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The effectiveness of variable speed limit strategies to improve freeway performance

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Abstract

The implementation of Smart Freeways in Western Australia have enabled road network operators to leverage investment in freeway infrastructure through implementation of Smart Freeway technology including variable speed limits. Since implementation, Main Roads Western Australia implements safety-based variable speed limit (VSL) strategies on Smart Freeways, supported by its investment in the Lane Use Management System. As pressure on the road network continues to grow, Main Rods is exploring whether performance-based VSL strategies on the Kwinana Freeway northbound can improve infrastructure efficiency by improving traffic speed and throughput on its Smart Freeway systems, In coordination with Curitn University, this research studies the effectiveness of performance-based VSL strategies in enhancing traffic flow and reducing congestion on the Kwinana Freeway northbound.

A literature review on performance-based VSL strategies highlighted several potential metrics which can be used to identify whether a freeway section would benefit from such strategies. This literature review found there to be four potential benefits of implementing such a strategy in cases where various traffic conditions were met.

These metrics are applied to five different sections of the Kwinana Freeway northbound and whether implementing a performance-based VSL strategy would be advantageous to performance along Kwinana Freeway. The study shows a significant improvement in performance after implementing the Smart Freeway solution on Kwinana Freeway, and that there exists further opportunity to improve the Western Australia freeway network through implementation of performance-based VSL strategies. Using the metrics implemented in this research provides a practical proven method in identifying potential locations where Main Roads can implement such strategies as the Smart Freeway network expands.

1 Introduction

Main Roads Western Australia is the Western Australian transport agency responsible for the state road network that aims to provide a safe, reliable, and sustainable transport system for Western Australians. In 2020, Smart Freeway Kwinana Northbound was officially introduced to the public to reduce the congestion situation, improve safety, and reduce the travel time from Roe Highway to Narrows Bridge by up to 10 minutes. Smart Freeways utilises a range of technologies including electronic signage, vehicle sensors, and CCTV cameras to support the road network operation centre to maintain the road network performance 24/7. Based on the information collected by the sensors and cameras, Main Roads Western Australia Real Time Traffic Operations can remotely close lanes, reduce speed limits, and mobilise response team to manage incidents occurring on the freeway to improve safety.

Figure 1: Overhead variable speed limit sign in operation on Smart Freeways

The infrastructure of Kwinana Freeway faced a limited ability to serve the traffic volume during peak hours, leading to traffic delays and risk of incidents. Kwinana Freeway has included several on-off ramps, merging lanes, and lane reduction over short distances. To enhance the effectiveness and efficiency of the freeway, Main Roads is considering utilising variable speed limit control strategies to aid performance of the Smart Freeway.

There are clear benefits when implementing safety-based variable speed limit (VSL) strategies to support incident management and protection of vehicles through speed reductions. These safety-based VSL strategies are used extensively on Western Australian freeways. When the focus changes and strategies are considered to improve throughput, total travel time, travel time reliability, overall productivity, travel speed, or capacity (collectively described as performance), there is no certainty on the effectiveness of the implementation of a VSL strategy to improve these metrics, nor are there warrants to support decision-making where VSL strategies should be applied.

This project aims to conduct a literature review to evaluate the effectiveness of performance-based VSL strategies in enhancing traffic flow and reducing congestion on freeways. Specifically, it undertakes a feasibility study on the implementation of the safety-based VSL strategy to improve freeway performance, as practiced by Main Roads Western Australia on the Smart Freeway Kwinana Northbound.

In addition to the literature review, this research analyses the post-implementation impact of VSL on the Kwinana Freeway northbound. Key indicators, including Blocking of Ramps effects, Discharge Rate and Capacity Drop, Compliance Level, and the Inversion Point, are examined to assess VSL's effectiveness and possible construction of future warrants to support Smart Freeway operations. These indicators form the basis for eight key findings, encompassing an analysis of traffic performance, throughput volume, hysteresis loop patterns, and VSL effectiveness.

The focus is primarily on the morning peak hour (06:00 am to 10:00 am) traffic on Kwinana Freeway northbound in 2023. Through this analysis, the research aims to provide a

comprehensive understanding of the impact and effectiveness of VSL strategies on traffic flow dynamics.

1.1 Variable speed limit control logic

The Variable Speed Limit (VSL) strategy operates continuously 24/7, with a heightened focus on morning peak hours from 6:00 AM to 10:00 AM. During this period, three types of VSL logic are implemented, with speed limits prominently displayed on gantries along the study freeway section.

