCCS *Traffic control devices municipal infrastructure standards 13* (2021) refers to the Austroads Guides noted below.

- Part 4A: Unsignalised and signalised intersections (Austroads 2023)
- Part 6: Intersections, interchanges and crossings management (Austroads 2020a)
- Part 9: Transport control systems – strategies and operations (Austroads 2020b)
- Part 10: Transport control – types of devices (Austroads 2020c).

This publication provides no specific guidance for right-turn filter arrangements.

2.1.2 New South Wales

Transport for NSW (TfNSW) provides the most comprehensive guidance for right-turn movements. The guidance provided aligns directly with the key recommendation provided by the UWA report. Guidance is provided on leading right-turn phase, and lagging right-turn phase, with respect to a right-turn phase operating with or without a right-turn filter.

The TfNSW guideline *Traffic signal design section 7 phasing and signal group display sequence* (2016) adopts Australian Standards and Austroads Guidelines as its primary technical references.

Crash data and phasing design

In terms of crash data analysis informing phasing design, severe crash data should be analysed to see whether any patterns emerge or whether a particular type of traffic crash is dominant. The phasing should ensure that any safety problems are eliminated or at least minimised. With emphasis on crashes involving filtering right-turn vehicles, this may be eliminated by displaying a right-turn red arrow in the through phase and providing a right-turn phase only.

Right-turn movements

A right-turn movement can be banned, allowed to filter through the opposing flow, or controlled by providing a right-turn phase.

A right-turn movement can operate as a filter only, phase only, phase, and filter in another phase. For a right-turn phase with filter turn operation, a repeat right-turn movement may be provided within a cycle to cater for heavier right-turn movements during specific flow periods. For right-turn phase only operation, the following repeat and optional right-turn movements may be provided within a cycle for specific flow periods: filter option, repeat turn, filter option, and repeat turn.

Regardless of the right-turn treatment selected, if the right-turn is stopped at any time when the corresponding through movement is running, it is preferable to provide a right-turn bay or an exclusive right-turn lane to help reduce the incidence of rear-end collisions.

Right-turn filter

The TfNSW definition of a right-turn filter is where right-turn vehicles select gaps in the opposing vehicle flow. This turn may be used where a right-turn bay exists or can be provided, or in a shared lane where the right

turn does not cause excessive delays to other vehicles and the flows are low enough to allow filtering without compromising safety or causing excessive delays.

The flow rate of the filter right-turn is affected by:

- the rate of the opposing flow
- the speed of the opposing flow
- the number of lanes (or width of road) that right-turn vehicles must cross
- the length of phase during which the filter may take place.

Any right-turn vehicle which has crossed the stop line during the green interval may legally complete the turn during the inter-green.

A filter right-turn is not permitted under the following conditions:

- Sight distance is insufficient for the right-turn vehicles to filter safely. The criterion for measuring the sight distance is the minimum gap sight distance, the details of which are found in the Austroads *Guide to Road Design Part 4A* (Austroads 2023).
- There is more than one right-turn lane.
- It is possible for a yellow signal to be displayed to the right-turn vehicles when the opposing approach has a green signal, e.g. the opposing approach has a trailing right-turn OR the approach with the right-turn has an early cut-off.
- The 85th percentile speed of the opposing traffic, measured in free-flow conditions, is greater than 70 km/h and the right-turn has to filter across more than two lanes.
- There is an adverse traffic accident history involving filtering right-turn vehicles (including rear-end collisions).
- The opposing approach is four lanes or more wide.

An optional filter is possible operation during off-peak and peak periods:

- At some sites a filter right-turn movement may operate efficiently during off-peak periods but not operate efficiently during peak periods because it becomes more difficult to accept gaps in the opposing flow. It is possible to make the filter optional.

Right-turn phase, with or without right-turn filter

A right-turn phase can be provided as the only means by which vehicles are permitted to turn right, or it can be provided in addition to a filter right-turn, permitted in another phase, for the same right-turn movement. When a right-turn filter does not provide sufficient safety and/or capacity for right-turn vehicles a right-turn phase should also be provided.

A right-turn phase must be provided without a right-turn filter where one or more of the following conditions apply:

- Sight distance is insufficient for right-turn vehicles to filter safely.
- There is a record of severe traffic accidents involving filtering right-turn vehicles.
- There is more than one lane turning right for that movement.
- The 85th percentile speed of opposing traffic is greater than 70 km/h and the right-turn must filter across more than two lanes.

A right-turn phase should be provided without a right-turn filter where one or more of the following conditions apply:

- Right-turn vehicles cause excessive delays to other vehicles using the same approach because a right-turn bay is not, or cannot be, provided.
- The right-turn flow exceeds 120 vehicles/hour and is opposed by at least:
 - 900 vehicles/hour for a one lane approach
 - 700 vehicles/hour/ lane for a two lane approach
 - 500 vehicles/hour/ lane for a three lane approach.

A right-turn phase can operate as a trailing right-turn or a leading right-turn. Both the leading and lagging right-turns can operate with or without the right-turn operating as a filter movement.

Conflict with controlled left turn

A problem occurs if a filter right-turn is provided when the opposing left turn is held by a left turn red arrow due to a late start or pedestrian protection. If a right-turn vehicle can pick a gap in the opposing through traffic while the left turn is stopped, the right-turn vehicle may filter. When the left-turn red arrow is extinguished, a conflict occurs between the left-turn vehicles and the filtering right-turn vehicles. The right-turn vehicles cannot see the signal group displayed to the left-turn vehicles and once the right-turn is established, the remaining right-turn vehicles tend to 'stream' (follow the leader) until there is no longer a gap in the opposing through vehicles. This not only increases the chance of collisions between vehicles but may also place pedestrians at risk.

This type of conflict does not happen very regularly because the duration of the left-turn red arrow is usually short. Therefore, the number of through vehicles is usually sufficient to prevent the right-turn vehicles from filtering until after the left-turn red arrow is extinguished. However, when the number of through vehicles is low (due to an exclusive left turn or low demand for the through movement), the conflict will occur.

The solution to this problem is to prevent the right-turn vehicles from filtering by displaying a right-turn red arrow for at least the same time as the opposing left-turn red arrow. If there is no right-turn phase (such as at a two-phase site), consideration should be given to using a four aspect lantern incorporating a right-turn red arrow. Full pedestrian protection (for the walk and clearance intervals) is not recommended in this case as the right-turn may not receive enough time to filter. Sites that require full pedestrian protection should have a separate right-turn phase.

2.1.3 Northern Territory

DIPL's *Traffic signals design technical directive and guideline 2020* (DIPL 2020) and its *Road safety treatments* web page (April 2022) provides guidance on the scope and application of road safety treatments on new road infrastructure.

DIPL advises that new and upgraded signalised intersections must have protected right-turn lanes on major roads. Protected turn lanes are a default requirement, where:

- a major road is an arterial road with a speed limit of 80 km/h or above
- filter turns are not permitted at signalised intersections.

2.1.4 Queensland

TMR has a series of guidelines to detail traffic signal design and inform practitioners on the practical use of these guidelines.

These are:

- *Guideline systems and procedures for arterial traffic control – traffic signals in Queensland (Guideline)* (TMR 2021).
- *Traffic and road use management (TRUM) Volume 1 – Guide to Traffic Management Part 9: Traffic Operations / Transport Control Systems – Strategies and Operations (2016) / (2020)* (TMR 2020).

The Guideline references *Austroads guide to traffic management Part 9 (Austroads 2020b)*, section 6.5: movements and phases. For control of right-turn movements TMR employs the following right control movements: filter turn, full control, partial control, part time filter, and uncontrolled. The definitions of these turns are noted in Table 2.2.

TMR also define a filter turn as an opposed turn.

Table 2.2: TMR right turn movements

Term	Definition
Filter turn	A turning movement that must give way to and find safe gaps in conflicting (opposing) vehicle or pedestrian before proceeding, for example, filter right-turn, slip-lane left turn, turn on red. Also called Opposed Turn.
Full Control	Filter turns are not permitted.
Partial control	Control of a turning movement by a green arrow display in one phase (as an unopposed movement) and by a green circle display in another phase (as a filter or opposed movement).
Part-time filter	The right-turn is fully controlled at certain predetermined times of the day (or in predetermined plans that are automatically selected by time of day or for certain traffic conditions), at other times it is partially controlled or, very unusually, uncontrolled.
Uncontrolled	No arrow phase (protected phase) is provided for the right-turn movement. Right-turning traffic must make a filter turn.

Factors to consider for right-turn movements

The TRUM provides guidance for phasing design and references the *Austrroads Guide To Traffic Management Part 9 Transport Control Systems – Strategies and Operations* (Austrroads 2020b). The following factors are to be considered for filter turns and opposing turns:

Number of lanes

- A bicycle lane shall be counted as a traffic lane when considering the risk factors for filter turns.
- A right-turning lane from an opposite approach shall be counted as a traffic lane when considering the risk factors for filter turns if it is at all offset to the right of the right-turn lane.

Road safety

- Low demand periods are the period when the majority of opposing-turning crashes occur. All movements and users of the intersection shall be considered.

Time of day

- Low demand periods are the period when the majority of opposing-turning crashes occur. All movements and users of the intersection shall be considered.

2.1.5 South Australia

DIT's *Manual of legal responsibilities and technical requirements for traffic control devices, Part 2 – Code of technical requirements* (Code) (September 2021) sets out the mandatory requirements for the variations from Australian Standards and Austrroads Guides for the use of traffic control devices in South Australia. *Austrroads Guide to traffic management, Part 6: Intersections, interchanges and crossings management* (Austrroads 2020a) is referenced for key traffic management considerations for traffic signals at intersections.

The Code notes crash history as a critical factor that needs to be taken into consideration when assessing the need for traffic signals. In this instance, for right-turn movements, as right-turn crashes may continue to occur if filter right-turn movements are permitted, new traffic signal installations shall not allow for filter right-turns.

Further guidance on phasing design standards is provided by DIT's *Traffic signal design – TS100* (DIT 2017). These design standards guide traffic signal performance, design and operational requirements, and design requirements. In general, the requirements for these design standards advise that filtering right-turns are not permitted, and all right-turns shall be fully controlled. The design standards and requirements are noted in Table 2.3.

Table 2.3: DIT design standards for right-turn movements

Design standard	Requirement
Traffic signal operational performance	All right-turn movements, in new or modified intersections, are to be controlled with right-turn arrows, and controlled separately from through movements. Opposed right-turns shall be designed to run concurrently to allow diamond right-turn operation.
Design and operational requirements	Filter right-turning movements are not permitted for new signal installations or where the intersection geometry is modified. This is to be reflected in the modelling of intersections and their design.
Design requirements	All right-turn movements shall be fully controlled and separate right-turn lanes provided

2.1.6 Tasmania

The Department of State Growth's *T3 – Road design guidelines and standards* (DSG 2020) has an interim update. It is currently being fully reviewed to identify and fully document specific policies and guidelines for the design of roads. Given the current status of this guide, no specific information is provided on right-turn filter turn movements.

DSG currently refers to Austroads guidelines and publications for the design traffic signals in Tasmania.

2.1.7 Victoria

The VicRoads *supplement to Austroads Guide to Traffic Management Part 9: Traffic Operations* (Austroads 2014) (VicRoads 2015) advises that, in general, right-turn vehicle movements can be controlled using either of three techniques: filter right-turn, partially controlled right-turn, and fully controlled right-turn.

Understanding all three techniques to control right-turn movements is necessary. While the filter right-turn and fully controlled right-turn are clearly defined, the partially controlled right-turn, in some circumstances, can employ a filter right-turn as part of its operation.

Filter right-turn

A right-turn movement which operates in the same phase as a conflicting vehicle (generally through and left-turn vehicles from the opposite direction) and/or pedestrian movements. The right-turn is therefore required to find safe gaps in that conflicting traffic before being able to turn.

Partially controlled right-turn

A right-turn movement which operates in two phases:

- in a phase in which it is controlled by a green right-turn arrow; it has priority over conflicting vehicle and/or pedestrian traffic movements
- in a phase in which it can operate as a filter right-turn (as refer definition in previous paragraph).

With this type of control, the right-turn movement is controlled with either two-aspect (yellow/green) right-turn arrow displays or three-aspect (red/yellow/green) right-turn arrow displays. Generally, these types of lanterns are also associated with normal three-aspect (red/yellow/green) circular displays.

In general, partially controlled right-turns (with 'red arrow drop-out operation') are replacing the traditional partially controlled right-turns at existing and new sites.

Fully controlled right-turn

A fully controlled right-turn is a right-turn movement which only operates in a phase in which it is controlled by a green right-turn arrow, and so it has priority over conflicting vehicle and/or pedestrian traffic movements.

However, unlike a partially controlled turn, it is unable to filter during any other phase. At the end of its own phase, the right-turn is terminated and held on a red arrow display (until it operates in the following traffic signal cycle or possibly in a repeat right-turn phase).

Operating a fully controlled right-turn every second cycle can be considered where:

- the intersection and/or the opposing through movement are/is at or above capacity
- the right-turn volume is low (e.g. < ~100 vph/lane)
- the volume of a right-turn movement can be accommodated in a relatively short phase
- the queue length can be accommodated within the available turn lane.

Table 2.4 presents the selection criteria that provide a guide to aid selection of the method of right-turn control.

Table 2.4: VicRoads selection criteria for method of right turn control

Method of right-turn control	Criteria considerations
Filter control	<p>A filter turn can be considered if there is:</p> <ul style="list-style-type: none"> • one turning lane • three opposing lanes or less • low-medium right-turn volumes • low-medium opposing through volumes • low-medium pedestrian volumes • a speed limit of 70 km/h or less.
Partially controlled	<p>A partially controlled turn can be considered if there is:</p> <ul style="list-style-type: none"> • one turning lane • three opposing lanes or less • medium-high right-turn volumes • low-high opposing through volumes • low-high pedestrian volumes • a speed limit of 70 km/h or less.
Partially controlled (with 'red arrow drop-out operation')	<p>A partially controlled turn with Red Arrow Drop Out can be considered if the site is in an urban location and there is:</p> <ul style="list-style-type: none"> • one exclusive right-turning lane • three opposing lanes or less • medium-high right-turn volumes • low-high opposing through volumes • low-high pedestrian volumes • a speed limit of 70 km/h or less • a requirement to control the right-turn and opposing through traffic/pedestrian conflict, while still maintaining the capacity of the right-turn movement by enabling filtering.
Fully controlled	<p>A fully controlled turn can be considered if there is:</p> <ul style="list-style-type: none"> • three opposing lanes or more • medium-high right-turn volumes • medium-high opposing through volumes • high pedestrian volumes • a speed limit of 80 km/h or more. • two or more right-turn lanes. • two or more opposing right-turn lanes. • road safety issues (e.g. poor sight distance). • a relevant crash trend (e.g. a significant amount of recorded casualty crashes that would be solved by this method of control, which have occurred over the latest five-year period) • a tram right-of-way. • linking/capacity benefits, (e.g. where the phasing implemented includes a lagging right-turn conflict)

2.1.8 Western Australia

Main Roads Western Australia (Main Roads) on-line guideline *Vehicular Signals* (2019) provides guidance on design procedures and traffic signal functions.

In terms of right-turn movements, Vehicular Signals advises that phasing shall generally be in accordance with the Austroads (2020b) *Guide to Traffic Management Part 9* with the following additions:

- Multi-lane right-turns shall be controlled by arrows and shall be prevented from filtering.
- Right-turn traffic across three or more through lanes should be prevented from filtering.
- Right-turn traffic shall be prevented from filtering where approach speeds are 70 km/h or more.
- Right-turn traffic shall be prevented from filtering where the road is classified District Distributor A and above.
- Right-turn movements under partial control shall operate in the 'red arrow drop out' mode only.

2.2 Current Practice

Six of the jurisdictions have documents in the forms of road safety policy, road safety plan or strategy, traffic engineering manuals, website information or treatment resource guides that provide current practice or strategies to treat right-turn crashes at intersections. Table 2.5 summarises the jurisdictional documentation and approaches to treating right-turn crashes at intersections.

Table 2.5: Jurisdictional practice

Jurisdiction	Current practice with filter right-turns and fully controlled right-turns
Australian Capital Territory	City Services <i>Roads and Paths</i> (TCCS n.d.) webpage (accessed September 2022) advises road users on ACT Government's practice of installing fully controlled right-turns on arterial roads.
New South Wales	Transport for New South Wales <i>2026 Road Safety Action Plan</i> (TfNSW 2022) highlights fully controlled right-turns as a treatment to improve safety at identified rural and urban signalised intersection.
Queensland	<i>Road Safety Policy</i> (TMR 2022) provides practitioner guidance and advocates for fully controlled right-turns at new and upgraded signalised intersections.
South Australia	<i>South Australia's Road Safety Strategy to 2031</i> (Government of South Australia Department for Infrastructure n.d.) draws attention to control of turning movements as a Safe System treatment at metropolitan intersections on major roads.
Victoria	<i>Guidance on Treating Pedestrian and Turning Vehicle Conflicts at Signalised Intersections</i> (VicRoads 2016) provides practitioner guidance on the application of fully controlled right-turns to eliminate or reduce conflicts.
Western Australia	The road trauma reduction guideline (<i>Treatment Resource Guide</i> (MRWA 2021a)) provides practitioner guidance on traffic signal phase improvements to address right-turn crashes at signalised intersections. Considerations are provided for the application of filter right-turns and fully controlled right-turns.

2.2.1 Australian Capital Territory

The ACT Government's City Services *Roads and Paths* (TCCS n.d.) webpage (accessed September 2022) provides information to road users about traffic signals. The public is informed that despite some drivers disliking fully controlled right-turns, these are provided where:

- the road has an arterial function
- the road has multiple lanes
- the speed limit is 80 km/h.

This is to improve the driving task of seeking an acceptable gap to cross the intersection. In terms of improving the waiting time for a green arrow in off-peak conditions, the ACT Government advises that changes are being made to increase the efficiency of signal operations.

2.2.2 New South Wales

The Transport for New South Wales *2026 Road Safety Action Plan* (2022) provides a framework to deliver its target to reduce road deaths by fifty percent and reduce serious injuries by 30% by 2030. This plan reports that urban intersection upgrades such as installing right-turn arrows can reduce dangerous turning crashes by up to 80%. Within the plan's new *Towards Zero Safer Roads Program by 2030* a reduction in right-turn crashes at signalised intersections in rural and urban environments is planned to be achieved by identifying

poor-performing intersections. The safety of these sites can be transformed by providing left in/left out restricted access and treating intersections with fully controlled turns and other intersection treatments.

2.2.3 Queensland

TMR's *Road Safety Policy (2022)*, advises that TMR will implement safety standards which will be actively applied in the planning and design of road infrastructure and operations projects. Within this policy intersection signalised filter turns are noted as a safety issue. New and upgraded signalised intersections shall have protected right-turn lanes on the major road and right-turns shall be fully controlled unless justified through a risk assessment.

2.2.4 South Australia

The South Australian Government's *South Australia's Road Safety Strategy to 2031* provides a framework to reduce the number of lives lost by 50 per cent and the number of serious injuries by 30% by 2031. The plan notes roads as a strategic focus area and provides high level information on Safe System road treatments. For metropolitan intersections on major roads example treatments include grade separation, separation of walking and cycling movements and control or separation of turn movements. The control of turn movements is supported by South Australian guidance for fully controlled right-turns. This strategy acknowledges the road safety benefit of this treatment in reducing right-turn crashes.

2.2.5 Victoria

VicRoads *Treatments to eliminate pedestrian and turning vehicle conflicts at signalised intersections (2017)* provides information about the appropriateness of fully controlled right-turn arrangements in certain road environments. Within the VicRoads road use classification hierarchy, this treatment is appropriate for:

- preferred traffic route
- tram priority route
- bus priority route
- pedestrian priority area (or network)
- bicycle priority route
- traffic route
- freight route
- collector road (without specific traffic priority)
- local road (without specific traffic priority).

This document also outlines further information about the application of fully controlled right-turn arrangements. Table 2.6 notes VicRoads' considerations for this treatment's potential locations, considerations, supporting treatments and benefits.

Table 2.6: VicRoads' considerations for fully controlled right-turn movements

Topic	Description
Potential locations	<ul style="list-style-type: none"> • At intersections within pedestrian priority areas as defined in the VicRoads SmartRoads strategy. • Within central activities areas including hospital and university campuses where pedestrian volumes are significant. • At intersections with multiple turn lanes. • At intersections with a history of crashes between turning vehicles and pedestrians. • At intersections with a high number of turning heavy vehicles. • Where there are high numbers of disabled or older pedestrians. • Where intersection geometry allows high-speed turning movements.

Topic	Description
Considerations	<ul style="list-style-type: none"> • Additional delays to public transport modes – e.g. where buses are delayed by traffic turning left or the bus route requires a left turn at the intersection. • Reduced intersection throughput due to increased waiting time – appropriate cycle lengths need to be determined. • Sufficient vehicle storage capacity is required in the turn lane or bay to cater for turning vehicles. • Auto-introduction of the pedestrian phase. • Late introduction of the pedestrian phase where there is sufficient remaining time for a crossing to be made.
Supporting treatments	<ul style="list-style-type: none"> • Raised platform on approach. • Raised intersection / pedestrian crossing. • Puffin crossing.
Pros	<ul style="list-style-type: none"> • Virtually eliminates the conflict between turning vehicles and pedestrians as vehicles have a separate turning phase. • The pedestrian movement can be as long as the vehicle through movement (i.e., 'run with green') phase.
Cons	<ul style="list-style-type: none"> • Increased intersection cycle times may reduce intersection throughput for other modes. Increased wait times for turning vehicles. • Potential delays to public transport modes, especially if they are trapped behind vehicles waiting to turn. • Increased queuing in the through lanes where there are short turn lanes with limited storage capacity.

The VicRoads website article *Rolling out controlled right-turns in Victoria* reported that, as of April 2021, 22 high-risk intersections across Melbourne were upgraded with controlled right-turns. This treatment allows vehicles to only turn right when there is a green turning arrow. It is anticipated that the intersection improvements described in Table 2.6 above will prevent approximately 129 serious crashes at intersections over the next 15 years. (Victoria State Government Department of Transport 2022). Funding was provided through the partnership between the Victorian Government and the Transport Accident Commission. This partnership's investment into road safety infrastructure is \$1.4 billion.

In an update to practice in Victoria, the 2024 Road Safety Policy provides the following advisory about the treatment of filter right-turns:

'Filter right-turns are not permitted at any time for all new or upgraded traffic signals. This may be achieved through right-turn bans or traffic signal phasing e.g. fully controlled right-turns or split phasing.

Additionally, no existing controlled right-turns shall be downgraded to a lower form of control e.g. fully controlled right-turns cannot become partially controlled or filter control; partially controlled right-turns cannot become filtered.

When designing new traffic signals with controlled right-turns it is important to ensure mobility of the road network is taken into consideration and appropriate capacity is built into the signals e.g. adequate number and length of auxiliary turn lanes, additional stand up lanes etc to be provided.

Where there may be impacts to the capacity of the intersection a review must be done of the surrounding road network to explore network solutions. This review should also ensure that if there is a likely redistribution of travel that no residual safety problems are created. If so, these should be addressed as part of the project to ensure the application of the policy provides the safest network solution.' (Department of Transport and Planning 2024).

2.2.6 Western Australia

Main Roads' *Road trauma reduction guideline* (2021) is part of the Road Safety Management (ROSMA) system and provides a suite of road safety treatments and countermeasures that are known to reduce killed and serious injury (FSI) crashes. This guide informs practitioners on the application of treatments, known issues, benefits and crash reduction factors. Treatments are based on (Austroads 2020d). Traffic signal phase improvements to address right-turn crashes at signalised intersections are documented and these include:

- partially controlled right-turn phase
- fully controlled right-turns
- banned right-turns.

The application, known issues and benefits of these treatments are noted in Table 2.7, Table 2.8 and Table 2.9 respectively.

Table 2.7: ROSMA right-turn phasing treatments – application

Treatment	Application
Partially controlled right-turn	<p>Typical reasons to consider this treatment:</p> <ul style="list-style-type: none"> • a high number of through-right casualty crashes over several consecutive years • two or more right-turn lanes on the opposite approach • right-turning traffic opposed by two or more through lanes of traffic • high operating speeds in two or more opposing through traffic lanes.
Fully controlled right-turn	<p>This treatment is applicable at intersections where:</p> <ul style="list-style-type: none"> • a history of through-right crashes has been recorded • two or more lanes turning right at one approach (double right-turn) • two or more right-turn lanes on the opposite approach • right-turning traffic opposed by two or more through lanes of traffic • high operating speeds in two or more opposing through traffic lanes • a service road adjacent to the opposing approach is continuous through the intersection (i.e. not truncated) • restricted horizontal and/or vertical sight distances.

Table 2.8: ROSMA right-turn phasing treatments – issues

Treatment	Known issues
Partially controlled right-turn	<ul style="list-style-type: none"> • The overall safety benefits of this treatment are much lower than that achieved by fully controlled right-turns, has a similar cost to a fully controlled right-turn. • The greatest road safety gains would be made at sites with a high crash rate from right-turning vehicles and a low rear-end crash rate.
Fully controlled right-turn	<ul style="list-style-type: none"> • This treatment reduces the efficiency of an intersection. Capacity analyses should be conducted prior to implementing fully controlled right-turn phase. • Providing or increasing capacity of right-turn lanes may be needed to compensate for the reduced efficiency of the intersection. This could be achieved by providing dual right-turn lanes or increasing the length of right-turn lane.
Banned right-turns	<ul style="list-style-type: none"> • The application of this treatment during peak periods may redistribute traffic to other intersections with similar safety issues, resulting in no net benefit. • Investigation of this treatment would require consideration of nearby intersections

Table 2.9: ROSMA right-turn phasing treatments – benefits

Treatment	Benefits
Fully controlled right-turn	<p>Benefits associated with this treatment are:</p> <ul style="list-style-type: none"> • substantial reduction in through-right crashes • reduction in severity of crashes throughout the intersection • reduction in vehicle-pedestrian conflict potential • removal of conflict between right-turners and pedestrians crossing the intersection road.

In practice Main Roads WA (MRWA 2021b) utilises the ROSMA system to identify and prioritise road safety projects across Western Australia.

2.3 Crash Reduction Factors

The Austroads *Guide to road safety part 2 safe roads (2022)* provides detail on crash modification factors (CMFs) which are also referenced as crash reduction factors (CRFs). Crash modification factors and crash reduction factors are similar in their assigning a numerical value to the effect on crash incidence; however, they are not interchangeable. These are an essential data component in the evaluation and prioritisation of road projects, used primarily to estimate economic savings in crashes for proposed road improvement works. This allows for various potential design options to be compared, works programs to be prioritised, and benefit-cost ratios to be estimated.

CMFs are defined as a relative metric to estimate the expected change in crash numbers associated with a particular treatment. Expressed as a decimal, a CMF is equivalent to 1 minus the CRF value. For instance, if a treatment has a CRF of 20%, then the equivalent CMF would be 0.8. A CMF of less than one indicates a reduction in the crash rate, whilst a CMF greater than one indicates an increase.

CRFs are a relative metric that estimates the expected reduction in crashes associated with a particular treatment and are expressed as a percentage. As it is a reduction, a negative CRF would refer to an increase in crashes.

Reliable information is provided on crash reduction for various treatment options for various Australian and New Zealand conditions. Crash countermeasure selection is not as simple as identifying the treatment with most likely CMF or CRF to reduce crashes. The practitioner should identify the most applicable treatment for the crash type and road environment considered, and then consider the relevant CMF or CRF.

Specific to treatments for intersection crashes at signalised intersections, a summary of CMFs provided by Austroads is provided in Table 2.10. With opposing turn crashes, an increase in crashes is noted with new traffic signals with no turn arrows, while a reduction in crashes is noted with new traffic signals with turn arrows or with remodelling signals.

Table 2.10: Summary of CMFs of various countermeasures for intersection crashes, specific to traffic signals

Treatment type	Description and Road Use Movement (RUM) code								
	Adjacent approach Intersecti on 11-19	Head-on 21	Opposing turns 22-27	Rear-end 31	Lane change 35-37	Parallel lanes-turning 38-39	Vehicle hits ped. 1-3	Loss of control L or R turns 52-56	Hit parked/ parking vehicle 61, 42-43
New traffic signals (no turn arrows)	0.3		1.9				0.7		
New traffic signals (with turn arrows)	0.3		0.55				0.7		
Remodel signals	0.7		0.6				0.7		
Ban left or U-turns			Note 1	0.5		0.5		0.5	
Indented right-turn island			0.7	0.6				0.8	0.8
Painted turn lane			0.8	0.8					0.8

Note 1: The treatment 'banning U turns' is a relevant treatment for crash type 27, with an estimated 50% reduction. Banning left turns is a relevant treatment for crash types 23, 25 and 26 with a 50% reduction.

Expert reasoning and engineering judgement needs to be applied whenever interpreting and using CRFs. All road safety infrastructure projects should be reviewed within the context in which they are proposed and consideration given to site specific as well as wider network conditions and the effects these may have on safety performance.

A summary of guidance on crash reduction factors for right-turn control movements is shown in Table 2.11.

Table 2.11: Jurisdictional guidance with crash reduction factors

Jurisdiction	Guidance with crash reduction factors
Queensland	<i>Development of Crash Reduction Factors (2018/19 – 2019/20)</i> McHeim (2020) provides an in-depth overview of CRFs across jurisdictions in Australia and New Zealand. This report was prepared for TMR to update its matrix of CRFs. Contemporary information on CRFs for filtered right-turn and fully controlled right-turns are provided.
Western Australia	A Road Trauma Reduction Guideline (MRWA 2021a) provides practitioner guidance on traffic signal phase improvements to address right-turn crashes at signalised intersections. CRFs are provided for the application of filter right-turns fully controlled right-turns and right-turn bans.

2.3.1 Queensland

R87: *Development of crash reduction factors (2018/19 – 2019/20)* by McHeim (2020) was prepared for TMR to update its crash reduction factors matrix. This project involved a comprehensive review of CRFs. Information was drawn from both local and international sources, including current practice and literature, as well as through the collective knowledge of Australian Road Research Board (ARRB) and Transport and Main Roads representatives in a series of intensive workshops.

This project provides a comprehensive review, across Australian and New Zealand jurisdictions, of CRFs for treatments. Specific to treatment options for intersection crashes at signalised intersections, a summary of CRFs is provided with commentary on whether this treatment reduces, or increases, the number of crashes. Notably, options with no filter turns were allowed and fully controlled right-turns demonstrated a higher reduction in opposing vehicles-turning crashes.

Install new traffic signals: Filter turns allowed

A summary of the CRFs is provided in Table 2.12. The CRF values suggested that this particular treatment could potentially increase the number of right through, opposing vehicles turning and rear-end crashes.

Table 2.12: Summary of CRFs for installing new traffic signals: filter turns allowed (% reduction)

No.	Crash type (DCA group)	TMR	NSW RMS	VicRoads	WA	SA	NZTA	Austrroads	Recent literature
1	Intersection, adjacent approaches	70	70*					50 (2012)	
2	Opposing vehicles turning	-30	-30						
3	Rear-end	-20	-20					-30 (2012)	
4	Lane change	30							
5	Hit pedestrian	30	30			30			
6	Casualty crashes	-		45*					
	Treatment life (years)	15		15*		15			

* VicRoads and Austrroads (2012) did not specify filter turns.

Install new traffic signals: No filter turns allowed

A summary of the CRFs used by jurisdictions is provided in Table 2.13. It shows that the treatment could effectively reduce some types of crashes such as intersection, right-through and crashes involving opposing vehicles turning. However, it could potentially increase rear-end crashes by 20% as specified by TMR and RMS NSW. VicRoads specified a 45% reduction in casualty crashes for new signals.

Table 2.13: Summary of CRFs for installing new traffic signals: no filter turns allowed (% reduction)

No.	Crash type (DCA group)	TMR	NSW RMS	VicRoads	WA	SA	NZTA	Austrroads	Recent literature
1	Intersection, adjacent approaches	70	70*			70		50 (2012)	
2	Opposing vehicles turning	70	70			50			
3	Rear-end	-20	-20					-30 (2012)	
4	Lane change	5	5			30			
5	All casualty crashes	-						-30 (2012)	35
	Treatment life (years)	15		15*		15			

* VicRoads did not specify filter turns.

Install fully controlled right-turn with arrows

A summary of the CRFs is provided in Table 2.14. The CRFs from different jurisdictions show consistency in some DCA groups. This treatment can effectively reduce the number of right- through, rear-end and U-turn crashes.

Table 2.14: Summary of CRFs for installing fully controlled right-turn with arrows (% reduction)

No.	Crash type (DCA group)	TMR	NSW RMS	VicRoads	WA	SA	NZTA	Austrroads	Recent literature
1	Intersection, adjacent approaches							45 (2012)	
2	Opposing vehicles turning	80	80	80*				60 (2012)	
3	U-turn	80		80*					
4	Hit pedestrian	30	30						
5	All casualty crashes							35 (2012)	50
	Treatment life (years)	10		15					

*The VicRoads reduction of 80% applies to crashes involving right-through movements and U-turns during right- turn periods.

Introduce right-turn phase while leaving filter

A summary of the CRFs used by jurisdictions is provided in Table 2.15. RMS NSW was the only other jurisdiction to report values specifically for this treatment.

Table 2.15: Summary of CRFs for introducing right-turn phase while leaving filter (% reduction)

No.	Crash type (DCA group)	TMR	NSW RMS	VicRoads	WA	SA	NZTA	Austrroads	Recent literature
1	Opposing vehicles turning	5	5	14*					
2	Hit pedestrian	5	5						
3	All casualty crashes			4				10 (2012)	
	Treatment life (years)	10							

*The VicRoads reduction of 14% applies to crashes involving right-through movements only during right-turn periods.

2.3.2 Western Australia

The Main Roads *Road trauma reduction guideline* (2021) notes crash reduction factors for the following right-turn treatments:

- Modify signals – install right-turn arrow (with filter)
- Modify signals – fully controlled right-turns from no control
- Modify signals – ban right-turn movements during am and pm peak.

The crash reduction factors are shown in Table 2.16. Potentially, the ‘install right arrow with filter’ option has a lower crash reduction rate than the fully controlled right-turn option.

Table 2.16: Summary of CRFs of various countermeasures for intersection crashes, specific to traffic signals (% reduction)

Treatment	Pedestrian	Rear-end	Right angle	Tight turn thru	Other right-turn	Other
Modify signals – install right-turn arrow (with filter)				35	35	
Modify signals – fully controlled right-turns from no control	30			50	80	
Modify signals – ban right-turn movements during am and pm peak	10	40	50	50		50

2.4 Guidance and Practice Conclusions

Australian and New Zealand jurisdictions apply Austroads technical guidelines to complement and support their own guidelines for the design of traffic signal phasing and arrangements at signalised intersections. Guidance on traffic signal phasing provided by all jurisdictions strongly aligns with the view to remove right-turn filter arrangements. This position needs to be considered for new traffic signal installations and where signalised intersections are to be modified.

Recommendations in the University of Western Australia UWA’s report align directly with guidance provided by New South Wales, which covers right-turn phasing, with or without right-turn filters. This indicates that the right-turn filter may be used in some circumstances to assist efficiency of vehicle movements through the intersection. The use of flashing arrows as an alternative to the circular green was not found within guidelines from any jurisdiction. However, Victorian guidance provides information for partially controlled right-turns. This introduces the right-turn movement being able to be controlled with either two-aspect (Yellow/Green) right-turn arrow displays or three-aspect (red/yellow/green) right-turn arrow displays, with a red arrow drop out.

