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ANNUAL SUMMARY REPORT

R77: Real-time determination of spare capacity of routes for enhanced management of congested road network – Stage 2 Year 2 (2019/2020)

ARRB Project No.: 014861

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SUMMARY

This report acts as the summary report for Year 2 (first year of Stage 2) of the project looking at real-time determination of spare capacity of routes for enhanced management of congested road networks. This report builds upon the findings of Stage 1, which utilised departure detectors to identify congestion and estimate spare capacity.

In Stage 2, practitioners from the state road authorities were consulted, to identify whether spare capacity was measured and to discuss the methodology outlined in Stage 1 of this project. Generally, the practitioners could see the potential benefits in estimating spare capacity across the network in real-time but expressed concerns as to the feasibility of developing a system. It was emphasised that the practical purposes of knowing spare capacity as well as the use cases should be identified upfront.

After reviewing the available data and utilising the knowledge gained, the methodology was reviewed and an algorithm was developed to estimate spare capacity. This was undertaken by using first principles to identify occupancy at the critical and maximum flow for each lane at each intersection. These thresholds identify when the traffic flow becomes unstable and saturated respectively, as the same traffic flow can be undersaturated or saturated. This highlighted the reliability of the data sources, with the highest reliability being the departure detectors, and the least reliable being the NPI average occupancy. Due to the reliability, speed was identified as a means of validating the arrival and NPI average occupancy when it is considered unstable or saturated. As only a few intersections have departure detectors, it is critical that arrival occupancy is also measured.

It is noted that departure detectors could be installed at critical corridors to help the operators in identifying saturation and spare capacity. Using the lane level rules for determining saturation, an intersection is considered to be saturated if >= 50% of the lanes are determined to be saturated. Using the state of flow, the operational capacity for a segment is compared with the design capacity. If the site is saturated, the operational capacity is the realised flow. Similarly, if the site is undersaturated, the operational capacity is the design capacity. After the operational capacity of each intersection is determined, this can be used to identify the operational capacity of each link between the intersections, effectively being equal to the lower of their upstream and downstream intersections' capacities.

Utilising the methodology and algorithm developed, a prototype was created. The prototype allows for the importation of the raw data and the output of site and link specific metrics. This prototype shall be used in assessing corridors as part of a case study.

Task 2.5 (case study, calibration and validation) identified some shortfalls of the arrival detector data, therefore the business rules have been revised, refer to the Year 3 (Stage 2 Year 2) report for changes. These reports should be read in conjunction.

ACKNOWLEDGEMENTS

This project was made possible through the contributions of Queensland Department of Transport and Main Roads and the consulted practitioners, sharing the lessons learnt from related projects and experience.

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1 INTRODUCTION

This report covers the work undertaken in Year 2 of the project, being:

Task 2.1 – Practitioner Consultation

Task 2.2 – Review of TMR Data

Task 2.3 – Develop and Refine Algorithm

Task 2.4 – Prototyping.

Task 2.1 Practitioner Consultation reviewed current practice in Australia in the application of real-time operational capacity estimation to determine the degree to which jurisdictions measure capacity across their road networks and their ability to measure operational capacity and spare capacity in real time.

Broadly, there are two ways in which spare capacity can be utilised:

1. Redirect traffic to where spare capacity exists
2. Extend movements at intersections to where spare capacity exists on opposing movements.

TMR foresee several use cases to utilise spare capacity if spare capacity can be identified across the network in real-time. These use cases include:

- Inputting measures of spare capacity into TMR's QLDTraffic navigation app to improve this app's route-choice algorithms.
- Colour-code mapping spare capacity across the network in STREAMS Explorer as a means of providing the TMC with a visualisation of where spare capacity exists at any moment in time. This could potentially allow TMC operators to make operational changes to redirect traffic in congested areas to alternative routes with spare capacity.
- Operational changes to better utilise spare capacity would predominantly be made to arterial traffic signals. These would include:
  - Allowing the main road through phase to gap out or terminate early when realised flow is low.
  - Repeating right-turn lagging phases when the opposing through movement flow is low.
  - Giving greater priority to buses or trams.
  - Extending pedestrian movement phases.
- The use of roadside VMS to provide motorists with traveller information on travel times for enhanced route choice decision making.
- The use of radio and other public media to advise motorists of alternative travel routes with greater spare capacity.

Practitioners were briefed on the methodology developed in Stage 1 for determining effective operational capacity at an arterial intersection or freeway detector site by determining the operational capacity of the upstream and downstream segments. Discussions predominantly revolved around the feasibility of implementing a system to measure the required occupancy and speed thresholds in real-time and effectively use this methodology to estimate operational capacity. Feasibility issues and potential use cases were discussed for both freeways and arterial roads. Measures of speed, volume and occupancy from in-road detectors on both freeways and arterials were discussed in depth and consideration was also given to the potential for additional data sources (Bluetooth and probe data) to provide greater coverage of travel times, travel speeds and delays to enhance the ability of the system to measure capacity across the network.

To develop a method for estimating operational capacity of a road corridor in real-time, TMR provided ARRB with some historic traffic data from Smith Street Motorway and surrounding arterial roads in the Gold Coast. This data from STREAMS detectors on both arrival and departure sides of intersections included volume, occupancy and signal phase data collected from the 11th to 31st March 2019. Speed data from Bluetooth and the Intelligent Hybrid Model (IHM) was also provided by TMR for these roads during the same period.

Task 2.2 Review of TMR Data utilises the learnings from the practitioner consultations to review the TMR data provided for operational capacity estimation and identify how it can be utilised in the algorithm for estimating operational capacity.

Task 2.3 Develop and refine algorithm looks at refining the methodology and algorithm through the data provided by TMR and investigates additional measures that can be used in determining when the road is operating under capacity and thus has spare capacity.

Task 2.4 Prototyping the algorithm developed as part of Task 2.3. The prototype will be tested to ensure the information is reported as intended. In year 3, the prototype shall be further calibrated and validated using video data while undertaking a case study of the following Gold Coast roads, Smith Street Motorway and adjoining North Street in both directions, as well as Kumbari Avenue, which crosses Smith Street Motorway, in both directions.

2 PRACTITIONER CONSULTATIONS

This section documents the main points of discussion during the consultations with practitioners from each of the jurisdictions.

At the start of each consultation, ARRB presented a project briefing with PowerPoint slides covering the methodology developed in Stage 1 for determining effective operational capacity at an arterial intersection or freeway detector site by estimating the operational capacity of the upstream and downstream segments. The practitioners were consulted for their views on this proposed methodology and the indicative thresholds for critical occupancy and critical speed proposed in this methodology for arterial roads and freeways.

Practitioners were also asked questions relating to:

- Whether they currently estimate real-time operational capacity on their motorway and/or arterial networks
- Variances in operational capacity on motorways and on arterial roads
- How real-time spare capacity could be better measured across motorways
- The feasibility of estimating spare capacity on arterial roads
- Issues relating to measuring speeds, volumes and occupancies in real-time to estimate operational capacity and spare capacity across the network
- Whether additional control strategies could be deployed to better optimise the network if we had greater awareness of spare capacity in real-time.

The minutes of each consultation are documented in Appendix A.

2.1 QUEENSLAND DEPARTMENT OF TRANSPORT

Consultation: Skype meeting held on the 21st November 2019.

Practitioners: David Stewart - Principal Engineer (Traffic)

Kelvin Marrett – Director – Active Network Operations

Mark Jones – Manager - Active Network Operations

David Johnston – Consulting Engineer (Intelligent Transport Services)

Key points of discussion:

- Potential use cases:
  - enable TMC operators to reroute traffic where possible from congested areas of the network to alternative routes with spare capacity.
  - identified spare capacity used in the routing algorithms of TMR’s QLDTraffic app or other third-party navigational app providers. This would improve network operations as it would reroute once spare capacity is utilised.
- May be more useful for re-routing connected automated vehicles in the future than current motorists.
- Adelaide currently uses travel speed from the AddInsight Bluetooth data to help inform the operators. It is believed that this is not perfect, but with operational experience it may be fine-tuned locally.
- AddInsight informs motorists of travel time delays in near real-time and effectively shifts traffic to alternative routes.
- Colour-coding the map in STREAMS Explorer by spare capacity (percentage or actual number) could lead to other strategies available inside of STREAMS or other automated procedures.
- Problems with STREAMS:
  - Bad data could be learnt as good data. All subsequent data monitoring accepts bad data and may reject good data. Needs a set of first pass sanity checks.

  - Currently processes at the detector site level and assumes standard vol-occ behaviour from the aggregated lane volume data. However, behaviour should be assessed at the individual lane level. Resultant maximum and sustainable flows at site level can be ‘crazy’ when one lane detector fails, or one lane breaks down.
  - If a site never reaches capacity, then it will never know the true spare capacity. A separate calculation, like the HCM theoretical capacity, should be included to work out what the true capacity should be for roads that never reach its full capacity.
- Derivation of capacity needs to come from a combination of learnt values and theoretical values to ensure immune to once-off events (e.g. 60 motorbikes in 1 minute) and faults in the system (e.g. chattering detectors). A data-aging process may be required to degrade the influence of major once-off events by 1% per day over the last 40 days.
- How do we define a roads level of service (LOS) when each lane has a different LOS?
- For arterial roads, capacity is more based on delay than density.
- Delay can be calculated from NPI speed converted into travel time, which can be compared against the flow.
- Need to be aware of where the data can lead you astray. Conduct sanity checks.
- Capacity can change based on the traffic plans.
- Real-time system would need to account for weather which influences travel speeds, traffic behaviours and hence operational capacity.
- Data 61 wrote and presented a paper with RMS for the 26th ITS World Congress in 2019 called Data-dependence in Traffic Forecasting. It looked at AI learning algorithms in relation to traffic controllers.

2.2 VICTORIAN DEPARTMENT OF TRANSPORT

2.2.1 SKYPE MEETING WITH ANTHONY FITTS

Consultation: Skype meeting held on the 2nd December 2019.

Practitioner: Anthony Fitts - Manager Signal Services East

Key points of discussion:

- DoT use SCATS Degree of Saturation (DS) for real-time capacity.
- SCATS DS = effectively utilised green time / total available green time.
- Occupancy = Headway - Space. These are all time variables measured in seconds.
- DS is a measure of congestion. It is independent of vehicle length and therefore vehicle mix.
- Critical occupancy is relative to the ratio of green time to cycle time as determined by demands
- Unutilised green time is the difference between total space during measured green time and the necessary space between each vehicle.
- Total available green time is the maximum allowable green time = measured GT + unused GT
- Unused GT is time left from when GT is cut to when it would reach its maximum allowable.
- It is useful to measure spare capacity for the counter-peak direction where there is a tidal flow situation.
- Various use cases to utilise spare capacity. E.g.:
  - Repeat right-turn lagging phases when opposing through movement has spare capacity
  - Allow the main road through phase to gap out or terminate early if the DS is low
  - Bus priority
  - Extend pedestrian movement phases.