1. Default Speed Limit: Under normal traffic conditions, the gantries display default speed limits of either 100 km/h or 80 km/h. The 80 km/h limit applies to the four northern-most VSL gantries from the midstream northbound after Canning Hwy on-ramp section. Otherwise, the default speed limit is set as 100 km/h.
2. Algorithm Triggered VSL: The VSL can be activated either by an algorithm based on the measured traffic speed using the STREAMS queue detection and queue protection algorithms. The VSL will show a 60 km/h speed limit on approach to a section of traffic moving at a speed of 40 km/h or less.
3. Field Response: Site operators manually adjust the VSL to modify speed limits, reopen or close lanes, or indicate lane changes in response to incidents occurring on the freeway mainline. Unlike the previous types, this category allows for a VSL reduction to 40 km/h when necessary.

In all cases, speed limit reductions are restricted to a maximum decrease of 20 km/h at a time, hence if a Field Response is applied, traffic will move past the operator's chosen location at 40 km/h, and then the speed limit will transition in 20 km/h increments on approach to the chosen location. There is no limit to the display to driver when the speed limit increases.

2 Literature review

In modern transportation systems, VSLs play a pivotal role by adjusting speed restrictions based on real-time traffic conditions and environmental factors. The implementation of VSLs integrate advanced technology with dynamic approach to traffic management strategies, offering adaptive solutions to optimize traffic flow and improve safety.

This research studies whether a VSL strategy can achieve the following, and whether presence of these factors can be mitigated through implementation of such a strategy.

2.1 Prevention of capacity drops

The mechanism underlying VSL's significant impact on traffic lies in its ability to prevent capacity drops and thereby avoid activating bottlenecks or maintain the outflow of activated bottlenecks close to their capacity levels.

2.2 Reduction in blocking of ramps

Carlson, Papamichail, and Papageorgiou (2011) managed to reduce the blocking of ramps (BOR) effect by employing a Mainstream Traffic Flow Controller (MTFC) using VSL. They utilized a two-loop feedback cascade control method to determine the optimal VSL in different traffic states. The method achieved network-wide throughput and TTS improvement, evaluated in the METANET simulator on a traffic network consisting of two on-ramps and one off-ramp. The cascade controller showed comparable performance to an optimal control strategy (open-loop control) regarding TTS reduction (15.1% and 15.4%, respectively). Additionally, the cascade controller displayed significant throughput improvement at off-ramp exits, demonstrating the effect of VSL in reducing the BOR effect.

2.3 Suppression of shockwaves

Hegyi, De Schutter, and Hellendoorn (2003) proposed a VSL strategy aimed at suppressing shockwaves, resulting in a 17% reduction in TTS within the scenario upon restoration of capacity. They used a VSL controller adopting Model Predictive Control (MPC) on a freeway stretch, evaluating the strategy in an extended version of METANET. They addressed issues of overly optimistic results due to linear downscaling of the fundamental diagram by adjusting the shape of the diagram for specific densities.

2.4 Harmonisation of speed

Reduction of the speed difference between vehicles and lanes, decreasing merging and lane-changing activities, leading to a more stable traffic flow. Speed homogenization aims to improve traffic flow by maintaining stability within the network. It has been widely researched and has proven effective in reducing speed differences (Zackor 1972; Van den Hoogen and Smulders 1994; Knoop et al. 2010; Duret, Ahn, and Buisson 2012), spacing and headway variance (Smulders 1990), and flow differences between lanes (Knoop et al. 2010; Duret, Ahn, and Buisson 2012). However, Jiang, Chung, and Lee (2011) conducted a micro-simulation using Aimsun 6.1 on a 30 km northbound Pacific Motorway (M3) and found that harmonization VSL was only beneficial during high flow conditions on low ramp density road architecture.

For a performance-based VSL strategy to be effective, high driver compliance and a robust control strategy are essential. While high compliance rates generally lead to safety benefits, they may also increase travel time. The effectiveness of the performance-based VSL strategy depends on balancing these factors to achieve optimal traffic performance and safety.

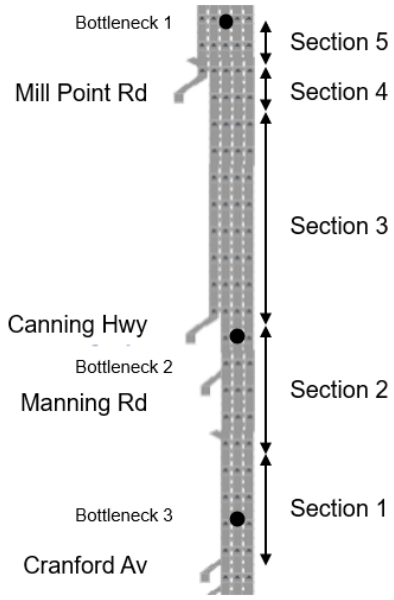
3 Methodology

A detailed explanation of the study area, VSL strategies applied in the study area, indicators to evaluate the current variable speed limit (VSL) strategies on Kwinana Freeway northbound during peak hours, date selection methods and analysis methods will be provided in this section.