Some jurisdictions have documentation and policy to support the removal of filter right-turn arrangements. Victorian and Western Australian documents advise on the appropriateness of fully controlled right-turns. In addition, they advise on the preferred road environments where this treatment needs to be applied. They also provide commentary on the impacts this arrangement would have on the operation of the subject signalised intersection in terms of efficiency of vehicle movement and queuing of vehicles. The Queensland Road Safety Policy takes a firm view on the installation of fully controlled right-turns, and Victoria has adopted a similar position; both note that new and upgraded signalised intersections shall have protected right-turn lanes on the major road and right-turns shall be fully controlled. Queensland consider that filter right-turn arrangements are only justified through a risk assessment. The current New South Wales road safety plan acknowledges the Safe System approach and supports intersection upgrades such as right-turn arrows at signalised intersections in rural and urban environments. The current South Australia road safety strategy also acknowledges the Safe System approach and notes an example treatment of controlled turns at intersections to reduce right-turn crashes at metropolitan intersections on major roads.

Crash reduction factors provided by Austroads point towards a reduction in crashes with new traffic signals or remodelled signals with turn arrows. Queensland has recently undertaken a comprehensive review of crash reduction factors across Australian and New Zealand jurisdictions. It is suggested that, where filter turns are allowed, this could potentially increase the number of crashes related to right through, opposing vehicles turning and rear-end movements. In comparison, a fully controlled right-turn can effectively reduce the number of right- through, rear-end and U-turn crashes.

2.5 Review of Surrogate Safety/Traffic Conflict Measures

Stokes & Woolley (2022) reviewed filter right-turn crashes by observing CCTV footage of real-world crashes. The study yielded valuable insights to potential contributing factors to the cause and severity of these types of crashes, including speed of the through road approach, dynamic visual obstruction, headlight glare and reduced driver 'ability to accurately estimate the distance of an oncoming vehicle'. In response, several recommendations for potentially mitigating crash risk were posed, including less use of filter right turns at intersections, the application of full control right turns during off-peak hours, and reducing the approach speed of approaching through traffic.

In the absence of similar CCTV footage or detailed crash investigation and reconstruction of filtered right crashes, it was necessary, for this WARRIP project, to adopt surrogate safety/traffic conflict measures that would aid in identifying near-miss incidents at the nominated intersection sites.

Legge & Goodsell (2022), referred to previously suggested identifying near-miss incidents relative to amber signal timing and the use of a selection of traffic conflict measures. For each of these the UWA report recommended the following:

Identifying near-miss crash events relative to amber signal timing - '...a combination of automatic and manual data extraction methods be used to identify, examine and rate the severity of traffic conflicts when vehicles are making filter right-turns at signalised intersections. Specifically, that an automated analysis be done to identify and classify the trajectories of vehicles to determine if a traffic conflict has occurred and rate its severity when vehicles are making a filter right-turn. And that manual methods be used to compare the timing of the filter right-turns with the timing of the amber stage of the signal phase'.

Selection of traffic conflict measure - '...that PET² be used to assess the severity of traffic conflicts between vehicles making a filter right-turn and opposing traffic and that T₂, a modification to TTC³, be used for interactions between vehicles and vulnerable road users. These are objective measures that are directly observable via video surveys'.

PET and TTC are two measures widely reported in the body of research literature as being suitable surrogate safety/traffic conflict measures. In setting the values for PET and TTC consideration needs to be given to the following:

1. Identifying a sufficient sampling of possible traffic conflicts from the field data. In this regard, larger PET and TTC values, say 3, 4 or 5 seconds, will flag a greater number of traffic conflicts as 'near-miss' incidents; however, the larger the values the less likely conflicts may be considered as viable near misses.
2. What constitutes a critical or high risk (hazardous) situation, i.e. a real concern of being a potential crash, against which contributing factors of interest could be flagged. Thresholds for both PET and TTC below 1.5 seconds appear to indicate a significantly higher likelihood of a crash.

Drawing from the literature, PET and TTC values for this WARRIP project were set as follows:

- PET and TTC values for sampling 'near-miss' incidents would be set at a maximum of 3 and 5 seconds, respectively.
- PET and TTC values for what may be considered critical or high risk (hazardous) situations would be set at a maximum of 1.5 seconds each.

² PET is 'post encroachment time'. It refers to the time gap between the departure of the encroaching vehicle from the conflict point and the arrival of the second vehicle with the right-of-way at the conflict point. PET can predict the probability of crashes without assessing their severity. A PET value of zero indicates a crash, while non-zero PET values indicate crash proximity.

³ TTC is 'Time to collision'. It is the delay remaining between the instant considered and the time of the collision between the subject vehicle and the target vehicle.

A study by Anarkooli et al. (2021) examined traffic conflict at intersections in Winnipeg, Manitoba, Canada used PET as an alternative to TTC, to measure conflict and to estimate the severity of crashes in relation to the vehicle movement. Models developed to estimate frequency and the severity of intersection conflicts and showed a strong relationship between the classified conflicts and crashes. The results also revealed that the contribution of conflicts to the risk of crashes varies based on speed dimension of their severity, suggesting that neglecting speed as a factor in conflict severity levels may be at the expense of losing meaningful information.

The research demonstrated that previous studies support extremely low PET thresholds, for example less than one second, to provide an optimal crash conflict relationship. The analysis undertaken by Anarkooli et al demonstrated that complementing PET thresholds with conflicting speed of vehicles can identify critical conflicts that may result in fatal or injury crashes. As such, Anarkooli et al concluded that having PET as a sole time-based measure does not necessarily demonstrate severity of conflicts within the data collected if conflicting speed was not included.

Following from Anarkooli et al, it was considered important to identify a suitable metric that could estimate the potential severity outcome of a near-miss incident, if it were to result in a collision, since this would aid in closing out an assessment of risk.

Laureshyn et al. (2017) describes '*...Extended Delta-V as a measure of traffic conflict severity in site-based observations*'; they outline that Extended Delta-V '*...is derived from the concept of Delta-V as it is applied in crash reconstructions, which refers to the change of velocity experienced by a road user during a crash*'. Laureshyn et al. go on to state that '*the concept of Delta-V is recognised as an important predictor of crash outcome severity*' and '*...is applicable to situations in which two road users are heading towards a common conflict area*'.

In simple terms, Delta-V is the change in the velocity vector (speed) experienced by a road user during a crash. The instantaneous change in both the magnitude and direction of this velocity vector (speed) implies the extensive forces acting on the road user (vehicle occupants) and from this the severity of injuries resulting from the collision can be estimated.

2.6 Review of Data Collection Methods and Technologies

A review of data collection and analysis techniques relating to proximity based surrogate safety/traffic conflict measures was undertaken. Identified were three potential methods, as applied by other similar data collection projects, and are broadly described as:

- video survey
- LIDAR
- drone video survey.

Each of the above data collection methods is briefly critiqued, below, to determine effectiveness in measuring traffic conflict measures.

2.6.1 Video Data Collection

Legge & Goodsell (2022) discussed the set-up for video surveys and data extraction from video surveys. For video surveys the report explores effective camera position, length of the video observation periods, and time of day of the video observation periods. For data extraction it explores manual data extraction, automated data extraction, and the pros and cons of manual versus automated data extraction methods.

A 2019 study of three four-legged intersections in Brisbane by Arun et al. (2022) investigated the application of traffic conflict methods in jointly predicting rear-end crash frequency and severity, with traffic conflicts extracted from video data using state-of-the-art computer vision analytics.

Four conflict metrics were chosen as a framework; one of relevance to this WARRIP project was modified time to collision (MTTC) and the other of relevance was Delta-V, providing a measure of expected post-collision change in velocity as a crash severity indicator.

This study demonstrated the effect of the longer duration of conflict observations on the accuracy and precision of crash estimates. Proximity based traffic conflict measures require large amounts of data. Previous studies noted by Arun et.al (2022) observed low accuracy and precision of crash estimates from previous studies may be because of low conflict observation durations. Conflicts for this study were observed for 24 hours (12 hours each for two days), which consequently provided a significantly higher number of joint extreme conflicts in all margins than similar previous studies. It is expected that larger conflict datasets will help improve the efficiency of joint frequency and severity prediction models even further.

While the study provides an evidence base to support video data collection for proximity-based traffic conflicts, there are some disadvantages of video data (Arun et. al. 2021). These include:

- privacy concerns especially with video-based methods
- the raw data size can become prohibitively large with video-based methods
- sample size issues with video-based methods, primarily when deriving crash-conflict relationships
- data collection is affected by weather conditions especially for non-embedded type sensors.

These factors needed to be considered for the data collection methodology task of this WARRIP project.

2.6.2 LiDAR

LiDAR provides a new solution for real-time data where high-resolution trajectories or movement, direction, and tracking of all road users can be obtained from this technology. In comparison to video data, the accuracy of LiDAR data collection is not impacted by reduced visibility conditions such as rain, reduced lighting, or other adverse weather since they do not impact the accuracy of 3D point clouds of LiDAR (Anisha 2022).

The trajectories of road users provided by roadside LiDAR are considered as a good data source for near-crash identification.

The feasibility of using LiDAR for safety and operation management at intersections has been investigated on several occasions (Wu 2018). Examples obtained for this literature review are noted below and represent Australian and overseas studies.

- Vehicle-pedestrian near-crash identification (Wu 2018)
- Red light running prediction (Kim et al. 2019)
- Calibration of automatic performance measures – speed and volume data (Saito 2016)
- Omni-Aware Roadside Adaptation of Automated Vehicle LiDAR (Austroads 2021)
- Vehicle conflict analysis at signalised intersections (Anisha 2022).

Only the trial by Austroads and the research by Anisha utilised LiDAR data for proximity-based traffic conflict measures.

Austroads (2021) reported on a 2019 Victorian on-road LiDAR trial at a signalised intersection. The trial noted that traffic conflict measures for intersection crash risk assessment was only partly demonstrated. Further software development would be required for these results to reflect the high levels of performance available with LiDAR technology. Notwithstanding this, the trial noted provision of detailed information of events of interest was demonstrated and this information was available for any event of interest regardless of whether it was a crash, a near-miss, or some other event of interest. The development of LiDAR sensors is ongoing and sensors suitable for long-term and economical installation in roadside environments should be available in coming years.

Anisha's research on one four-way signalised intersection in Orlando, Florida, USA, computed only PET. That research captured data using three methods – low-resolution video technology, solid-state LiDAR

technology, and a fusion of video and LiDAR technology. This approach was applied to study rear-end, side-swipe, head-on and angle crash conflicts.

The data was collected on several occasions during morning and afternoon peak periods. The vehicle movements captured by camera showed they were dense and substantial on the approaches to the intersection and shallow at the intersection. Comparatively, vehicle movements captured by LiDAR were dense on the approaches to the intersection and for capturing turning movements. When video and LiDAR were fused together, a clearer picture of vehicle movements on the approach and turning movements at the intersection resulted.

It was observed that the most conflicts were side-swipe and rear-end conflicts. In terms of measuring PET, the fused method provided more conflicts than the individual video and LiDAR techniques. However, the distribution of these conflicts throughout the intersection differs with each of the data collection methods. Notwithstanding this, the fused method performed significantly better than the single sensor-based systems in terms of the number of detections and localisation. This research concluded that it would be expected that the fused method can be employed to diagnose road safety problems and inform the required countermeasures and to experiment with deep learning-based object detection algorithms to increase the recall of LiDAR based detections.

2.6.3 Drone Technology

Drone technology provides a comprehensive 'bird's eye view' of an entire location, although the limited flying time and air space regulations concerning operations are significant disadvantages (Arun 2021).

A 2018 research study carried out in Thessaloniki, Greece (Papaioannou et al. 2021) reported that drone technology has several uses for traffic monitoring. Capabilities include identifying, tracking and monitoring specific vehicles, and several parameters can be extracted, such as densities, travel times, turning counts, and queue lengths. Other tasks include determining level of service, estimating average annual daily travel (AADT), measuring intersections, operating conditions and creating origin destination flows can also be evaluated.

The study recognised this technology as a more suitable means of capturing traffic measures than a fixed camera, as it has the capability to film a larger area and deal with certain other limitations, such as moving to any area to select the optimal location and avoiding positions that prevent the complete recording of an object. Drone technology was applied to examine driver behaviour at a signalised four-way intersection. The data captured was analysed to measure vehicle distance to stop lines, approach speed, acceleration/deceleration, driver aggression and relative position. Data was not captured specifically for the purposes of measuring PET and TTC. The total duration time of the collection period was 720 minutes, collected over a 12-day period.

The data collection implications of this technology relevant to this study are important to consider. This study reported that there were disadvantages related to battery life, resulting in limited flight time, and weather conditions, as it is not possible to use drones in case of rain and strong wind, for reasons of safety and protection of the equipment. In addition, prior to the data collection task, flight plans were required to be submitted to the Greek Civil Aviation Authority to provide necessary approvals. The official permission was required for security reasons, due to the subject site's proximity to the airport, as well as for privacy issues mainly related to sensitive personal data of people recorded in video footage.

A 2019 research study conducted in Brooklyn, New York, USA (Yang 2021) using drone technology focused on rear-end conflict at a signalised four-way intersection, with TTC being a key metric analysed from this study. Like the Greek study, there were limitations to the effectiveness in data collection; use of a drone needed to comply with Federal Aviation Administration (FAA) guidelines. Brooklyn was chosen as airspace restrictions for flying a drone are relatively more relaxed compared to other New York boroughs, especially Manhattan. The drone was flown at 400 ft (120 m), the maximum allowable altitude for a drone set by the FAA regulations (this limitation also applies in Australia under CASA regulations).

The battery life of the drone impacted on the data collection duration of the study. Subsequently, two videos were recorded with the total duration of approximately one hour over two consecutive mornings, with staggered times of 6:00 to 7:00 am on the first morning, and 7:00 to 8:00 am on the second. Only one drone was used to capture traffic movements, which limited the spatial and temporal coverage of the recorded traffic. This study recommended to use multiple drones and record simultaneously to increase the coverage and sample size for more investigation.

2.6.4 Data Collection Methods and Technologies Conclusions

The UWA report provides recommendations for identifying near-miss crash events and amber signal timing as well as selection of traffic conflict measures for filter right-turn crashes. Data collection using video technology is the preferred method with an automated analysis to determine rate and severity of the crashes using traffic conflict measures of PET and modified TTC.

The 2021 Canadian study (Anarkooli et al, 2021) found that while PET is useful to demonstrate conflicts where the PET threshold is extremely low, critical conflicts to effectively estimate crash severity may not be captured. As such, it is suggested that speed data as a complimentary dataset could identify such critical conflicts. The data collection process employed used video technology. Data was collected for the most part, over a 24 hour period with observation primarily over peak and non-peak periods.

The use of video data technology demonstrates the best fit for analysis of PET and TTC. The 2019 Brisbane study (Arun et al. 2021) provides evidence of video surveys and a matured, automated approach to measuring the conflict measures. Multiple cameras can be used to capture all road user movements. Data was collected for four consecutive weekdays, with observation of twelve hours data over two consecutive days.

LiDAR technology has advantages over video technology in terms of accuracy of identifying objects within its field of view and adverse weather conditions do not impact the performance of data collection. LiDAR has many applications to measure operations of a signalised intersection. However, there is limited evidence that demonstrates reliable capabilities in utilising LiDAR data for measuring traffic conflicts.

Drone technology is capable of providing comprehensive views of a signalised intersections, however, to ensure a reliable data set for the measurement of traffic conflicts, the duration of continuous data collection for a minimum twelve hours (Arun et al. 2021) should be attained. The constraints associated with drone technology, i.e. short battery life, weather restrictions and CASA regulations for licensing and location limits the viability to obtain quality data.

Video data technology-based studies were considered more reliable in terms of collecting longer data sets and could be coupled with video analytics software to examine intersection conflicts.

A conclusive best practice data collection duration was not identified from the literature. Drone and LiDAR studies produced limited data to analyse as a result of short data collection periods. In comparison, video technology-based studies provided longer data collection durations of 12 or 24 hours, with data observed over peak and non-peak periods.

For this WARRIP project, it is suggested that a data collection period over a four-day period (Thursday to Sunday), for 12 hours per day, capturing peak traffic periods, be applied. Non-peak traffic periods can also be included, dependent on available traffic data that demonstrates unique activity outside of peak hours. It is also suggested that three surrogate safety measures be used to define near-miss and assess the risk, i.e. likelihood and potential severity, as a means of estimating the significance of the crash potential at each site.

3 Data Collection Plan and Analysis Methodology

This section sets out the approach to site data collection to support the project research objectives; the analysis method, based on the data collected, is also outlined.

3.1 Introduction

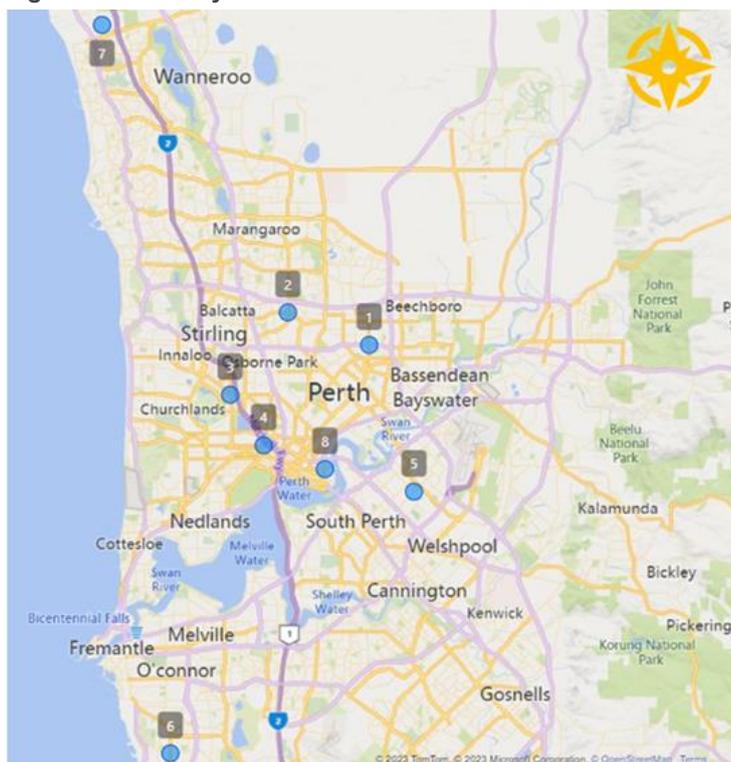
Main Roads confirmed eight study sites for inclusion in this research project to understand right-turn crashes at signalised intersections, refer to Table 3.1 and Figure 3.1.

One site was selected as a pilot study site to validate the quality of video data collection, video analytics, reporting, and identify any learnings (limitations and opportunities) of the adopted process; these learnings could then be applied to the remaining seven sites with refinement of the data collection plan and/or analysis method to address the research objectives.

Table 3.1: Study sites

No.	Location	Suburb	Right-turn arrangements
1	Mirrabooka Ave/Ravenswood Dr/Yirrigan Dr. (4-way leg intersection)	Nollamara	All approaches have 2x through lanes and 1x dedicated right-turn lane.
2	Southport St/Cambridge St. (4-way leg intersection)	West Leederville	All approach legs have 2x through lanes with right-turns permitted.
3	Karrinyup-Morley Rd/Crimea St. (4-way leg intersection)	Morley	All approaches have 2x through lanes and 1x dedicated right-turn lane.
4	Connolly Dr/Selkirk Dr. (T-intersection)	Kinross	The northbound carriageway has 2x through lanes and 1x dedicated right-turn lane.
5	Spearwood Ave/Rockingham Rd (4-way leg intersection)	Spearwood	North-south carriageway have 2x through lanes with right-turns permitted. East-west carriageways have 2x through lanes + 1x dedicated right-turn lanes.
6	Harborne St/Scarborough Beach Rd/Frobisher St. (4-way leg intersection)	Osbourne Park	Northbound carriageway has 2x through lanes + 1x dedicated right-turn lane. Southbound carriageway has 2x through lanes with right-turns permitted. East-west carriageways have protected right-turn lanes and 2x through lanes.
7	Belmont Ave/Wright St. (4-way leg intersection)	Kewdale	Three legs have 2x through lanes + 1x dedicated right-turn permitted; one leg has a protected right-turn lane and one through lane.
8	Plain St and Royal St. (Pilot study site) (4-way leg intersection)	East Perth	North-south carriageway have 2x through lanes with right-turns permitted. East-west carriageways 2x through lanes with right-turns permitted.

Figure 3.1: Study site location distribution



Drawing from the findings of the literature review, it was determined that video data collection methods, combined with automated analysis of the imagery to determine rate and severity of detected incidents at the nominated sites, would be the most reliable and cost effective method for collecting the required information for subsequent evaluation.

Analysis of the video survey data outputs would then assist identifying and quantifying risk factors and provide insight to potential mitigating measures to improve safety. This would permit Main Roads to inform and develop improved policy, design, and operation of signalised intersections to reduce the likelihood and severity of right-turn crashes on the Western Australia road network.

3.2 Pilot Survey (Plain Street and Royal Street)

A Pilot survey site was selected from the eight nominated sites. The purpose for running the pilot survey was to:

1. validate and report on the performance of video data to determine its effectiveness in accurately collecting vehicle counts, vehicle classification, and vehicle speed
2. validate whether video data collected is suitable, for video analytics and that surrogate safety measures such as time-to-collision (TTC) and post encroachment time (PET) or others that may be applied can be appropriately determined from the collected footage.

Specific deliverables from the Pilot Study included the following:

- A data collection and data management plan.
- Reporting of data validation for review in written description, dashboard format and presentation to confirm:
 - video data collection is accurate in terms of traffic counts, measurement of speed and classification of vehicles
 - identification of vehicle movements at each site best demonstrating right-turn conflicts
 - video data suitability for analytics and measurement of surrogate safety measures
 - limitations and opportunities of data collection, analytics, and reporting.

- Video Analytics:
 - identify near-miss and actual events using the following surrogate safety measures to a defined range of threshold values:
 - time-to-collision (TTC)
 - post encroachment time (PET)
 - kinetic energy/delta V/speed combined with angle, to further classify video clips showing potential near-misses into a high FSI (fatal or serious injury outcome) risk category.
 - description of the expected road user combinations of near-miss events output from the analytics; for example, pedestrian/light passenger vehicles (LPV), bicycle/truck, LPV/LPV, bus/truck, etc.
 - near-miss events disaggregated by crash types of Main Roads RUM Code 22, 23, 24, and 27 (MRWA n.d.)
 - road user counts by road user type
 - road user speed analysis by road user type
 - a predictor of crashes with a high probability of a fatal or serious injury (FSI)
 - for all the above, the levels of accuracy that the analytics will deliver.
- Reporting and analysis dashboard.
- Data files.

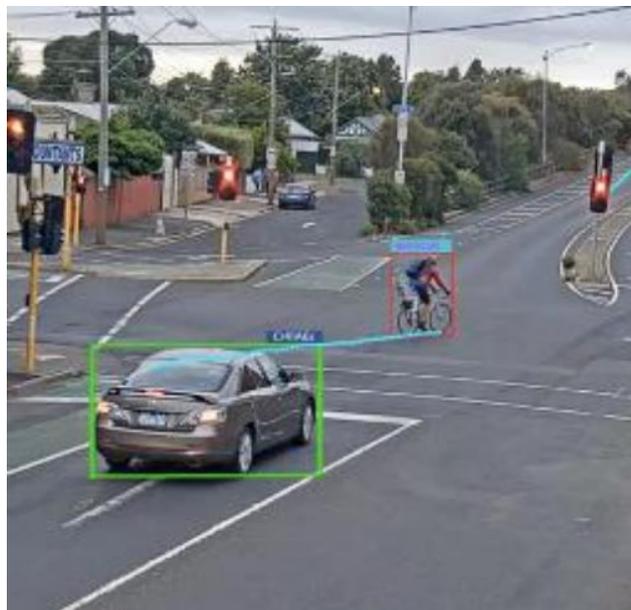
3.3 Data Collection Plan

The site video survey was undertaken by Real Time Traffic, a commercial entity experienced with in-field traffic surveys, including the use of video technology. An example image of the video camera installations installed by Real Time Traffic is shown in Figure 3.2; an example of the tracking and coding of traffic units involved in a detectable conflict incident is shown in Figure 3.3.

Figure 3.2: Example Realite Safety Camera installation



Figure 3.3: Example traffic unit detection for conflict assessment



The data collection plan for the site survey component of the project is presented in Table 3.2.

At the conclusion of the defined survey period, the data collected by the RSC units was analysed by Real Time Traffic to identify detectable conflict incidents. Information relating to the surrogate safety measures for each incident and other information pertaining to observed driver behaviours, turning movements, timing in signal phasing, etc. were recorded and provided for analysis to identify relevant trends and potential risk factors.

Table 3.2: Data collection plan outline

Item	Data collection component	Arrangement	Comments/Notes
1.	Site installation	<ul style="list-style-type: none"> • 2x Realite Safety Cameras (RSC): <ul style="list-style-type: none"> – solar battery powered – local and cloud-based data storage – 4G communications link. 	<ul style="list-style-type: none"> • Traffic control signal lanterns to be within RSC field of view to observe signal phasing. • RSC to capture vehicle categorisation, driver hesitance and conflict analysis.
		<ul style="list-style-type: none"> • 2x Automatic Traffic Counters (ATC). 	<ul style="list-style-type: none"> • ATC used to 'ground-truth' video survey data (speed – mean and 85th%, vehicle classification, volume).
		<ul style="list-style-type: none"> • Appropriate approvals from MRWA/LGA required. 	
2.	Survey period	<ul style="list-style-type: none"> • Four 'typical traffic' days of data collection for each site. • 16 hours of observations per day, 6 am to 10 pm. 	<ul style="list-style-type: none"> • Days to include weekends and week days, but not public/school holidays. • Fine weather days.
3.	Video imagery	<ul style="list-style-type: none"> • Colour. • Personal identifiable information pixelated for privacy. 	
4.	Video analytics - near-miss detection criteria	<ul style="list-style-type: none"> • Surrogate safety measures: <ul style="list-style-type: none"> – Post encroachment time (PET) – Time to collision (TTC) – Delta-V, a measure of severity – Stop line compliance – Lane positioning – Time headway. • Road user traffic unit combinations. • Classified traffic counts. • Traffic speed. • MRWA RUM code to describe detectable incidents. 	<ul style="list-style-type: none"> • Surrogate safety measures for detected incidents form output of site surveys and inputs for data analysis as part of risk factor assessments. • Values for PET and TTC to identify 'near-miss' incidents set at 4.0 seconds. • PET and TTC values for critical, or high risk, near-miss incidents set at 1.5 seconds, each. • Road user combinations include <ul style="list-style-type: none"> – pedestrian/light passenger vehicles (LPV) – bicycle/truck – LPV/LPV – bus/truck, etc.
5.	Site traffic set-up	<ul style="list-style-type: none"> • Information about the set-up for each of the nominated locations. 	<ul style="list-style-type: none"> • Assist in identifying risk factors

3.4 Analysis Method

The analysis of data collated from the video survey involves a frequency and distribution analysis followed by a relationship and correlation analysis.

The approach to each of these analyses is outlined in the table Table 3.3.

Table 3.3: Analysis methods applied to the collated survey dataset

Analysis	Arrangement	Comments/Notes
Frequency and distribution analysis		
Road user combinations and signal colours	<ul style="list-style-type: none"> • histogram road user combination 	This function calculates the frequency of different types of road users involved in traffic conflicts (e.g., 'Car-Car', 'Car-Bike'). It then generates a histogram to visualise these frequencies, making it easy to identify the most common types of conflicting road users.
	<ul style="list-style-type: none"> • frequency traffic signal colour 	This function analyses the frequency of traffic signal colours ('Red', 'Yellow', 'Green') at the time of right-turn incidents. A bar plot is created to display these frequencies, which can help in identifying potential issues related to signal compliance or timing
Speed and safety metrics (TTC and PET)	<ul style="list-style-type: none"> • histogram speed user 	This function generates histograms of vehicle speeds for both right-turning and opposing traffic. This allows for a direct comparison of their speed distributions and helps in understanding the speed dynamics at the time of the conflict.
	<ul style="list-style-type: none"> • kde TTC PET 	A Kernel Density Estimation (KDE) plot is created for Time to Collision (TTC) and Post Encroachment Time (PET). KDE plots are used to visualise the probability density of these critical safety metrics. The script also includes vertical lines at 1.5 seconds on these plots, a commonly used threshold to distinguish between high-risk and low-risk events.
	<ul style="list-style-type: none"> • hist PET TTC 1 • hist PET TTC numbers • hist PET TTC with percentage 	These functions create detailed histograms for PET and TTC with 0.25-second intervals. These plots provide a more granular view of the distribution of these metrics and can display either the absolute counts or the percentage of events in each bin. A vertical line at the 1.5-second threshold is also included for easy identification of high-risk events.
Crash severity indicators (delta V and kinetic energy)	<ul style="list-style-type: none"> • plot delta v histogram 	This function generates a histogram of Delta V (the change in velocity during a crash). Delta V is a key indicator of crash severity, and its distribution can provide insights into the potential for injury.
	<ul style="list-style-type: none"> • KE histogram numbers • KE histogram percentages 	Histograms of Kinetic Energy (KE) are created for both the right-turning and opposing movements. This analysis helps in assessing the potential severity of a crash by visualizing the energy involved.
Relationship and Correlation Analysis		
Relationship between PET and TTC	<ul style="list-style-type: none"> • scatter plot PET TTC numbers • scatter plot PET TTC percentages 	These functions generate scatter plots to visualize the relationship between PET and TTC. Events where both PET and TTC are below the 1.5-second threshold are highlighted as 'hazardous situations'. The plots also provide a quantitative measure of these high-risk events, either as a total number or as a percentage of all events.
	<ul style="list-style-type: none"> • plot PET TTC scatter interactive 	For a more dynamic exploration of the PET vs. TTC relationship, this function creates an interactive scatter plot using plotly.express. This allows for hovering over individual data points to get more detailed information about each event.
Relationship between Kinetic Energies	<ul style="list-style-type: none"> • plot kinetic energy relationship • plot kinetic energy relationship normalised 	These functions create scatter plots to visualise the relationship between the kinetic energies of the two conflicting vehicles. The total kinetic energy of the event is represented by a color gradient, providing a quick visual assessment of the potential crash severity.

4 Study Sites Overview

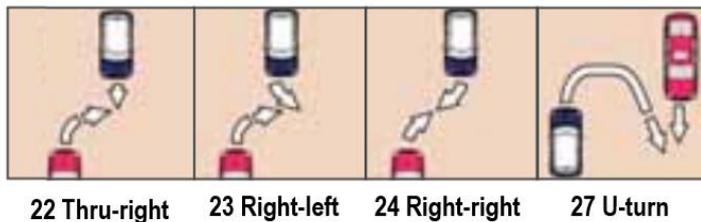
A summary of the sites and crash performance for the nominated sites included in the study is provided in this section. More detailed information about each site is provided in Appendix A.

4.1 Site Selection

The eight study sites were selected based on the following criteria:

- Right-turn arrangements, which may be composed of filter right-turns, partially controlled right-turns or fully controlled right-turns.
- Road safety performance in terms of RUM 22, 23, 24 and 27 crashes (see Figure 4.1) reported between 2017 and 2021.
- Geometric location to ensure project coverage across the Perth metropolitan area.
- Land use adjacent to the intersections, representing urban, residential and commercial activities, likely to comprise of a mix of light vehicles, commercial vehicles and active transport.

Figure 4.1: Right turn crash types



For the purposes of this project, these four crash types will be known as the 'right-turn crash types'.

4.2 Crash Summary of All Sites

Main Roads provided crash data for all eight intersections for the period 1 January 2017 to 31 December 2021. The crash types reported included rear-end, head on, sideswipe opposite direction, sideswipe same direction, right-turn through-through, hit pedestrian, hit animal, hit object, non-collision, other/unknown.

For the purposes of this project, this group of crash types will be known 'as all crash types'.

The crash severity definitions in Western Australia applied and are defined as follows:

- **Killed** – a crash where any person who is involved in the crash dies within 30 days of the crash. Also known as a fatal crash.
- **Serious injury** – a crash where any person who is involved in the crash is admitted to hospital. Also known as a hospitalisation crash.
- **FSI Crash** – killed and serious injury crash.
- **Medical** – a crash where any person who is involved in the crash receives medical treatment, but no person in the crash is admitted to hospital.
- **Property Damage Only (Major)** – any property damage crash over \$3,000 in value.
- **Property Damage Only (Minor)** – any property damage crash below \$3,000 in value.

The combined crash history of all crash types reported across the eight intersections is as follows:

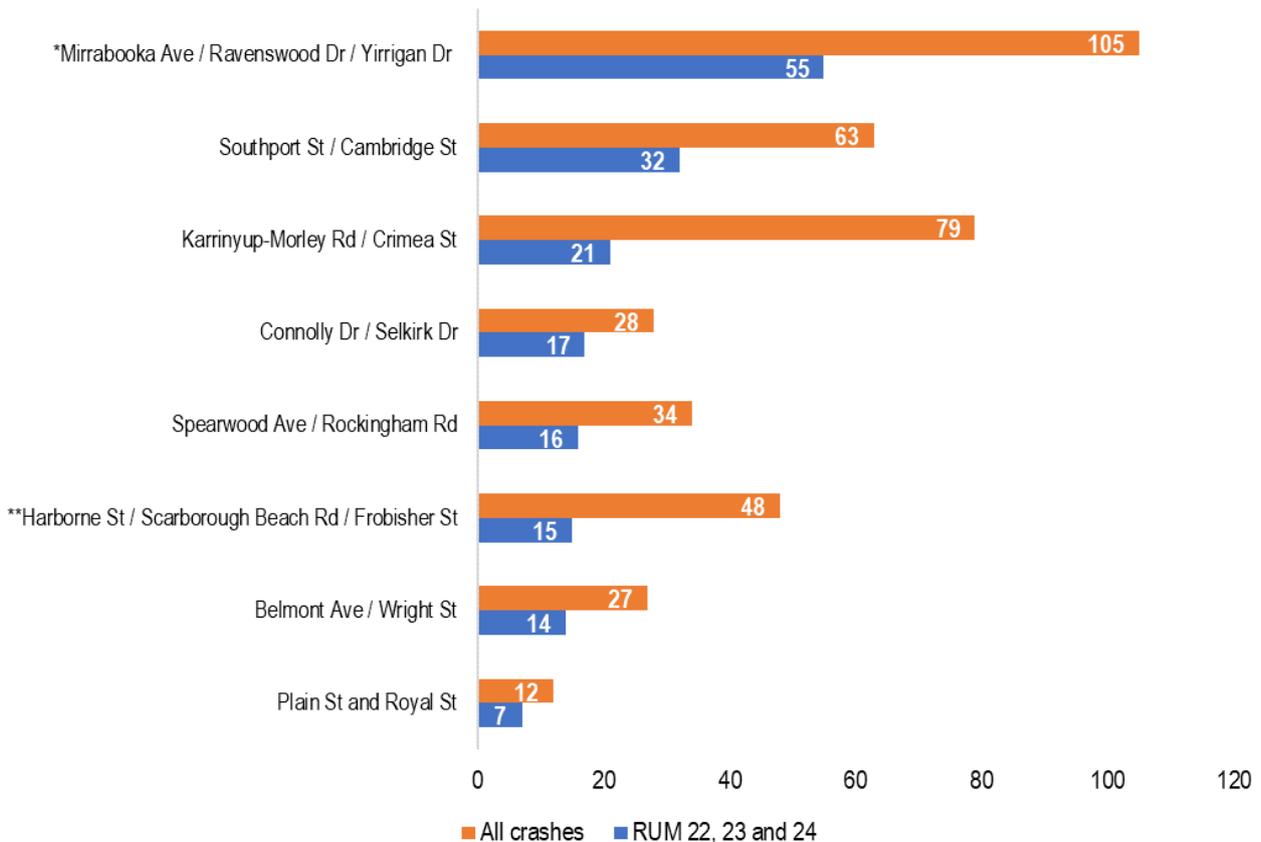
- 396 all crash types were reported.
- 177 right-turn crash types were reported, representing 45% of all crash type crashes reported.
- 169 RUM 22 crashes, representing 43% of all crash type crashes reported.