- Problems are site specific, meaning a complex solution required for network optimisation. Different priority movements at different intersections. Need higher resolution and accuracy of speed and travel time data to improve network optimisation.
- For network optimisation, DoT prefer to make changes to signal group control rather than changing phases at each site independently. SCATS signal group control is the best way to utilise spare capacity for other movements.
- Only if volumes are low will DoT consider breaking co-ordination between intersections to allow for site-specific optimisation. Such a decision is only considered if volumes drop below a minimum threshold.
- VR83, the SCATS routine for congestion, is based on Vk/Vo being high, high occupancy with low flow. This indicates a congested network with downstream spillback. Only useful for short mid-block segments.
- There are no departure side detectors in SCATS. Mid-block detectors are not practical to use due to the cost associated with setup and maintenance. It is believed that data such as AddInsight Bluetooth or probe vehicle data would be more helpful.
- Bluetooth, if it covered more of the network, could potentially be used to measure delays at the intersections and link travel times. In so doing, it could potentially identify bottlenecks and inform decisions on phase splits.
- There are currently no point-to-point Bluetooth measures for turning movements, but it could be possible to assume a turning movement if vehicles could be matched at three Bluetooth locations.
- DoT tend to use Bluetooth only for historical purposes (i.e. before/after treatment comparisons). Latency of Bluetooth may be too long for operational purposes.
- Probe data could potentially be used as virtual mid-block detectors.
- HERE are looking at a measure of ride along flow, which indicates the number of stops under 10 km/h.
- DoT discontinued their use of TomTom data and are now using SUNA.
- The best time to get people to consider changing their route is at the start of their journey. Less likely to change route mid-trip.

2.2.2 FACE-TO-FACE MEETING WITH DEPARTMENT OF TRANSPORT AT KEW

Consultation: Face-to-face meeting at DoT Kew on 3rd December 2019.

Practitioners: Matthew Hall – Manager, Managed Motorways and Network Optimisation, Road and Traffic Design, Engineering and Road Management

John Gaffney – Strategic Engineering Advisor, Managed Motorways and Network Optimisation Road & Traffic Design

Chris Harper – Manager Tactical Network Management

Key points of discussion:

- The methodology shown is alright. However, while the methodology proposes single critical occupancy and speed thresholds for arterials, and likewise for motorways, these thresholds are likely to be site-specific, varying significantly from site to site.
- For freeways, there is a difference between per lane occupancy and carriageway occupancy.
- Occupancy is a measure of time within a period. To calculate properly, divide the total time occupied across all lanes by the number of lanes. DO NOT flow-weight the occupancy for each lane.
- A critical occupancy of 25% for a 4-lane freeway is too much. DoT generally use an occupancy of 12-14% for the freeway carriageway.
- Is critical occupancy the threshold for maximum capacity flow or maximum sustainable flow?
- Occupancy measures differ for different detectors. I.e. studs give different measures to loops, depends on the ‘footprint’ of the detector.

- Need to assess critical occupancy relative to the speed limit. Particularly important where there are variable speed limits. Headways reduce when speeds drop, and occupancy increases.
- The critical speed of 80% for freeways seems reasonable. This is 80 km/h in 100 km/h zone and 64 km/h in 80 km/h zone.
- Breakdown for freeways is generally around 64 km/h.
- The realised operational flow may in fact be the 'collapse' flow at which breakdown occurs.
- It is believed that a threshold for the maximum flow may be a better indicator than occupancy.
- Motorway SVO measures are taken at a point, but failure may be 200 m upstream or downstream of that point.
- The underlying problem is the issues of bottlenecks. In most cases, no detector site would be at the perfect location for the bottleneck. Downstream or upstream of the bottleneck may never reach the threshold values.
- If a downstream bottleneck has spare capacity, so if it can be identified and released, the bottleneck spare capacity may be utilised.
- For arterials, DoT look at utilisation rather than capacity. i.e. time that is effectively used, time that is unused and total time. The challenge for arterials is to balance the competing demands. Capacity is when it cannot serve more traffic.
- Utilisation is a site-specific measure. E.g. If there is parking just before an intersection, vehicles wanting to get into the left lane may not fully utilise the lane due to the parked cars, which may affect the utilisation. i.e. there may be 70% utilisation, but it is fully saturated.
- Change in green time allocation changes capacity.
- Even if able to identify spare capacity, you cannot always make use of spare capacity. (e.g. spare capacity immediately downstream of a bottleneck.)
- The network is very fluid. If you increase delay for a movement then demand moves elsewhere, which increases capacity at the intersection.
- If you want to optimise a network, you may need to compromise some nodes.
- Variable demands on arterials make it very difficult to optimise the arterial network in real-time. E.g. One cycle can have 1 right-turn vehicle and the next cycle might have 10 right-turn vehicles. Vehicle mixes also vary cycle by cycle.
- For managed motorways, demands are known and controlled at the entry points.
- DoT monitor and dynamically control demands on their managed motorways at 20 second frequencies.
- In regards to diverting traffic to where there is spare capacity, most people pick their routes before they begin their journey and are reluctant to change route mid-trip, especially if on a regular journey.
- The management of motorways is based on looking at a whole suite of fundamental diagrams and the relationships change daily. Vehicle mixes and OD patterns change daily.
- You need a statistical model to work out the probability percent flow breakdown. For design, a probability of 1% may be used, but in operation a probability of 0.1% is used.
- Maximum sustainable flow is around 1550 v/h/ln for unmanaged motorways and 1800 v/h/ln for managed motorways. The desired maximum operational flow should be the maximum sustainable flow.
- Must be a system treatment, not a local treatment.
- Really need to manage real-time operation at minute or sub-minute frequency.
- Perimeter control and mid-block feedback sensors could be more effective for stabilising the network, but this would be expensive to implement.
- Reporting spare capacity can be misconstrued and can be a risky political message. Arterial networks always have ‘spare capacity’ across most mid-blocks but this does not mean they are underutilised. They are interrupted flow facilities where vehicles move in platoons.

- Bluetooth data gets dropped after 20 minutes, which means if there is excessive delay, it may not get picked up.
- Bluetooth sampling is biased to trucks and probe data has a high percentage of gap fill.
- Bluetooth speeds should just be as measured from motor vehicles. Need to be confident average Bluetooth speeds not including speeds of cyclists or pedestrians.

2.3 TRANSPORT FOR NEW SOUTH WALES

Consultation: Skype meeting held on the 10th December 2019.

Practitioner: Christian Chong-White - Strategic Design and Performance Leader, SCATS Congestion Improvement Program

Key points of discussion:

- Agrees with the fundamental methodology but believes that site-specific calibrated values should be used for the critical occupancy and critical speeds.
- SCATS calibrates the capacity, but only uses it for optimising the signal controllers. This is done at a site level, not for a corridor.
- SCATS calibrates the maximum flow of every detector (lane). It is noted that every vehicle movement has different characteristics. It is believed that instead of using a static threshold, each detector should be calibrated due to every site and lane being different. Occupancy is calibrated from the day before.
- It would be interesting to see if different sites have different occupancy thresholds.
- TfNSW currently is calibrating sites based on density (occupancy), but this does not extend to calibrate for seasonal variations.
- You can infer traffic jam from arrival side stop line detectors. If you make assumptions about arrival side occupancy based on departure side occupancy it may be harder to accurately use for arrival side detectors.
- SCATS uses previous time-of-day flows from the previous day as assumed maximum flows. If flows well below these then assumes congested conditions.
- The calibrated data is good but suffers from situations such as inside lanes that are underutilised due to lane drop or parking, leading to vehicles not using the inside lane. This causes alarms in SCATS indicating that the lane is not calibrated properly, although it usually is. SCATS learns this and can recalibrate. The values don't change much day by day for each site, but the values change site to site.
- The proposed methodology could compromise the current signal controllers. E.g. Giving buses greater priority may deviate from the current operation. Must have very good justification to do so.
- Routes with spare capacity are usually part of the current network optimisation plan.
- If able to guide people to alternative routes it would be a win-win. Like the idea of giving motorists better information about alternative routes through greater knowledge of where spare capacity exists.
- The estimation of operational capacity and spare capacity in real-time would be very hard to do. It should be done retrospectively at first and then draw out the real-time aspects. This could help to identify where there are static issues. (i.e. Locations that experience recurrent congestion.)
- DS is relative to capacity and cycle time is an indication of capacity. However, these measures can give false negatives. E.g. The signal logic is based on a false assumption that the side roads have no capacity.
- Could undertake modelling using SCATSSIM and Aimsun to investigate how proposed changes could improve network performance but this would be a costly exercise, particularly if wanting to deploy across wide areas of the network.
- Take home message: static general thresholds will not be sufficient. Would really require calibration and the lane/detector level.

2.4 MAIN ROADS WESTERN AUSTRALIA

Consultation: Skype meeting held on the 10th December 2019.

Practitioners: Kamal Weeratunga - Acting Manager, Network Performance, Network Operations Directorate

Graham Jacoby – Manager, Network Operations Analysis

Key points of discussion:

- SCATS detectors in presence mode can provide more data and truer measures of occupancy and speed for mid-blocks. i.e. They are back of queue detectors, usually located 50m upstream of the intersection.
- SCATS detectors in passage mode essentially just determine the number of vehicles. i.e. stop line.
- STREAMS differs from SCATS by having arrival side detectors 35m back from intersection, except for turns which are located at the stop line.
- MRWA primarily operate the arterial network with SCATS, but there is an interface to STREAMS in SCATS for the motorways.
- Flow breakdown is instantaneous on unmanaged motorways but is a bit more predictable on managed motorways.
- If capacity could be identified and reported it could help motorists make an informed choice.
- Another piece of research could look at what would motivate people to change their route.

2.5 USE OF ADDITIONAL DATA SOURCES

This section documents discussions around using Bluetooth and probe data as additional data sources to supplement detector data as inputs into a real-time operational capacity estimation system.

2.5.1 BLUETOOTH DATA

It was generally agreed by the practitioners that Bluetooth could potentially provide improved measures of travel times, travel speeds and intersection delays to identify bottlenecks and enhance the ability to measure operational capacity. However, more Bluetooth readers would be required across Queensland urban road networks to provide the necessary resolution of speed profiles at the mid-block level. Currently, most pairings of Bluetooth readers span multiple mid-blocks so the mean speeds across each mid-block can only be roughly estimated from the Bluetooth travel times.

There was, however, concern that the latency of Bluetooth may be too long for operational purposes. Bluetooth gets dropped after 20 minutes, which means if there is excessive delay, it may not get picked up. (i.e. A vehicle's detection at point B cannot be matched if its initial detection at point A occurred more than 20 minutes earlier.) TMR has a data screening rule that eliminates any detected vehicles where their average travel speed between two Bluetooth detection points is below 5 km/h. This filters out vehicles that may have stopped somewhere between the two points.

Other comments about Bluetooth were that the sampling can be biased towards trucks as a higher proportion of heavy vehicles are fitted with Bluetooth devices compared to cars and light commercial vehicles. Bluetooth readings from cyclists and pedestrians must also be filtered out before calculating average travel speeds for general traffic.