The study area is located on the northbound Kwinana Freeway in Perth, Western Australia, beginning at the Cranford Avenue on-ramp and ending just after the Narrows Bridge, downstream of the Mill Point on-ramp exit. This section of the freeway spans 9.05 km. To gain better understanding on the influences of road infrastructures such as on-ramp, off-ramp and numbers of lanes, this study area is divided into five sections, starting from Mount Henry (upstream section 1) and ending at After Narrows Bridge (downstream section 5). The route features four on-ramps and two exits.

The study area is impacted by two primary merge bottlenecks. The first, Bottleneck 1, occurs downstream of the Mill Point Road Exit and Mill Point Road on-ramp. The second, Bottleneck 2, is located midstream and involves the Canning Highway on-ramp and the Manning on-ramp. VSL are implemented at these bottlenecks to manage traffic flow. However, Bottleneck 3 at the Cranford Avenue on-ramp had not yet implemented VSL at the time of this research. The bottlenecks activate during both morning and afternoon peak periods on weekdays. This study focuses specifically on the weekday morning peak period from 6:00 am to 10:00 am.

Figure 2: Layout of Kwinana Freeway northbound study area



The study area is divided into five sections by MRWA, each identified by unique "MLink" numbers that represent geometric points connecting various locations. The MLink numbering system enables precise calculation of traffic-related variables, such as throughput, for each section. This ensures that performance data for each section is directly derived from the corresponding MLink data. The following Smart Freeway assets are located on each section.

Table 1: Count of Smart Freeway technology locations within study area

Section	Number of vehicle detector sites	Number of variable speed limit sites
Section 1	2	1
Section 2	1	1
Section 3	9	6
Section 4	5	4
Section 5	4	0

3.1 Source data

To analyse the traffic performance on the Kwinana Freeway (northbound), the following data sources on traffic details from Main Roads Western Australia (MRWA) are used:

3.1.1 Variable speed limit sign data

Main Roads Western Australia through its traffic control system STREAMS collects records of every change made to variable speed limit signs. The records provide the time of each change made on a variable speed limit sign at both the site and sign level. Additional information to validate the quality of the data is made through records of the device status which report as OK when the device is operating normally and using the recorded reason of the change at each site. As explained in section 1, Main Roads utilizes safety-based variable speed limit strategies along the study area.

3.1.2 NetPReS data

NetPReS (Network Performance Reporting System) is a database containing the speed and volume of every link on the Main Roads network since 2013. Data from various Main Roads

controlled data sources, including detector data list below, is absorbed by NetPReS and is filtered, fused and patched to provide reliable statistical information.

A M Link is the shortest length of spatial information held by NetPReS. It is defined as starting from one node (a join between a freeway ramp and the freeway) or intersection and ending at another node or intersection. While this provides suitable information at the network level, it is necessary to use more granular information to apply a VSL strategy.

3.1.3 Detector site data

Detector data refers to the speed, volume and occupancy data recorded by sensors placed in the roadway at fixed positions. Detectors are either induction loop detectors which detect changes in electrical inductance in wire loops or magnetometers which provide information back to a cabinet at the roadside before transmitting information through the Main Roads to a central database. A detector site consists of multiple detectors which are typically installed with one detector in each lane. Site data refers to a volume-weighted average of speed and occupancy data, and the sum of volume data collected across all lanes in a particular detector site.

Figure 3: Magnetometer detector buried in road surface prior to final surfacing

3.1.4 Detector lane data

Detector data refers to the speed, volume and occupancy data recorded by sensors placed in the roadway at fixed positions. This data source has been used to calculate the compliance level and the inversion point indicator. From the dataset, some instances of data loss have been identified, occurring on February 10th, 2023, and February 15th, 2023, at detectors 1146 MIN and 1163 KWN, respectively. Additionally, on August 30th, 2023, detector 1148 MUL lane 1 experienced data loss in occupancy, speed, and volume. On June 1st, 2023, there was a 15-minute data loss at detector 1146 MUL, specifically between 08:15 and 08:30, in lane 5. Lastly, detector data 1154 KWN were receiving a data loss for the whole six selected days.

3.1.5 Western Australia public holiday calendar

Australian public holidays combined (since 2019) was utilized to exclude observations related to public holidays from both the detector data and M Link data.

3.1.6 Crash data

Crash data, which records the time and location of all crashes on the Main Roads network was utilised to exclude observations related to incidents from both the detector data and MLink data.

3.2 Metrics

Based on the data, five metrics were calculated consistent with the methodologies used in the Literature Review.

3.2.1 Blocking of ramps ratio indicator

The blocking of ramps effect was first studied by Papageorgiou and Kotsialos (2022) which occurs when congestion at the upstream of a bottleneck propagates further upstream. This blocks further on-ramps and off-ramps along the road network, and creates difficulty for drivers to merge in or exit the mainline. Vehicles driving towards exits located upstream of an active bottleneck also experience delays due to congestion, further contributing to a heightened spatial expansion of the congestion.