- RUM 23 and 24 crashes were reported as follows:
 - 7 RUM 23 crashes were reported at Mirrabooka Ave/Ravenswood Dr/Yirrigan St.
 - 1 RUM 24 crash was reported at Harborne St/Scarborough Beach Rd/Frobisher St.
- None of the intersections reported a RUM 27 crash.
- Thru-right crashes and rear-end crashes were the dominant crashes at all intersections. The following sites had a higher representation of rear-end crashes:
 - Karrinyup-Morley Rd/Crimea St, Morley (rear-end 56%, thru-right 27%)
 - Harborne St/Scarborough Beach Rd/Frobisher St, Osbourne Park (rear-end 44%, thru-right 29%).
- RUM 22 accounted for 95% of all right-turn crash type crashes. The severity distribution for this crash type by total and percentage is as follows:
 - fatal 0
 - hospitalisation 19 (11%)
 - medical 21 (12%)
 - Property Damage Only (PDO) major 114 (67%)
 - PDO minor 15 (9%).

In terms of FSI crashes, RUM 22 crashes accounted for 5% of all crash type crashes across the eight intersections.

Distribution of all crash types and severity of the right-turn crash types for each of the eight intersections can be found in site details reported in Appendix A. As a summary, a comparison of all crash types against all right-turn crash types by site is provided in Figure 4.2.

Figure 4.2 Comparison of total crashes against total right turn crash types



*Includes RUM 23 crashes (7) ** Includes RUM 24 crashes (1).

5 Analysis of Near-miss Data

This section of the report provides a brief discussion of the results of the analysis undertaken and presents insights drawn from across the eight intersection sites. It also highlights specific issues identified at particular intersections, which may provide some additional points of interest for further consideration.

5.1 Introduction

Video analytics software applied to the field survey video of the eight TCS intersection sites permitted near-miss incidents to be identified and the capture of key data about the vehicles involved in any identified near-miss incidents. For each identified near-miss, this data included:

- time and date of detected incident
- type of vehicle involved – i.e. passenger car, light commercial, bus, motorcycle, bicycle, pedestrian (Note: no pedestrians were observed involved in a near-miss incident)
- speed of vehicle – for both turning and through movement trajectories
- bearing of travel trajectory – to aid in angle of impact and delta-v calculation
- type of crash – RUM code (note: potential right turn crashes only identified)
- traffic signal phase – for the right-turn manoeuvre, being red, amber, or green phase.

Values for certain other data fields were either assigned or calculated to assist describing the near-miss incident and permit analysis of key safety performance indicators. These other data fields included:

- PET and TTC – in seconds
- road user combination – categorising which vehicles/road users were involved in the near-miss incident
- vehicle mass – a stereotype value was assigned based on the vehicle types detected; these being 1500 kg for a car, 3000 kg for light commercial, 11,000 kg for a bus, 180 kg for a motorcycle, 81 kg for a bicycle
- kinetic energy and delta-v values – calculated based on the captured/assigned data.

The analysis of this data permitted a series histograms and scatter plots to be developed to illustrate the distribution and relationships associated with the three primary surrogate safety/traffic conflict measures. The charts illustrating this analysis are:

- Road user combination – indicating the frequency of vehicle types in the near-miss incident conflicts
- Speeds – indicating the frequency of vehicle speeds by movement, i.e. right-turning and opposing movement
- Traffic signal colour – frequency of when the right-turn movement occurred in the traffic signal phasing
- PET vs TTC scatter plot – to show the prevalence of highest risk thru-right conflict
- Delta-V – to show the potential severity of the near-miss incident in a crash
- Kinetic energy – plotting right-turn v through movements to show the relative collision energies.

Analysis of the data permitted the plotting of variables to understand exposure, likelihood, relative risk and to illustrate relationships of different surrogate safety/traffic conflict metrics to one another. Charts showing consolidated data plots for the traffic movement and speed analysis along with a brief commentary are presented in Section 5.2, while observations about the surrogate safety/traffic conflict measures are presented in a table format for each movement at each intersection.

The full scope of charts plotted for each site are provided in Appendix B.

In addition to the above analysis, the video of identified near-miss incidents was reviewed to try and understand driver behaviours leading to the crossing of vehicle paths through the intersection. Key observations from this review are also provided in Section 5.3.

5.2 Key Observations from Video Analytics Data

There were no actual collisions observed at any of the eight sites during the multiple periods of video survey. Therefore, the analysis and observations reported here are based on near-miss incident data supplemented by a review of the traffic management arrangements at each site and driver behaviour captured by the video of these near-miss incidents.

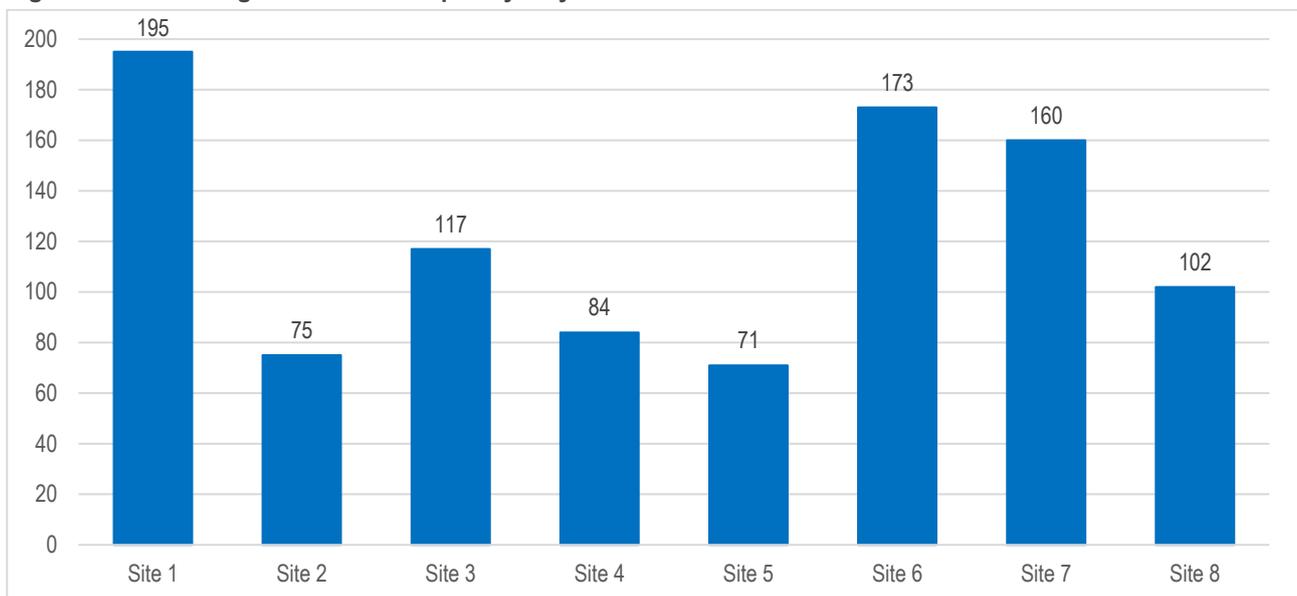
5.2.1 Traffic Movement and Speed

The survey of the eight sites was conducted for selected days over a three week period between 9 and 25 February 2024 for the hours between 6.00 am and 10.00 pm on these survey days.

A total of 977 near-miss incidents were detected from the field survey video, as defined by the adopted PET and TTC metrics. The longest PET value was 4.0 seconds (average 2.2 seconds) and the longest TTC value was 44.54 seconds⁴ (average 1.12 seconds). Values of PET and TTC less than 1.5 seconds are considered to be indicative of a higher likelihood of crash and more likely to require some form of positive driver input to avoid a collision.

Total traffic counts were not collected for the study sites so the occurrence of daily traffic peak flows could not be precisely determined. However, it is accepted that the degree of demand (for the right-turn) and congestion at the intersections will influence the frequency of filter right-turn manoeuvres occurring and this will vary throughout the course of the day. The total count of near-miss incidents for each site is shown in Figure 5.1; the spread of near-miss incidents detected for the combined survey periods is shown in Figure 5.2. []

Figure 5.1: Thru-right near-miss frequency – by site



⁴ This TTC was an outlier event and the next longest TTC was 14.47 seconds, then 13.25 seconds, and thereafter below 8 seconds.

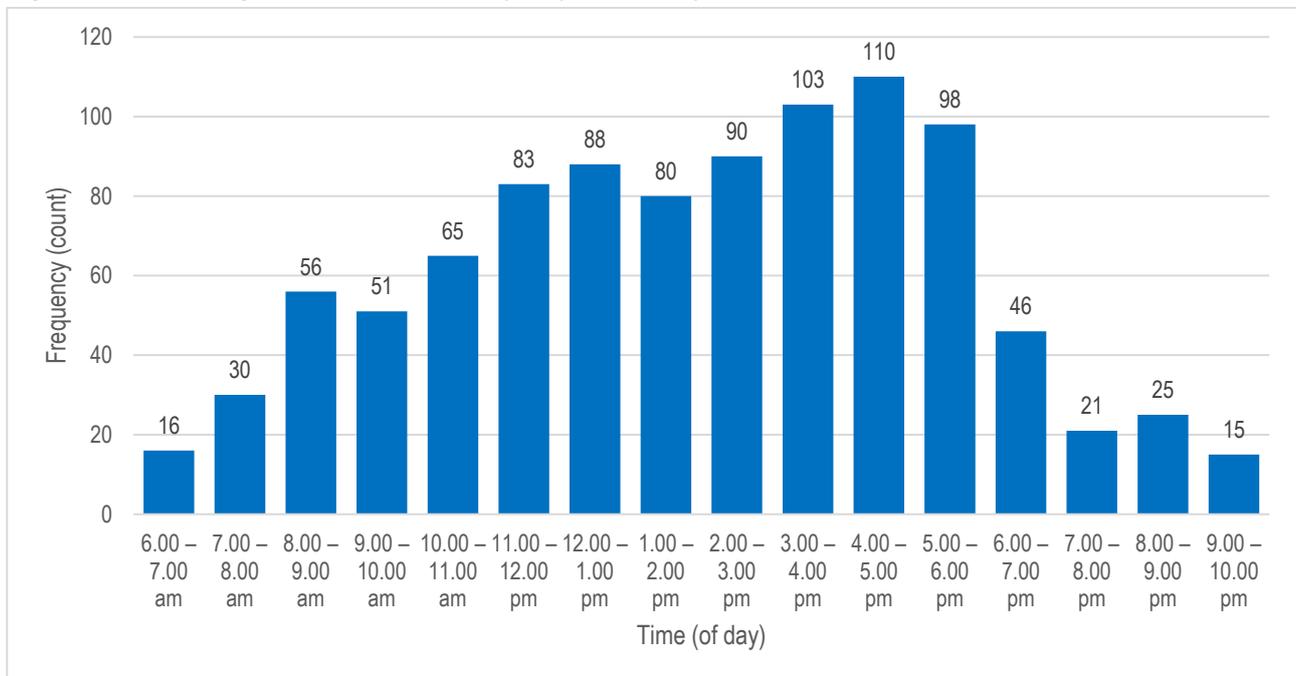
Table 5.1: Speed data for each site – right-turn movement

Site no.	Count	Min of Speed (km/h)	Max of Speed (km/h)	Average of Speed (km/h)	StdDev of Speed (km/h)
Site 1	195	8.31	38.52	17.37	4.83
Site 2	75	11.34	35.50	23.56	4.95
Site 3	117	10.74	32.47	22.89	5.10
Site 4	84	12.54	28.70	20.95	3.42
Site 5	71	8.75	59.03	22.74	8.92
Site 6	173	7.73	57.29	21.19	6.92
Site 7	160	9.05	56.44	31.10	9.45
Site 8	102	15.68	38.49	26.56	5.14
Total	977				

Table 5.2: Speed data for each site – opposing movement

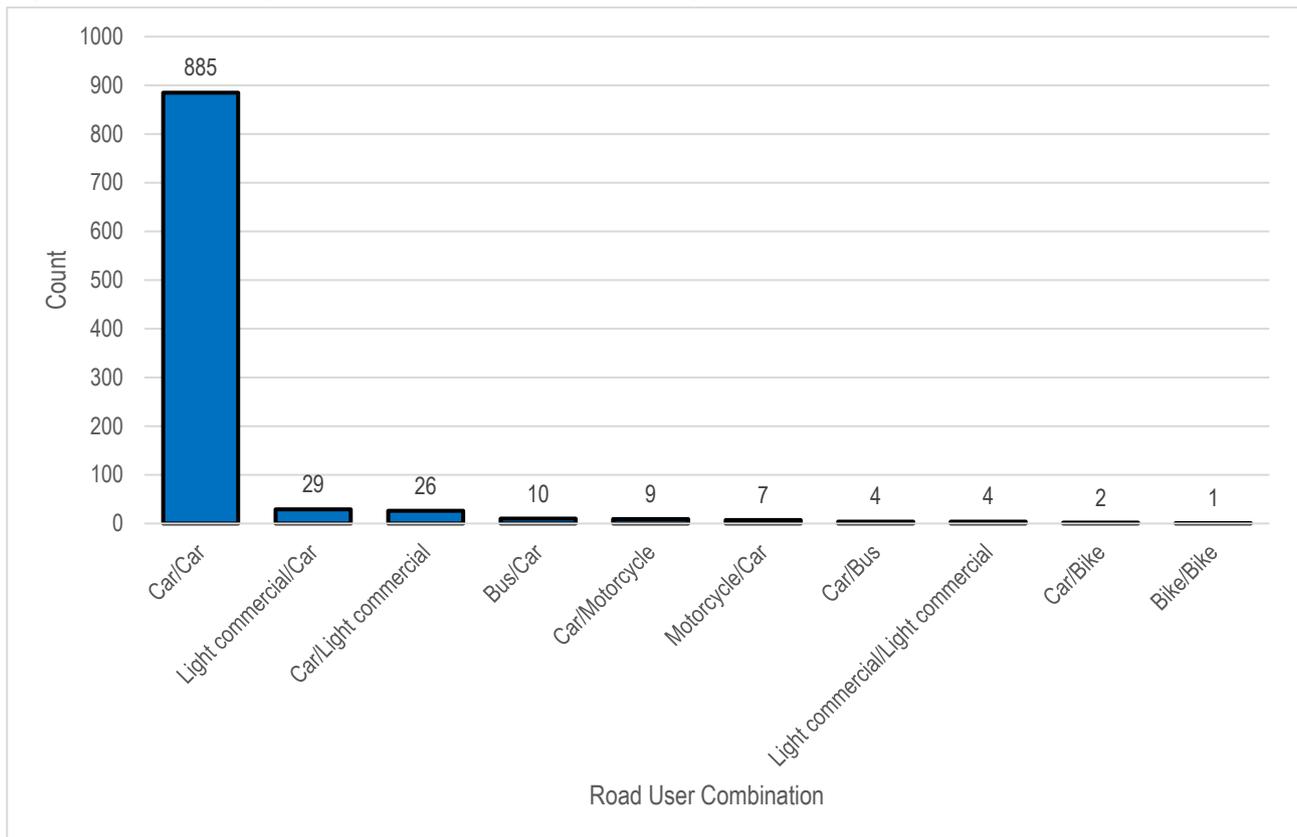
Site no.	Count	Min of Speed (km/h)	Max of Speed (km/h)	Average of Speed (km/h)	StdDev of Speed (km/h)
Site 1	195	15.21	75.99	52.50	10.99
Site 2	75	31.63	78.62	57.98	9.20
Site 3	117	24.73	78.25	53.42	10.03
Site 4	84	28.11	63.02	50.08	8.18
Site 5	71	13.83	86.48	56.26	15.42
Site 6	173	17.00	81.34	54.18	15.65
Site 7	160	13.87	80.60	54.65	9.51
Site 8	102	11.42	99.80	57.73	30.26
Total	977				

Figure 5.2: Thru-right near-miss frequency – by time of day



With reference to Figure 5.3, review of the road user groups assigned in a near-miss incident highlights that just over 90% involved two light passenger vehicles (i.e. car/car); noting the first listed vehicle was turning right, 3.0% were light commercial vehicle/passenger vehicle; 2.7% were bus/passenger vehicle, and a combined 1.6% involved a car and a motorcycle (i.e., 0.9% car/motorcycle + 0.7% motorcycle/car).

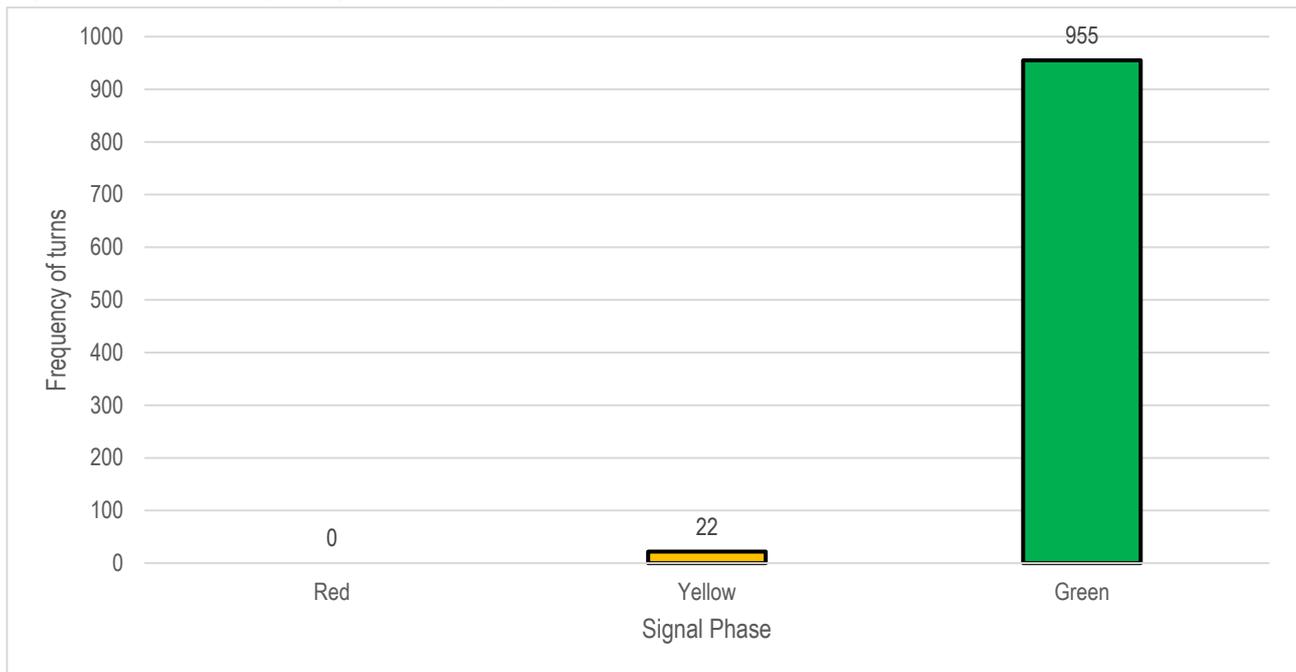
Figure 5.3: Frequency of road user combination in filter right-turn near-miss incidents



Note: First listed vehicle is turning right; second listed vehicle is the opposing movement

In terms of the signal phasing when filter right-turns were observed to occur, with reference to Figure 5.4, almost 98% of the identified near-miss incidents occurred during the green phase of the traffic signal cycle; just under 3% occurred during the yellow phase, and none were observed to occur during the red and all red phase. It should be noted that, while there were no instances of filter right-turns observed during the red (and all red) phase, broader network observation and experience shows that this does occur and the *Western Australia Road Traffic Code 2000* outline rules cater for this by permitting right-turning drivers who have ‘...fully entered the intersection...’ to clear the intersection ‘...as soon as the driver can do so safely’ during a red signal display.

Figure 5.4: Frequency of right-turns in signal phase



The speed of a vehicle as it enters an intersection, to either turn right or pass directly through, impacts a right-turn driver's decision to select an appropriate gap in traffic as well as their safe completion of the manoeuvre through the double factor of ability to avoid a collision and the severity of a crash (if it is to occur). The speed of right-turning and opposing vehicles for the near-miss incidents documented are illustrated in Figure 5.5 and Figure 5.6. A summary of vehicle speed for right-turn and opposing movements for each site is provided in Table 5.1 and Table 5.2, respectively.

It is worth noting that the highest sign posted speed limit across the eight intersections is 70 km/h (at two sites⁵), with 50 km/h and 60 km/h speed limits applying at other sites. The widely accepted Safe System speed for situations where there is the potential for a side-impact collision, such as occurs for thru-right crashes, is 50 km/h (being the speed of the through vehicle). Almost 68% of opposing vehicles in the identified near-miss incidents are approaching the subject collision points at speeds greater than the 50 km/h Safe System speed threshold. A breakdown of speed for right-turn and opposing traffic movements is provided in Figure 5.5 and Figure 5.6, respectively.

⁵ Not all intersection legs at these were signed with 70 km/h speed limit.

Figure 5.5: Frequency of speed bins for right-turn movement vehicles

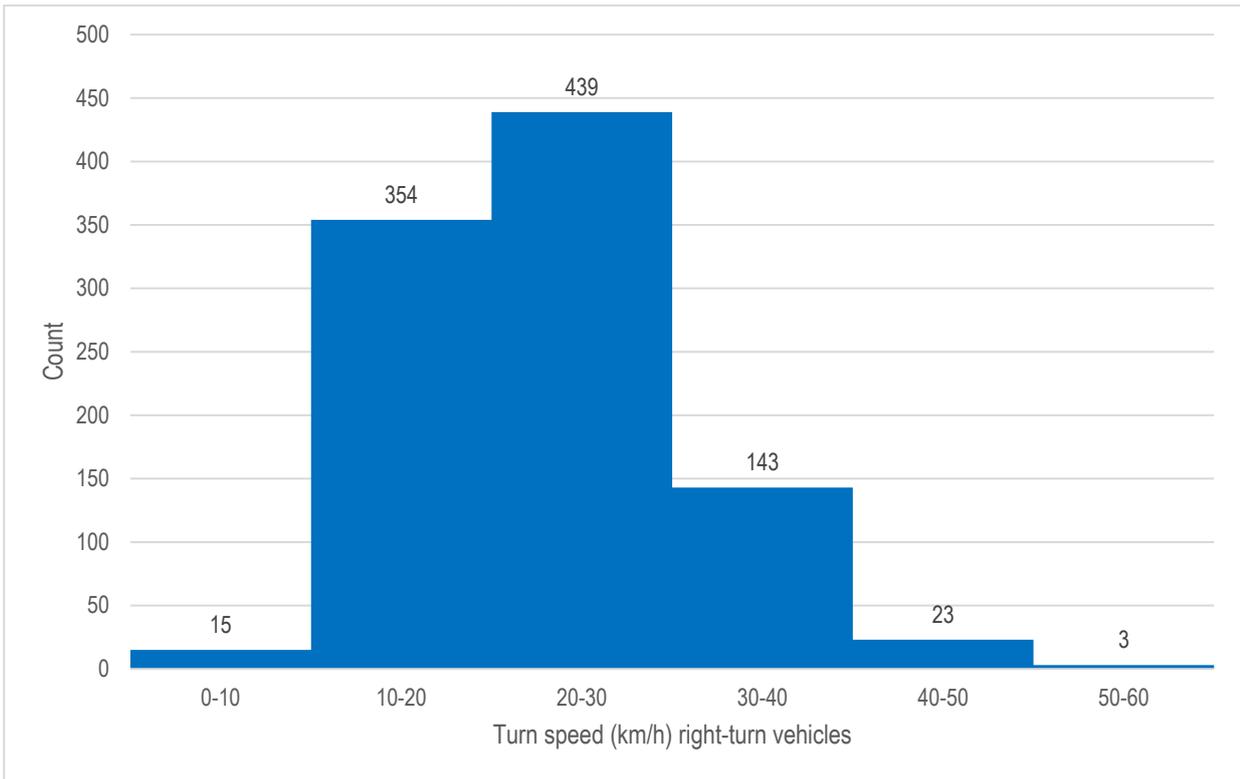
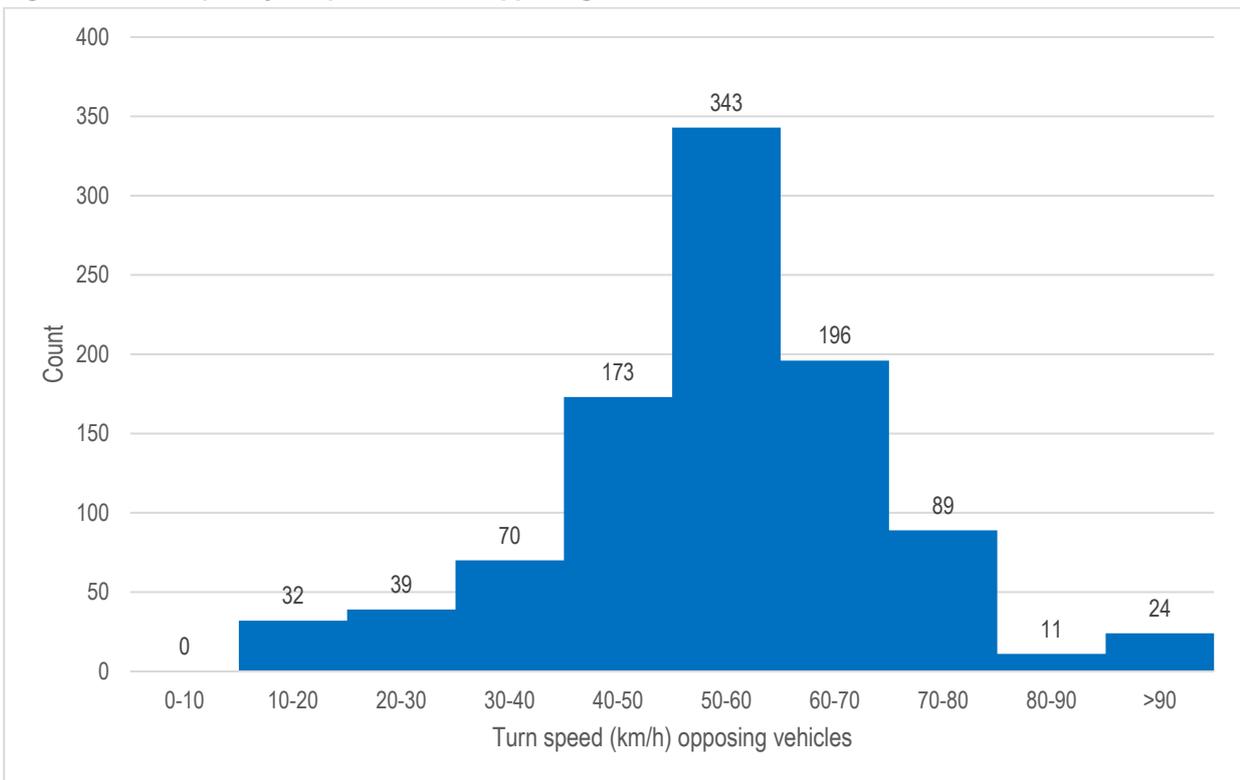


Figure 5.6: Frequency of speed bins for opposing movement vehicles



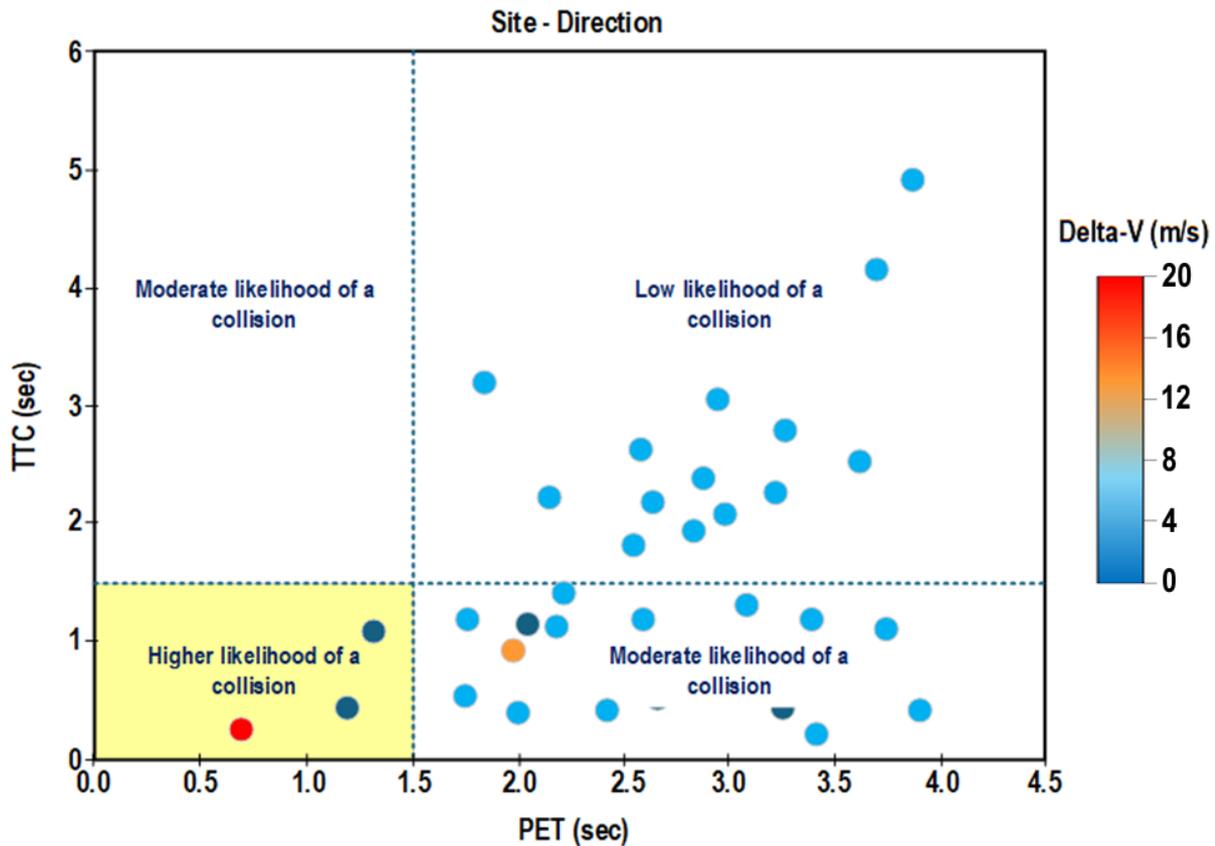
5.2.2 Surrogate Safety/Traffic Conflict Measures

Determining risk of right-turn crashes involves consideration of both likelihood and severity. In projecting the potential severity of possible crashes from the near-miss data collected across the eight study sites, the measures of Delta-V and Kinetic Energy (KE) have been calculated from the video-analytics data. Plots showing these for each movement at each intersection are provided in Appendix B.

Scatterplots of PET and TTC were also developed, and delta-v was added as an overlay to provide a coded visual link between crash likelihood and severity.

Values for both PET and TTC below 1.5 seconds indicate a significantly higher likelihood of a crash and when prepared as a scatterplot, a prevalence of incidents positioned in the lower left quadrant, as shown in the yellow area of the example plot in Figure 5.7, indicates a location of higher likelihood of filter right-turn crashes. The severity of the potential crash is identified by the delta-v colour slider, with red representing higher delta-v values and therefore greater potential for high severity injury outcomes. Near-miss incidents in the lower left quadrant and at the red end of the colour spectrum indicate an overall higher risk (i.e. likelihood x severity).

Figure 5.7: Likelihood and severity framework plot of a near-miss event.



The plotting of PET and TTC, overlaid with Delta-V, was completed for each right-turn of interest at each of the eight study sites and presented in Appendix B. A review of these plots shows that all sites have a moderate number of near miss incidents falling into the lower left quadrant, and that almost all near miss incidents have a delta-v greater than 5 m/s⁶ (18 km/h), with subtle colour graduations indicating some are higher. In the context of Safe System speed thresholds, a delta-v up to 8 m/s (28.8 km/h) places the potential severity in the low to moderate range and above 13 m/s (46.8 km/h) the potential for more serious casualty outcomes increases significantly.

A review of the Delta-V histogram plots for each direction at each intersection provides more detail about the range of delta-v values for the identified near-miss incidents. It can be seen through these plots that all locations have delta-v values exceeding 30 km/h, most exceeding 40 km/h and not an insignificant number exceeding 50 km/h; there are instances that extend to 60, 70, and even 80 km/h, although the frequency at these upper ends is limited.

⁶ 1 m/s = 3.6 km/h; therefore 5 m/s = 18 km/h

The following is a summary observation of the PET v TTC, delta-V, and kinetic energy results plotted in the site movement histograms in Appendix B:

Table 5.3: Summary of observation of the PET v TTC, Delta-V, and Kinetic Energy plots

No.	Location	Suburb	PET v TTC plot	Delta-V and Kinetic Energy plots
1	Mirrabooka Ave/Ravenswood Dr/Yirrigan Dr. (4-way leg intersection)	Nollamara	Both directions of approach have near-miss incidents in the 'higher likelihood quadrant and a majority of incidents with a TTC < 1.5 seconds, but PET > 1.5 seconds.	Direction 1 experienced values from a low of about 6 km/h to a high of 60 km/h with a majority < 40 km/h. Direction 2 experienced a more even spread ranging between 7 and 45 km/h. The KE values for the right-turn movement (most vulnerable) are generally <50 kJ. Of some concern, there are some incidents recording high KE values for both right-turn and the opposing movement.
2	Southport St/Cambridge St. (4-way leg intersection)	West Leederville	Both directions of approach have near-miss incidents in the 'higher likelihood' quadrant and a majority of incidents with a TTC < 1.5 seconds, but PET > 1.5 seconds.	Direction 1 experienced values from a low of about 6 km/h to a high just above 50 km/h with a majority < 40 km/h. Direction 2 experienced more incidents between 20 and 40 km/h. The KE values for both directions tend to be in the lower ranges for all movements. There are a couple of high KE value incidents, which would be considered outliers.
3	Karrinyup-Morley Rd/Crimea St. (4-way leg intersection)	Morley	Direction 1 approach has no incidents in the 'higher likelihood' quadrant and Direction 2 just two. Approximately two-thirds of incidents have TTC < 1.5 seconds, but PET > 1.5 seconds.	Direction 1 experienced values from a low of about 13 km/h to a high of 63 km/h with a majority < 50 km/h. Direction 2 has more incidents between 20 km/h and 48 km/h and a cluster above 30 km/h. The KE values for Direction 1 are tightly clusters in the low range, while Direction 2 is more scattered and at moderate to high KE values above 200 kJ.
4	Connolly Dr/Selkirk Dr. (T-intersection)	Kinross	Both directions of approach have a moderate number of near-miss incidents in the 'higher likelihood' quadrant and a large proportion of incidents with a TTC < 1.5 seconds, with PET > 1.5 seconds and a cluster of incidents with PET around 1.5 to 2 seconds.	Direction 1 and 2 have a high number of incidents spread across about 5 km/h to 65 km/h and each an incident approximately 75 km/h. Both Directions record a higher number of high KE values above 400 kJ for the Opposing movement. While Direction 1 has a distributed range of KE values for the right-turn movement, Direction 2 is tightly clustered <50 kJ, but higher for the Opposing movement.