2.5.2 PROBE DATA

Probe data has the potential to be used as virtual mid-block detectors but needs to improve in its reliability. Currently, a high percentage of speeds reported from probe data are based on historic gap fill due to insufficient sampling rates. However, enough samples are usually obtained during high congestion periods to identify when and where flow breakdown occurs.

2.6 CONSULTATION CONCLUSIONS AND RECOMMENDATIONS

Practitioners consulted could see the potential benefits in being able to estimate spare capacity across the network in real-time but expressed concerns as to the feasibility of developing a system to achieve this objective. These concerns were mainly around the variability of traffic movements on the network and the ability to measure speeds, volumes and occupancies at the required frequency, accuracy and lane-level resolution at each site. There were also concerns around data latency being too long for a real-time system.

Arterial networks are currently optimised based on green time utilisation rather than utilisation of spare capacity. The goal is to balance competing demands. Saturation flows are automatically calibrated for each lane detector and measures of the degree of saturation determine the cycle lengths and phase splits. Capacity is said to be reached when no more traffic can be serviced. Signal sites along major corridors are controlled in groups to ensure signal coordination and there must be good reason to make any changes to signal phasing outside of the current control strategies.

Even during peak periods, arterial networks should have a degree of spare capacity on their mid-block as they are interrupted flow facilities. This spare capacity is a necessity for arterial networks to properly function and it should not be misconstrued as unutilised capacity. It was also noted then even if spare capacity can be identified, we may not be able to make use of this spare capacity. An example of such was spare capacity immediately downstream of a freeway bottleneck.

The variability of traffic was also a discussion point whereby traffic volumes and vehicle mixes can vary cycle by cycle. Every intersection has its own characteristics (e.g. on-street parking reducing left lane utilisation) and therefore critical occupancy and speed thresholds will differ at each intersection. Consequently, critical occupancy and speed thresholds would need to be calibrated for each lane detector at each site.

Vehicle mixes and OD patterns on freeways/motorways change daily and traffic flows are very stochastic. As such, the management of motorways is based on looking at a whole suite of fundamental diagrams for which the relationships change daily. Managed motorways are finely tuned systems with speeds, volumes and occupancies detected at regular intervals along the motorway feeding into the system at minute or sub-minute frequency. Treatments are system-wide rather than localised. Coordinated ramp metering controls entry flows to optimise flows along the entire motorway.

The analysis of Centenary Hwy in the Stage 1 case study was made using 5-minute resolution data. The highway could be more effectively managed using 1-minute resolution data to reduce the latency of identifying potential flow breakdown conditions and the consequent reduction in operational capacity. This would allow more proactive measures, such as ramp metering, to be implemented to maintain stable flows and avoid flow breakdown. While there will still be several issues to address to deploy the planned system for motorways, the task of doing so will be much more feasible for motorways than for arterials.

In progressing this project towards a system to determine real-time spare capacity, it was emphasised that TMR should be clear on the practical purposes for wanting to know spare capacity and the use cases that could be applied if where and when existence of spare capacity is known in real time. It was recommended that spare capacity should first be identified retrospectively using historic data to identify recurrent patterns of capacity across the network before attempting to develop a real-time estimation system. It was also suggested that further research could be undertaken to help identify what would motivate motorists to change the travel routes mid journey.

3 DETERMINATION OF THRESHOLDS USING FIRST PRINCIPLES

This section looks at refining the methodology and creating an algorithm using the data supplied by TMR. The conditions of the corridor were reviewed to identify the sites which have arrival and departure detectors. The data was reviewed to identify the potential use and limitations in regards with determining operational capacity in real-time. The point at which maximum volume and the threshold of occupancy for saturation are then determined using first principles. This will allow for an indication as to whether there is spare capacity on the mid-block downstream of the traffic intersection. Based on Stage 1 (Espada 2019), if the road is saturated, the operational capacity will be the realised traffic flow. Otherwise, when the road is undersaturated, the operational capacity will be the design capacity, with the spare capacity being the difference between the realised traffic flow and the design capacity.

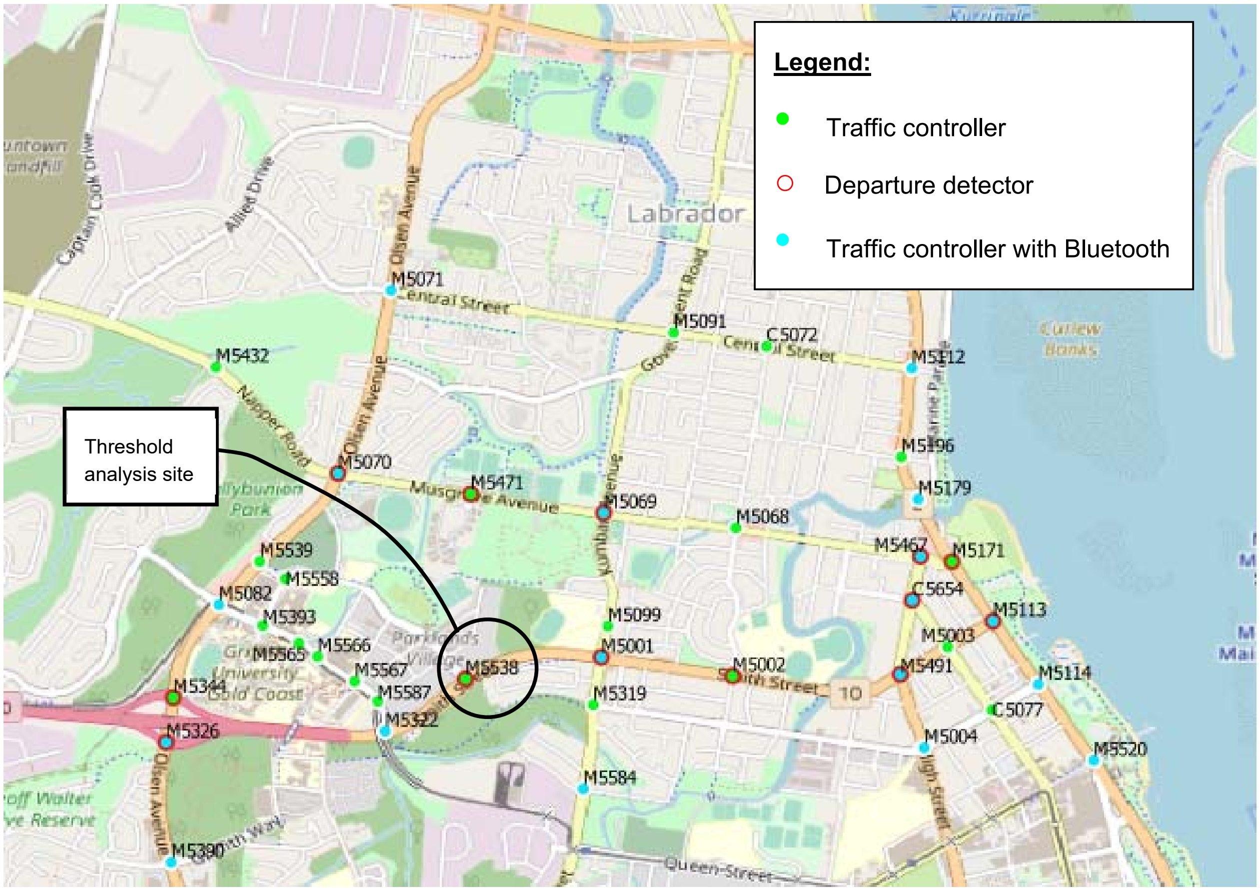
The breakdown of this section is:

- Corridor conditions – Section 3.1
- Review of data (Task 2.2) – Section 3.2
- Threshold analysis (Task 2.3) – Section 3.3

3.1 CORRIDOR CONDITIONS

Gold Coast was used as part of the assessment for the development of the algorithm. The area was chosen due to the number of intersections with detectors located at the departure-side. Departure-side detectors were used as part of Stage 1 of this project to identify whether the intersection is at or exceeding capacity. It is believed that measures of occupancy from departure-side detectors provide the best available indication of downstream congestion. Thus departure-side detectors are a good reference to determine the reliability of other indicators for congestion. Other indicators include upstream occupancy from arrival-side detectors or average speeds as measured by Bluetooth. A map of the locations of the data provided in the Gold Coast region and whether the site has departure-side detectors or Bluetooth is shown in Figure 3.1.

Figure 3.1 Site location - Gold Coast



Source: OpenStreetMap (2020), "Gold Coast", map data, © OpenStreetMap contributors, CC BY-SA.

3.2 REVIEW OF DATA

The various sources of data provided by TMR are reviewed, as part of Task 2.2, in the following sections:

- Intersection signal drawings – refer Section 3.2.1
- Signal operation plan – refer Section 3.2.2
- STREAMS – refer Section 3.2.3
  - Detector volume
  - Detector occupancy
  - Phase cycle data
- STREAMS BI – refer Section 3.2.4
  - NPI average occupancy
  - NPI cycle time
  - NPI green time
- Bluetooth – refer Section 3.2.5
  - Link length
  - Travel time
- Intelligent Hybrid Model – refer Section 3.2.6
- Limitations of data – refer Section 3.2.7.

All data provided was collected from 11 March 2019 to 31 March 2019.

3.2.1 INTERSECTION SIGNAL DRAWINGS

The intersection signal drawings indicate the layout of the traffic intersection. The layout includes the location and identification number of the detectors. This allows for the determination of the direction that traffic is flowing and whether the detector is an arrival or departure detector. The intersection signal drawing can be used in conjunction with the STREAMS data to identify the volume and occupancy for the intersection in the analysed direction of travel. These drawings also include the signal phasing diagrams which can be used in conjunction with the signal operation plan and phase cycle data to get an indication of the green split for the through movements.

3.2.2 SIGNAL OPERATION PLAN

The signal operation plan provides the thresholds for time for each phase and its associated signal plan. This gives an indication of what the maximum values for the green split may be.

3.2.3 STREAMS

The data that was output from STREAMS provides the following parameters:

- Detector volume
- Detector occupancy
- Phase cycle data.

The vehicle detector data provides the detector information for volume and occupancy. This was provided in a different document to the phase cycle data.

Detector volume

The detector volume provides an indication of the number of vehicles that are entering/exiting the intersection per minute. This can be used to determine the realised traffic flow for an intersection. Once a design capacity is known, this can be used in conjunction with other parameters to identify if there is spare capacity. This can also be used as part of a time-series analysis, to identify if there has been a reduction in traffic flow due to saturation.

It is noted that the data is provided in the format of vehicles per minute per lane, which contains data from green and red time. A sample of the raw data that was provided is shown in Figure 3.2.