To calculate this indicator, we developed a normalised queue discharge ratio formula, which is derived by dividing the average flow of a ramp during peak hours over 39 research dates by the maximum flow observed on the same ramp during the morning peak across these 39 research dates. This is a modified formula based on the Knoop and Hoogendoom study in 2022 suited to assess the blocking of ramps effect. The flow of a ramp refers to the number of vehicles that can enter or exit the ramp during a given time period.

The numerator represents the expected flow of a ramp during peak hours, while the denominator indicates the theoretical maximum flow that should be observed during the morning peak. The difference between these two values reflects the potential number of vehicles that may experience delays due to ramp blockage.

3.2.2 Queue discharge rate to capacity ratio indicator

To calculate the Queue Discharge Rate (Qr), we followed the method outlined by Knoop and Hoogendoorn in their 2022 study. They measured the queue discharge rate downstream of the bottleneck location, which, in our case, is located to the north of the ramp. According to their definition, a queue forms when the flow into a bottleneck exceeds its capacity, leading to the creation of a virtual queue of vehicles.

In their study, Knoop and Hoogendoorn emphasized that the mean value is the most relevant measure for the queue discharge rate. Consequently, for our analysis, we utilized detector data from the immediate downstream of each ramp in our road network. We summed the volume measurements from the moment a capacity drop occurred until 9:30 am and then calculated the average to represent the queue discharge rate.

To ensure the accuracy of our calculations, we focused exclusively on volume measurements, as the dataset indicated a decrease in traffic after 9:30 am.

3.2.3 Capacity drop indicator

We adopted a method from the study by Saberi and Mahmassani (2013) to determine the capacity drop and the capacity drop level. This method focuses on the capacity and volume of traffic just before it enters the recovery stage within a traffic cycle.

To calculate the capacity drop level, we determined the difference between the capacity value and the last recorded volume measurement at a vehicle detector site before traffic began to recover. The resulting value represents the extent of the capacity drop.

3.2.4 Compliance level indicator

To assess the compliance level across the project traffic network, we analysed data from sources 1 and 5. This analysis involved calculating the average speed at detector sites and subtracting the posted or fixed speed limit for each section. We then compared the difference with the designated speed limit. It is important to note that we excluded any VSL that were implemented for less than 15 minutes within each interval, as the data intervals were 15 minutes in duration.

3.2.5 Inversion point indicator

To calculate the Inversion Point for the Inversion Indicator, this report used Occupancy data from data source 5. The Inversion Point relates to the relationship between the occupancy between the median lane and the central lane at a given point in time. An inversion point is

defined as the moment when the throughput of the median lane surpasses that of the central lane, indicating a shift from light to heavy traffic.

4 Findings

This section of the research findings will begin by comparing traffic performance between 2019 and 2023, focusing on changes in speed, volume, and throughput. This comparison will offer valuable insights into the shifts in traffic demand and flow before and after the implementation of VSL in the study area.

After discussing these performance metrics, the findings from the five metrics presented and analysed.

4.1 Findings 1: Speed and volume comparison over 2019 and 2023 at the 5 sections

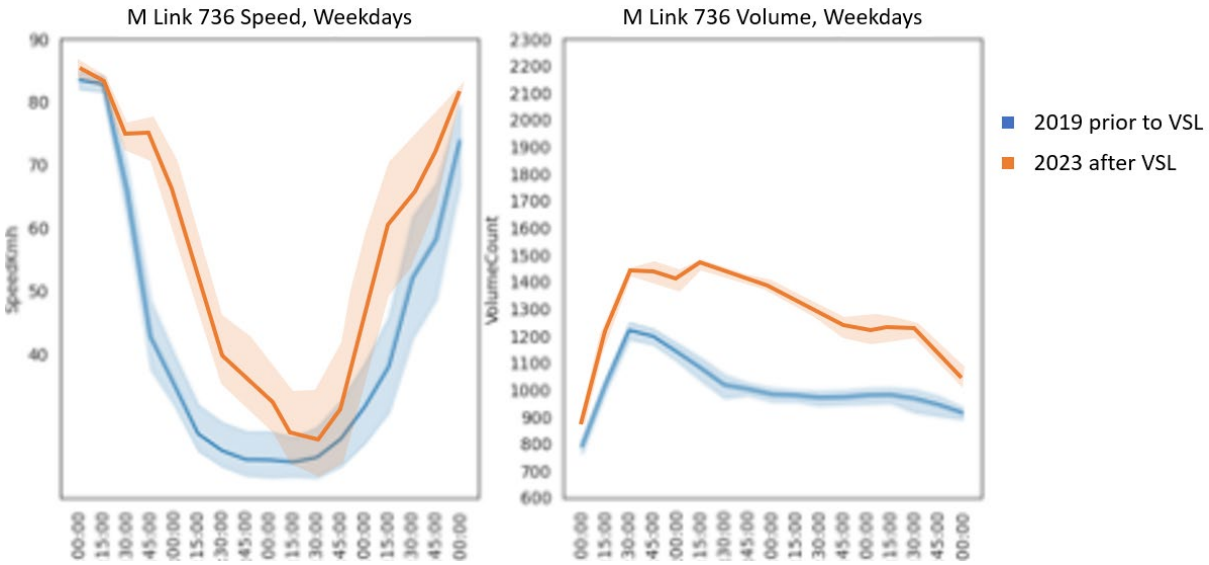
The analysis compared traffic conditions during peak hours in 2019 and 2023, focusing on speed-related variables and volume between 6:00 AM and 10:00 AM. The results revealed an overall increase in volume of over 20% across all sections in 2023 compared to 2019, with Sections 3 and 4 experiencing more than a 50% increase.