No.	Location	Suburb	PET v TTC plot	Delta-V and Kinetic Energy plots
5	Spearwood Ave/Rockingham Rd (4-way leg intersection)	Spearwood	Both directions of approach have near-miss incidents in the 'higher likelihood' quadrant, although Direction 1 has more than Direction 2. A large number of incidents have a TTC < 1.5 seconds, but PET > 2.0 seconds.	Direction 1 experienced values from a low of approximately 5 km/h to a high just over 50 km/h with an even distribution across this range. Direction 2 has a shorter range spread between 5 and 45 km/h. The KE values for Direction 1 and 2 are significantly different with Direction 1 tightly clustered in the lower left area, while Direction 2 is more scattered and showing a majority of incidents in the higher KE range for both movements.
6	Harborne St/Scarborough Beach Rd/Frobisher St. (4-way leg intersection)	Osbourne Park	Both directions of approach have a large number of near-miss incidents in the 'higher likelihood' quadrant and about three-quarters of all incidents with TTC < 1.5 and evenly distributed across PET from 1.5 to 3.0 seconds. Direction 2 has notably more incidents than Direction 1 and more with TTC < 1.5 seconds compared to Direction 1, but a similar number in the 'higher likelihood' quadrant.	Direction 1 has delta-v values from a low of approximately 5 km/h up to 40 km/h and distribution largely around 20 to 35 km/h. Direction 2 delta-v values have a similar overall range with most incidents between 20 and 38 km/h. The KE values for Direction 1 and 2 tend to be <40 kJ for the right-turn movement but are higher for the opposing movement. There are a couple of outlier incidents with high KE values, above 300 kJ.
7	Belmont Ave/Wright St. (4-way leg intersection)	Kewdale	Both directions of approach have a moderate number of near-miss incidents in the 'higher likelihood' quadrant and about three-quarters of all incidents with TTC < 1.5 and evenly distributed across PET from 1.5 to 3.0 seconds. Direction 1 has notably more incidents than Direction 2 and more with TTC < 1.5 seconds compared to Direction 2, but a similar number in the 'higher likelihood' quadrant.	Direction 1 has a relatively low frequency of low delta-v values ranging between 5 km/h to 37 km/h. Direction 2 differs with delta-v ranging from 5 km/h to just over 80 km/h and a frequency clustered around 25 to 50 km/h. The KE values are generally low for the right-turn movement for both directions. The opposing movement for Direction 1 has moderate KE values up to 225 kJ; Direction 2 is tightly clustered between 50 and 200 kJ.
8	Plain St and Royal St. (Pilot study site) (4-way leg intersection)	East Perth	Both directions of approach have near-miss incidents in the 'higher likelihood' quadrant and about three-quarters or more of all incidents with TTC < 1.5 and evenly distributed across PET from 1.5 to 3.0 seconds. Direction 1 has notably more incidents than Direction 2 and more with TTC < 1.5 seconds compared to Direction 2, and more in the 'higher likelihood' quadrant.	Direction 1 has more frequent incidents between 20 km/h and 40 km/h while Direction 2 has a wider range (from 5 km/h to 70 km/h) but with more incidents below 37 km/h. The KE values for Direction 1 and 2 are generally scattered, with lower values for the right-turn movement and higher values for the opposing movement. There are considerably more incidents for Direction 2 and more above 200 kJ.

5.3 Key Observations from Video Reviews

Video of near-miss incidents was reviewed providing a site context understanding of the driver behaviours leading to the detection of the incident.

Arrangements for managing traffic, particularly right-turning traffic, generated varying behaviours amongst drivers passing through each intersection. Common across all sites were instances of right-turn vehicles not adequately yielding to opposing vehicles travelling straight through the intersection. This often caused the opposing through vehicles to slow and in some instances effectively stop to permit the right-turning vehicle to clear the intersection. This behaviour was observed to occur in wet weather and at night and in some cases resulted in the priority through vehicle clearing the intersection late in the yellow.

Reflecting a greater demand for right turning traffic, some sites in the study had dedicated and protected right turn traffic lanes in place. There were instances observed at these sites, of right turn vehicles moving through the intersection in small platoons, which on occasion adversely impacted the flow of through traffic during the filter turn phase. The queuing and storage of traffic in the turn lane permits drivers to close gaps between vehicles and to move more cohesively as a group when signals permit and apparent gaps in through traffic occur. Drivers may take cues from the vehicles in front and on occasion the last few vehicles in a platoon pressed forward through less than ideal gaps in the through traffic. This then required approaching vehicles to slow and sometimes stop to avoid a collision, and contributed to a late clearance of the intersection.

Observation of sites that did not have dedicated and protected right turn lanes, i.e. through and right turn traffic used the same lanes, found instances of drivers making poor gap selection; this caused through vehicle drivers to slow and/or right turn drivers to increase turning speeds to clear the intersection and avoid a collision. Multiple factors may contribute to this type of interaction, including:

1. drivers' turning during gaps that are too short
2. pressure from traffic queued behind the turning vehicle
3. unexpected appearance of a vehicle travelling through the intersection due to dynamic visual obstruction.

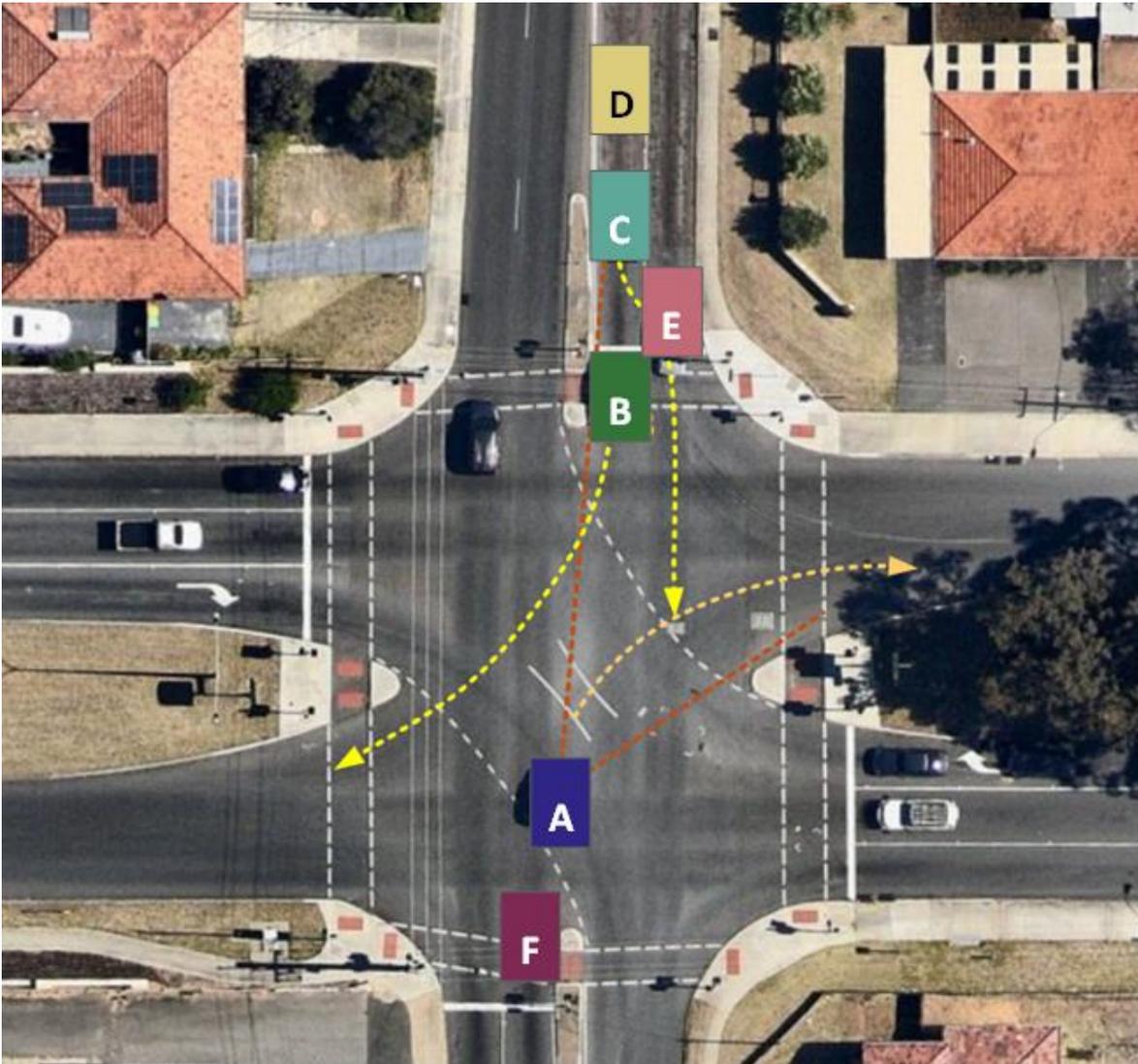
Of these, the last was observed on multiple occasions and found to lead to quite close near-miss incidents. An example of the effect of dynamic visual obstruction at an intersection in this study occurred at Site 5, Spearwood Avenue and Rockingham Road, Spearwood, and is illustrated in Figure 5.8. With reference to this figure, an assessment found that:

- The line of sight for the right-turning vehicle (Vehicle A) toward the through traffic (Vehicles C and E) was obstructed by the lead vehicle (Vehicle B), which is also waiting to turn right.
- The line of sight through the intersection for Vehicles C and D queued behind Vehicle B is obstructed.
- Drivers in Vehicle C and/or Vehicle D may decide to change lanes and bypass the waiting right-turning Vehicle B by moving to the adjacent lane and proceed straight through the intersection under a green signal.

This set-up potentially results in:

- Driver in Vehicle A yields to Vehicle E and then proceeds to turn right, but does not anticipate either Vehicle C and/or D moving into the intersection, typically at accelerating speed.
- Drivers of Vehicle C and/or D do not anticipate Vehicle A moving across their lane, since they have right of way.
- A RUM code 22 collision occurs.

Figure 5.8: Dynamic visual obstruction arrangement for filter right-turn traffic



The obstruction of lines of sight for through and turning drivers may be for a relatively brief period. However, it occurs at a critical time in the decision-making by drivers to discern a safe gap in traffic and make their decision to proceed with their manoeuvre. This same dynamic was observed and reported by Stokes and Woolley (2022) who reviewed CCTV footage of real-world crashes involving filter right-turn traffic at signal controlled intersections.

It should be noted that the fundamental road geometry for each site included in this study is good and free of typical road and roadside obstructions; drivers approaching the intersection, waiting at the holding line, and travelling through the intersection therefore all have good lines of sight to and from all other road legs. However, the nature of the queued traffic and alignment of traffic lanes appears to create this dynamic visual obstruction. Additional specific examples of the presence of dynamic visual obstruction are illustrated in the following series of still images captured from the video survey files collected from across the study sites. Notations on the images highlight the issues and potential factors for the nominated near-miss.

Figure 5.9: Cambridge Street (west) to Southport Street (south) opposing right-turn vehicle masks the following vehicle for the right-turn of interest

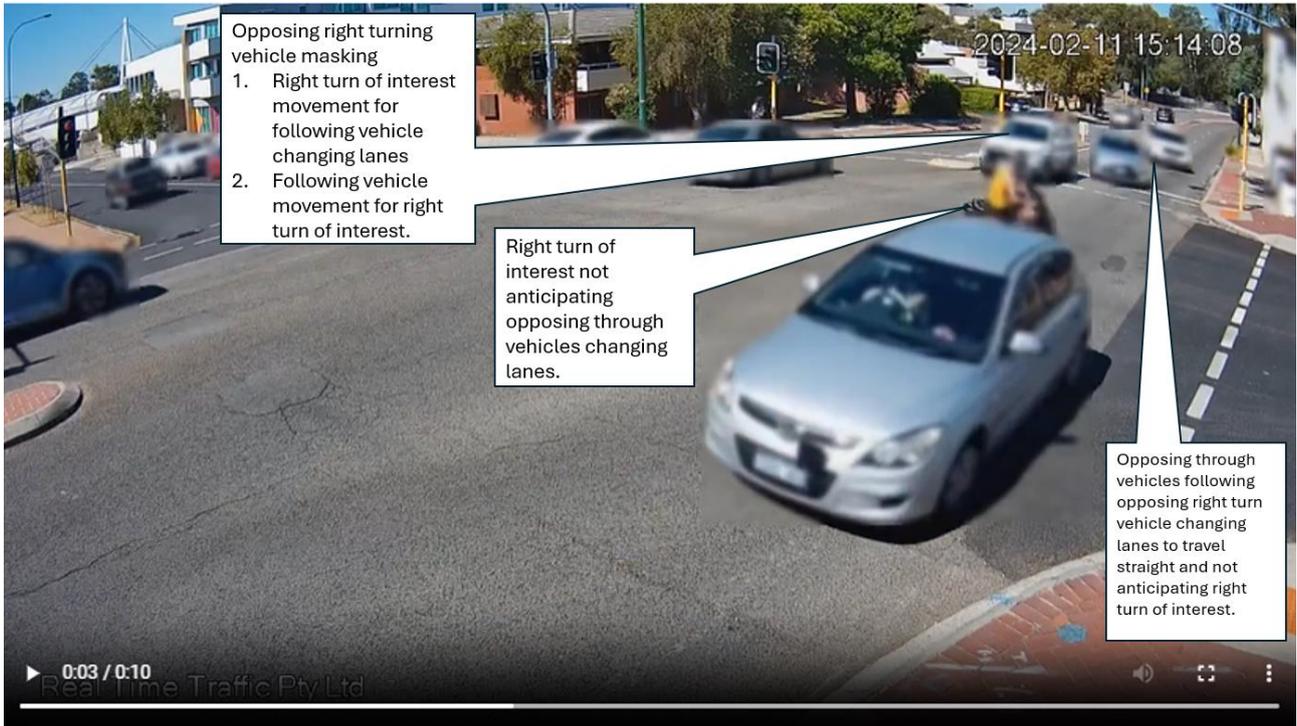


Figure 5.10: Wright Street (north-east) to Belmont Street (north-west) opposing right-turn vehicle masking the following vehicle and right-turn of interest



Figure 5.11: Rockingham Road (south) to Spearwood Avenue (east) opposing right-turn vehicle masking following vehicle and right-turn of interest



Figure 5.12: Spearwood Avenue (north) to Rockingham Road (west) opposing right-turn vehicle masking following vehicle and right-turn of interest



Figure 5.13: Harborne Street (south) to Scarborough Beach Road (east) opposing right-turn vehicle masking following vehicle and right-turn of interest

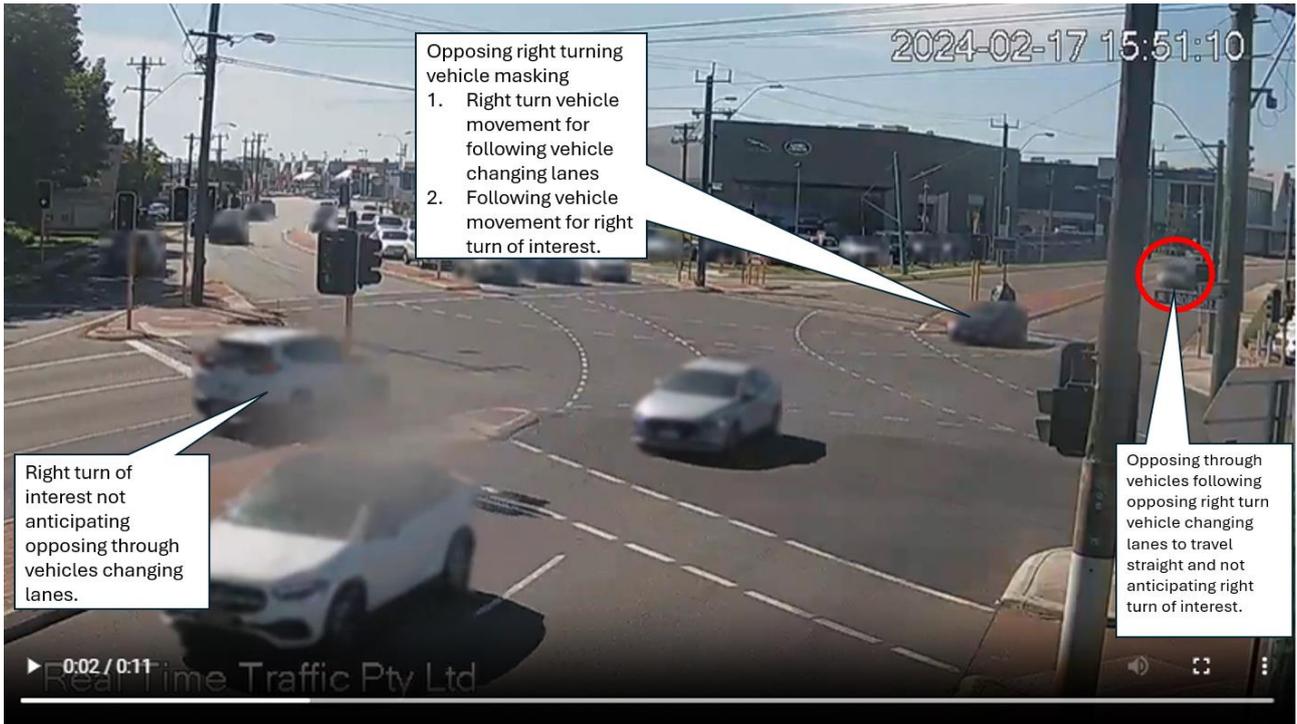


Figure 5.14: Wright Street (north-east) to Belmont Street (north-west) through vehicle in combined right-turn-through lane



Figure 5.15: Belmont Avenue (north-west) to wright Street (south-west) through vehicle in combined right-turn-through lane



Figure 5.16: Harborne Street (south) to Scarborough Beach Road (east) through vehicle in combined right-turn-through lane



6 Conclusions

An examination of thru-right crashes and near-miss incidents at eight signalised intersections under right-turn filter control was undertaken with the purpose of improving the understanding of factors contributing to these crashes. This included investigating when, during the signal phasing, these types of crashes were most likely to occur, and the arrangements providing for right-turn movements.

Crash history involving right-turn crashes (RUM code 22, 23, 24 and 27) was used to select candidate intersections, across metropolitan Perth, to be included in the study. The eight sites selected were all found to have good layouts with open lines of sight clear of roadside objects or other infrastructure that might cause undue distraction, clutter or obscure a driver's vision. Notwithstanding this, a total of 396 crashes, of all types, were reported across the eight intersections for the five-year period 2017 to 2021, inclusive. Right-turn-related crashes accounted for just under 45% (n=177) of these, with RUM code 22 crashes being the dominant type at just under 43% (n=169) of all crashes, resulting in approximately 5% of FSI crashes at these sites.

Video analytics software was used to interrogate field video surveys collected at each of the eight intersections. Using the surrogate safety/traffic conflict metrics of PET and TTC, near-miss incidents involving thru-right vehicle movements were identified. Assuming there was a collision, estimates of potential crash severity were informed using delta-v and kinetic energy of the vehicles involved.

On first review, the frequency of near-miss incidents across the eight sites appeared to be influenced by the level of traffic rather than a particular geometric feature of the intersections. Higher occurrence of near-miss incidents tended to occur at sites where dedicated right-turn lanes were in place; this arrangement would tend to reflect greater traffic flows at these sites since they are provided to improve intersection efficiency and safety. Sites where right-turns were made from lanes also serving through traffic recorded a lower frequency of near-miss incidents, by comparison; however, the numbers were still significant and measures of PET, TTC, delta-v and kinetic energy indicated the potential for collisions with moderate and at times higher severity outcomes.

In terms of when during the signal phasing the near-miss incidents occurred, the video data indicated that almost 98% occurred during the green phase, and just under 3% during the yellow phase. No near-miss incidents were recorded during the red phase, although experience would suggest that some clearing of the intersection would occur during the red (inter-green) phase.

Overall, factors potentially contributing to thru-right type collisions included the following.

- Permitting right-turns to occur by filtering through opposing traffic – without a temporal separation provided by the phasing of traffic signals, right-turn and through traffic movements will cross travel paths and thus create a potential conflict.
- Permitting both right-turn and through movements from the one lane – right-turn drivers waiting for a safe gap in the opposing through traffic create:
 - an obstruction to the lines of sight for opposing right-turn drivers
 - an obstruction to lines of sight to opposing through traffic following behind the opposing right-turn vehicles
 - a delay to following through traffic.

With regard to the first point, operational differences were observed between sites with dedicated right-turn lanes and those with combined thru-right lanes; this flows on to potentially exacerbate conflict between filter right-turn and opposing through traffic.

Dedicated right-turn lanes provide a physical separation between right-turn and following through traffic streams and additional storage for right-turn traffic.

Where right-turns are made from through lanes, situations were observed where drivers following behind a vehicle stopped to turn right abruptly changed lanes to avoid being delayed. Near-miss incidents then occurred due to the line of sight for opposing right-turn drivers being obstructed by the queued right-turn traffic and apparent safe gaps in traffic being unexpectedly reduced at a critical point in the decision to execute the right-turn.

The data and observations from this analysis indicated a limited number of effective measures to mitigate the risk of thru-right type crashes. Options include:

1. Eliminating filter right-turn manoeuvres through re-phasing traffic signals. The approach might involve prioritising sites based on crash risk with consideration of:
 - a. available lines of sight
 - b. demand for the right-turn and viable alternative locations
 - c. approach speed to the intersection for through traffic movements.
2. Altering traffic arrangements at priority intersections. This might include:
 - a. providing dedicated right-turn lanes, improving storage and reducing conflict with following through traffic
 - b. facilitating right-turns by allocating more green time to right-turn movements to reduce the need for filter right-turn movements.
3. Measures to improve lines of sight for drivers in stacked right-turn traffic. This might include:
 - a. increasing the offset of opposing traffic lanes, although available space at the intersections will limit this
 - b. technology solutions to provide warning to drivers – right-turners and through movement – of the potential conflict or when suitable gaps are available. This may involve dynamic signing in the short-term and infrastructure-to-vehicle connectivity solutions in the longer-term.
4. Reducing speed in the through traffic stream. This could be delivered by:
 - a. reducing speed limits on approach
 - b. only permitting filter right-turns at sites where the sign posted speed limit is 50 km/h or lower (aligning with the Safe System speed thresholds)
 - c. introducing vertical deflection approaching and through the intersections where filter right-turns are permitted (note: raised intersections are effectively applied in other jurisdictions with safety improvements and minimal impact on intersection efficiency).

The analysis reported has highlighted some areas of risk and provided some level of evidence to the factors contributing to crashes across the right-turn crash codes (RUM 22, 23, 24, and 27). Additional insights could be obtained through a similar analysis of real-world crashes, which could be facilitated via the Main Roads CCTV network. Adopting a Safe System Crash Review process, similar to that being applied in Queensland and some other jurisdictions, would also provide insights to a driver's decision-making processes and where breakdowns occurred that permitted collisions to occur. A Safe System Crash Review would also provide insight as to how vehicle design and technology aids crash avoidance and reduces injury severity outcomes.

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Appendix A Study Site Details

Details of each of the study sites, including their proximity to the Perth CBD, adjacent land use, intersection type and lane configuration, turning lane types, and speed limits is provided in this appendix. Right-turn movement arrangements, intersection layout (via an aerial view), and a summary of 2017-2021 crash data, including crash type distribution and crash severity for the right-turn crash types, are also provided.

A.1 Mirrabooka Avenue/Ravenswood Drive/Yirrigan Drive, Nollamara

This intersection is located approximately 11 km north of the Perth CBD in an urban area with residential and retail land uses. Key features of the intersection are:

- it is a four-leg, channelised intersection, providing two lanes of travel in all directions
- channelised left turn slip lanes are provided on all approaches
- channelised right-turn lanes are provided on all approaches
- the speed limit for all roads is 60 km/h.

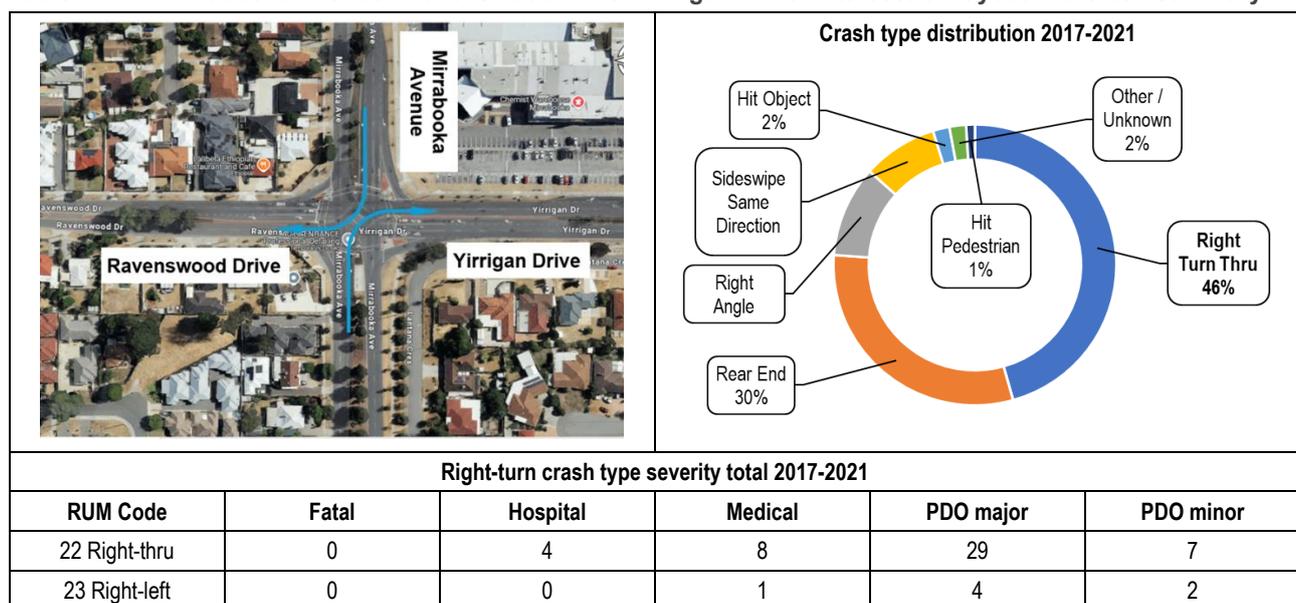
Table A.1 notes the intersection’s turning approaches and respective right-turn movement arrangements that have been in place since 1994.

Table A.1: Mirrabooka Avenue / Ravenswood Drive / Yirrigan Drive: Right turn movement arrangements

Turning approach	Right-turn movement arrangements
Yirrigan Dr, northbound RT into Mirrabooka Ave	All approaches: Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Mirrabooka Ave, eastbound RT into Yirrigan Dr	
Ravenswood Dr, southbound RT into Mirrabooka Ave	
Mirrabooka Ave. westbound RT into Ravenswood Dr	

Crash type distribution and analysis of crash types relevant to the project, in terms of severity, for the period 2017-2021, are presented in Table A.2. RUM 22 thru-right crashes accounted for 46% of all crashes at this site; the other right-turn crash type recorded was RUM 23 right left.

Table A.2: Mirrabooka Avenue / Ravenswood Drive / Yirrigan Drive: Intersection layout and crash summary



A.2 Southport Street / Cambridge Street, West Leederville

This intersection is located approximately 3 km northwest of the Perth CBD in an urban area with commercial and residential land uses. Key features of the intersection are:

- it is a four-leg intersection, providing two lanes of travel in all directions
- travel lanes are separated by medians along Cambridge Street
- travel lanes are separated by barrier pavement markings along the north and southbound approaches of Southport Street
- the speed limit for all roads is 60 km/h.

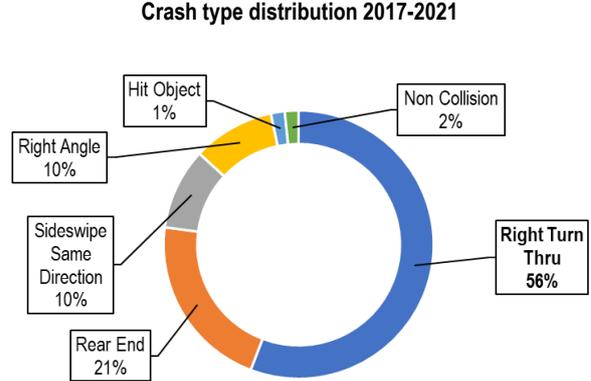
The intersection's turning approaches and respective right-turn movement arrangements, that have been in place since 1998, are presented in Table A.3.

Table A.3: Southport Street / Cambridge Street: Right turn movement arrangements

Turning approach	Right-turn movement arrangements
Cambridge St, RT northbound into Southport St	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning.
Cambridge St, RT southbound into Southport St	Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Southport St, RT eastbound into Cambridge St	Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Southport St, RT westbound into Cambridge St	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning.

The crash type distribution and analysis of crash types relevant to the project, in terms of severity, for the period 2017-2021 are presented in Table A.4. RUM 22 thru-right crashes accounted for 56% of all crashes at this site; no other right-turn crash types were recorded.

Table A.4: Southport Street / Cambridge Street: Intersection layout and crash summary

					
Right-turn crash type severity total 2017-2021					
RUM Code	Fatal	Hospital	Medical	PDO major	PDO minor
22 Right-thru	0	3	5	20	4

A.3 Karrinyup-Morley Road / Crimea Street, Morley

This intersection is located approximately 9 km northeast of the Perth CBD in an urban area with residential and retail land uses. Key features of the intersection are:

- it is a four-leg intersection, providing two lanes of travel in all directions
- channelised left turn slip lanes are provided on all approaches
- channelised right-turn lanes are provided on all approaches
- Karrinyup-Morley Road and Crimea Street have a speed limit of 60 km/h and 70 km/h respectively.

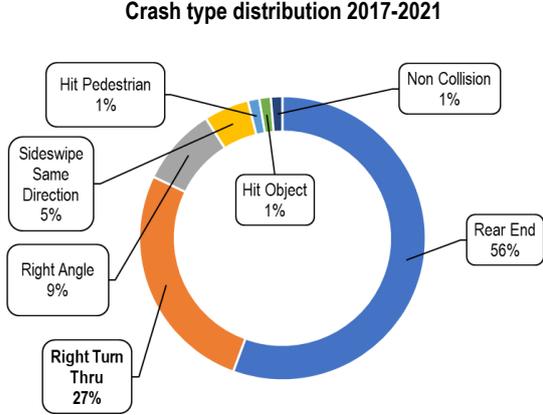
The intersection's turning approaches and respective right-turn movement arrangements, that have been in place since 1997, are presented in Table A.5.

Table A.5: Karrinyup-Morley Road / Crimea Street, Morley: Right turn movement arrangements

Turning approach	Right-turn movement arrangements
Karrinyup-Morley Rd, northbound RT into Crimea St	All approaches. Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Crimea St, eastbound RT into Karrinyup-Morley Rd	
Crimea St, westbound RT into Karrinyup-Morley Rd	
Karrinyup-Morley Rd, southbound RT into Crimea St	

Crash type distribution and analysis of crash types relevant to the project, in terms of severity, for the period 2017-2021 are presented in Table A.6. RUM 22 thru-right crashes accounted for 27% of all crashes at this site; no other right-turn crash types were recorded. Worthy of noting is that rear-end crashes accounted for 56% of all crashes.

Table A.6: Karrinyup-Morley Road / Crimea Street, Morley: Intersection layout and crash summary

					
Right-turn crash type severity total 2017-2021					
RUM Code	Fatal	Hospital	Medical	PDO major	PDO minor
22 Right-thru	0	4	2	14	1

A.4 Connolly Drive / Selkirk Drive, Kinross

This intersection is located approximately 30 km northwest of the Perth CBD in an urban area with commercial and residential land uses. Key features of the intersection are:

- it is a three-leg intersection with Selkirk Drive terminating at Connolly Drive (the only T-intersection in the study sites)
- there are two lanes of travel in each direction along Connolly Drive; Selkirk Drive has a single lane in each direction
- a wide median separates traffic along Connolly Drive; a narrow median separates traffic along Selkirk Drive
- a channelised right-turn lane is provided along Connolly Drive (northbound direction)
- the speed limits for Connolly Drive and Selkirk Drive are 70 km/h and 50 km/h respectfully.

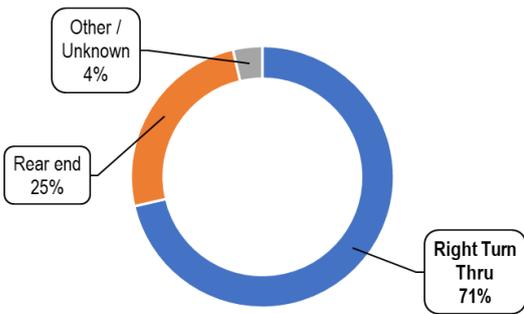
The intersection's turning approaches and respective right-turn movement arrangements, that have been in place since 2009, are presented in Table A.7.

Table A.7: Connolly Drive / Selkirk Drive: Right turn movement arrangements

Turning approach	Right-turn movement arrangement
Selkirk Dr northbound right-turn into Connolly Dr	Fully controlled right-turn. Green right-turn arrow display.
Connolly Dr eastbound right-turn into Selkirk Dr	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning.

Crash type distribution and analysis of crash types relevant to the project, in terms of severity, for the period 2017-2021, are presented in Table A.8. RUM 22 thru-right crashes accounted for 71% of all crashes at this site; no other right-turn crash types were recorded.

Table A.8: Connolly Drive / Selkirk Drive: Intersection layout and crash summary

		<p>Crash type distribution 2017 - 2021</p> 			
Right-turn crash type severity total 2017-2021					
RUM Code	Fatal	Hospital	Medical	PDO major	PDO minor
22 Right-thru	0	1	4	12	0

A.5 Spearwood Avenue / Rockingham Road, Spearwood

This intersection is located approximately 25 km south of the Perth CBD in an urban area with commercial, and residential land uses. Key features of the intersection are:

- it is a four-leg, channelised intersection, with two lanes of travel in all directions
- a wide median separates traffic lanes along Spearwood Avenue; narrow medians separate traffic lanes along Rockingham Road
- channelised right-turn lanes are provided on Spearwood Avenue (both approaches); right-turns are permitted from the centre through lanes on Rockingham Road
- the speed limit for all roads is 60 km/h.

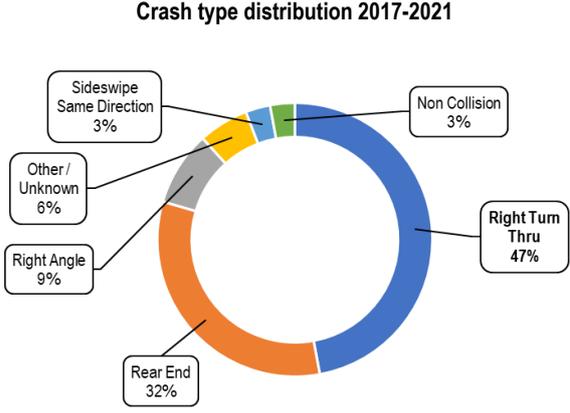
The intersection's turning approaches and respective right-turn movement arrangements, that have been in place since 2019, are presented in Table A.9.

Table A.9: Spearwood Avenue / Rockingham Road: Right turn movement arrangements

Turning approach	Right-turn movement arrangement
Spearwood Ave northbound right-turn into Rockingham Rd	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning. During pedestrian demand, red right-turn arrow drops off to allow filter right-turn.
Rockingham Road eastbound right-turn into Spearwood Ave	Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Rockingham Road westbound right-turn into Spearwood Ave	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning. During pedestrian demand, red right-turn arrow drops off to allow filter right-turn.
Spearwood Ave southbound right-turn into Rockingham Rd	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning. During pedestrian demand, red right-turn arrow drops off to allow filter right-turn.