Figure 3.2 Vehicle detector data - sample data

Local time	LogTime	DetectorId	Occupancy	Volume	DetectorInfo.Name
11/03/2019 0:00	10/03/2019 14:00	12979767	35	0	M5538/VD1
11/03/2019 0:00	10/03/2019 14:00	12979791	35	0	M5538/VD13
11/03/2019 0:00	10/03/2019 14:00	12979799	50	2	M5538/VD17
11/03/2019 0:00	10/03/2019 14:00	12979803	43	0	M5538/VD19
11/03/2019 0:00	10/03/2019 14:00	12979777	53	2	M5538/VD6
11/03/2019 0:00	10/03/2019 14:00	12979769	35	0	M5538/VD2
11/03/2019 0:00	10/03/2019 14:00	12979779	41	1	M5538/VD7
11/03/2019 0:00	10/03/2019 14:00	12979781	48	2	M5538/VD8
11/03/2019 0:00	10/03/2019 14:00	12979783	54	2	M5538/VD9
11/03/2019 0:00	10/03/2019 14:00	12979787	35	0	M5538/VD11
11/03/2019 0:00	10/03/2019 14:00	12979795	41	1	M5538/VD15
11/03/2019 0:00	10/03/2019 14:00	12979797	62	3	M5538/VD16
11/03/2019 0:00	10/03/2019 14:00	12979801	35	0	M5538/VD18
11/03/2019 0:00	10/03/2019 14:00	12979771	35	0	M5538/VD3
11/03/2019 0:00	10/03/2019 14:00	12979775	48	2	M5538/VD5
11/03/2019 0:00	10/03/2019 14:00	12979789	35	0	M5538/VD12
11/03/2019 0:00	10/03/2019 14:00	12979805	50	2	M5538/VD20
11/03/2019 0:00	10/03/2019 14:00	12979773	35	0	M5538/VD4
11/03/2019 0:00	10/03/2019 14:00	12979785	43	1	M5538/VD10
11/03/2019 0:00	10/03/2019 14:00	12979793	35	0	M5538/VD14
11/03/2019 0:01	10/03/2019 14:01	12979783	10	1	M5538/VD9
11/03/2019 0:01	10/03/2019 14:01	12979767	0	0	M5538/VD1
11/03/2019 0:01	10/03/2019 14:01	12979793	0	0	M5538/VD14
11/03/2019 0:01	10/03/2019 14:01	12979803	21	3	M5538/VD19
11/03/2019 0:01	10/03/2019 14:01	12979779	6	1	M5538/VD7
11/03/2019 0:01	10/03/2019 14:01	12979797	10	1	M5538/VD16
11/03/2019 0:01	10/03/2019 14:01	12979799	15	2	M5538/VD17
11/03/2019 0:01	10/03/2019 14:01	12979771	0	0	M5538/VD3
11/03/2019 0:01	10/03/2019 14:01	12979795	0	0	M5538/VD15
11/03/2019 0:01	10/03/2019 14:01	12979781	10	1	M5538/VD8

Detector occupancy

The detector occupancy gives an indication of the percentage of time that the detector has a vehicle occupying the loop. This can be used as a proxy for density. Occupancy is reviewed in conjunction with speed and volume to determine whether a site is saturated.

The detector occupancy data was provided in percentage time occupied per minute per lane. However, in this 1-minute interval data, each minute can contain a varying proportion of green and red time. Furthermore, to report these occupancies as integers, the actual percentages are one-tenth of the values provided. Thus, these values must be divided by 10 to obtain the actual percentages. For example, a value of 10 equates to 1% occupancy for that minute.

Occupancy values, as provided in the raw data, are also shown in Figure 3.2 above.

Phase cycle data

The phase cycle data provides the time that a cycle starts and the duration of each phase. This is to be read in conjunction with the signal operation plan and the intersection signal drawings to get an indication of the duration and time that the green time occurs in each direction of flow. This can be used to calculate the percent green time. Percent green time is used for determining the operational capacity of an intersection.

The data was provided based on the cycle time.

Figure 3.3 Phase cycle data - sample data

Intersection:	M5538/CTLR															
Plan:	<Any>															
Start:	Monday	11 March 2019	0:39:02													
End:	Monday	18 March 2019	0:39:02													
No of Cycles:	4089															
No of Discarded Cycles:	1															
Day	Time	Cycle No	Cycle Length	1A	1B	1C	2A	2B	2C	3A	3B	Phase Combo	Ped Combo	Plan	CT>60	CT<250
1	11/03/2019 0:48	1	711	698		13						AC	None	Isolated	TRUE	FALSE
1	11/03/2019 1:00	2	682	668		14						AC	None	Isolated	TRUE	FALSE
1	11/03/2019 1:11	3	2114	2100		14						AC	None	Isolated	TRUE	FALSE
1	11/03/2019 1:46	4	2286	2272		14						AC	None	Isolated	TRUE	FALSE
1	11/03/2019 2:24	5	1203	1190		13						AC	None	Isolated	TRUE	FALSE
1	11/03/2019 2:45	6	588	574		14						AC	None	Isolated	TRUE	FALSE
1	11/03/2019 2:54	7	790	776		14						AC	None	Isolated	TRUE	FALSE
1	11/03/2019 3:07	8	5720	5707		13						AC	None	Isolated	TRUE	FALSE
1	11/03/2019 4:43	9	173	160		13						AC	None	Isolated	TRUE	TRUE

3.2.4 STREAMS BI

STREAMS BI is a reporting system which integrates a data warehouse from ITS assets to allow for analytics and reporting.

One of the metrics STREAMS BI can create is NPI average occupancy, which gives an indication of the average occupancy across all lanes on the arrival side for a site during the green by a link length. This can be used as another measure for occupancy in determining whether the site is saturated.

The data was provided based on the cycle time.

Figure 3.4 STREAMS BI - sample data

Controlled Intersection	Intersection Description	NPI Link Name	Minute	14 Mar 19 NPI Avg Occupancy	14 Mar 19 NPI Cycle Time	14 Mar 19 NPI Green Time
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:00	13.9	42	17
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:01	1.531764706	85	33
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:02	0	40	14
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:03	2.464634146	82	30
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:04	0	40	14
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:05	0	86	33
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:06	0	37	11
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:07	4.15	84	32
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:08	3.6	40	14
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:09	1.712195122	82	29
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:10	0	40	14
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:11	0	43	17
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:12	0	79	27
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:13	0	41	15
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:14	1.603883495	103	36
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:15	3.6	39	13
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:16	8.3	39	13
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:17	1.86835443	79	26
M5538/CTLR	Smith Street & Hospital Blvd	Smith St NEB between Parklands Dr & Smith St And Hospital Bld	00:18	3.1	43	17

3.2.5 BLUETOOTH

The Bluetooth data provides the travel time for a designated link as well as the length of the link. This can be used to the determine the average travel speeds of vehicles on the links.

The limitations of Bluetooth speed data for the Gold Coast is the low spatial resolution. The average spacing for Bluetooth detectors is at every second intersection. The Bluetooth detectors can only determine speed based on vehicles with Bluetooth devices and vehicles need to go from start of the link to end of the link to record the speed. This means that if data is required on a 1 to 5-minute frequency, multiple vehicles need to go through the whole link and be registered in the exit Bluetooth site for this time period. As not all vehicles or phones have an active Bluetooth device, there are times where no data will be recorded.

The data was provided in 5-minute bins, which means that this includes both the green and red time. A sample of the Bluetooth data is shown in Figure 3.5.

Figure 3.5 Bluetooth - sample data

Link	Origin Site Id	Origin Longitude	Origin Latitude	Origin Description	Destination Site Id	Destination Longitude	Destination Latitude	Destination Description	Link Length
1	1607	153.385674	-27.96509	Smith Street and Parklands Drive (N583840)	1669	153.395057	-27.961897	Smith Street and Kumbari Avenue (Camera ID 17)	1.01km
2	1669	153.395057	-27.961897	Smith Street and Kumbari Avenue (Camera ID 17)	1274	153.40782	-27.96288	North Street and High Street (M5491)	1.26km
3	1274	153.40782	-27.96288	North Street and High Street (M5491)	1236	153.411776	-27.960388	Gold Coast Highway and North Street (M5113)	0.47km
Origin Site Id	Dest Site Id	Interval End	Mean Travel Seconds	85th Percentile Travel Seconds	Volume				
1607	1669	11/03/2019 0:05	null	null	1				
1607	1669	11/03/2019 0:10	null	null	1				
1607	1669	11/03/2019 0:15	null	null	0				
1607	1669	11/03/2019 0:20	54.67	63	3				
1607	1669	11/03/2019 0:25	null	null	0				
1607	1669	11/03/2019 0:30	null	null	2				
1607	1669	11/03/2019 0:35	null	null	2				
1607	1669	11/03/2019 0:40	null	null	0				
1607	1669	11/03/2019 0:45	null	null	1				
1607	1669	11/03/2019 0:50	null	null	1				

3.2.6 INTELLIGENT HYBRID MODEL

The Intelligent Hybrid Model (IHM) is a model which integrates data from various data sources, including STREAMS, Bluetooth and HERE. The model determines the best data source and method to use for speed, volume and flow. The method indicates which data source is used (i.e. STREAMS, NPI, Bluetooth, HERE, historical). The IHM is extremely useful, as the accuracy of the different data sources change based on the state of flow. The IHM provides the information at a link level using the streams links in 5-minute intervals. The use of the IHM data can provide an accurate indication of the speed in the prototype. Like the Bluetooth data, the limitation of the IHM is that it reports the data at a 5-minute interval, while other data such as the volume and occupancy is every minute. A sample of the IHM data is provided in Figure 3.6.

Figure 3.6 Intelligent Hybrid Model - sample data

NPI_Link_ID	localDate	localTime	Lanes	Speed	Speed_ Method	Volume	Volume_ Method	Flow	Flow_ Method	Length	Num_Dets	NPI_Speed	NPI_Speed_ Quality	NPI_ Volume	NPI_ Volume_ Quality
3372363	1/03/2019	12:00:00 AM	1	61	-32511	0	3	0	0	800	1		0	0	1
3372757	1/03/2019	12:00:00 AM	1	24.8254	779	0	515		0	416			0		0
12278496	1/03/2019	12:00:00 AM	1		0	0	4611		0	130			0		0
12296437	1/03/2019	12:00:00 AM	1	30	-14335	3	2049		0	120			0		0
12296441	1/03/2019	12:00:00 AM	1	43	-14335	0	3	0	0	308	1		0	0	1
12298357	1/03/2019	12:00:00 AM	1	9	-14335	0	-32767		0	358			0		0
12298349	1/03/2019	12:00:00 AM	1	9	265		0		0	128			0		0
12298350	1/03/2019	12:00:00 AM	1		0	0	3	0	0	40	1		0	0	1
12414585	1/03/2019	12:00:00 AM	1		0		0		0	53			0		0
12530313	1/03/2019	12:00:00 AM	1	41	3	2	3	24	0	182	1	41	1	2	1
12530320	1/03/2019	12:00:00 AM	1	40	3	2	3	24	0	151	1	40	1	2	1
12530309	1/03/2019	12:00:00 AM	1	49	3	5	3	60	0	149	1	49	1	5	1
12414583	1/03/2019	12:00:00 AM	1	36	-32767	0	515		0	123			0		0
12414586	1/03/2019	12:00:00 AM	1	41	4617	0	3	0	0	149	2		0	0	1
12530311	1/03/2019	12:00:00 AM	1	48	-14335	0	3	0	0	123	2		0	0	1
13019177	1/03/2019	12:00:00 AM	1	59	3	2	3	24	0	594	1	59	1	2	1