Regarding minimum average speed during the morning peak, Sections 1 and 2 showed positive increments, with variations influenced by weekdays. Section 1 experienced increases ranging from 9.8 km/h to a peak of 23.83 km/h on Fridays. Section 2 consistently saw increases of over 10 km/h on weekdays, except for Tuesday. In contrast, Section 3 showed a decrease in minimum average speed of 5 to 9 km/h, except on Fridays. Section 4, however, displayed a significant decrease, with minimum average speed dropping from around 72 km/h in 2019 to between 57 km/h and 63 km/h in 2023. Section 5, the mainline exit, also witnessed a decrease in minimum average speed, from around 72 km/h in 2019 to approximately 60 km/h in 2023.

When examining average speeds during the morning peak hours, significant improvements were observed in Sections 1, 2, and 3, with Section 2 showing the most notable improvement. For example, the upstream of Section 2, MLink735, fluctuated between 63 km/h and 70 km/h on weekdays, reaching 78.7 km/h on Fridays. In 2019, however, MLink735's average speeds ranged from 43 km/h to 56 km/h during peak hours. Within MLink736 and MLink737, the increase in average speed ranged from 14.31 km/h to 22.43 km/h. On the other hand, both Section 4 and Section 5 experienced decreases in average speed, ranging from 3.38 km/h to 5.63 km/h in 2023 compared to 2019.

Analysing traffic volume during peak hours in 2019 and 2023 provided valuable insights into changes in average speeds. In 2019, Sections 1 and 2 did not reach capacity during the morning peak, as their speeds remained above 74 km/h, despite the posted speed limit being 80 km/h. This suggests that traffic conditions were relatively free flowing in these sections. However, other sections experienced higher traffic volumes during the morning rush.

Figure 4: Speed and volume in section 4, before and after installation of Smart Freeways



In 2023, Sections 3 and 4 saw a volume increase of 49% to 56% compared to 2019, highlighting a significant change in traffic dynamics. Despite a decrease in minimum average speed in Section 3, the overall average speed increased, indicating that the higher volume was being managed effectively. The mainline exit, Section 5, experienced a volume increase of 23% to 36%, coupled with a slight decrease in average speed during peak hours, from approximately 74 km/h in 2019 to 69 km/h in 2023. Even at the most congested period, Section 5's average speed remained around 59 km/h, reflecting some level of congestion management.

Key findings from analysis on throughput of the five sections are

Increase in Throughput: A significant increase in throughput is observed across the five sections when comparing 2019 to 2023.

Stability of Throughput: Throughput stability is indicated by the Normalized Throughput Ratio, which is mostly above 95%. This suggests that, despite increases in throughput, the system has maintained a relatively stable flow of traffic.

Variability in 2019: There exists a greater variability in throughput, as the interquartile range of the traffic speed in 2019 is greater than compared to 2023. This indicates that the throughput during the 54 research dates in 2019 was more variable compared to the 39 research dates in 2023.