Crash type distribution and analysis of crash types relevant to the project, in terms of severity, for the period 2017-2021, are presented in Table A.10. RUM 22 thru-right crashes accounted for 47% of all crashes at this site; no other right-turn crash types were recorded.

Table A.10: Spearwood Avenue / Rockingham Road: Intersection layout and crash summary

Crash type distribution 2017-2021					
					
Right-turn crash type severity total 2017-2021					
RUM Code	Fatal	Hospital	Medical	PDO major	PDO minor
22 Right-thru	0	2	1	12	1

A.6 Harborne Street / Scarborough Beach Road / Frobisher Street, Osbourne Park

This intersection is located approximately 7 km northwest of the Perth CBD in an urban area with commercial, office space, recreation, and retail land uses. Key features of the intersection are:

- it is a four-leg, channelised intersection, providing two lanes of travel in all directions; channelised left turn slip lanes are provided on Scarborough Beach Road (eastbound approach) and Harborne Street (northbound approach)
- channelised right-turn lanes are provided on all approaches, except Frobisher Street (southbound approach)
- the speed limit for all roads is 60 km/h.

The intersection's turning approaches and respective right-turn movement arrangements, that have been in place since 2008, are presented in Table A.11.

Table A.11: Harborne Street / Scarborough Beach Road / Frobisher Street: Right turn movement arrangements

Turning approach	Right-turn movement arrangement
Scarborough Beach Rd, northbound right-turn into Frobisher St	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning.
Harborne St, eastbound right-turn into Scarborough Beach Rd	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning.
Frobisher St, westbound right-turn into Scarborough Beach Rd	Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Scarborough Beach Rd, southbound right-turn into Harborne St	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning.

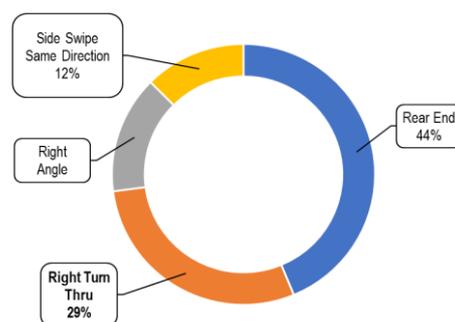
Crash type distribution and analysis of crash types relevant to the project, in terms of severity, for the period 2017-2021 are presented in Table A.12. RUM 22 thru-right crashes accounted for 29% of all crashes at this site. The other right-turn crash type recorded was RUM 24 right-left. Rear-end crashes accounted for 44% of all crashes.

Table A.12: Harborne Street / Scarborough Beach Road / Frobisher Street: Intersection layout and crash summary

Right-turn crash type severity total 2017-2021					
RUM Code	Fatal	Hospital	Medical	PDO major	PDO minor
22 Right-thru	0	3	1	10	0
23 Right-left	0	0	0	1	0



Crash type distribution 2017-2021



A.7 Belmont Avenue / Wright Street, Kewdale

This intersection is located approximately 9 km southeast of the Perth CBD in an urban area with commercial residential and retail land uses. Key features of the intersection are:

- it is a four-leg, channelised intersection, providing two lanes of travel in all directions, except Wright Street (southwest bound)
- a channelised right-turn lane is provided in Wright Street (south westbound); all other approaches have lanes combining through and turning movements
- the speed limit for all roads is 50 km/h.

The intersection's turning approaches and respective right-turn movement arrangements, that have been in place since 1994, are presented in Table A.13.

Table A.13: Belmont Avenue / Wright Street: Right turn movement arrangements

Turning approach	Right-turn movement arrangement
Wright St, north-westbound right-turn into Belmont Ave	Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Belmont Av, north-eastbound right-turn into Wright St	Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Wright St, south-eastbound right-turn into Belmont Ave	Partially controlled filter right-turn. Green arrow drops off, then green circular display into the next phase, right-turn movement is required to find safe gaps in oncoming traffic before turning.
Belmont Ave, south-westbound right-turn into Wright St	Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.

Crash type distribution and analysis of crash types relevant to the project, in terms of severity for the period 2017-2021 are shown in Table A.14. RUM 22 thru-right crashes accounted for 52% of all crashes at this site; no other right-turn crash types were recorded.

Table A.14: Belmont Avenue / Wright Street: Intersection layout and crash summary

Right-turn crash type severity total 2017-2021					
RUM Code	Fatal	Hospital	Medical	PDO major	PDO minor
22 Right-thru	0	2	0	10	2

Crash type distribution 2017 - 2021	
Right Turn Thru	52%
Rear End	29%
Hit Pedestrian	4%
Other / Unknown	4%
Right Angle	



A.8 Plain Street and Royal Street, East Perth (Pilot study site)

This intersection is located within the Perth CBD. It has commercial, residential, and retail land uses. Key features of the intersection are:

- it is a four-leg, channelised intersection with two lanes of travel in all directions
- Plain Street has a channelised right-turn lane in each direction and Royal Street has two lanes in each direction controlling through and turning movements.
- A speed limit of 50 km/h applies to all approaches.

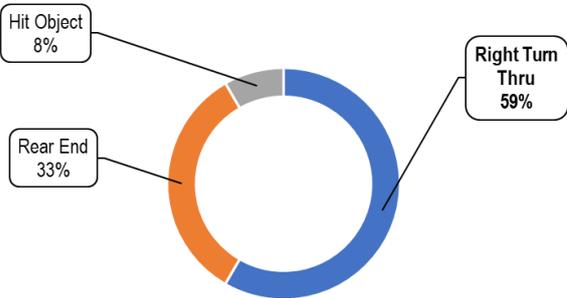
The intersection's turning approaches and respective right-turn movement arrangements, that have been in place since 1994, are shown in Table A.15.

Table A.15: Plain St and Royal St: Right turn movement arrangements

Turning approach	Right-turn movement arrangement
Royal St northbound right-turn into Plain St	All approaches. Filter right-turn. On green circle display right-turn movement is required to find safe gaps in oncoming traffic before turning.
Plain St eastbound right-turn into Royal St	
Plain St westbound right-turn into Royal St	
Royal St southbound right-turn into Plain St	

Crash type distribution and analysis of crash types relevant to the project, in terms of severity for the period 2017-2021 are shown in Table A.16. RUM 22 thru-right crashes accounted for 59% of all crashes at this site; no other right-turn crash types were recorded.

Table A.16: Plain St and Royal St: Intersection layout and crash summary

		<p>Crash type distribution 2017-2021</p> 			
Right-turn crash type severity total 2017-2021					
RUM Code	Fatal	Hospital	Medical	PDO major	PDO minor
22 Right-thru	0	0	0	7	0

Appendix B Site Analysis of PET, TTC and Delta-V

B.1 Mirrabooka Avenue/Ravenswood Drive/Yirrigan Drive, Nollamara

B.1.1 Histograms of Road User Combination

Figure B.1: Histograms of road users combination Dir 1

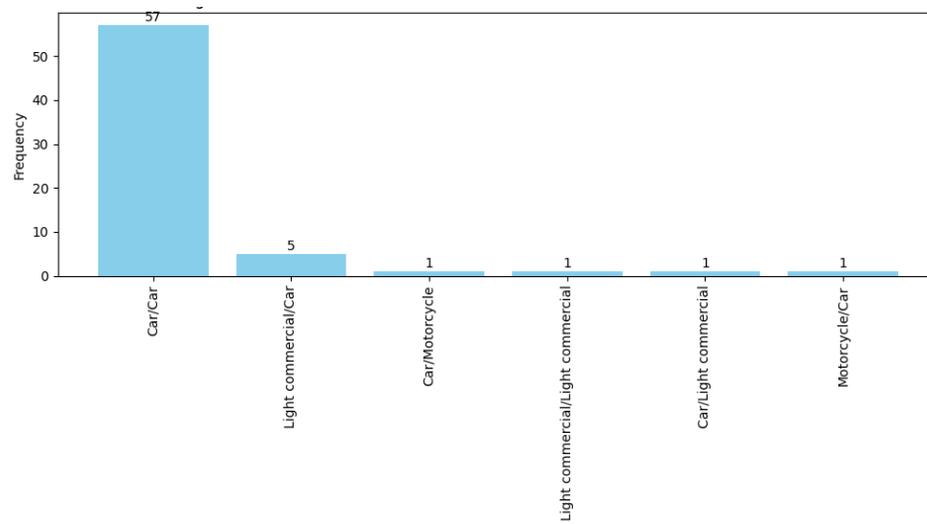
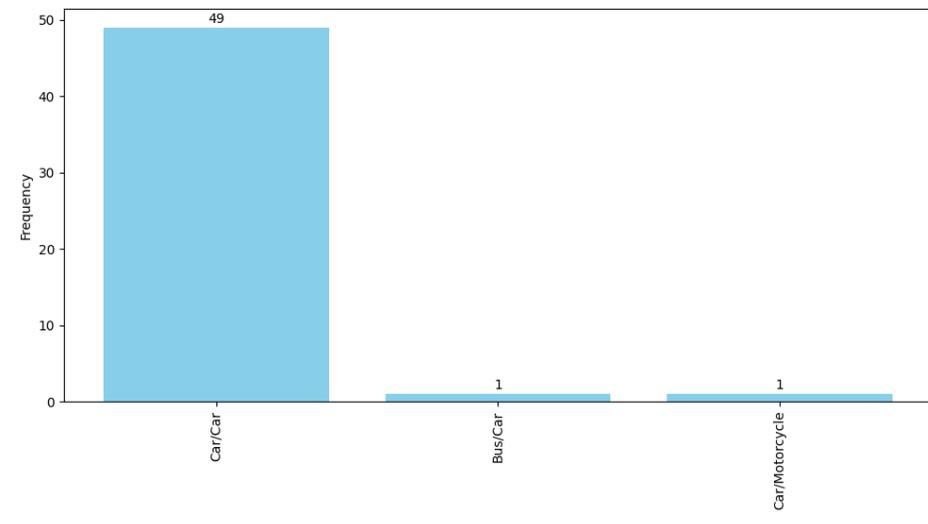


Figure B.2: Histograms of road users combination Dir 2



B.1.2 Histograms of Speeds

Figure B.3: Histograms of speeds Dir 1

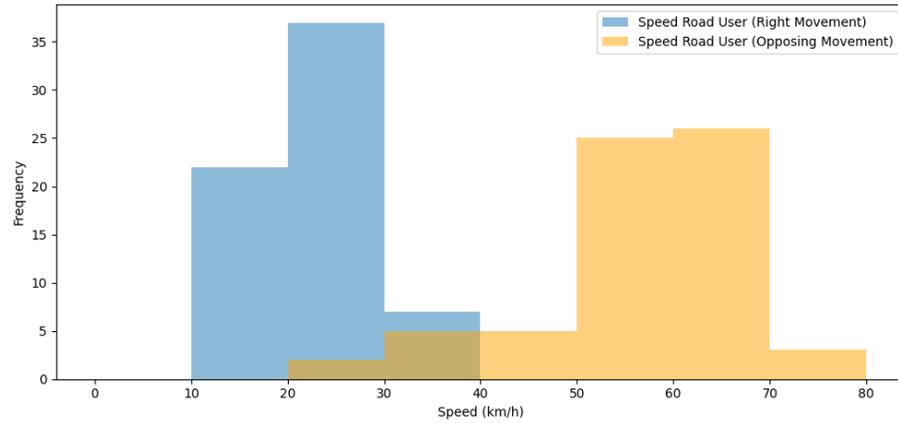
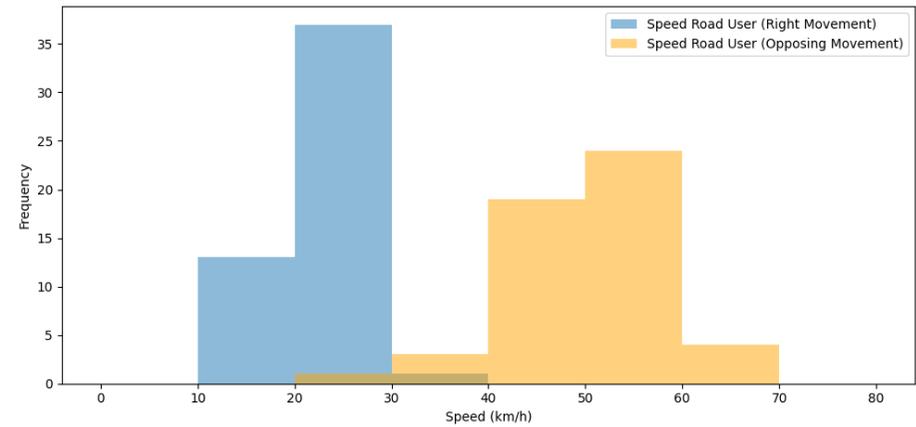


Figure B.4: Histograms of speeds Dir 2



B.1.3 Frequency of Traffic Signal Colour at the Time of Right Movement Incidents

Figure B.5: Frequency of traffic signal colour at the time of right Movement incidents Dir 1

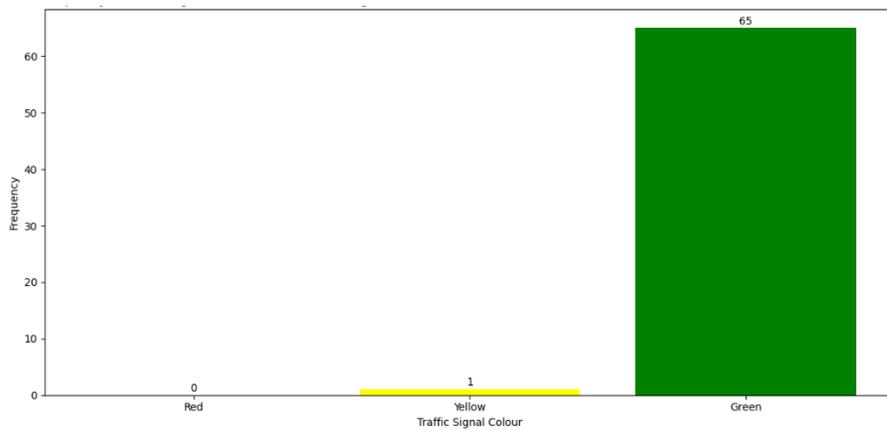
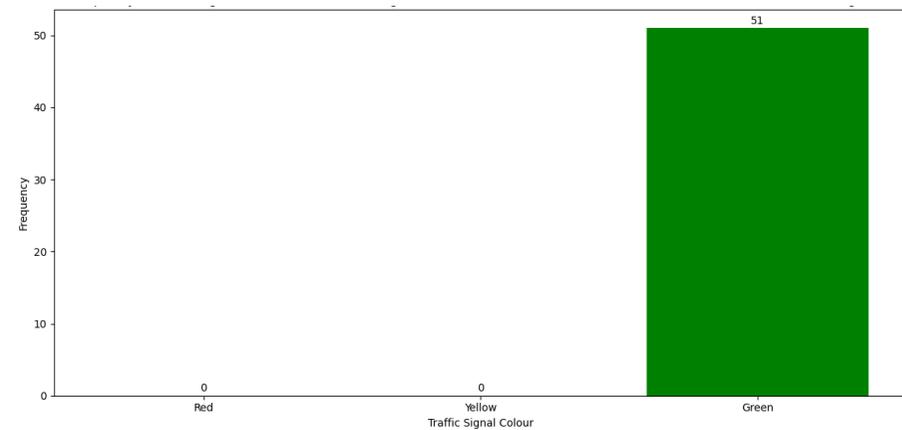


Figure B.6: Frequency of traffic signal colour at the time of right Movement incidents Dir 2



B.1.4 Scatter Plot of PET and TTC

Figure B.7: Scatter Plot of PET and TTC Dir 1

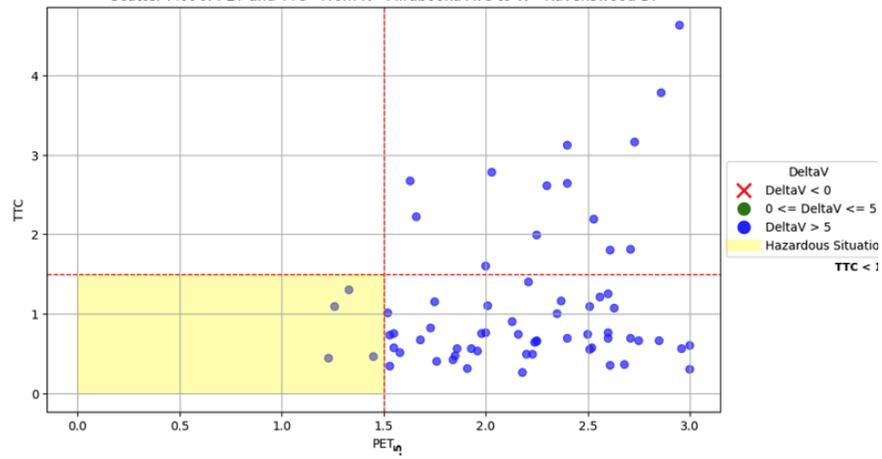
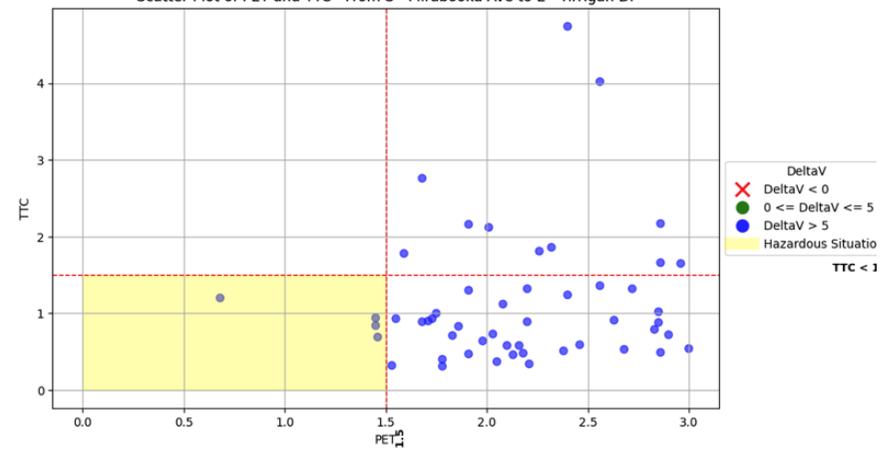


Figure B.8: Scatter Plot of PET and TTC Dir 1



B.1.5 Histograms of Delta V

Figure B.9: Histograms of Delta-V Dir 1

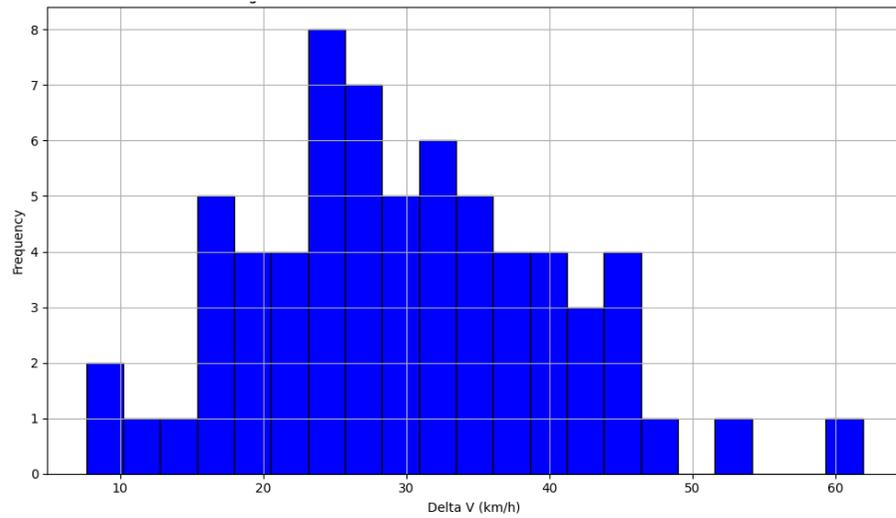
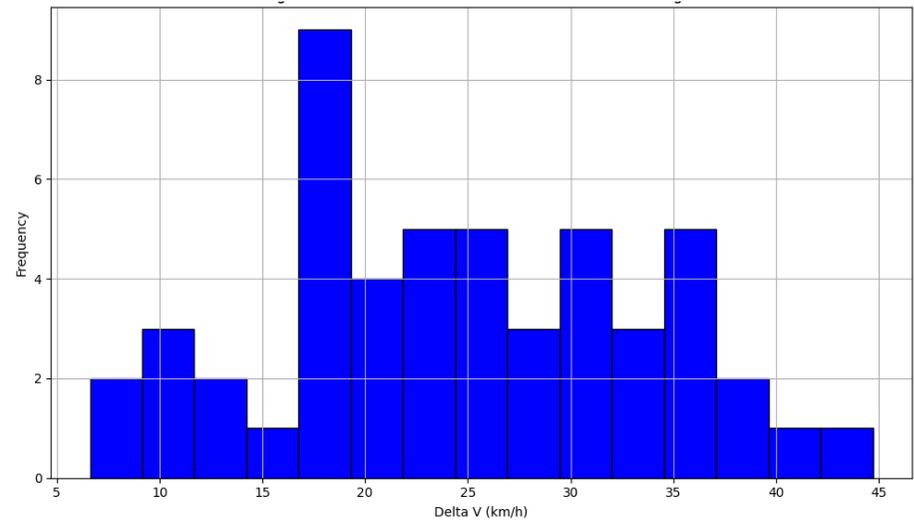


Figure B.10: Histograms of Delta-V Dir 2



B.1.6 Relationship of Kinetic Energy between Two Movements

Figure B.11: Relationship of Kinetic Energy between Two Movements Dir 1

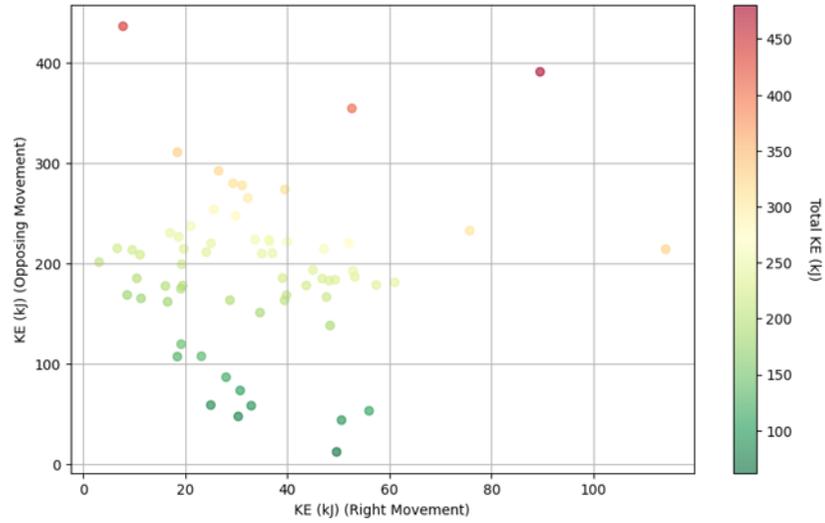
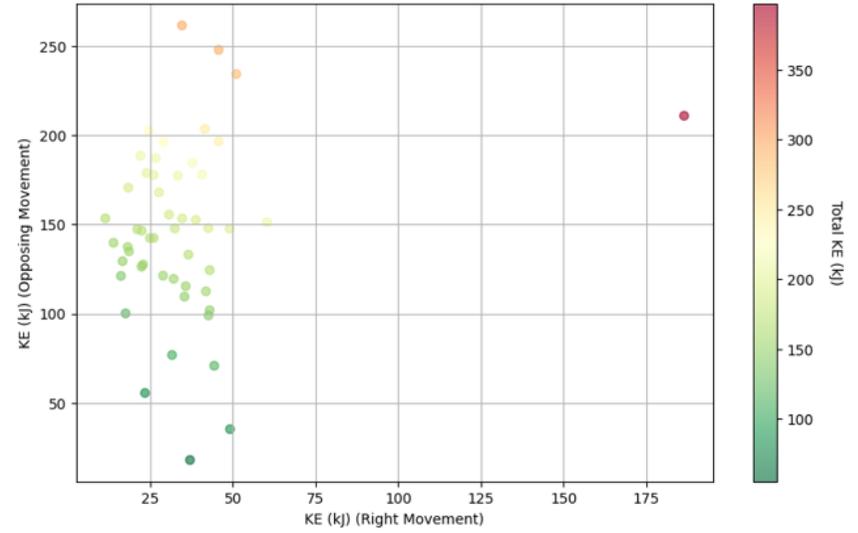


Figure B.12: Relationship of Kinetic Energy between Two Movements Dir 2



B.2 Southport Street / Cambridge Street, West Leederville

B.2.1 Histograms of Road User Combination

Figure B.13: Histograms of road users combination Dir 1

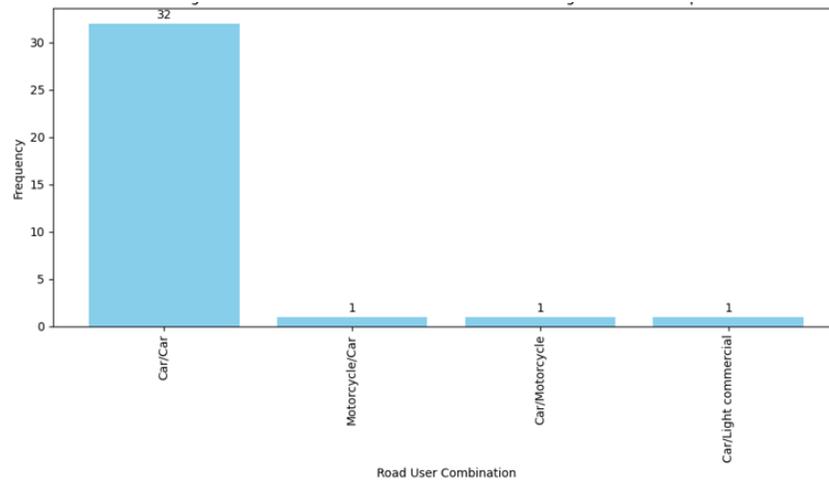
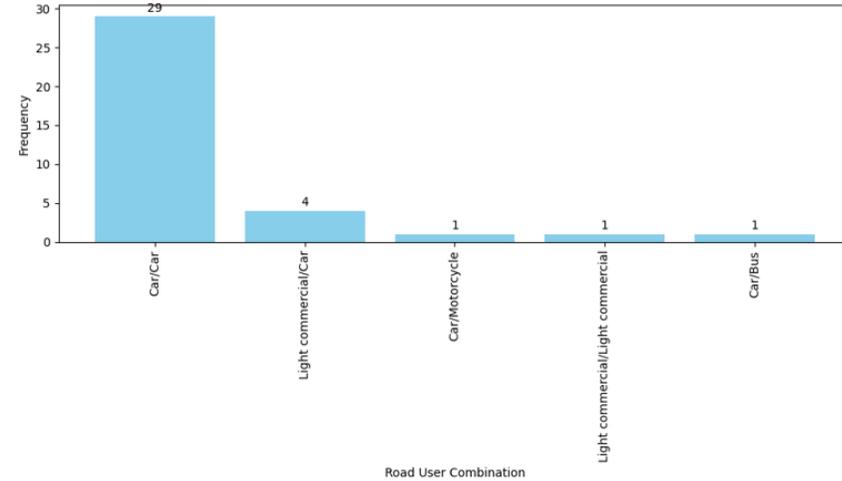


Figure B.14: Histograms of road users combination Dir 2



B.2.2 Histograms of Speeds

Figure B.15: Histograms of speeds Dir 1

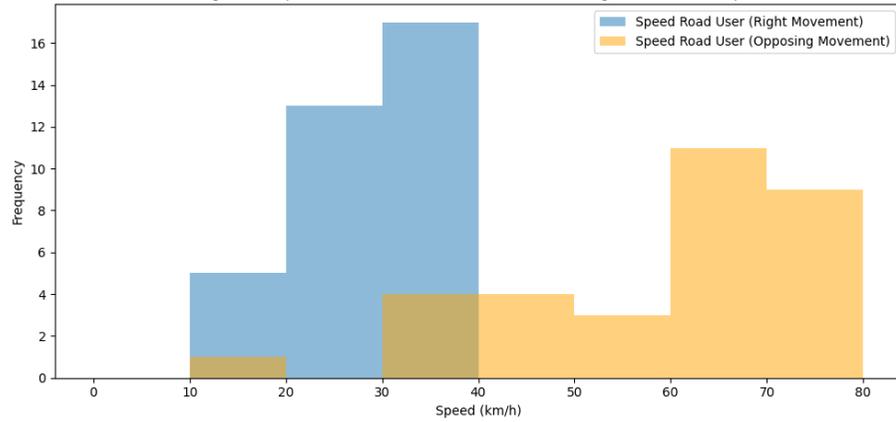
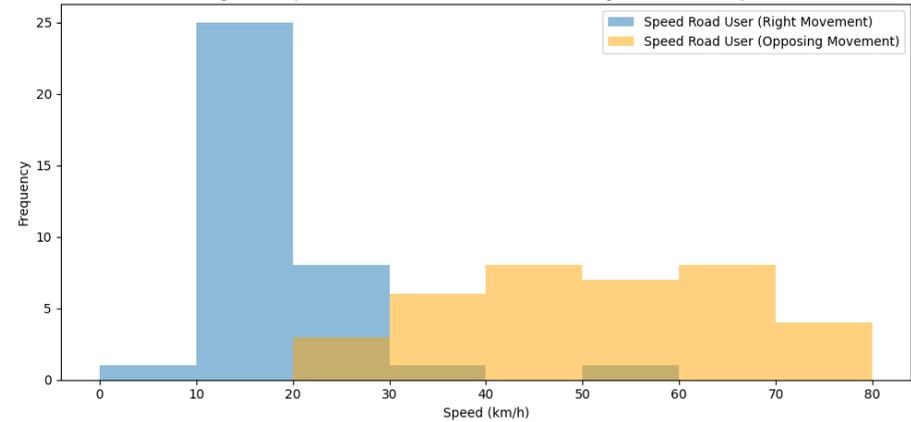


Figure B.16: Histograms of speeds Dir 2



B.2.3 Frequency of Traffic Signal Colour at the Time of Right Movement Incidents with Counts

Figure B.17: Frequency of traffic signal colour at the time of right Movement incidents with counts Dir 1

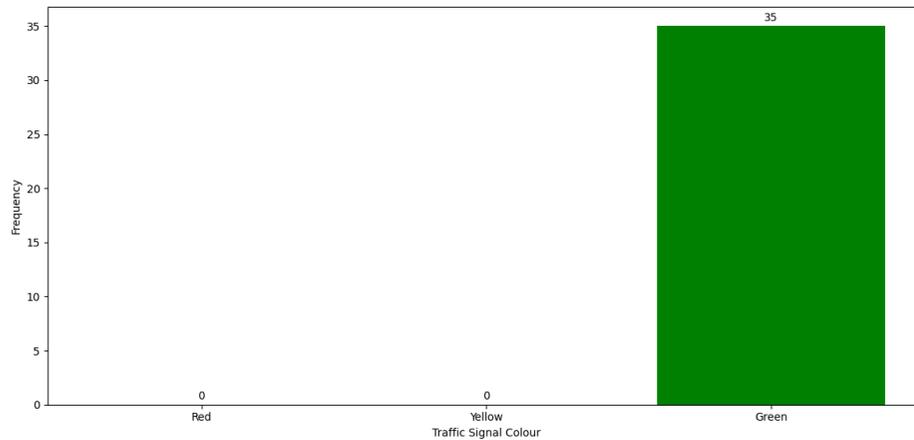
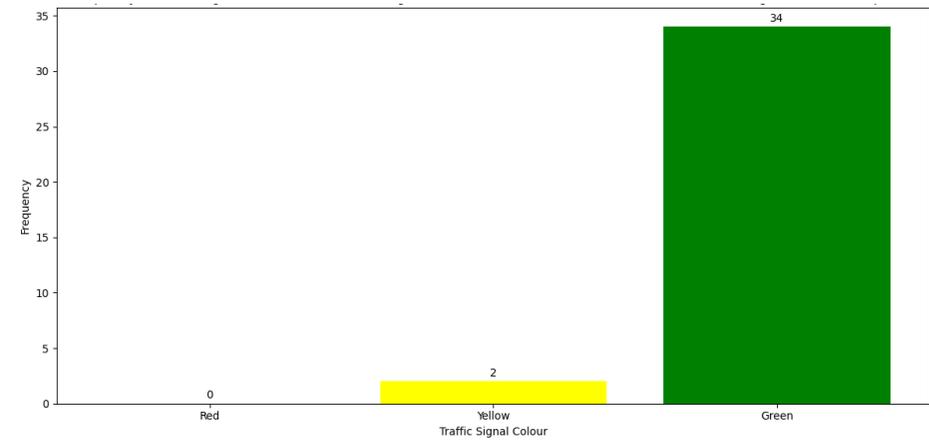


Figure B.18: Frequency of traffic signal colour at the time of right Movement incidents with counts Dir 2



B.2.4 Scatter Plot of PET and TTC

Figure B.19: Scatter Plot of PET and TTC Dir 1

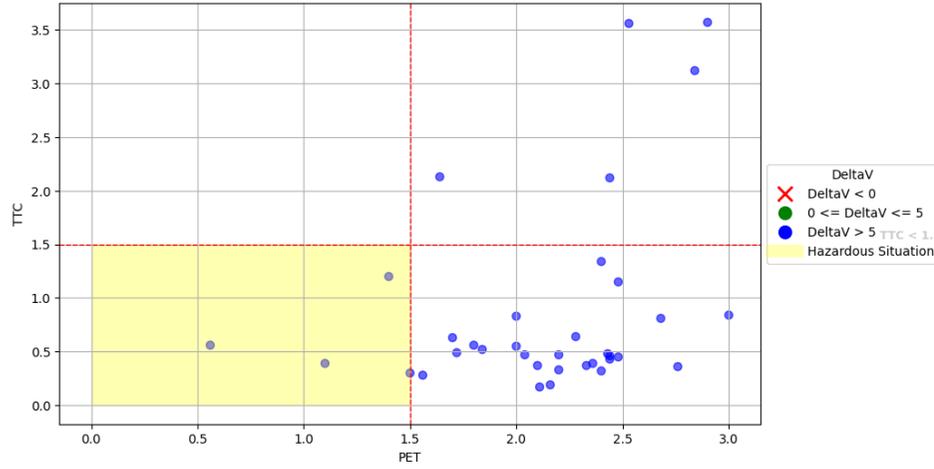
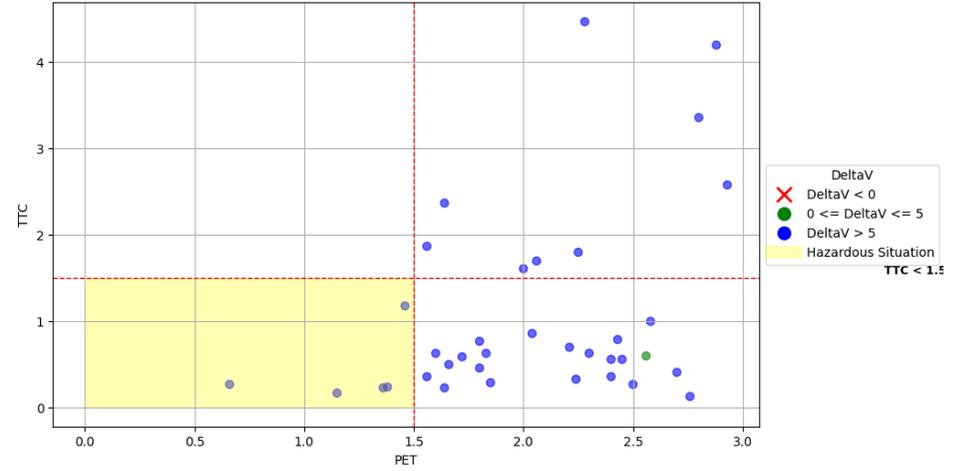