NPI_Link_ID	NPI_ Occupancy	NPI_ Occupancy _Quality	NPI_ CycleTime	NPI_ GreenTime	NPI_ Saturation	Here_ Mean_ Speed	Here_ P15_ Speed	Here_ P50_ Speed	Here_ P85_ Speed	Here_ Confidence	Here_ Speed_ Quality	Here_L ink_ Count	BT_Speed	BT_Speed _Quality	BT_ Samples	SpeedW15	SpeedW15_ Method
3372363	0	1	238	20	0.5						0			0		44.852943	-32501
3372757											0			0		24.825397	779
12278496											0			0			0
12296437											0			0		26.011013	-14335
12296441	0	1	256	189	12.333333						0			0		42.24271	-14335
12298357											0			0		9.8400002	-14335
12298349											0			0		9	265
12298350	0	1	300	57	28						0			0		11	777
12414585											0			0			0
12530313	3.5999999	1	342	272	21.200001						0			0		46.97253	-14333
12530320	4.6666665	1	517	472	34.666668						0			0		44.243793	-14333
12530309	10.5	1	665	637	36.5						0			0		40.125984	-14333
12414583											0			0		32.84119	-14335
12414586	0	1	427	11	78						0			0		41	4617
12530311	0	1	258	183	13						0			0		39.079662	-14333
13019177	2	1	238	208	8.5						0			0		58.74678	-14333

3.2.7 LIMITATIONS OF DATA

Upon review of the data, some limitations were noted.

- The occupancy from the STREAMS data is measured during the 1-minute interval period but does not distinguish between red or green lights. This means that, depending on the length of the phase time in the direction of flow, a vehicle may remain stationary on the arrival detector for over 1-minute, resulting in 100% occupancy.
- The STREAMS arrival and departure loops in the through direction can be offset from the intersection, in some cases up to 25m away from the intersection. This means that vehicles can be counted even when there is a red light. This also means that there can be no vehicles during a green, due to going over the detector while the light was red.
- The data is provided in different time intervals. This means that the comparison of the data is indicative. The relevant time intervals for the data are:
  - NPI average occupancy* - Total cycle time per site
  - STREAMS occupancy and volume - Per minute per lane
  - Bluetooth - Per 5-minutes per link between two readers
  - IHM - Per 5-minutes per STREAMS NPI link.

*Note: The NPI average occupancy for a period shall be based on the average of the values that occur during the relevant time intervals.

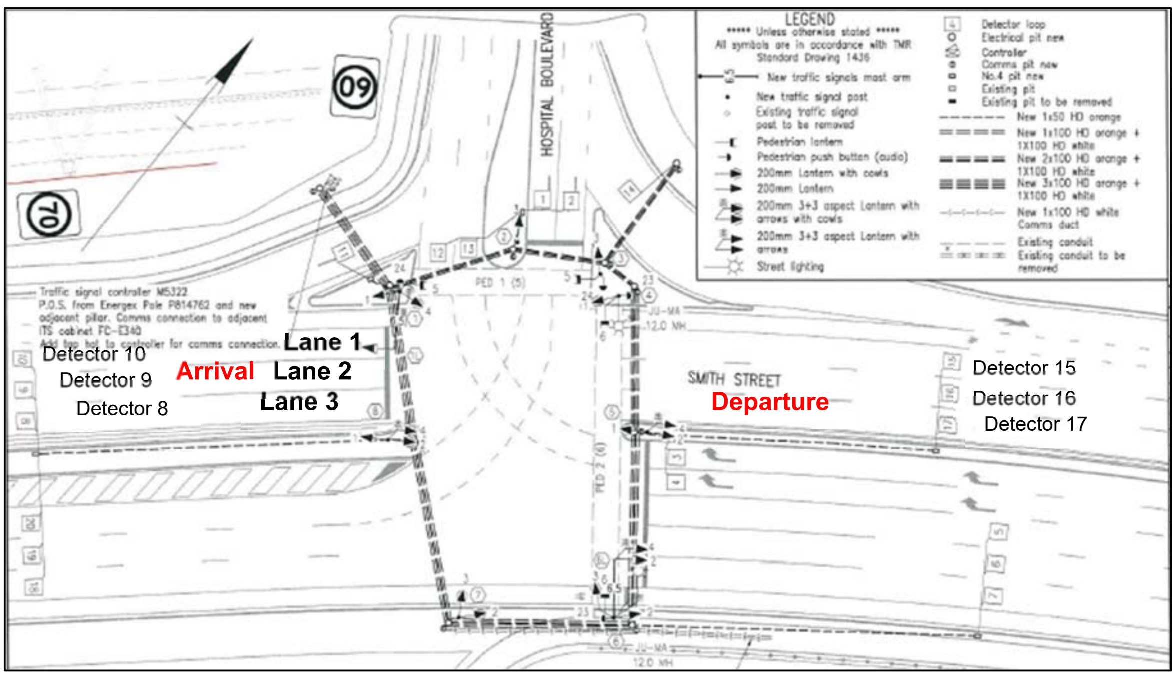
- Bluetooth data is reliant on vehicles having Bluetooth. If no vehicles have Bluetooth within the time period, then no values are recorded. Additionally, if vehicles are under a set speed on the link they are not recorded in the system (e.g. does not record the data if average speed is under 5 km/h). This is undertaken to remove data from vehicles which may have exited or parked in the mid-block for a quick drop-in trip or pedestrian traffic. This could also occur during extreme congestion, which the system does not have a means of distinguishing. Bluetooth signals could also be blocked due to obstructions, such as larger vehicles or buses between vehicles and the Bluetooth. A Bluetooth reader is currently installed at approximately every second intersection along the major routes. This means that the data received does not necessarily represent the average speed of vehicles arriving from upstream, nor the average speed of vehicles departing downstream of the intersection but provides an indicative average speed for both arriving and departing vehicles.

3.3 THRESHOLD ANALYSIS

Stage 1 of the project (Espada 2019) identified a process to determine the real-time operational capacity, utilising occupancy from departure side detectors. Task 2.3 of this stage of the project was to develop and refine an algorithm to identify whether there is spare capacity on the network using design capacity and operational capacity. The algorithm is based on the learnings of Stage 1 and the practitioner consultations, which utilised the occupancy from departure-side detectors. This section acts as part of the refinement of the algorithm methodology.

Figure 3.7 uses the traffic intersection plan for Smith Street and Hospital Boulevard (site M5538) to define the location of arrival and departure side detectors. This also shows the convention that is used for determining the lane number. Lane 1 is the through lane which is located closest to the outside of the road.

Figure 3.7 Intersection Signal Drawing - Site M5538



Source: Queensland Department of Transport and Main Roads (2015).

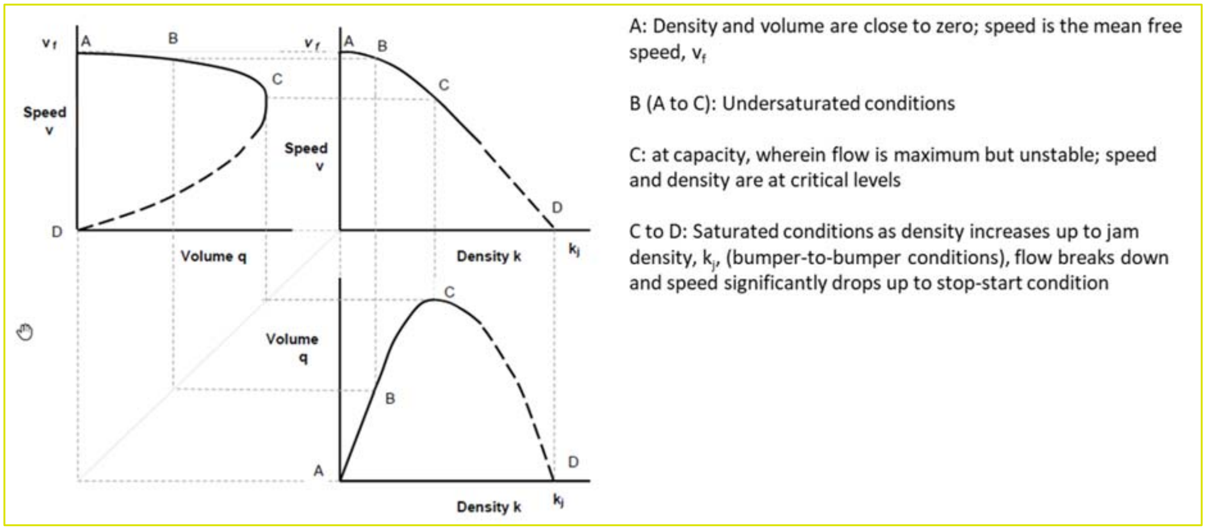
There is a direct inter-relationship between flow, density and speed which is a well-established concept in traffic flow theory (Austroads 2015) with the following fundamental relationship (illustrated in Figure 3.8):

- flow is the product of density and speed
- speed is a function of density, wherein speed decreases as density increases.

The saturation levels shall be investigated using first principles, as illustrated in Figure 3.8, with occupancy as a proxy for density. Using this relationship, the occupancy at which maximum volume occurs can be identified. This occupancy can then be used as a threshold for identifying when saturation occurs (i.e. point C of the Figure). When flows are at or approaching capacity, the flow is unstable and is effectively saturated.

Adding more traffic should not be considered at these times. The operational capacity is the point at which the flow becomes unstable. For the first iteration of the algorithm, a value of 90% of the maximum volume will be used to identify the corresponding occupancy being the critical threshold. This is shown in Figure 3.9.

Figure 3.8 Theoretical speed, flow (or volume) and density relationship



Source: Austroads Guide to Traffic Management Part 2 (Austroads 2015).

Departure-side detectors are considered to give the best indication as to whether an intersection is saturated. As the number of sites with departure-side detectors installed is limited, alternative measures which can complement departure-side detectors were investigated. This included arrival-side detectors and NPI average occupancy. As part of the analysis of this section, the reliability of the information shall be reviewed. This is to get an indication of which parameters should be used if there is conflicting information.

Once saturation levels have been identified, the traffic flow can be used in determining the spare capacity. If the road is saturated, then the operational capacity is the realised traffic flow. If saturation has not occurred, the spare capacity is the design capacity minus the observed traffic flow.

Design capacity, which is the theoretical capacity flow that the intersection can carry, can be defined in several ways. These include:

- maximum flow
- density
- speed.