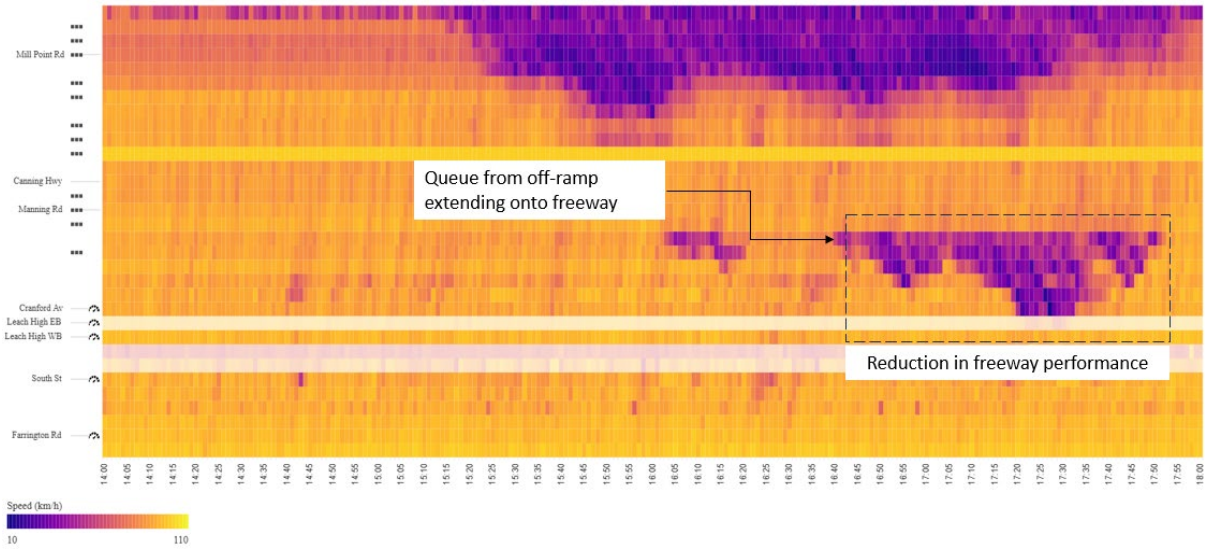
Based on this comparison, it can be concluded that the Smart Freeway had a positive impact on both speed and volume, helping to manage traffic more effectively during peak hours and reduce congestion, particularly in high-traffic sections.

4.2 Findings 2: Blocking of ramps effect

An analysis was conducted to assess the extent of blocked ramps along the research freeway stretch. The study assumed a consistent demand for merging and exiting at the ramps, providing a baseline for comparison of actual traffic behaviours. Key findings are:

Mill Point Road Off-Ramp: This ramp had the highest blockage rate, with 29.34%. Theoretically, the Mill Point Road Exit should have allowed 1101 vehicles to exit during peak hours (Qr_max), but only 778 vehicles actually exited, resulting in a significant discrepancy between expected and observed performance. Cranford Ave On-Ramp: This ramp also experienced substantial blockage, with a blockage rate of 20.50%.

Figure 5: Effect of blocking of ramps on freeway performance



At Mill Point on-ramp, despite expectations that 5605 vehicles should merge from the Mill Point On-Ramp, only 5301 vehicles were observed to merge on average. This resulted in a low Blockage of Ramps (BOR) ratio of 5.42%. Interestingly, the low BOR suggests that vehicles merging from the Mill Point On-Ramp were not significantly delayed by lane-changing manoeuvres associated with vehicles exiting at the Mill Point Exit.

4.3 Finding 3: Capacity drop ratio

After analysing congestion, we then investigated the recovery efficiency of each ramp after traffic breakdown in 2023, using metrics such as the Queue Discharge Rate to Capacity Ratio (Q/Cap ratio) and hysteresis loops. The highest average Q/Cap ratio, 92%, was observed at the Mill Point Road on-ramp and off-ramp, followed by the Canning Hwy on-ramp and Manning Road on-ramp, both at 88%. Cranford Avenue on-ramp exhibited the slowest recovery, with a Q/Cap ratio of 85%.

The low standard deviation in Q/Cap ratios, ranging from 2.5% to 3.1%, suggests stability in the discharge capability during congestion. Furthermore, our analysis of hysteresis loops over six selected dates revealed distinct patterns at different ramp areas. At Mill Point Road on-ramp and off-ramp, the volume decreased during the recovery portion of the cycle. In contrast, at Canning Ave on-ramp and Canning Hwy exit, the volume did not decrease during recovery. A unique hysteresis loop phenomenon was observed at the Canning Hwy and Manning Road on-ramps, a previously undocumented pattern in existing literature (Saberi and Mahmassani, 2013). This loop indicated that after traffic cooled down, from 9:30 am to 10 am, occupancy levels were lower for the same volume compared to the traffic loading period from 6:15 am to around 7 am. This pattern was observed at Canning Hwy on-ramp during the morning peak on 4 out of 5 selected dates, suggesting a potential area for further study to understand the underlying causes.

Figure 6: Hysteresis loop of detector within section 4 exhibiting low-capacity drop

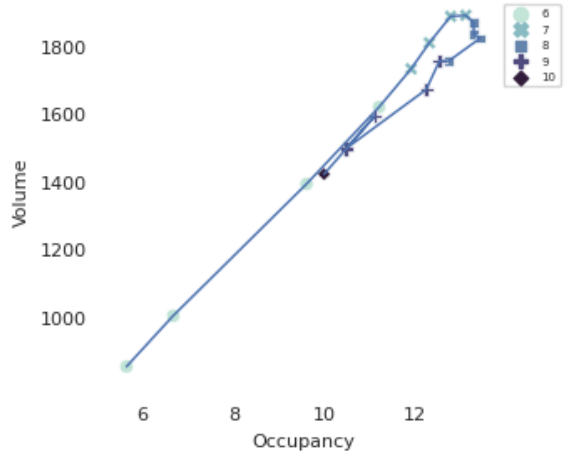
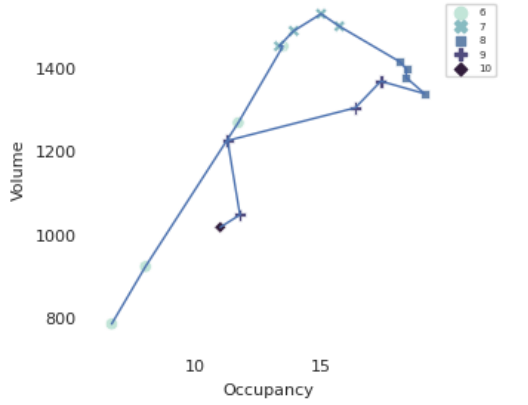