Figure B.20: Scatter Plot of PET and TTC Dir 1



B.2.5 Histograms of Delta V

Figure B.21: Histograms of Delta-V Dir 1

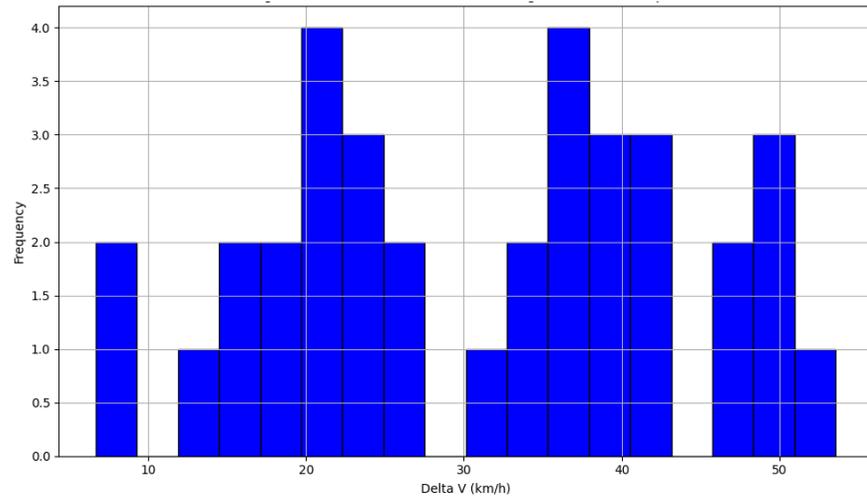
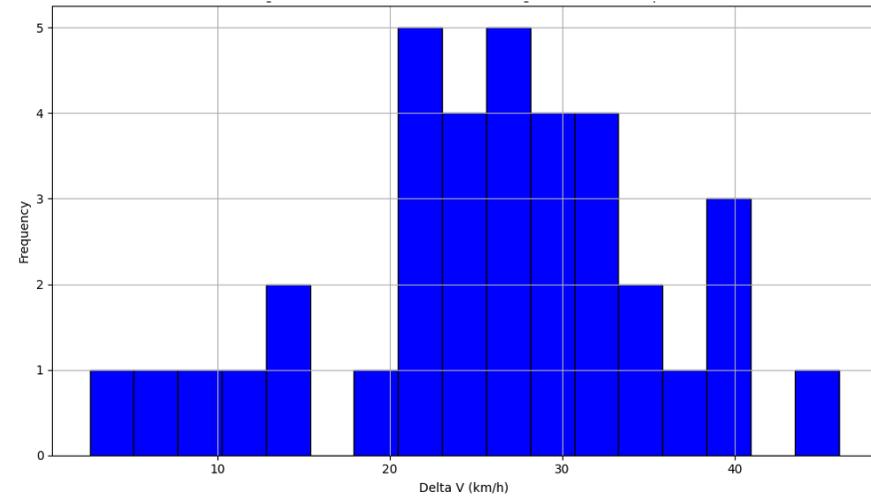


Figure B.22: Histograms of Delta-V Dir 2



B.2.6 Relationship of Kinetic Energy between Two Movements

Figure B.23: Relationship of Kinetic Energy between Two Movements Dir 1

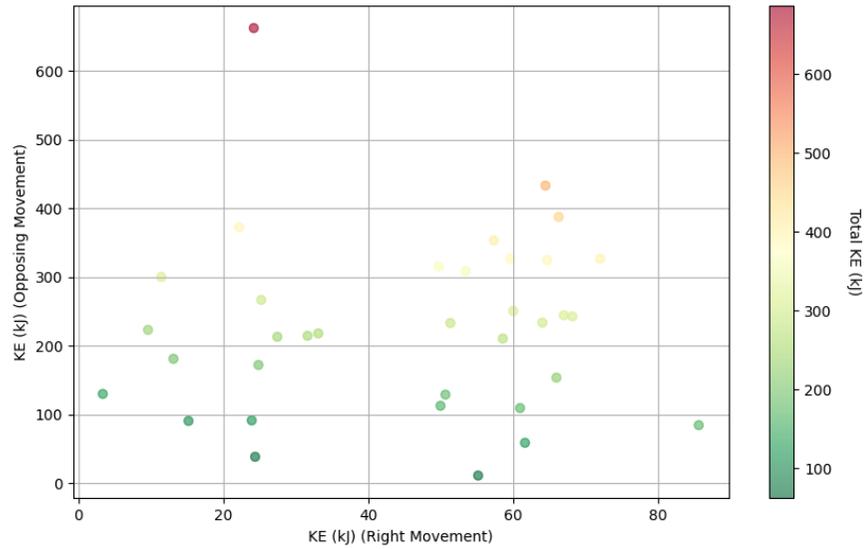
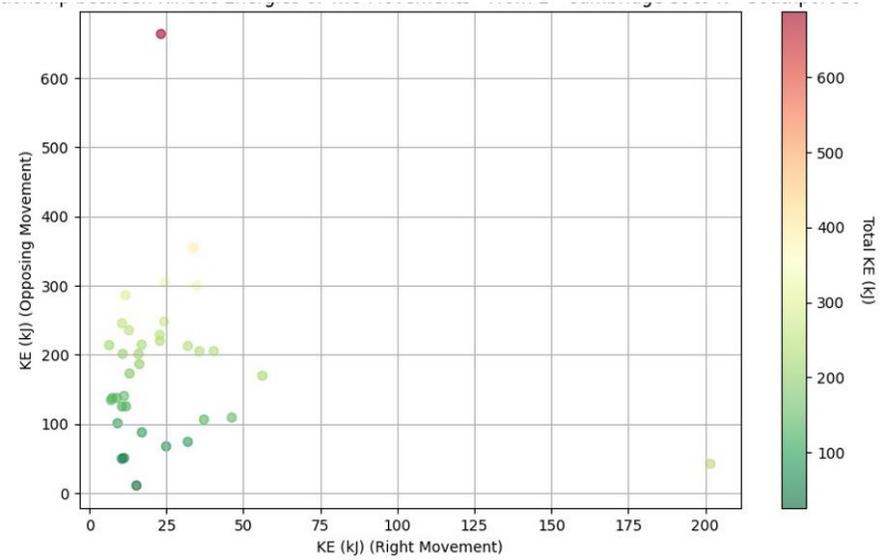


Figure B.24: Relationship of Kinetic Energy between Two Movements Dir 2



B.3 Karrinyup-Morley Road / Crimea Street, Morley

B.3.1 Histograms of Road User Combination

Figure B.25: Histograms of road users combination Dir 1

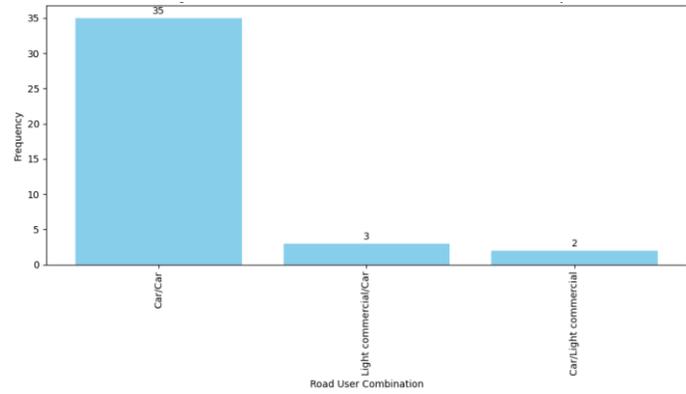
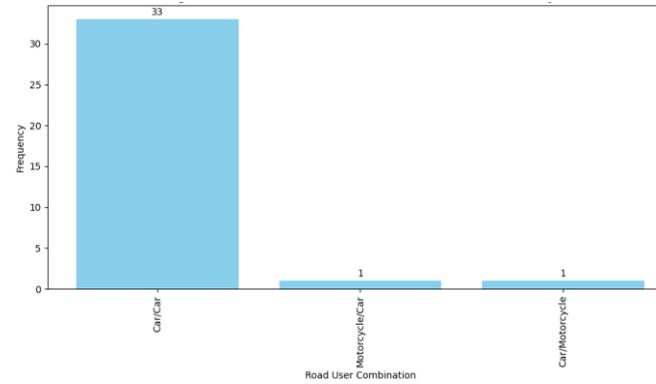


Figure B.26: Histograms of road users combination Dir 2



B.3.2 Histograms of Speeds

Figure B.27: Histograms of speeds Dir 1

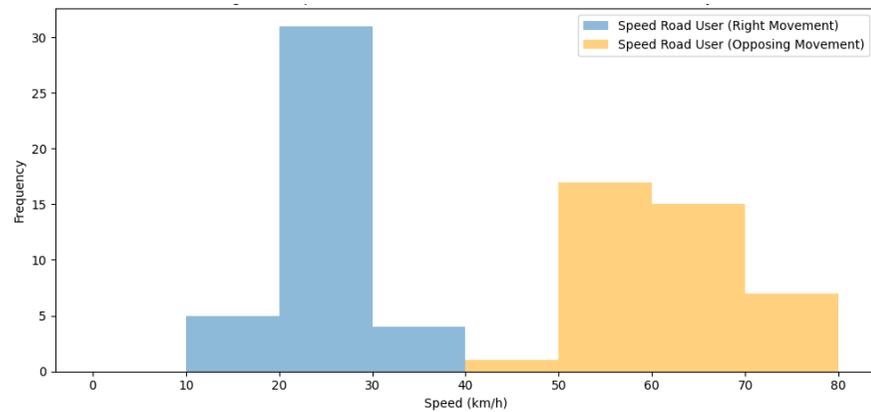
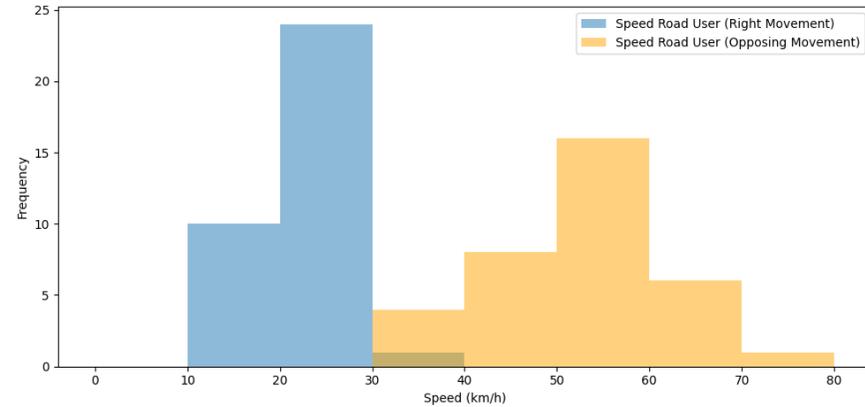


Figure B.28: Histograms of speeds Dir 2



B.3.3 Frequency of Traffic Signal Colour at the Time of Right Movement Incidents with Counts

Figure B.29: Frequency of traffic signal colour at the time of right Movement incidents Dir 1

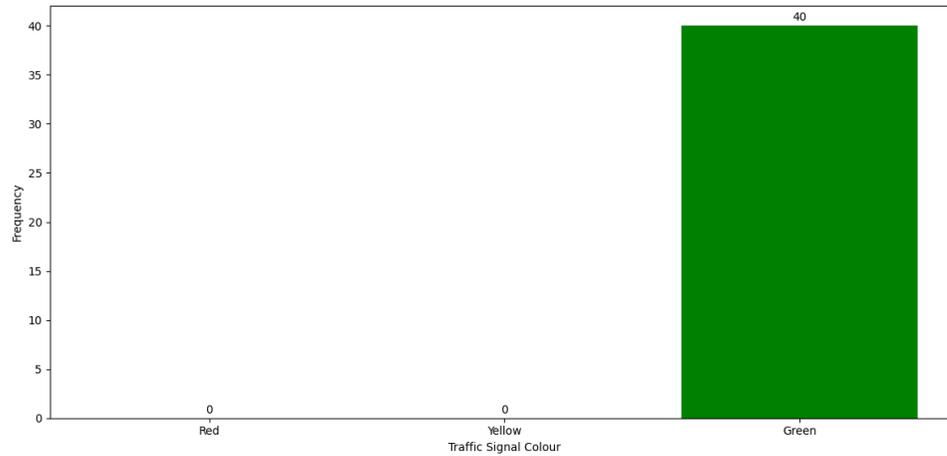
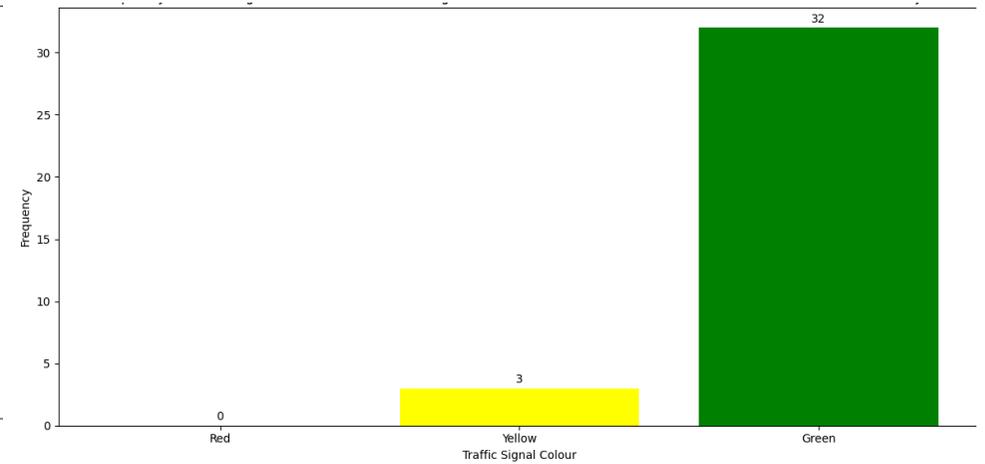


Figure B.30: Frequency of traffic signal colour at the time of right Movement incidents Dir 2



B.3.4 Scatter Plot of PET and TTC

Figure B.31: Scatter Plot of PET and TTC Dir 1

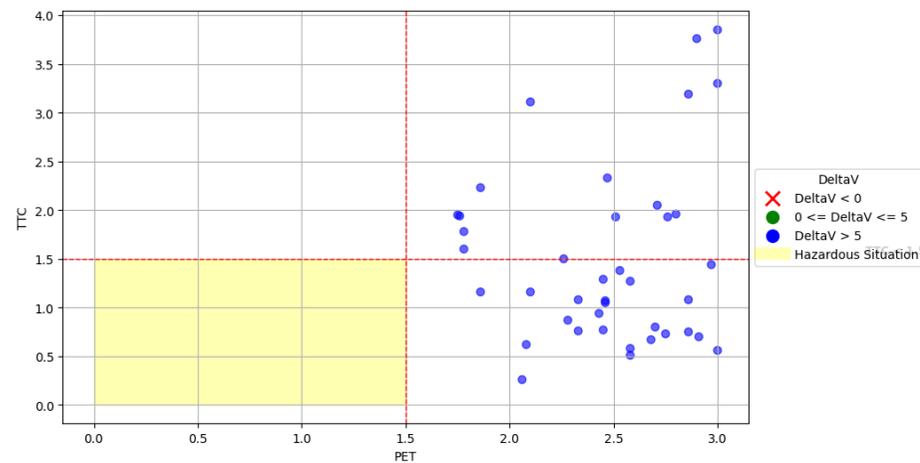
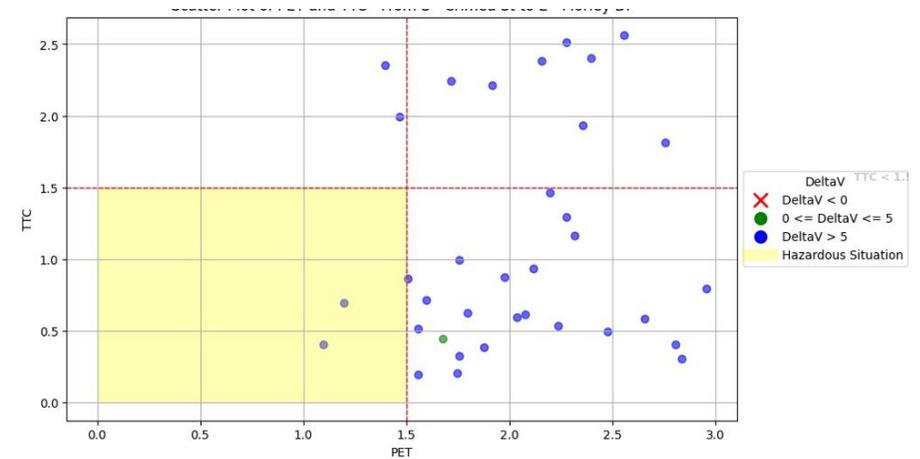


Figure B.32: Scatter Plot of PET and TTC Dir 1



B.3.5 Histograms of Delta V

Figure B.33: Histograms of Delta-V Dir 1

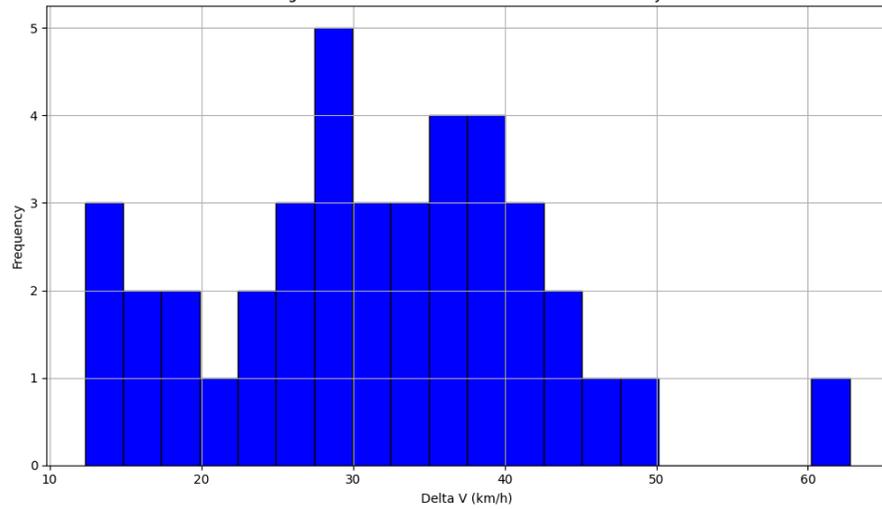
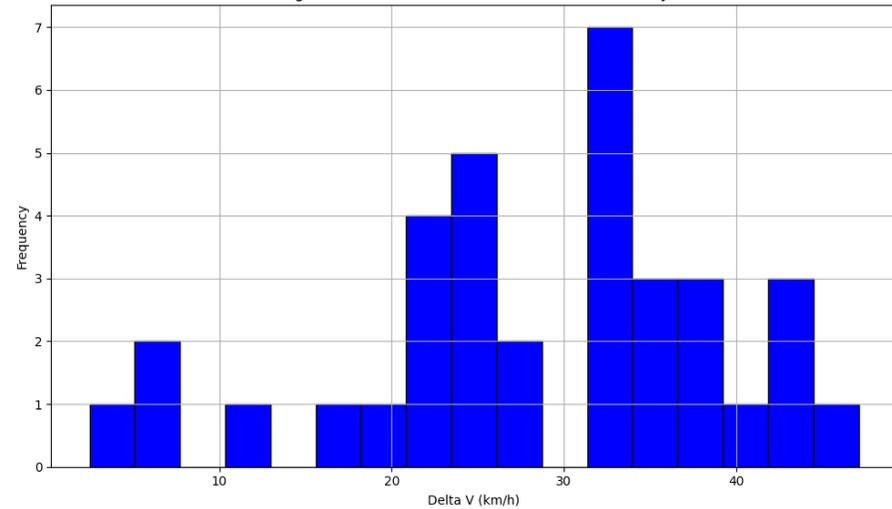


Figure B.34: Histograms of Delta-V Dir 2



B.3.6 Relationship of Kinetic Energy between Two Movements

Figure B.35: Relationship of Kinetic Energy between Two Movements Dir 1

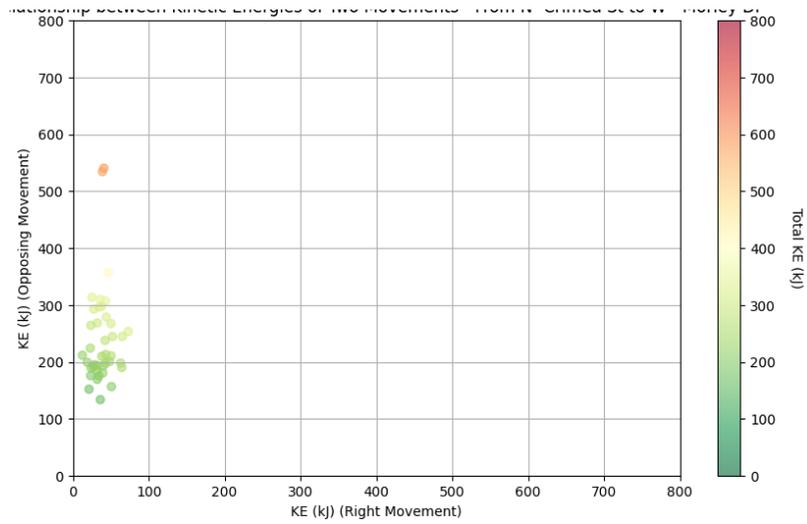
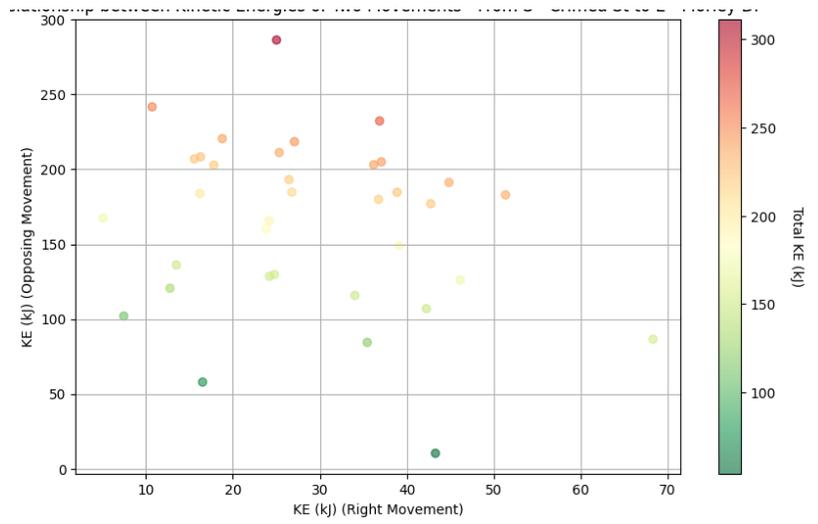


Figure B.36: Relationship of Kinetic Energy between Two Movements Dir 2



B.4 Connolly Drive / Scarborough Beach Road, Spearwood

B.4.1 Histograms of Road User Combination

Figure B.37: Histograms of road users combination Dir 1

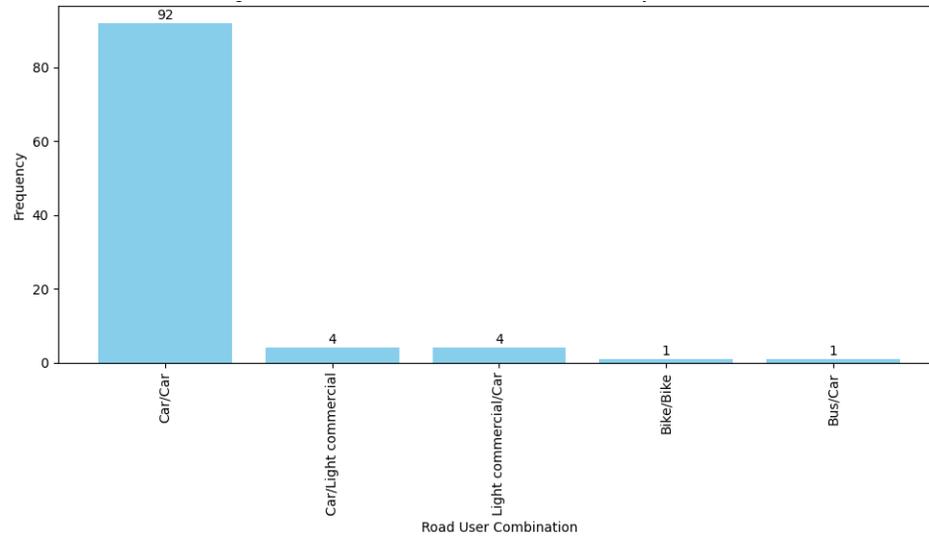
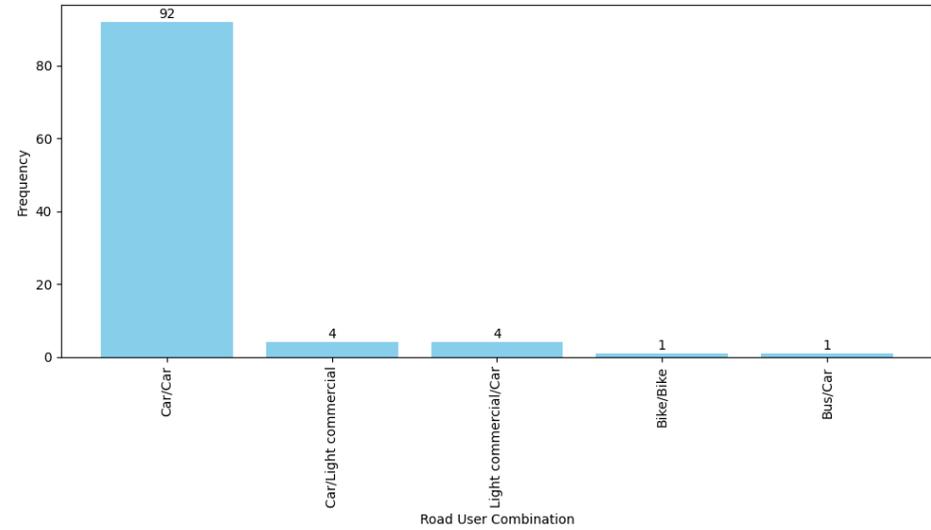
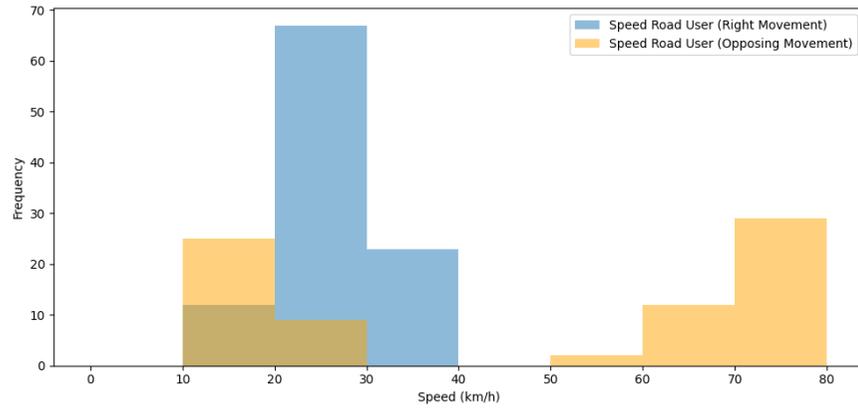


Figure B.38: Histograms of road users combination Dir 2



B.4.2 Histograms of Speeds

Figure B.39: Histograms of speeds Dir 1



B.4.3 Frequency of Traffic Signal Colour at the Time of Right Movement Incidents

Figure B.40: Frequency of traffic signal colour at the time of right Movement incidents Dir 1

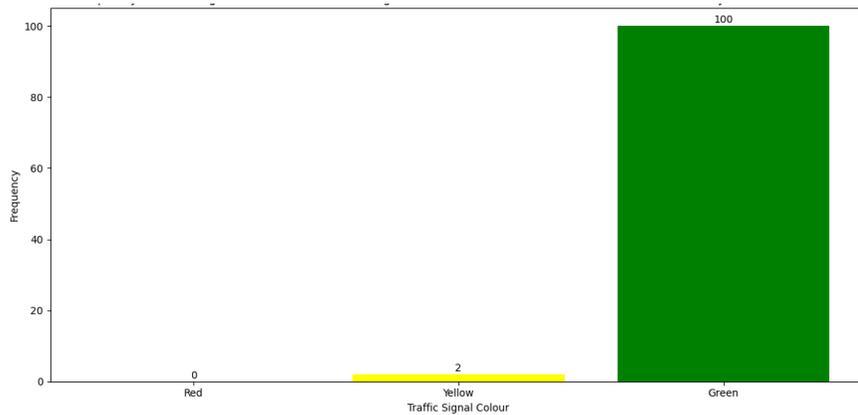
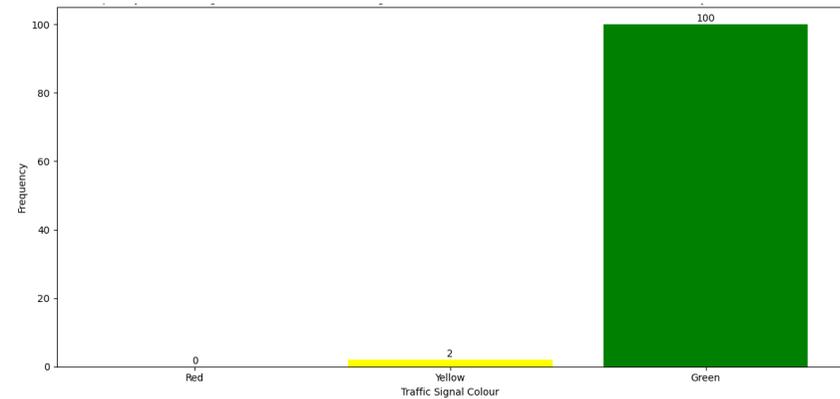


Figure B.41: Frequency of traffic signal colour at the time of right Movement incidents Dir 2



B.4.4 Scatter Plot of PET and TTC

Figure B.42: Scatter Plot of PET and TTC Dir 1

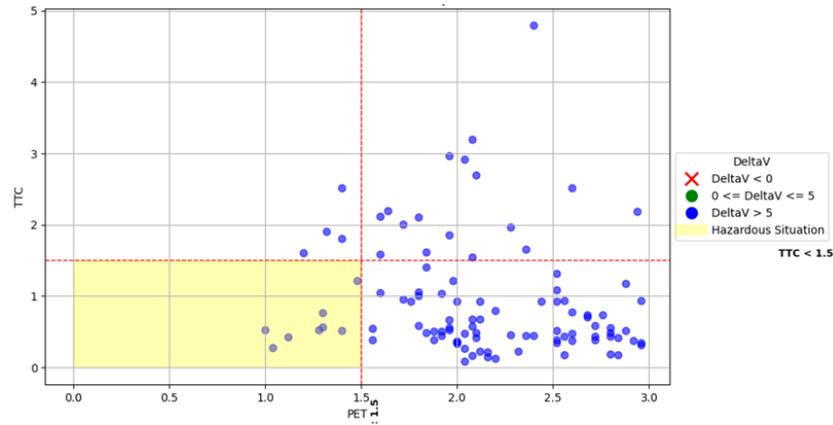
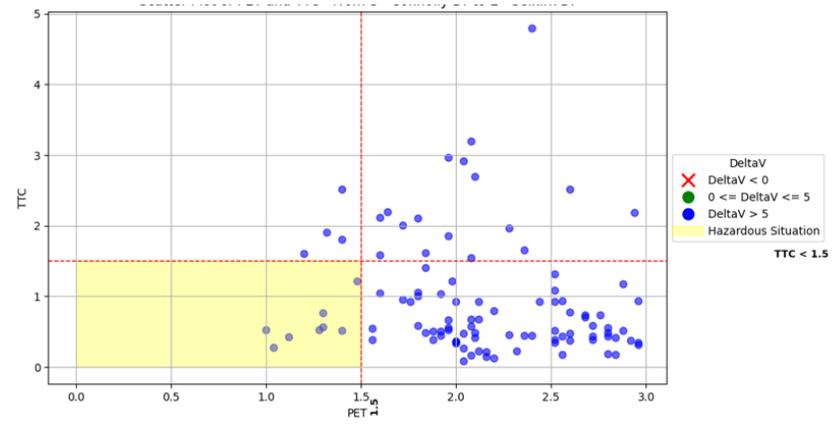


Figure B.43: Scatter Plot of PET and TTC Dir 1



B.4.5 Histograms of Delta V

Figure B.44: Histograms of Delta-V Dir 1

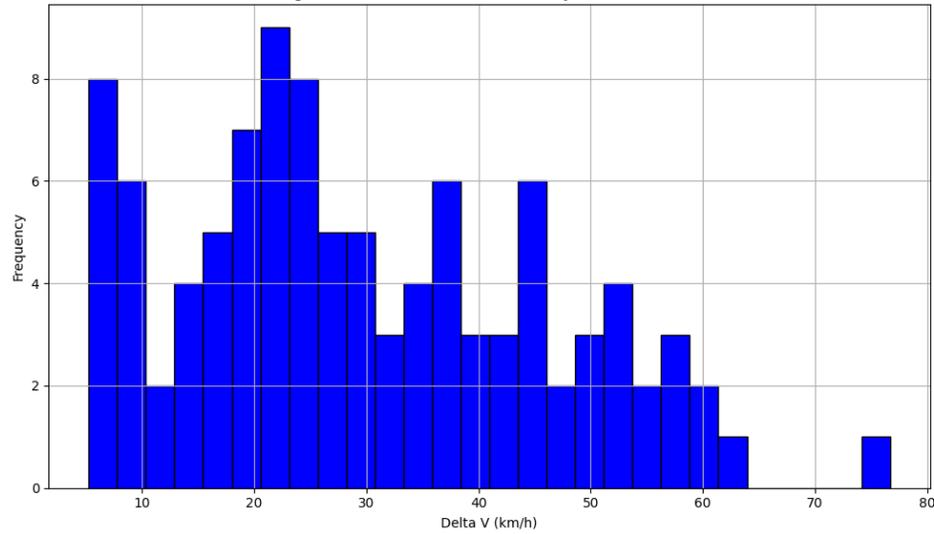
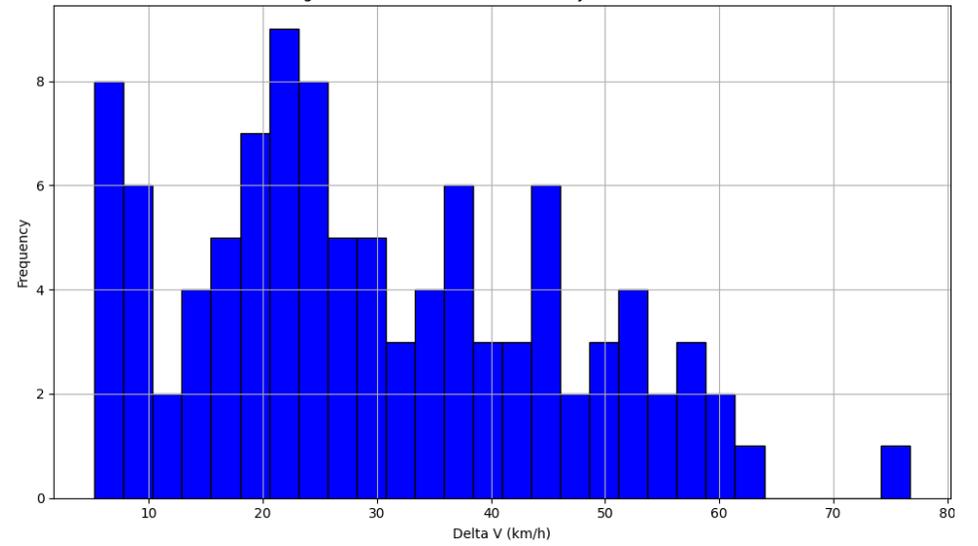