Based on first principles, the following were reviewed and discussed:

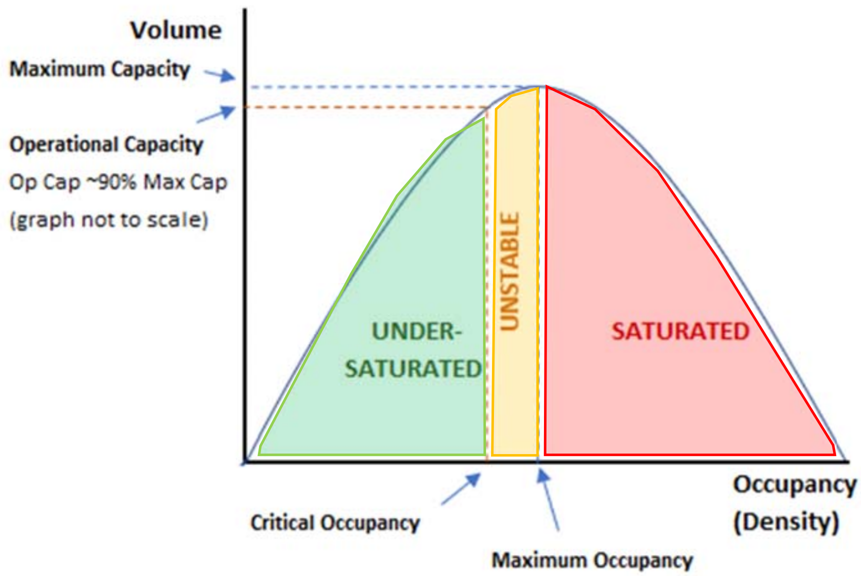
- Occupancy versus volume – Section 3.3.1
  - NPI average occupancy versus arrival volume
  - Arrival occupancy versus arrival volume
  - Departure occupancy versus arrival volume
- Speed versus occupancy – Section 3.3.2
  - Speed versus NPI average occupancy
  - Speed versus arrival occupancy
  - Speed versus departure occupancy
- Design capacity – Section 3.3.3
- Time series analysis – Section 3.3.4.

Occupancy versus occupancy was reviewed but did not provide a conclusive result. This has been provided for consideration in Appendix D.

3.3.1 OCCUPANCY VERSUS VOLUME

This section investigates the occupancy versus volume at signalised intersections. Occupancy versus volume provides a similar measure to the volume and density relationship as illustrated in Figure 3.9. This shows that there are different traffic states of the roadway for the same traffic volume, undersaturated and saturated. As the volume approaches the saturation point, this is considered to be unstable. The occupancy at which the maximum volume occurs will be reviewed as it gives an indication of when the traffic state turns from undersaturated to saturated. Using this volume, 90% of the maximum capacity shall be used to determine the critical occupancy, the point at which the traffic becomes unstable. This section aims to determine the value of occupancy at which the state change occurs. Site M5538, in the eastbound direction, was reviewed for occupancy versus volume. Appendix B provides the occupancy versus volume for additional sites with departure detectors along the same corridor in the eastbound direction.

Figure 3.9 Occupancy vs volume - sample graph



NPI Average Occupancy Versus Arrival Volume

This section looks at the NPI average occupancy against the arrival volume. The NPI average occupancy is reviewed as it gives the calculated occupancy for a site during the green time.

Reviewing the data for site M5538 in the eastbound direction at lane level provides different thresholds for volume and occupancy. Refer to Figure 3.8 for the layout of the site that was reviewed. Figure 3.10 represents the information for the Lane 1, Figure 3.11 shows the information for the Lane 2 and Figure 3.12 provides the information for the Lane 3. As NPI average occupancy is determined from all lanes representing the same movement on the arrival side, the same occupancy was used with the lane specific volume. In general, Figure 3.10, Figure 3.11 and Figure 3.12 demonstrate similar profiles in terms of NPI occupancy, which is not surprising considering the NPI occupancy is at link level. The graphs show that there is no clear envelope profile in the site shown below. There are slight variances in the envelopes drawn for volume and occupancy, which indicates that calibration should be undertaken at lane level.

Figure 3.10 Arrival volume vs NPI Average Occupancy - M5538 EB - Lane 1

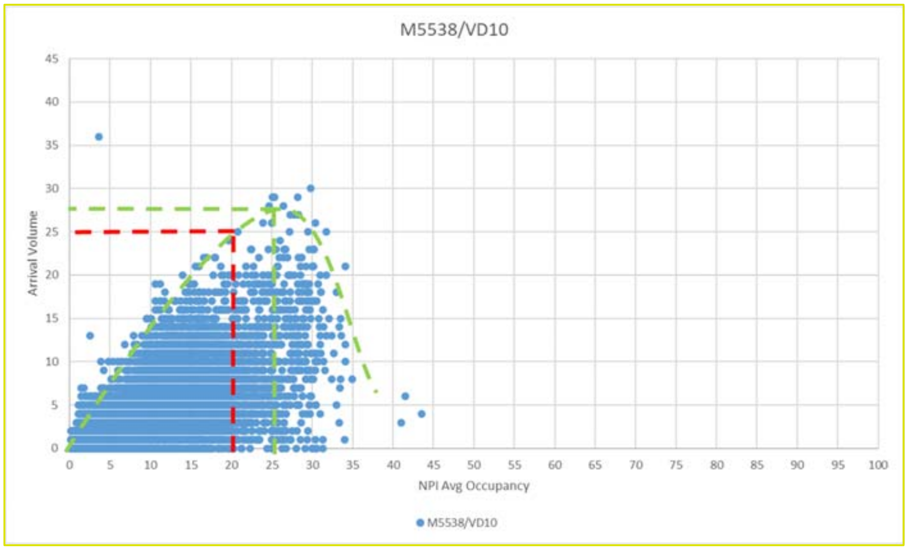


Figure 3.11 Arrival volume vs NPI Average Occupancy - M5538 EB - Lane 2

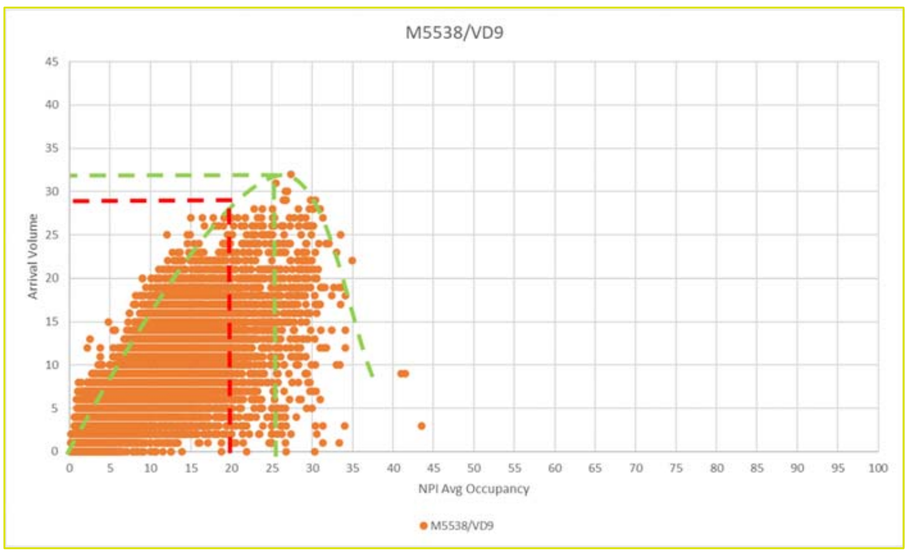


Figure 3.12 Arrival volume vs NPI Average Occupancy - M5538 EB - Lane 3

Based on the envelope for the occupancy versus volume from Figure 3.10 to Figure 3.12, the point in which the occupancy and volume changes from undersaturated to saturated was tabulated in Table 3.1. The point at which the site becomes unstable is also shown, using 90% of the volume, is shown in brackets. This indicates that the occupancy threshold is similar for each lane, with the volume generally increasing from outer lanes to inner lanes. It is believed that the threshold value for saturation would be more reliably determined if the process is automated using a longer period of data.

Table 3.1: Arrival volume vs NPI Average Occupancy - M5538 EB Threshold

Lane	Maximum flow (vehicles per minute)	Occupancy at maximum flow (%)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 1	28	25	25	20
Lane 2	32	25	29	20
Lane 3	41	25	37	20

Arrival Occupancy Versus Arrival Volume

This section illustrates the arrival occupancy against the arrival volume. The arrival occupancy is reviewed as arrival detectors are the most common detectors at sites.

Reviewing the data for site M5538 in the eastbound direction at lane level provides different thresholds for volume and occupancy. Refer to Figure 3.7 for the layout of the site that was reviewed. Figure 3.13 provides the information for the Lane 1, Figure 3.14 provides the information for the Lane 2 and Figure 3.15 provides the information for the Lane 3.