Figure 7: Hysteresis loop of detector within section 2 exhibiting high-capacity drop



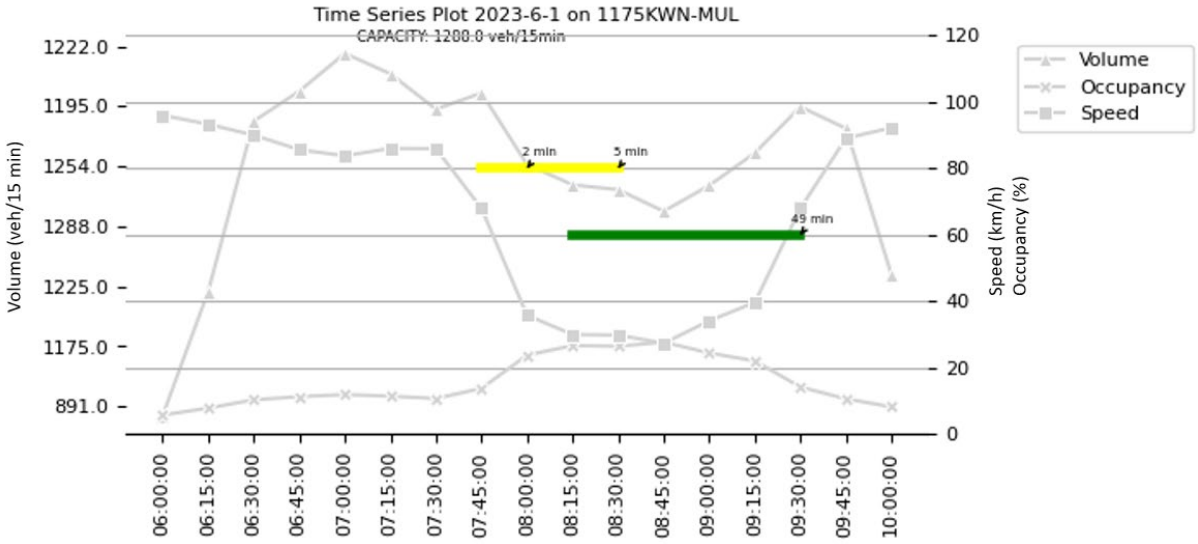
Capacity drop can be visualised using the hysteresis loop graphs. Observe the difference in maximum volume to the volume at maximum occupancy in section 4 (Figure 6), where there is low capacity drop. In section 2 (Figure 7) there is a significant difference between the maximum volume to the volume at maximum occupancy, indicating a higher degree of capacity drop.

4.4 Finding 4: Compliance rates

The compliance levels on the selected days, incorporating the VSL-implemented speed limit for durations exceeding 15 minutes across the network. To calculate the compliance level, we used a method that subtracts the average speed of the detector section from the posted speed. A negative result indicates that the average speed is lower than the posted speed, and a positive result indicates the opposite.

During extended periods of VSL activation, the average speed significantly drops below the VSL rate. This indicates the formation of congestion, where the displayed VSL rate does not directly affect speed but serves as a signal to drivers about impending congestion. This pattern is frequently observed in Bottleneck 2 and the upstream Canning Hwy exit area. The time series plots for each section consistently display this pattern across the analysis.