Figure B.45: Histograms of Delta-V Dir 2



B.4.6 Relationship of Kinetic Energy between Two Movements

Figure B.46: Relationship of Kinetic Energy between Two Movements Dir 1

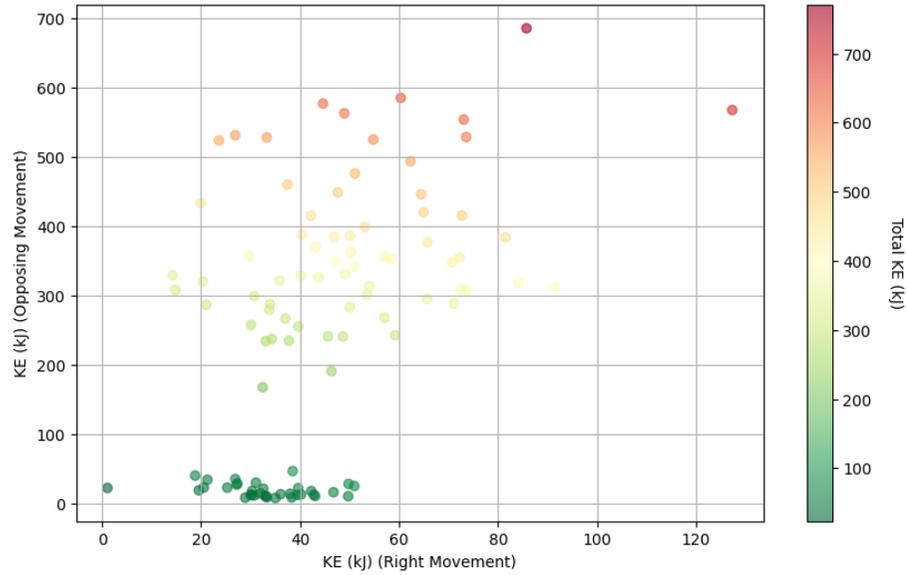
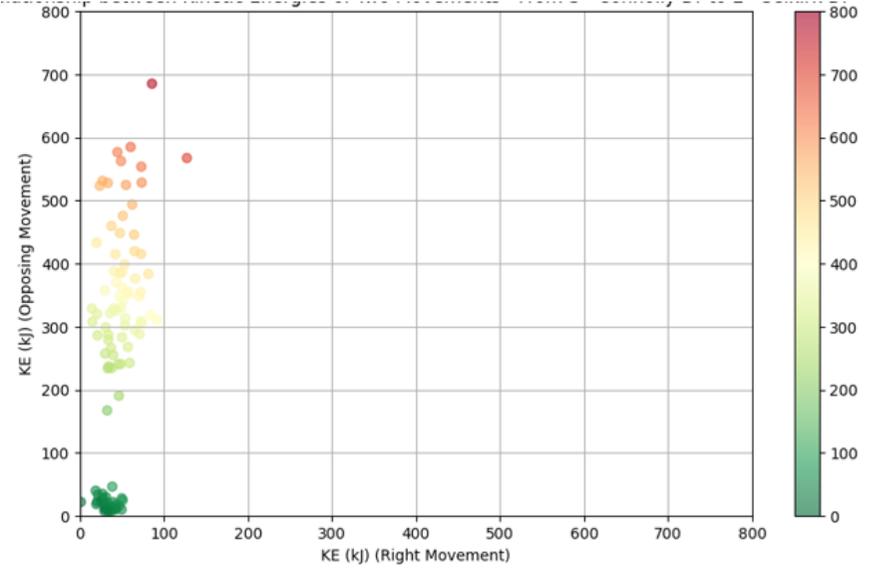


Figure B.47: Relationship of Kinetic Energy between Two Movements Dir 2



B.5 Spearwood Avenue / Rockingham Road, Spearwood

B.5.1 Histograms of Road User Combination

Figure B.48: Histograms of road users combination Dir 1

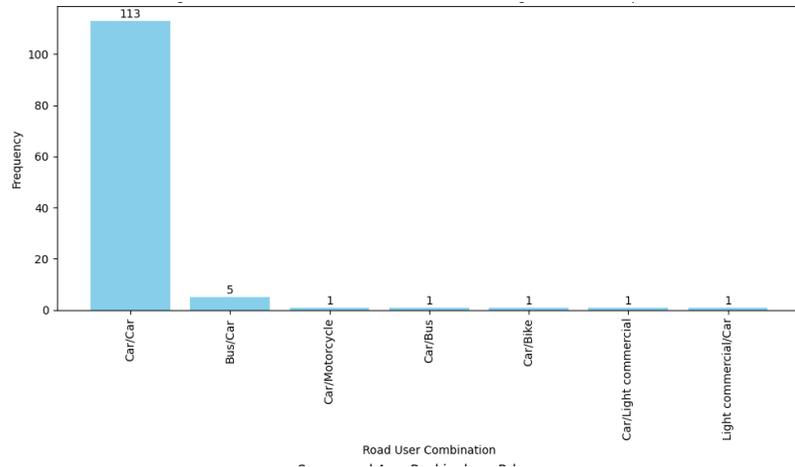
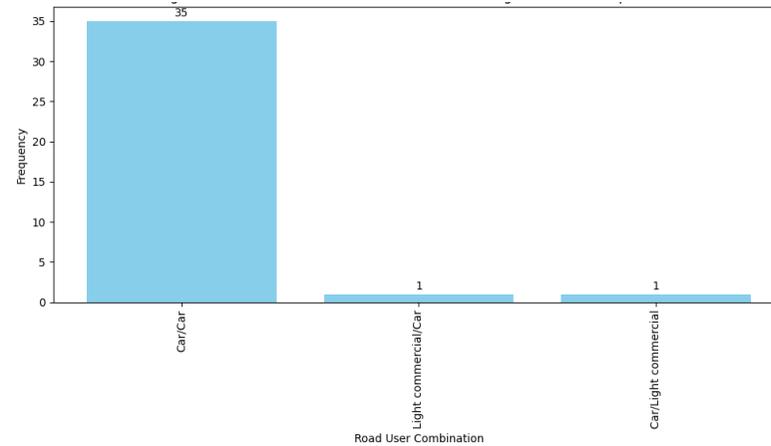


Figure B.49: Histograms of road users combination Dir 2



B.5.2 Histograms of Speeds

Figure B.50: Histograms of speeds Dir 1

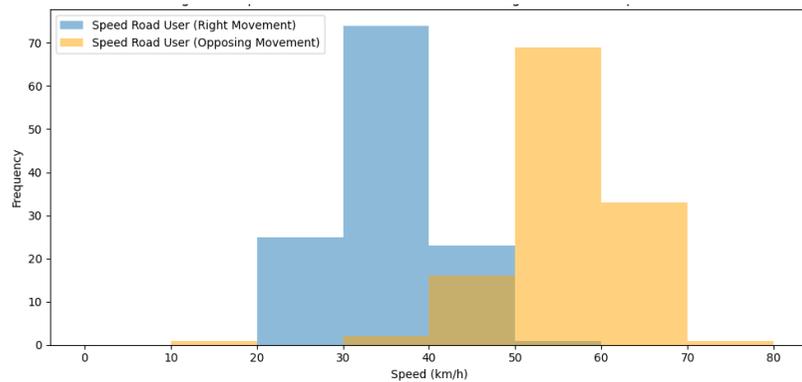
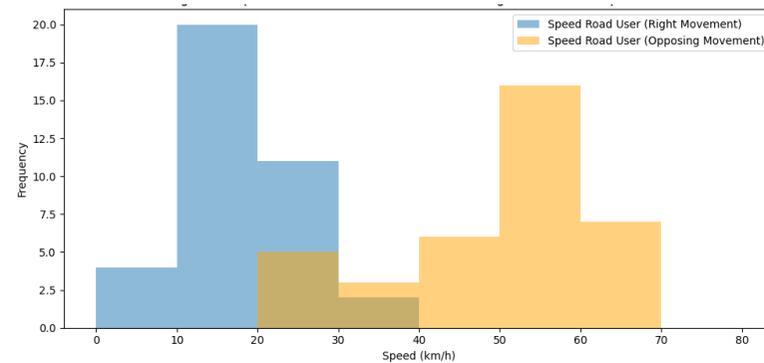


Figure B.51: Histograms of speeds Dir 2



B.5.3 Frequency of Traffic Signal Colour at the Time of Right Movement Incidents

Figure B.52: Frequency of traffic signal colour at the time of right Movement incidents Dir 1

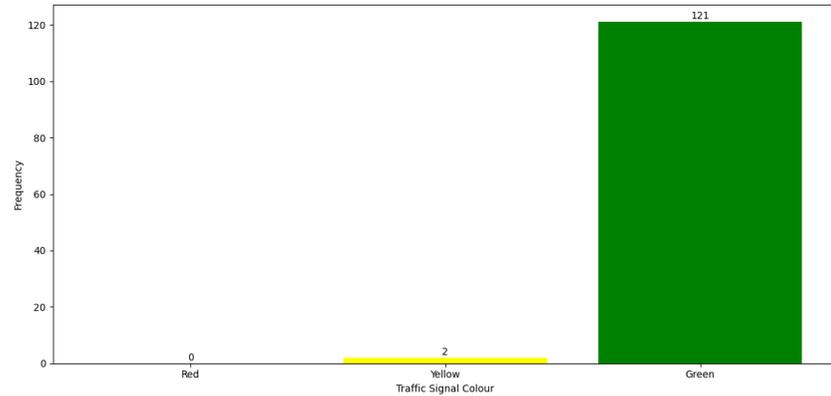
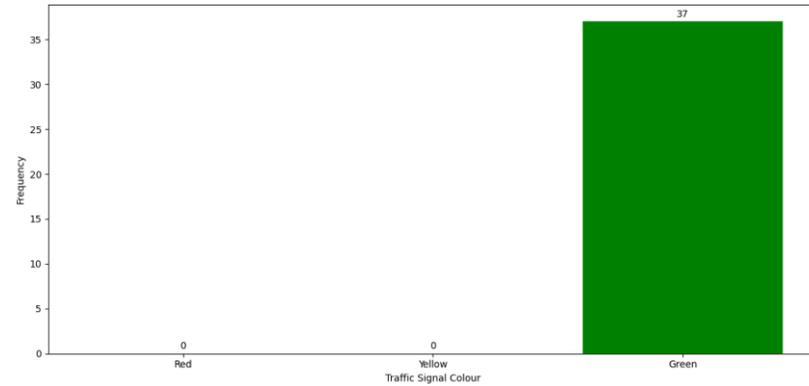


Figure B.53: Frequency of traffic signal colour at the time of right Movement incidents Dir 2



B.5.4 Scatter Plot of PET and TTC

Figure B.54: Scatter Plot of PET and TTC Dir 1

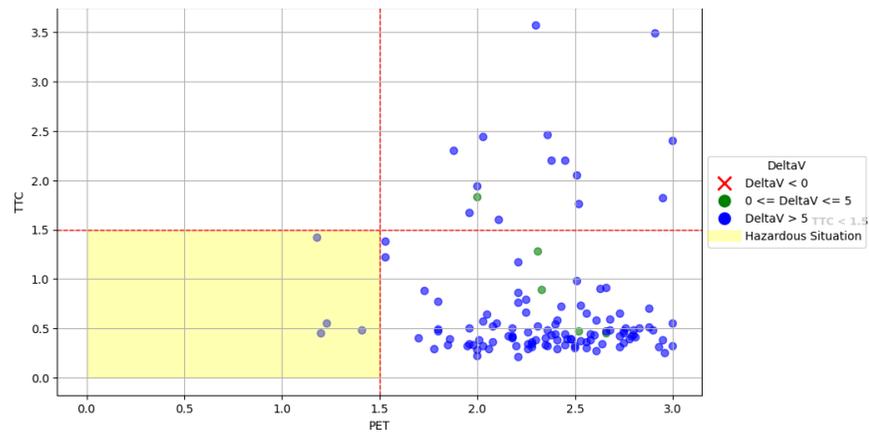
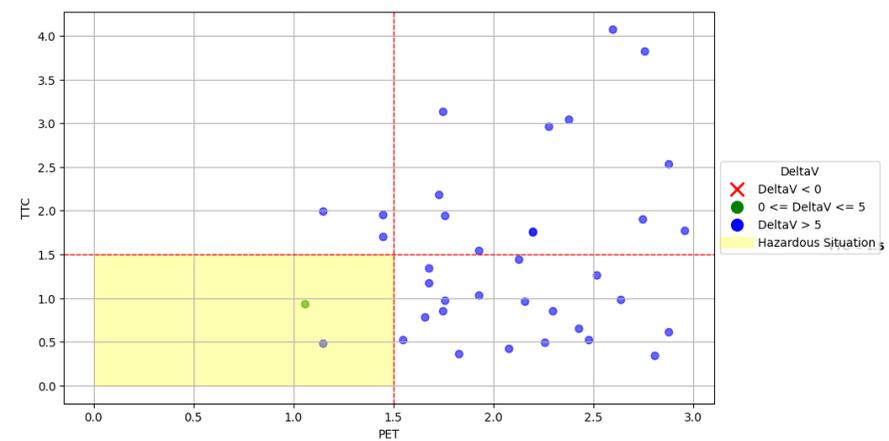


Figure B.55: Scatter Plot of PET and TTC Dir 1



B.5.5 Histograms of Delta V

Figure B.56: Histograms of Delta-V Dir 1

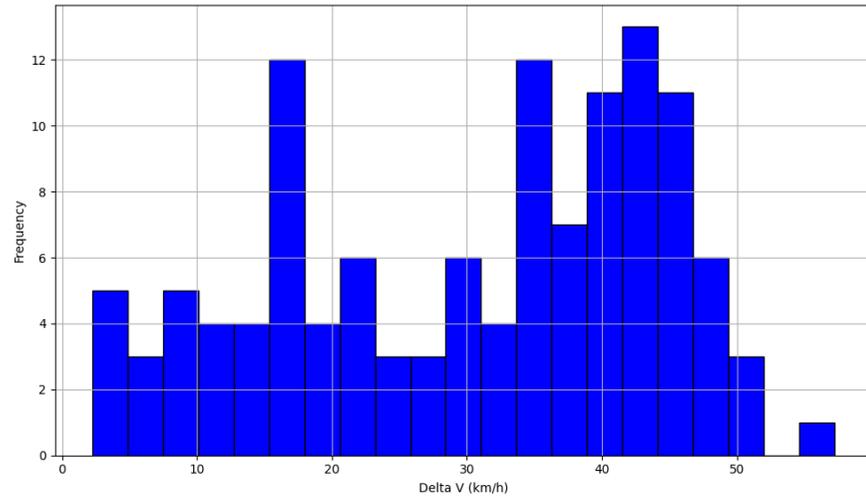
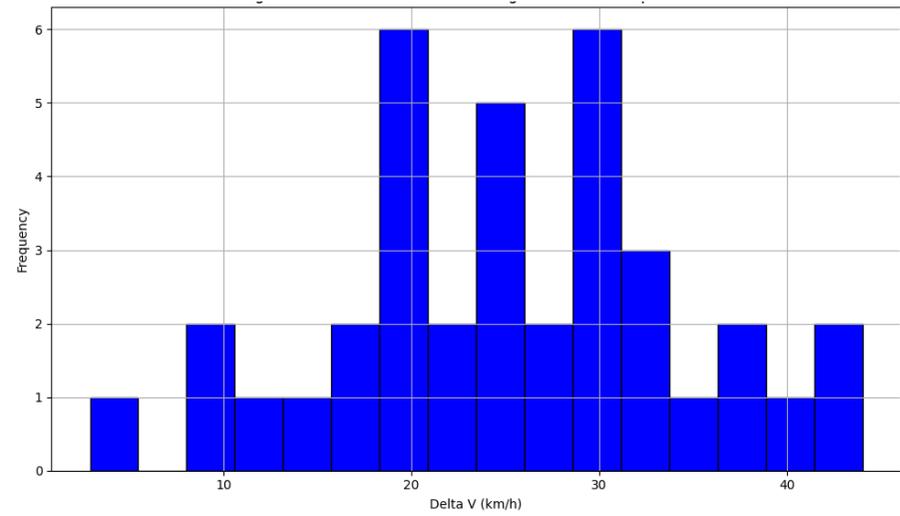


Figure B.57: Histograms of Delta-V Dir 2



B.5.6 Relationship of Kinetic Energy between Two Movements

Figure B.58: Relationship of Kinetic Energy between Two Movements Dir 1

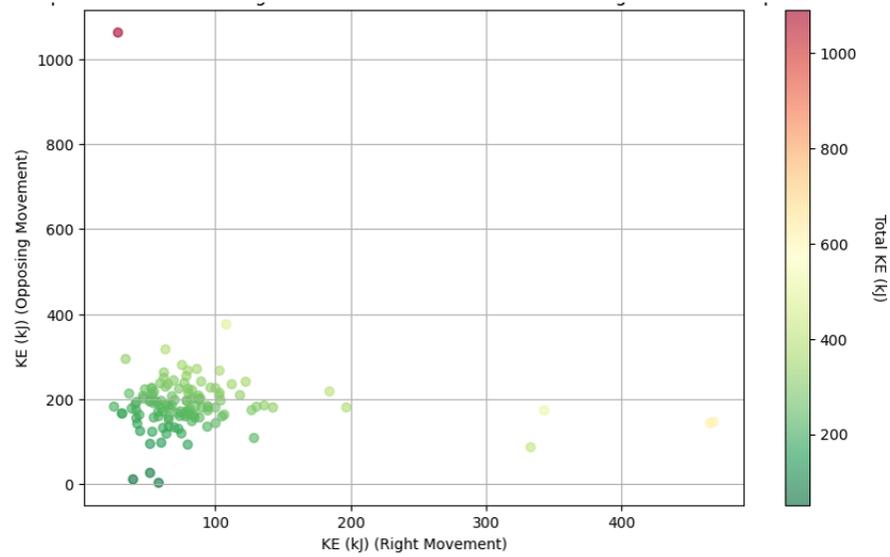
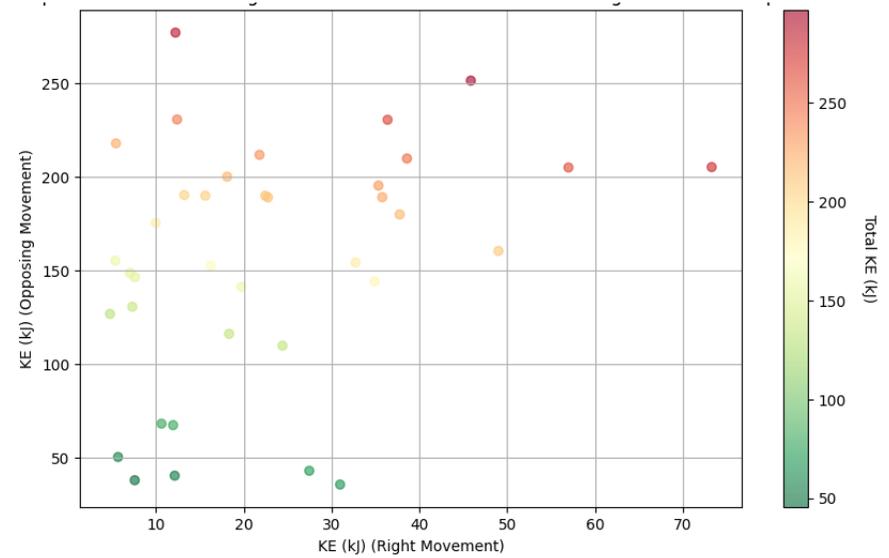


Figure B.59: Relationship of Kinetic Energy between Two Movements Dir 2



B.6 Harborne Street / Scarborough Beach Road / Frobisher Street, Osbourne Park

B.6.1 Histograms of Road User Combination

Figure B.60: Histograms of road users combination Dir 1

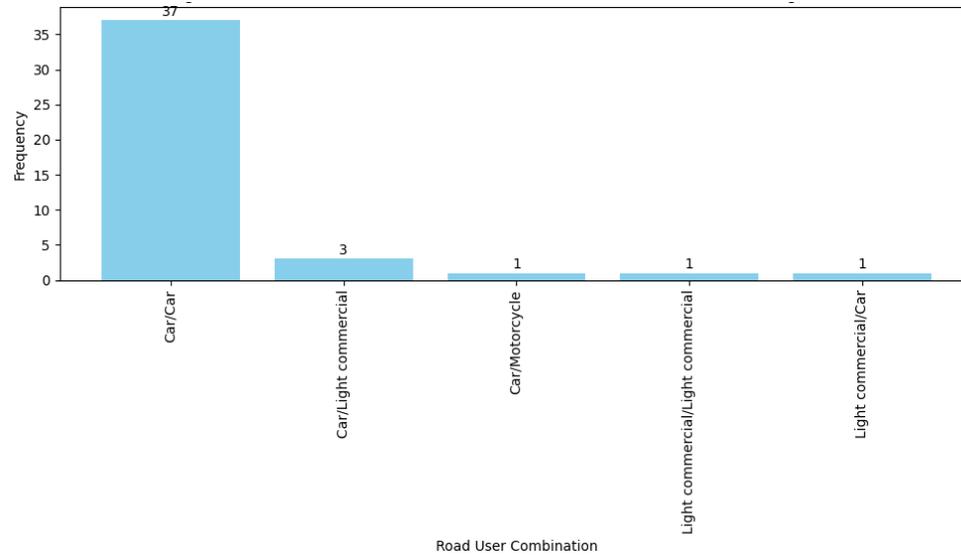
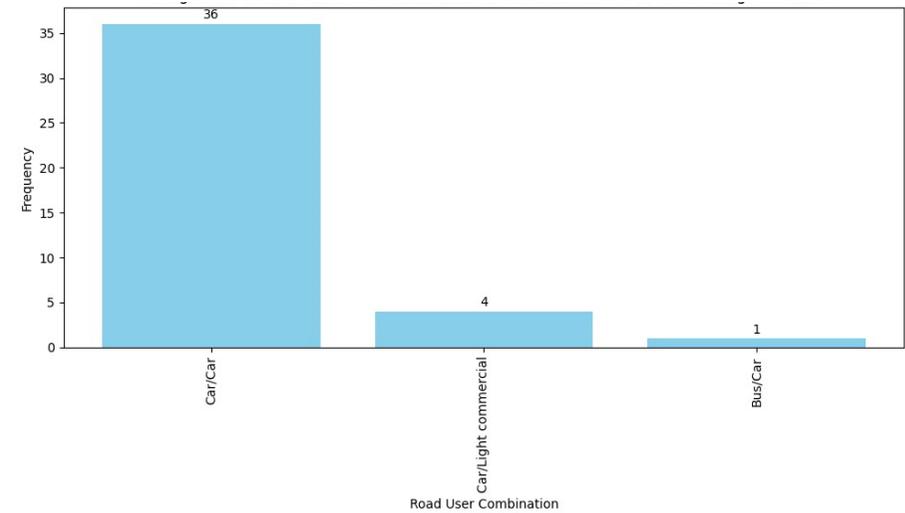


Figure B.61: Histograms of road users combination Dir 2



B.6.2 Histograms of Speeds

Figure B.62: Histograms of speeds Dir 1

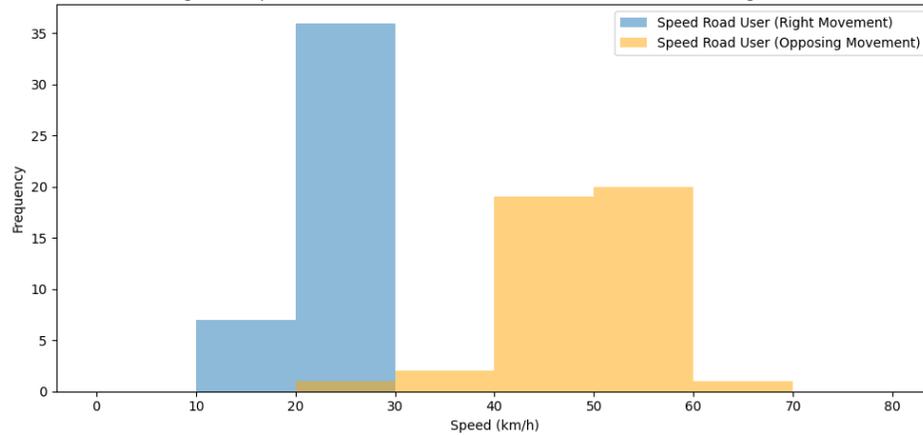
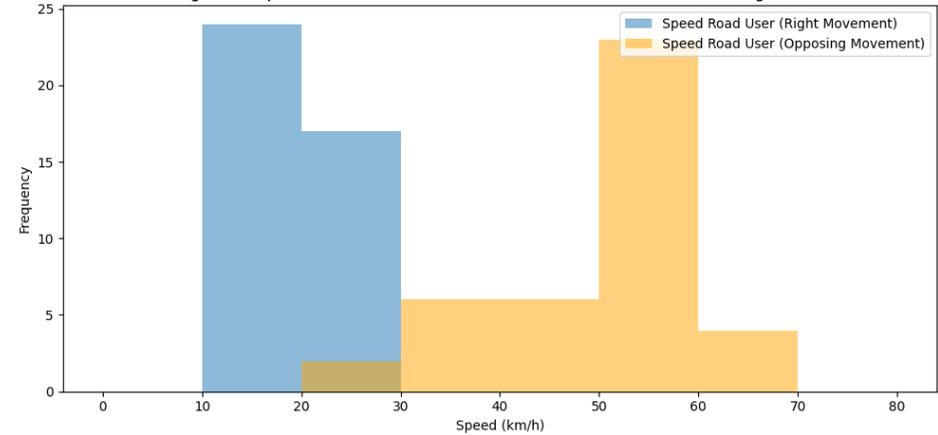


Figure B.63: Histograms of speeds Dir 2



B.6.3 Frequency of Traffic Signal Colour at the Time of Right Movement Incidents

Figure B.64: Frequency of traffic signal colour at the time of right Movement incidents Dir 1

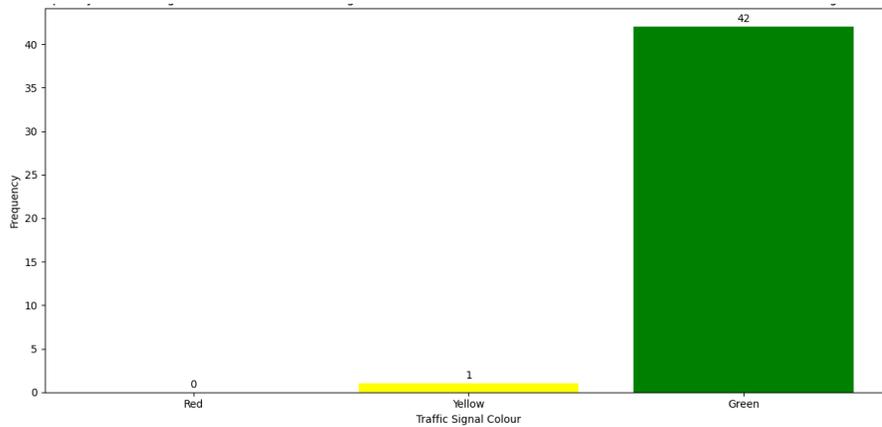
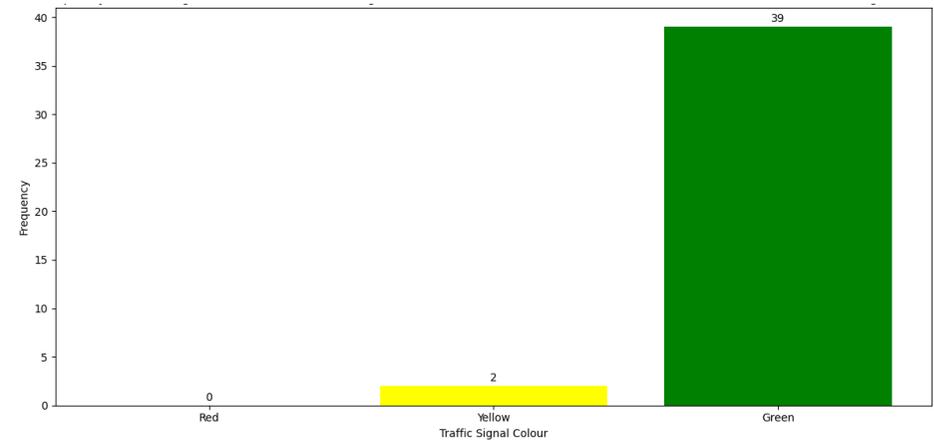


Figure B.65: Frequency of traffic signal colour at the time of right Movement incidents Dir 2



B.6.4 Scatter Plot of PET and TTC

Figure B.66: Scatter Plot of PET and TTC Dir 1

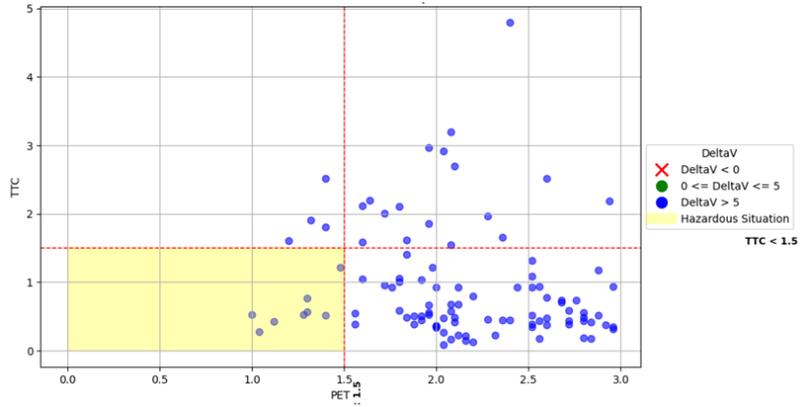
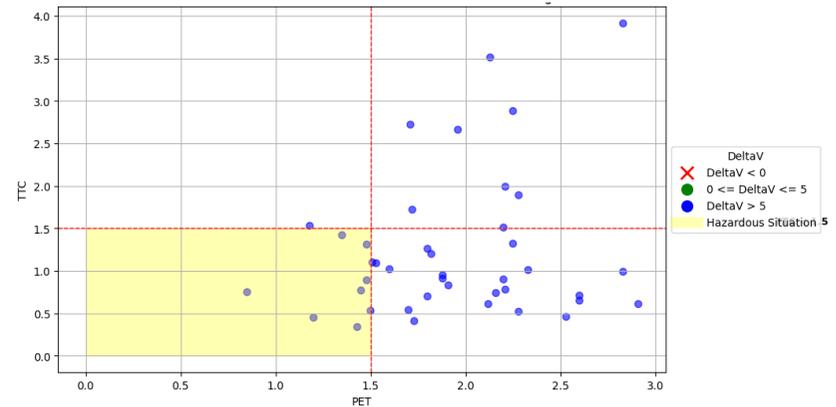


Figure B.67: Scatter Plot of PET and TTC Dir 1



B.6.5 Histograms of Delta V

Figure B.68: Histograms of Delta-V Dir 1

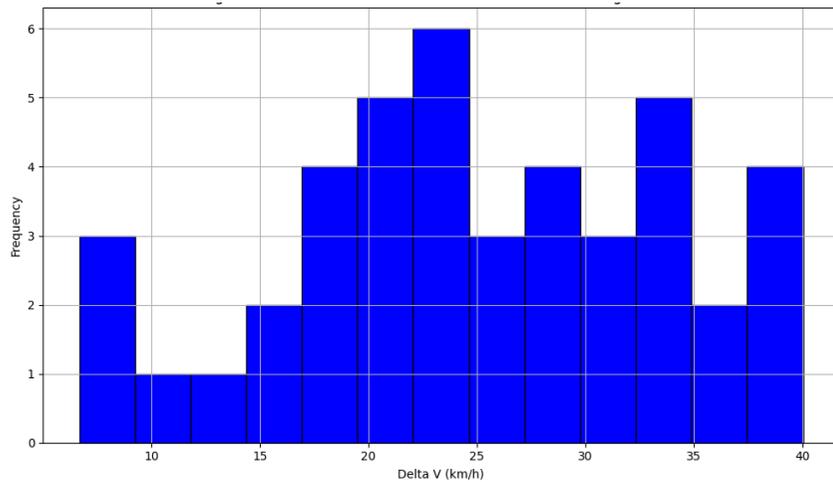
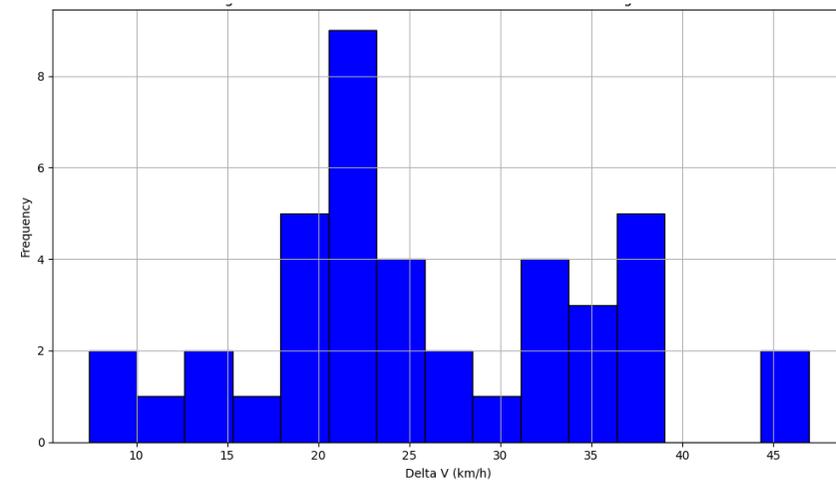


Figure B.69: Histograms of Delta-V Dir 2



B.6.6 Relationship of Kinetic Energy between Two Movements

Figure B.70: Relationship of Kinetic Energy between Two Movements Dir 1

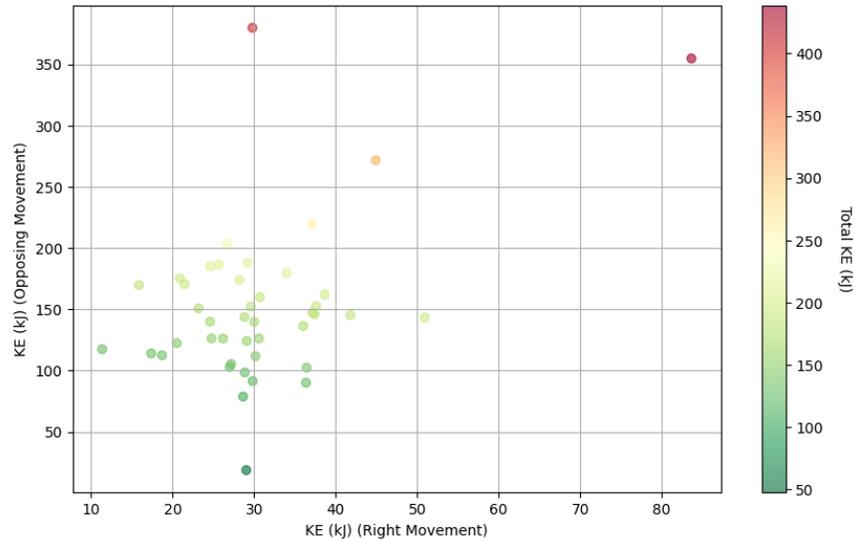
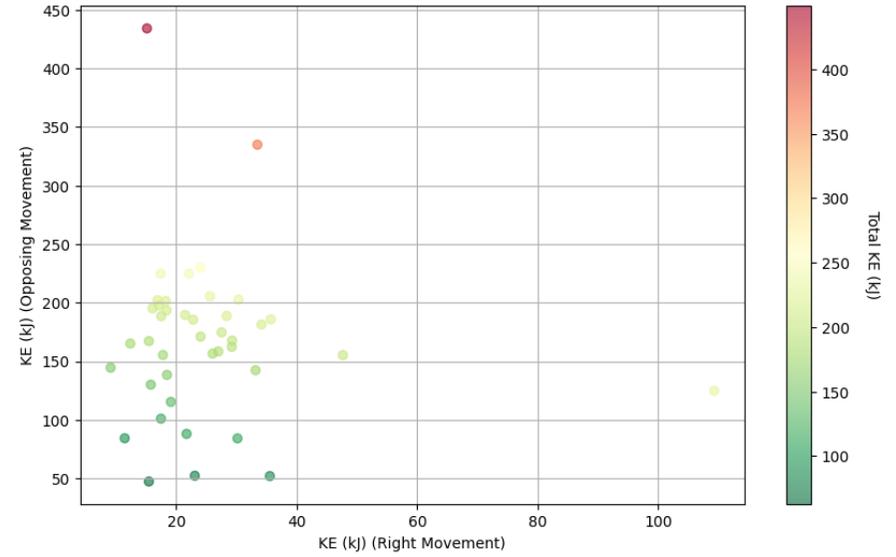