Figure 3.13 Arrival volume vs Arrival Occupancy - M5538 EB - Lane 1

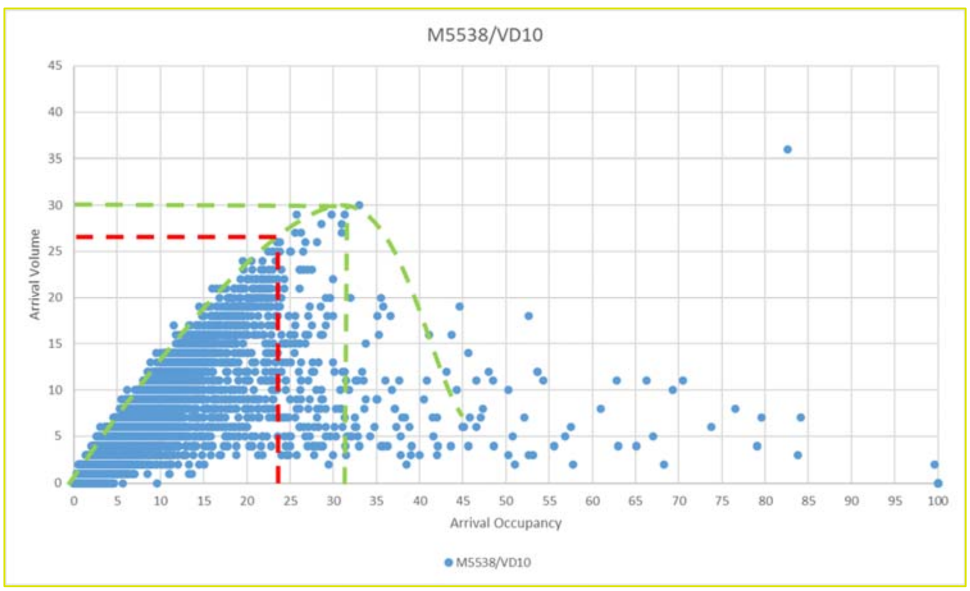


Figure 3.14 Arrival volume vs Arrival Occupancy - M5538 EB - Lane 2

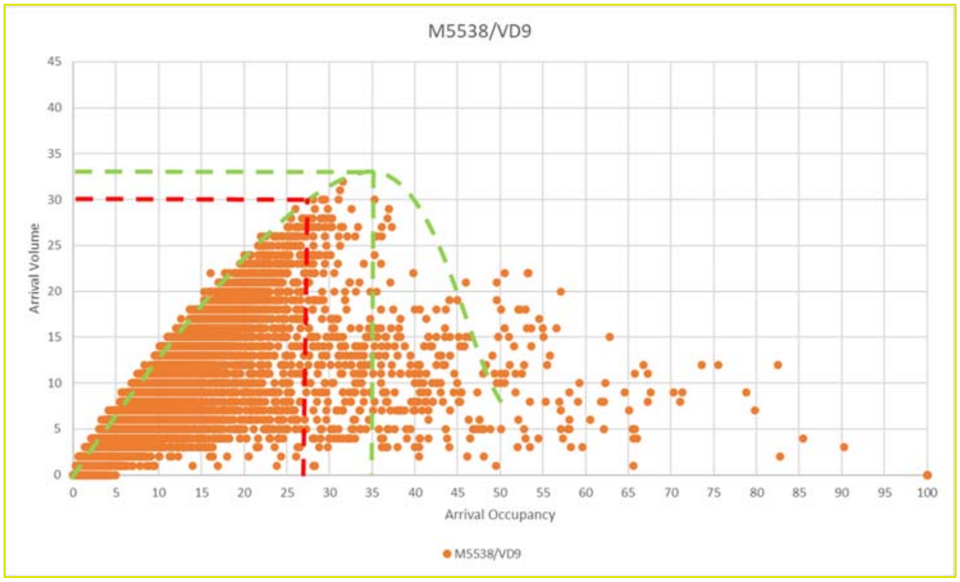
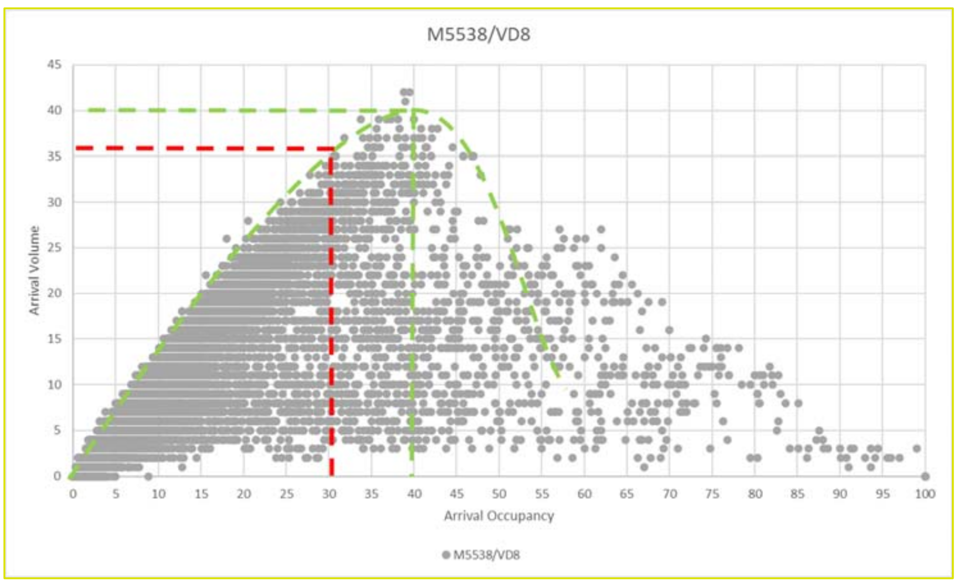


Figure 3.15 Arrival volume vs Arrival Occupancy - M5538 EB - Lane 3



Based on the envelope for the occupancy versus volume from Figure 3.13 to Figure 3.15, the point at which the occupancy and volume changes from undersaturated to saturated was tabulated in Table 3.2. The point at which the site becomes unstable is also shown, using 90% of the volume, is shown in brackets. Similar to the NPI occupancy versus volume, the volume increase from outer to inner lane. Unlike the NPI occupancy, the arrival occupancy also increases with the increase in volume. While there is no clear envelope shown, the cluster of points are tighter than the NPI occupancy versus volume. These differences may be due to the arrival occupancy being lane specific instead of an averaged value for the site.

Table 3.2: Arrival volume vs Arrival Occupancy - M5538 EB Threshold

Lane	Maximum flow (vehicles per minute)	Occupancy at maximum flow (%)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 1	30	32	27	24
Lane 2	33	35	30	27
Lane 3	40	40	36	30

Departure Occupancy Versus Arrival Volume

This section looks at the departure occupancy against the arrival volume. The departure occupancy is considered the most informative measure for congestion, as if the departure-side detector has a high occupancy, this is likely due to overspill. However, departure-side detectors are not commonly used at intersections.

Reviewing the data for site M5538 in the eastbound direction at lane level provides different thresholds for volume and occupancy. Refer to Figure 3.7 for the layout of the site that was reviewed. Figure 3.16 provides the information for the Lane 1, Figure 3.17 provides the information for the Lane 2 and Figure 3.18 provides the information for the Lane 3.

Figure 3.16 Arrival volume vs Departure Occupancy - M5538 EB - Lane 1

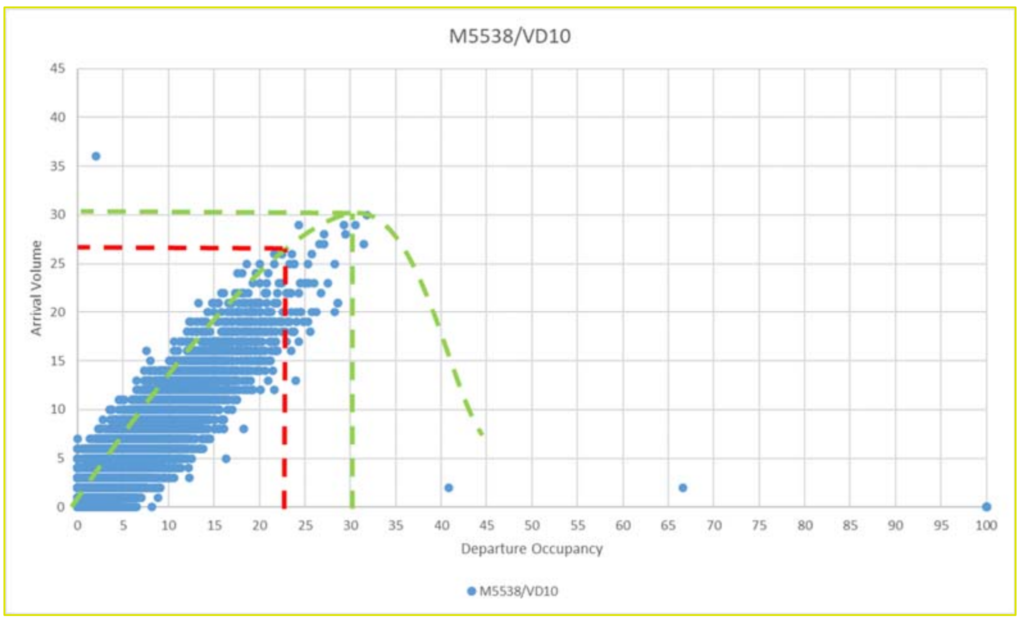


Figure 3.17 Arrival volume vs Departure Occupancy - M5538 EB - Lane 2

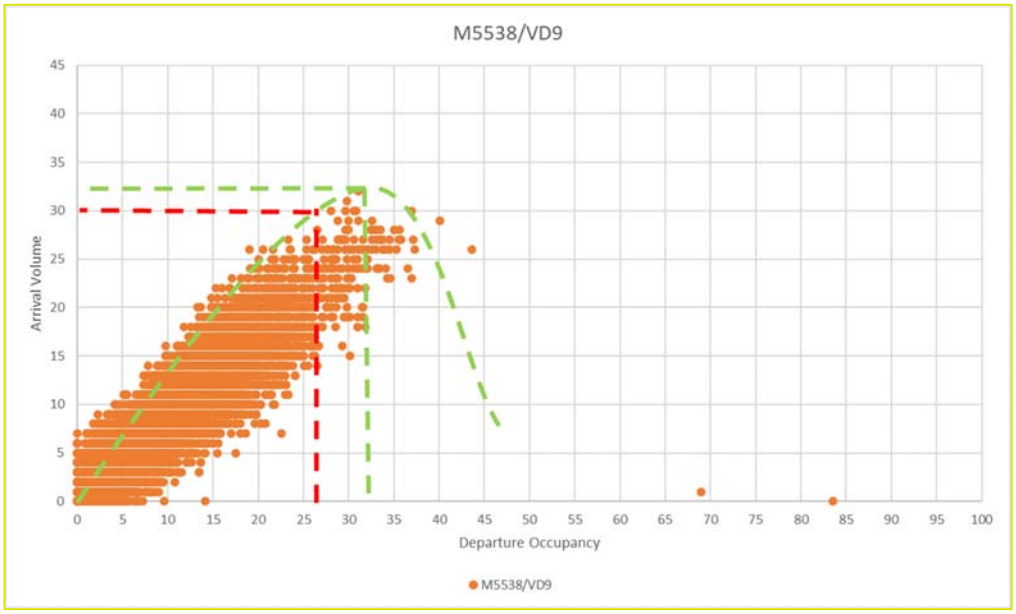


Figure 3.18 Arrival volume vs Departure Occupancy - M5538 EB - Lane 3

Based on the envelope for the occupancy versus volume from Figure 3.16 to Figure 3.18, the point at which the occupancy and volume changes from undersaturated to saturated was tabulated in Table 3.3. The point at which the site becomes unstable is also shown, using 90% of the volume, is shown in brackets. Similar to NPI average occupancy and departure occupancy, saturation occupancy and volume is higher for the inner lanes. The arrival occupancy versus volume has a relatively tight cluster of points. This indicates that there is little variability in the volume and occupancy. While the occupancy appears to be in line with arrival occupancy, the arrival volume should not be used in determining the maximum departure occupancy. The graphs show that there is vehicle flow when there is zero occupancy and vice versa. This highlights that the placements of the arrival and departure detectors are too far away from each other, with the arrival detector approximately 25 meters prior to the stop line and the departure detector 25 meters after the intersection and side street movements.

Table 3.3: Arrival volume vs Departure Occupancy - M5538 EB Threshold

Lane	Maximum flow (vehicles per minute)	Occupancy at maximum flow (%)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 1	30	30	27	23
Lane 2	33	32	30	26
Lane 3	40	35	36	28

Departure Occupancy vs Departure Volume

This section looks at using the departure volume, instead of arrival volume, when assessing the departure occupancy to determine if there is a difference when identifying the maximum occupancy. This is critical, as departure occupancy is considered the most informative measure for congestion. If the departure-side detector has a high occupancy, this is likely due to overspill. However, departure-side detectors are not commonly used at intersections.

Reviewing the data for site M5538 in the eastbound direction at lane level provides different thresholds for volume and occupancy. Refer to Figure 3.7 for the layout of the site that was reviewed. Figure 3.19 provides the information for the Lane 1, Figure 3.20 provides the information for the Lane 2 and Figure 3.21 provides the information for the Lane 3.