Figure 8: Variable speed limits and the effect of congestion on compliance

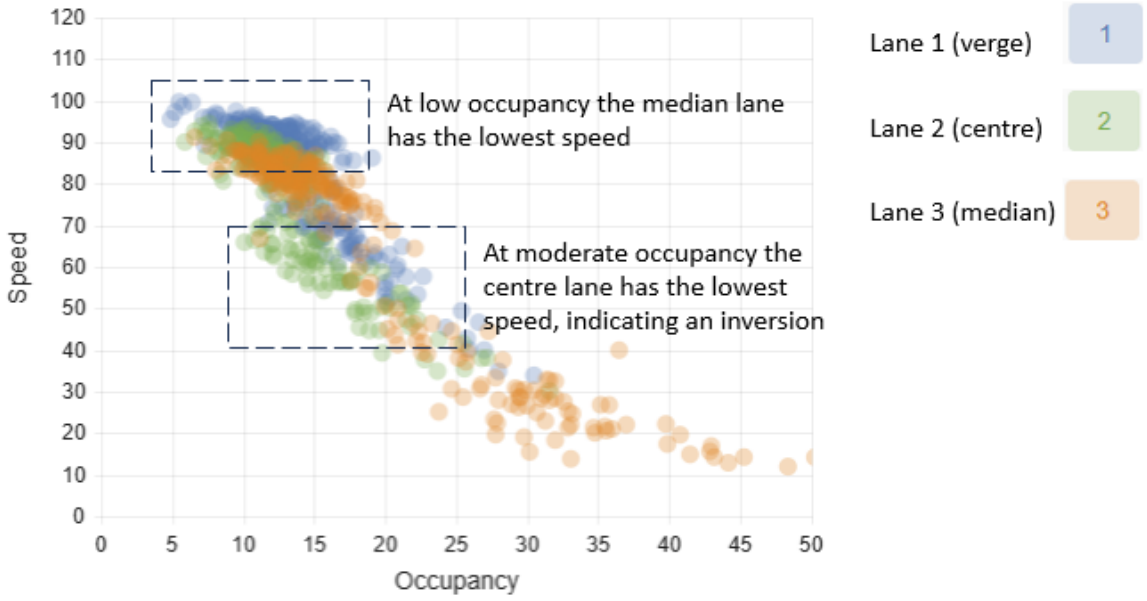


Where high levels of congestion are experienced, there is a noticeable increase in the compliance rates. The solid bars indicate the posted speed limit, and as congestion onsets (indicated by a decrease in volume and increase in occupancy), the speed rapidly decreases to well below the variable speed limit. The observed compliance levels across the sections align with the findings of Hellinga and Mandelzys (2011), which suggest a higher level of compliance in Western Australia.

4.5 Finding 5: Inversion point

An inversion point is defined as the moment when the throughput of the median lane surpasses that of the central lane, indicating a shift from light to heavy traffic. This shift is a critical moment in understanding traffic behaviours and congestion patterns, as highlighted by Soriguera et al. (2017).

Figure 9: Inversion point visible on a speed occupancy diagram for a single day



In this analysis, occupancy was used as the variable of interest, where the average point corresponds to the detector's typical handling capacity, while the critical point reflects the

current section's occupancy. The inversion points represent key moments when traffic conditions transition and are typically marked by shifts in the throughput between the median and central lanes.

It was noted that in sections with more than three lanes, particularly when two or more central lanes were present, multiple inversion points were observed. This phenomenon suggests that the network's complexity and lane distribution can lead to multiple transition points between light and heavy traffic, further complicating the analysis. To address this, the analysis focused on the lowest critical point or inversion point among the comparisons, providing a more consistent and representative measure of the traffic state for the selected days.

This analysis of inversion points is essential for understanding the flow of traffic, as it reflects the interplay between lane usage, traffic volume, and congestion. Identifying the points at which these transitions occur helps in optimizing traffic management strategies, particularly in addressing bottlenecks and ensuring efficient traffic flow in areas with varying traffic density.

5 Conclusion

When comparing traffic data from 2019 (before the VSL implementation) with 2023 (after full deployment), we observed a significant improvement in throughput across all five sections during the morning peak hours in 2023. Notably, throughput at the mainline exit, Section 5, increased by 26% during the morning peak in 2023. Additionally, throughput in Section 3 and Section 4 saw increases of 55% and 51%, respectively, in 2023 compared to 2019.

Five different metrics are studied – the blocking of ramps ratio, describing the condition for when a freeway off-ramp experiences significant enough congestion that it starts to disturb traffic condition on the mainline; the queue discharge to storage ratio, where flow into an existing freeway bottleneck exceeds capacity; the capacity drop ratio, the proportion by which the capacity of a freeway is reduced when flow breakdown occurs; the compliance level, describing the percentage of drivers who follow variable speed limits; and the inversion point, a description of when the congestion in the centre lane of a freeway exceeds the congestion in the verge lane.

The analysis indicates that some ramps, particularly the Mill Point Road Exit and Cranford Ave On-Ramp, experience notable blockage during peak hours. However, the Mill Point On-Ramp appears to function more efficiently in terms of merging, with minimal delay caused by lane-changing behaviours related to the Mill Point Exit. Further analysis may be required to understand the causes of blockage and improve traffic flow at the identified bottlenecks.

Regarding inversion points, our findings indicated that the primary inversion point occurred most frequently at Section 3 (After Canning Highway On-Ramp), while the lowest inversion points were primarily observed in Sections 2 (After Mount Henry) and 4 (Before Narrows Bridge). These sections correspond to the network's lowest manageable occupancy levels, providing insights into how each section manages traffic flow and indicating the maximum capacity each detector section can handle. This information serves as a promising reference for traffic control centers to better manage traffic flows through a performance-based VSL strategy.

6 References

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