Figure B.71: Relationship of Kinetic Energy between Two Movements Dir 2



B.7 Belmont Avenue / Wright Street, Kewdale

B.7.1 Histograms of Road User Combination

Figure B.72: Histograms of road users combination Dir 1

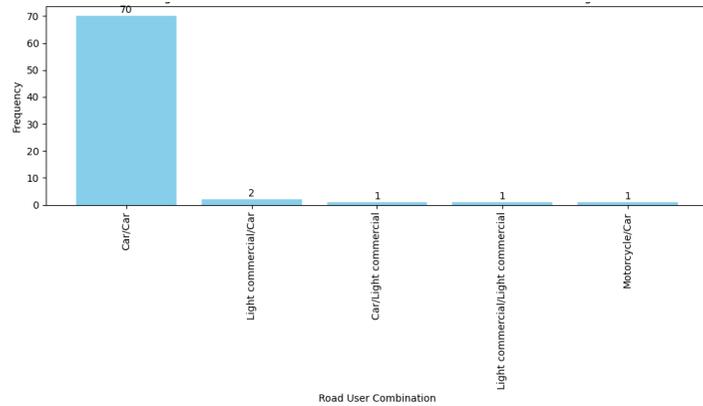
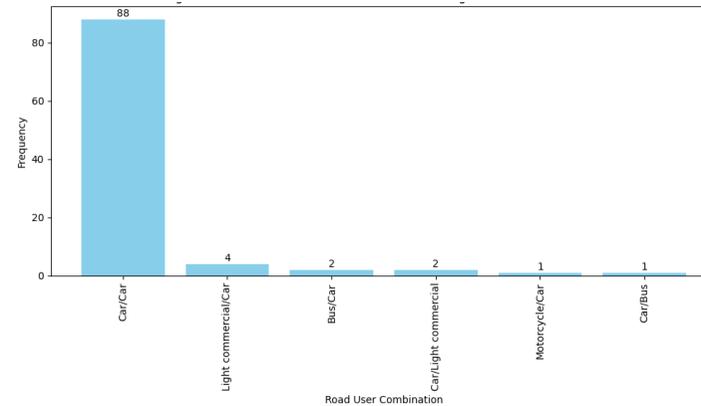


Figure B.73: Histograms of road users combination Dir 2



B.7.2 Histograms of Speeds

Figure B.74: Histograms of speeds Dir 1

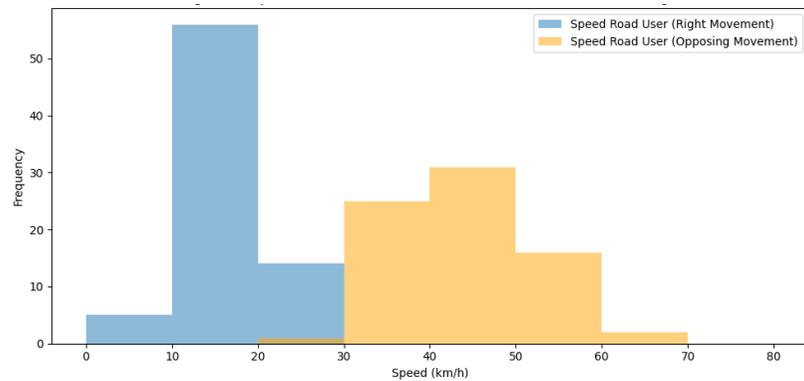
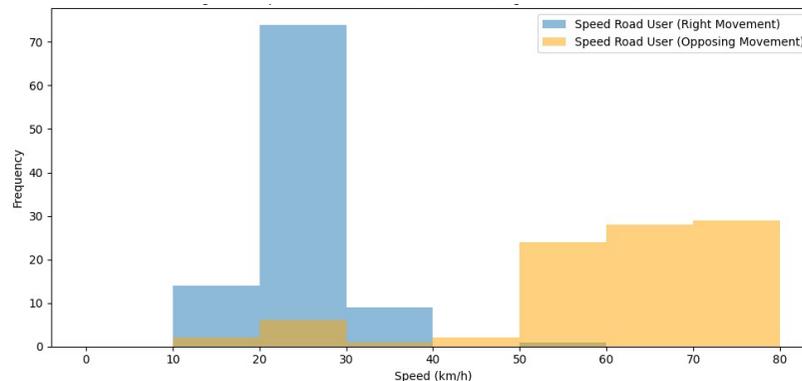


Figure B.75: Histograms of speeds Dir 2



B.7.3 Frequency of Traffic Signal Colour at the Time of Right Movement Incidents

Figure B.76: Frequency of traffic signal colour at the time of right Movement incidents Dir 1

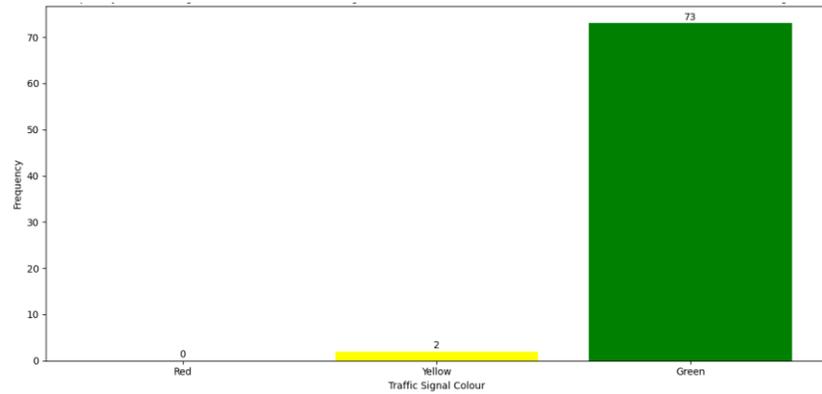
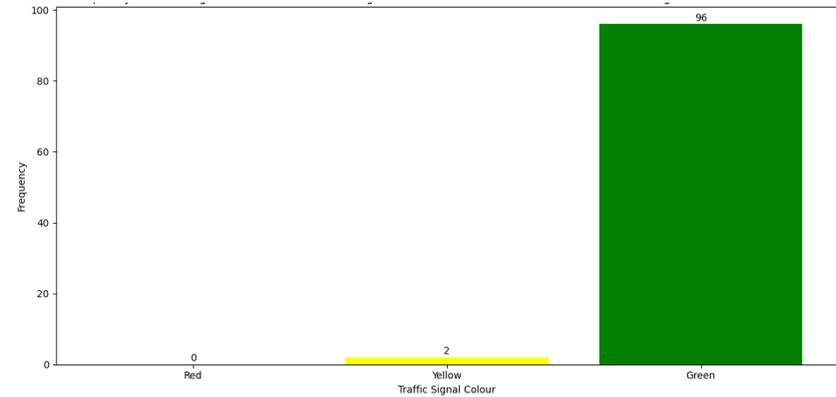


Figure B.77: Frequency of traffic signal colour at the time of right Movement incidents Dir 2



B.7.4 Scatter Plot of PET and TTC

Figure B.78: Scatter Plot of PET and TTC Dir 1

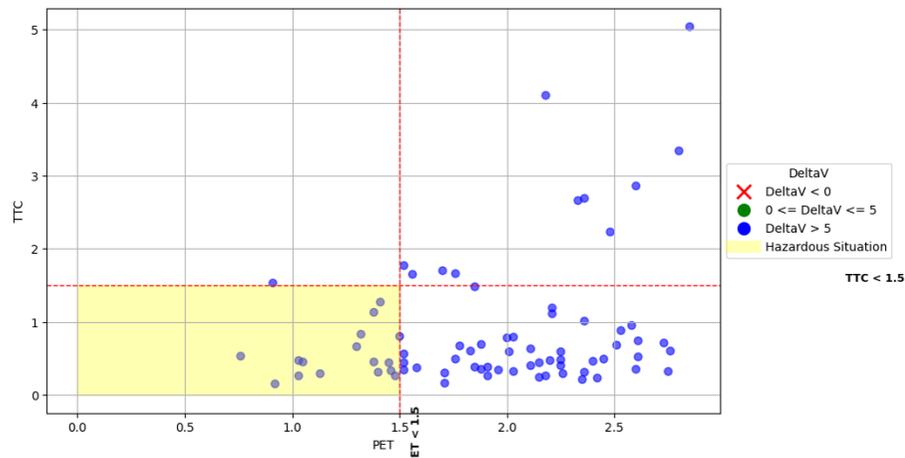
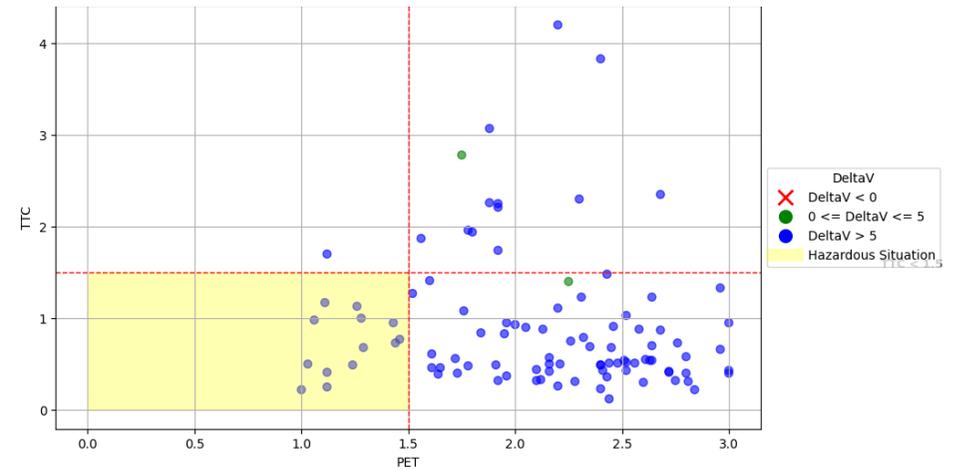


Figure B.79: Scatter Plot of PET and TTC Dir 1



B.7.5 Histograms of Delta V

Figure B.80: Histograms of Delta-V Dir 1

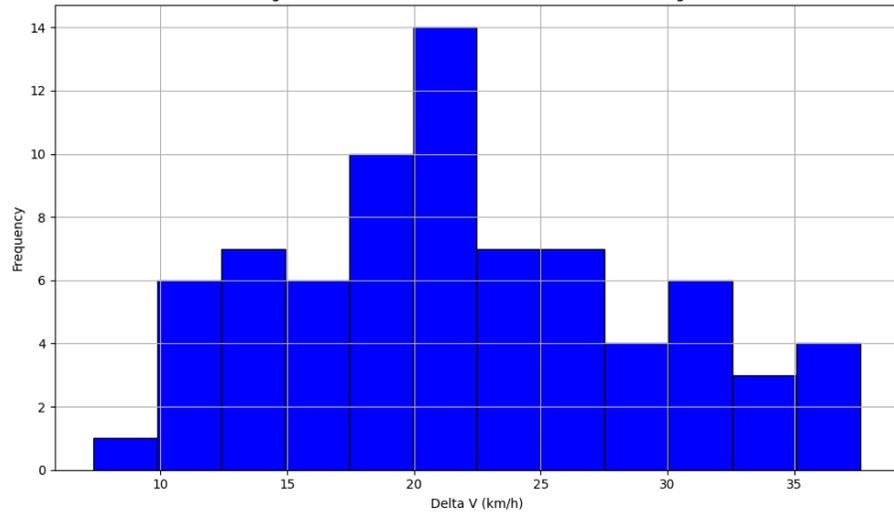
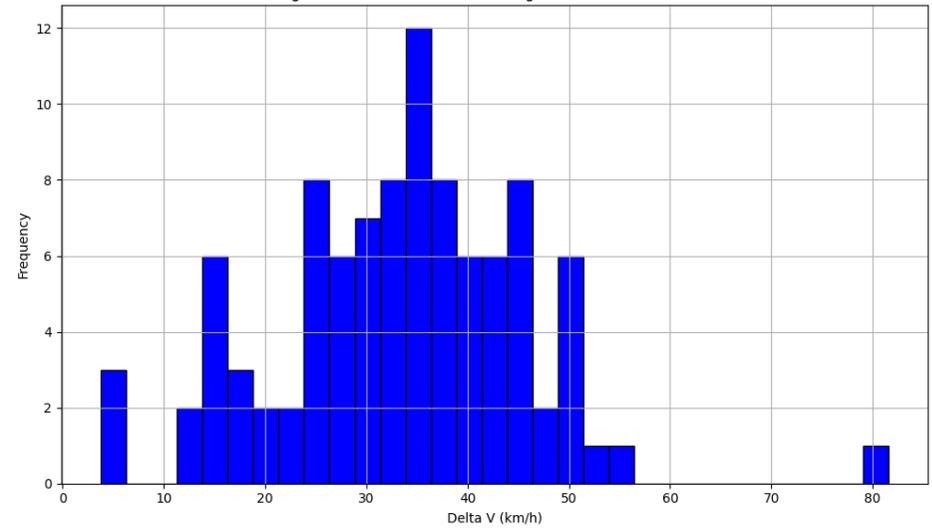


Figure B.81: Histograms of Delta-V Dir 2



B.7.6 Relationship of Kinetic Energy between Two Movements

Figure B.82: Relationship of Kinetic Energy between Two Movements Dir 1

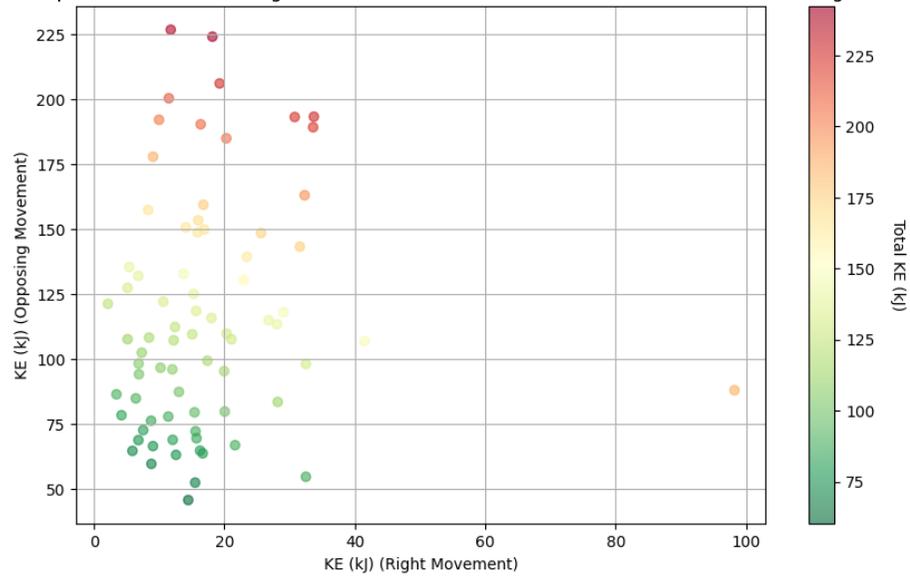
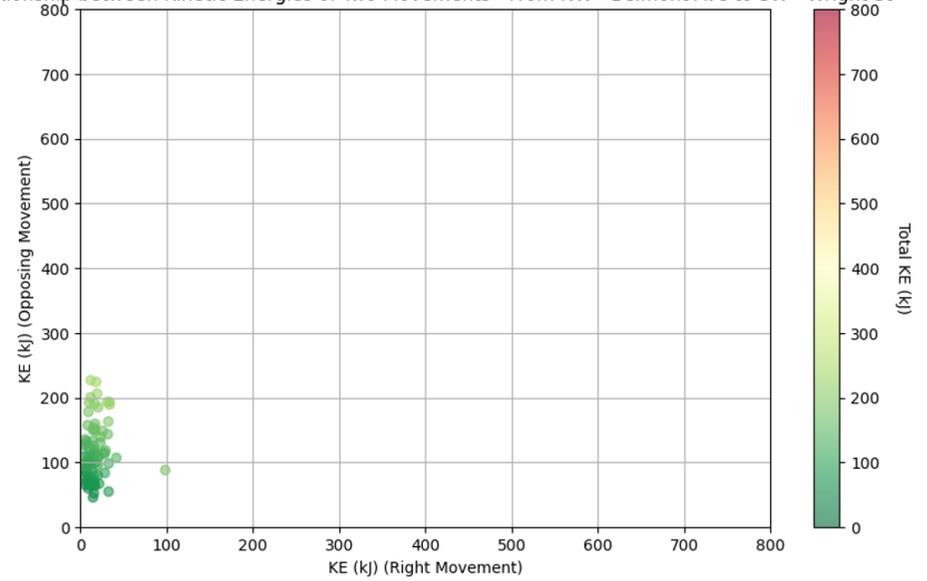


Figure B.83: Relationship of Kinetic Energy between Two Movements Dir 2



B.8 Plain Street and Royal Street, East Perth (Pilot study site)

B.8.1 Histograms of Road User Combination

Figure B.84: Histograms of road users combination Dir 1

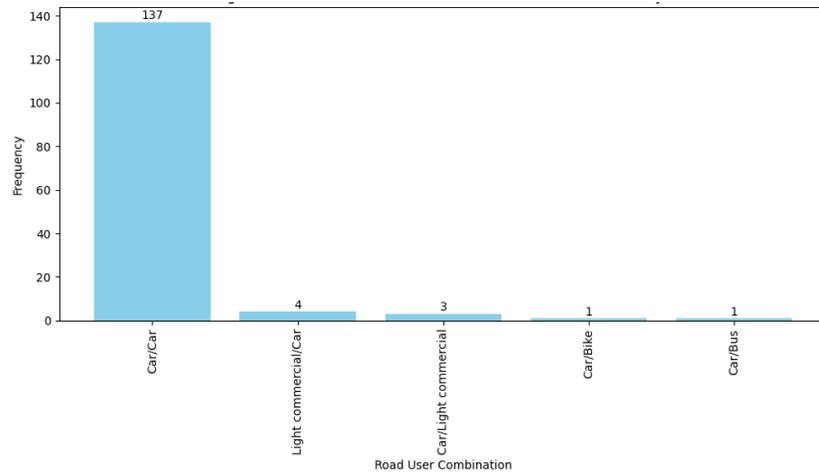
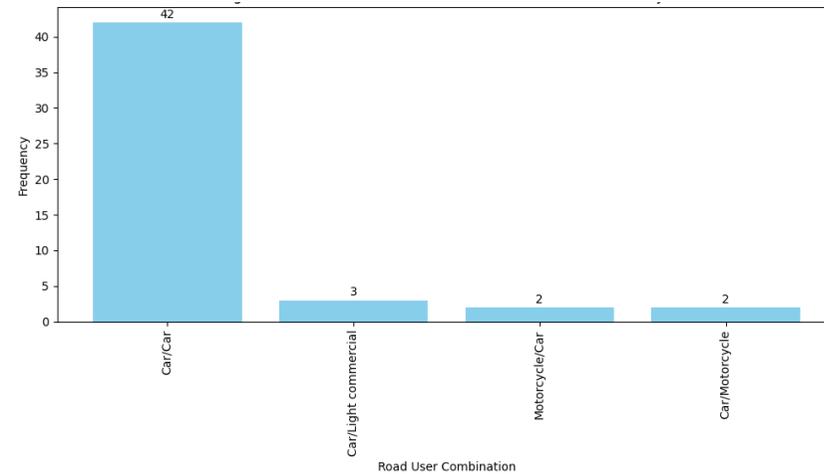


Figure B.85: Histograms of road users combination Dir 2



B.8.2 Histograms of Speeds

Figure B.86: Histograms of speeds Dir 1

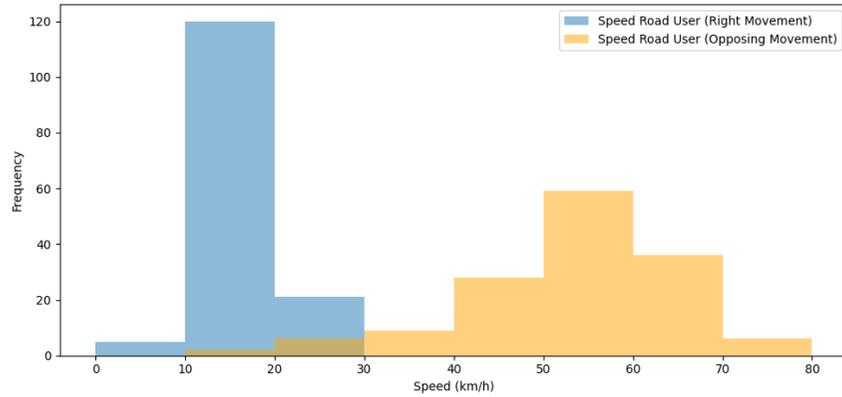
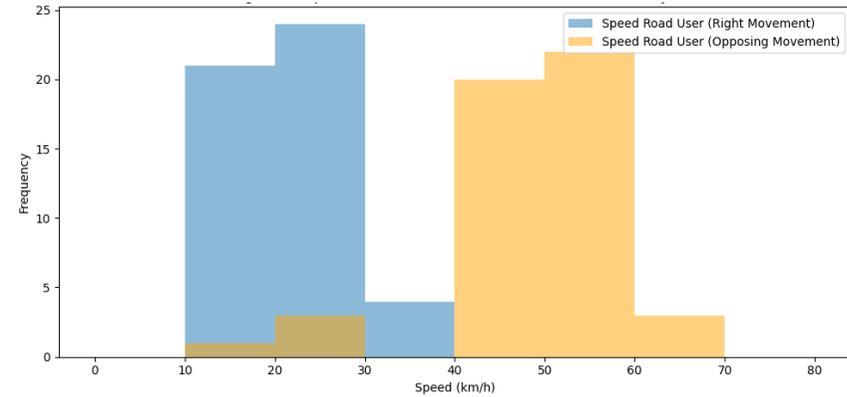


Figure B.87: Histograms of speeds Dir 2



B.8.3 Frequency of Traffic Signal Colour at the Time of Right Movement Incidents

Figure B.88: Frequency of traffic signal colour at the time of right Movement incidents Dir 1

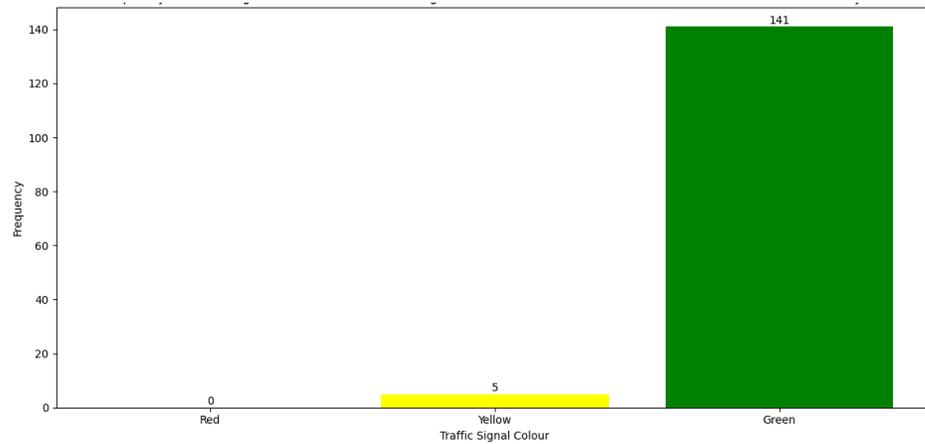
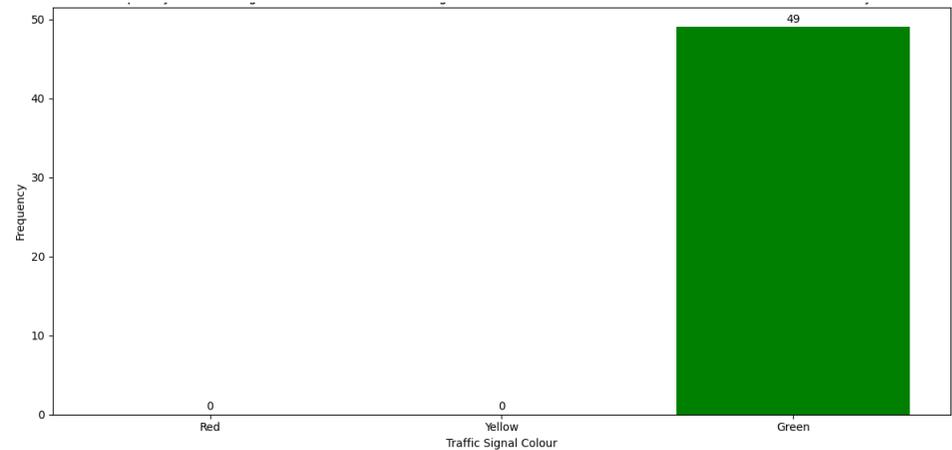


Figure B.89: Frequency of traffic signal colour at the time of right Movement incidents Dir 2



B.8.4 Scatter Plot of PET and TTC

Figure B.90: Scatter Plot of PET and TTC Dir 1

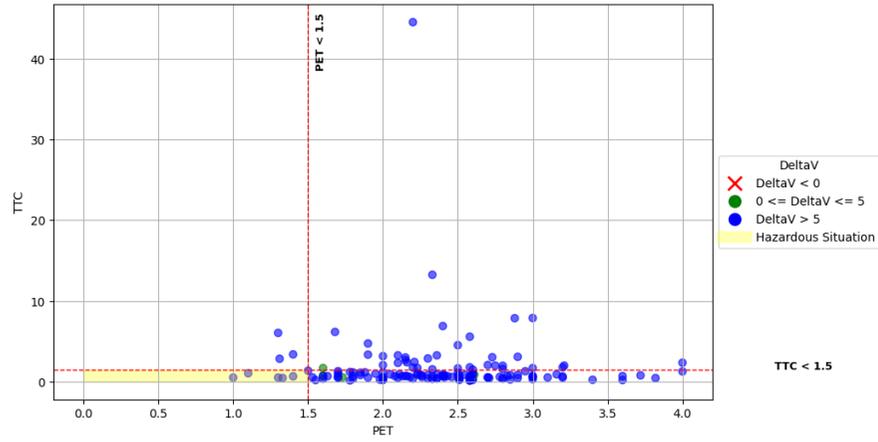
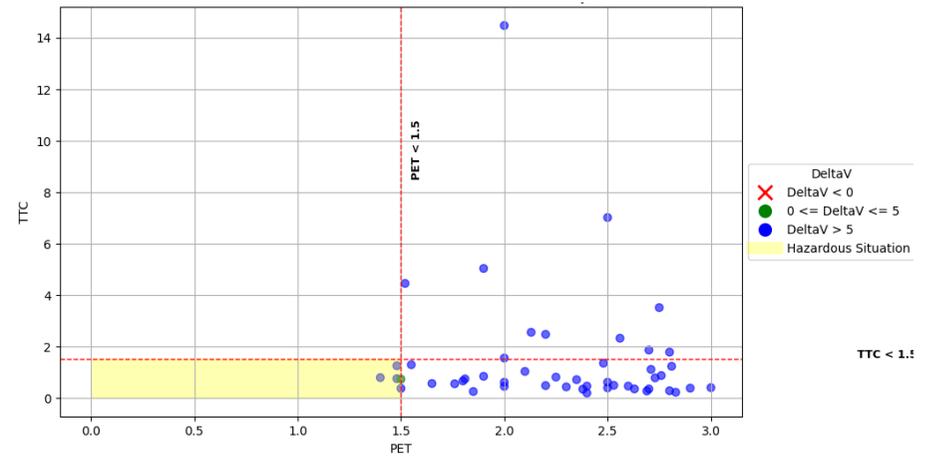


Figure B.91: Scatter Plot of PET and TTC Dir 1



B.8.5 Histograms of Delta V

Figure B.92: Histograms of Delta-V Dir 1

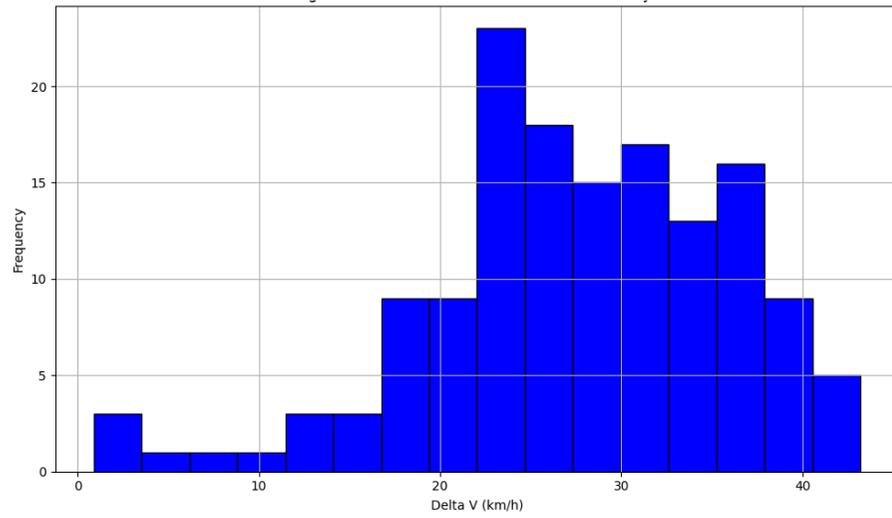
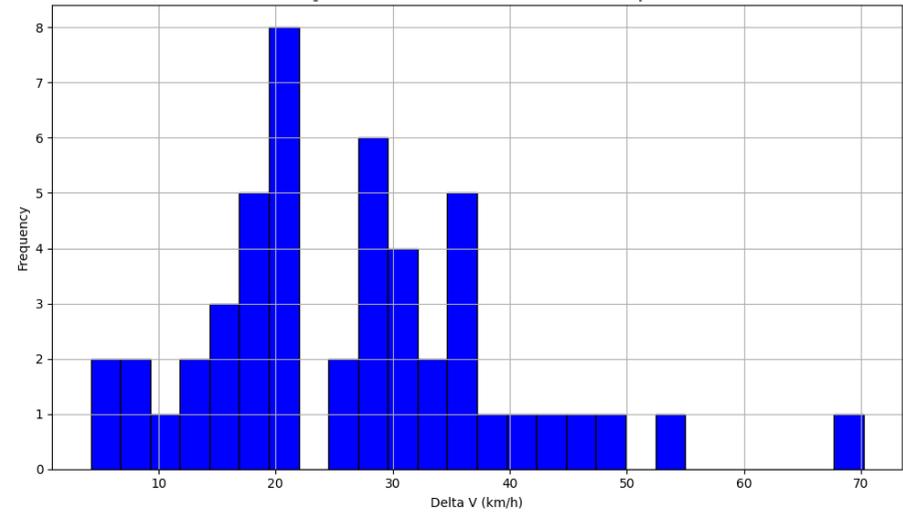


Figure B.93: Histograms of Delta-V Dir 2



B.8.6 Relationship of Kinetic Energy between Two Movements

Figure B.94: Relationship of Kinetic Energy between Two Movements Dir 1

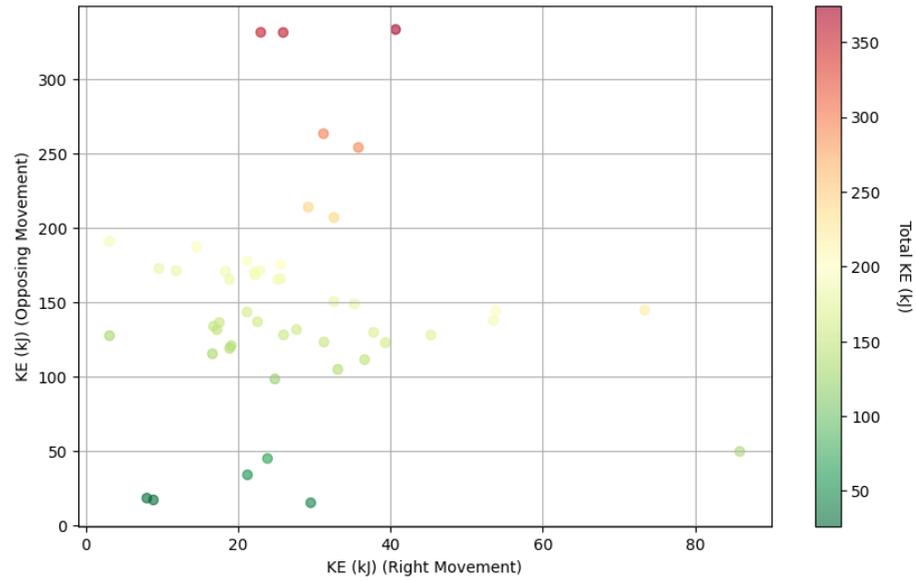
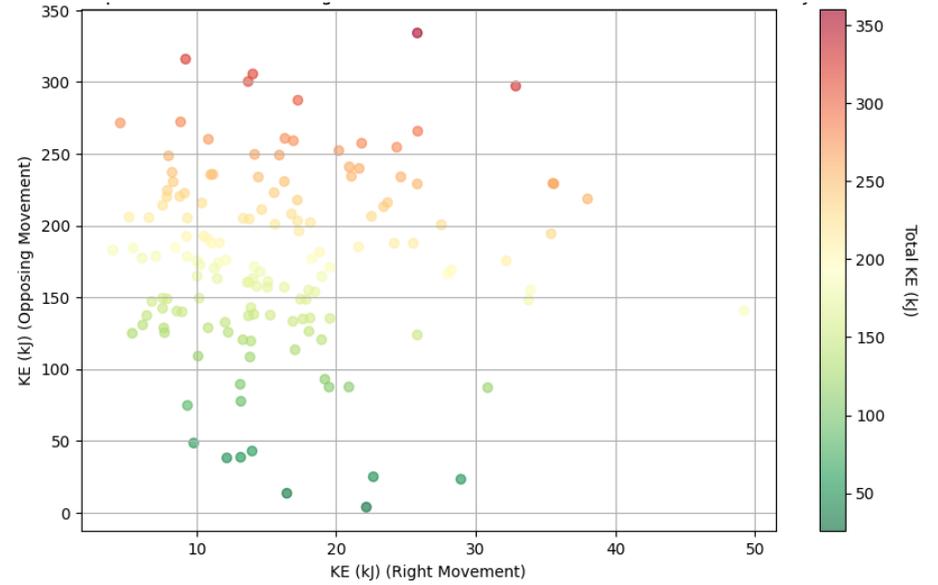


Figure B.95: Relationship of Kinetic Energy between Two Movements Dir 2





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