Figure 3.19 Departure volume vs Departure Occupancy - M5538 EB - Lane 1

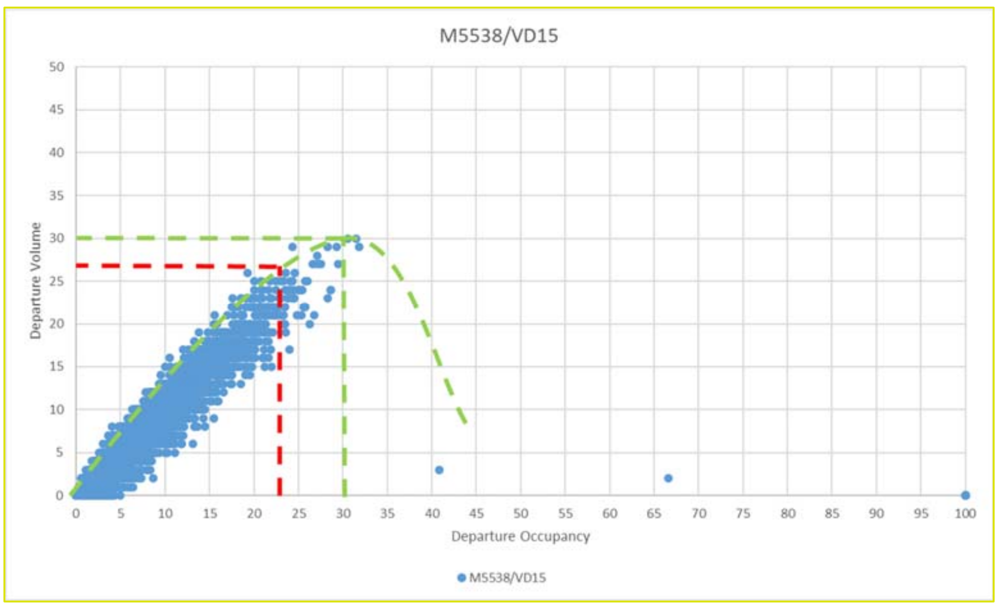


Figure 3.20 Departure volume vs Departure Occupancy - M5538 EB - Lane 2

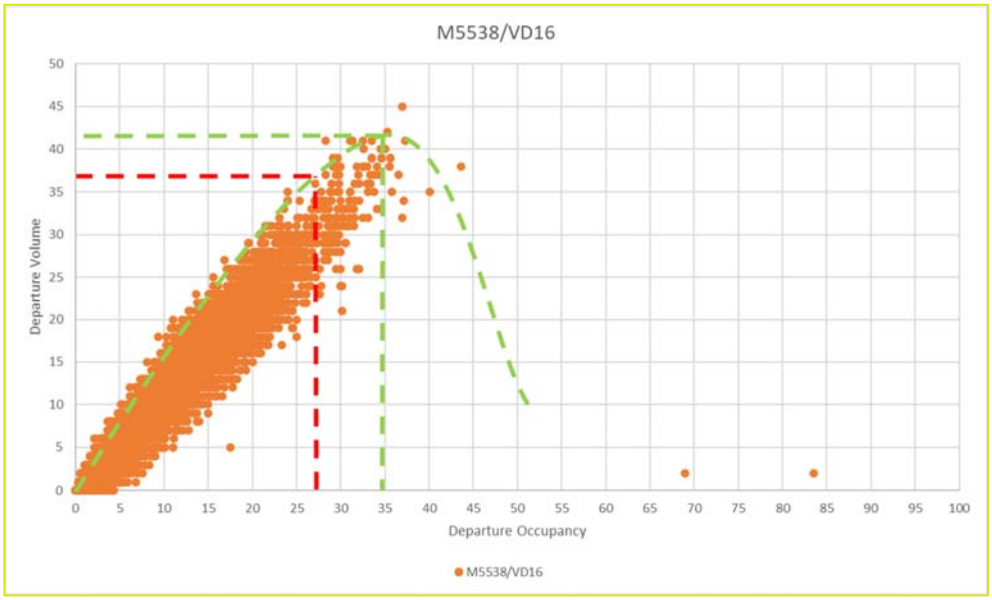
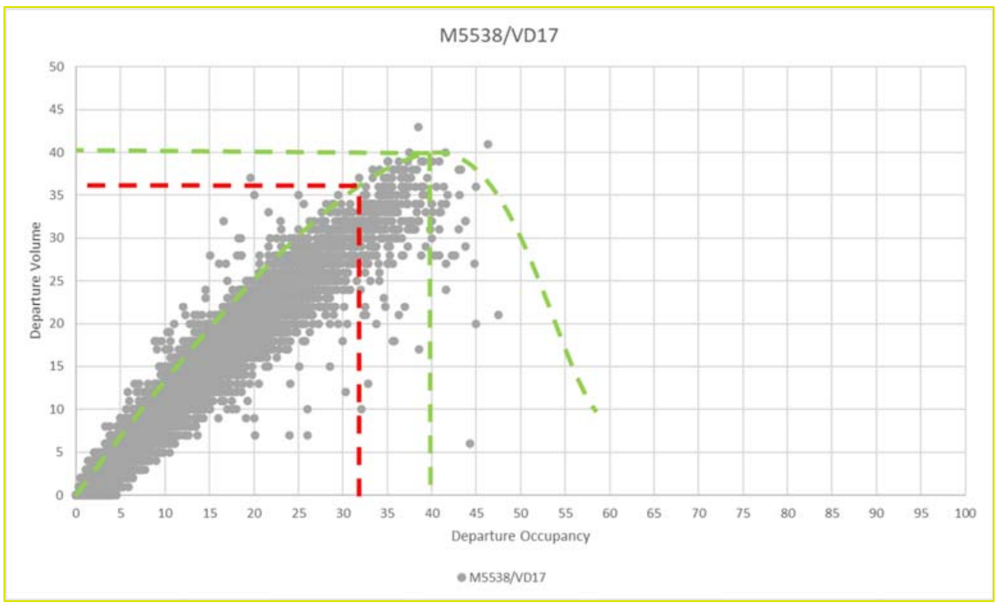


Figure 3.21 Departure volume vs Departure Occupancy - M5538 EB - Lane 3



Based on the envelope for the occupancy versus volume from Figure 3.19 to Figure 3.21, the point at which the occupancy and volume changes from undersaturated to saturated was tabulated in Table 3.4. The point at which the site becomes unstable is also shown, using 90% of the volume, is shown in brackets. The departure volume and occupancy thresholds for the detectors compared with the arrival volume and departure occupancy are different, with the occupancy generally being higher. The results of the departure volume and occupancy is more in line with the thresholds of the arrival occupancy and volume. Similar to the other occupancy vs volume graphs, the saturation occupancy and volume is higher for the inner lanes. There appears to be no clear envelope shown, but a relatively tight cluster of points. This indicates that there is some variability in the volume and occupancy.

Table 3.4: Departure volume vs Departure Occupancy - M5538 EB Threshold

Lane	Maximum flow (vehicles per minute)	Occupancy at maximum flow (%)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 1	30	30	27	23
Lane 2	41	35	37	27
Lane 3	40	40	36	32

3.3.2 SPEED VERSUS OCCUPANCY

This section looks at the speed versus occupancy relationship. This review is to confirm that the occupancy is increasing as the speeds decrease, which is what should be happening based on first principles. A review of site M5538 indicates that the speed limit for the segment is 70 km/h. The Bluetooth link is noted to start and finish at intersections either side of the site. This means that the speed is representative of the arrival and departure speed.

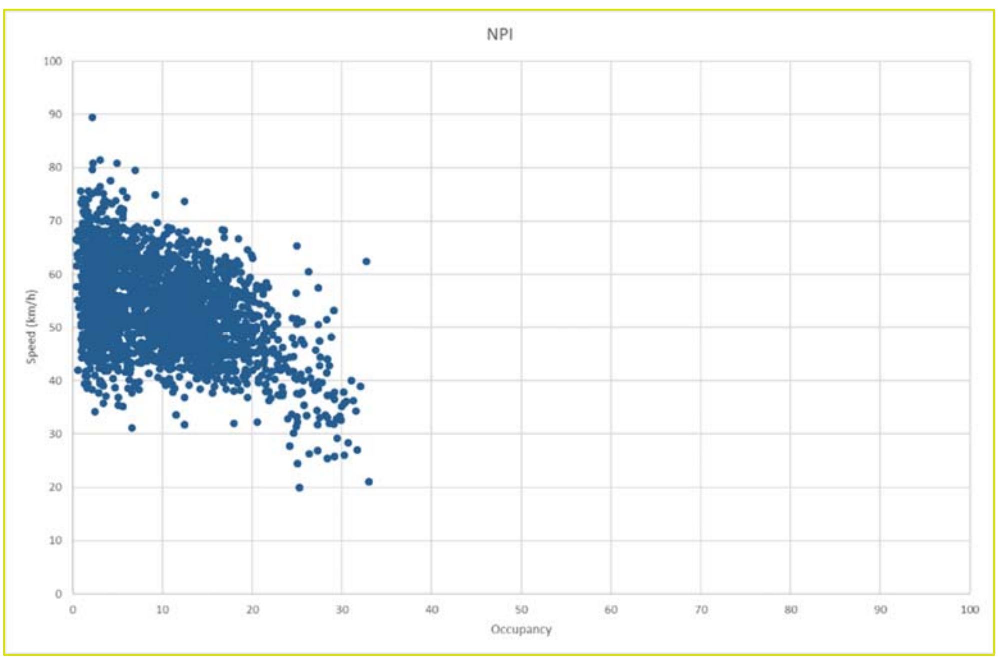
This section is broken up into:

- Speed versus NPI average occupancy
- Speed versus arrival occupancy
- Speed versus departure occupancy
- Speed versus occupancy line of best fit.

Speed versus NPI Average Occupancy

Figure 3.22 shows the relationship between the speed and the NPI average occupancy. The trend of the data is consistent with what is expected, in that occupancy increases as speed reduces. It is noted that the Bluetooth data is averaged for every 5 minutes, while the NPI average occupancy is per cycle. This means that the points only occur when the Bluetooth data aligns with the NPI average occupancy. As both values are site level, this may be why there is a good relationship between the values, with minimal outliers.

Figure 3.22 Speed vs NPI Average Occupancy - M5538 EB



Speed versus Arrival Occupancy

This section looks at the lane level speed versus arrival occupancy. Figure 3.23 shows the relationship on the Lane 1, Figure 3.24 shows the relationship on the Lane 2 and Figure 3.25 shows the relationship on the

Lane 3. The trend of the data is consistent with what is expected, in that occupancy increases as speed reduces. The occupancy tends to increase from the outer to inner lanes. This is likely due to a higher volume of vehicles getting through. The points with an occupancy greater than 30% appear to be outliers. This may be due to the data having different granularity, with the occupancy data being in 1-minute intervals while the speed data is in 5-minute intervals.

Figure 3.23 Speed vs Arrival Occupancy - M5538 EB - Lane 1

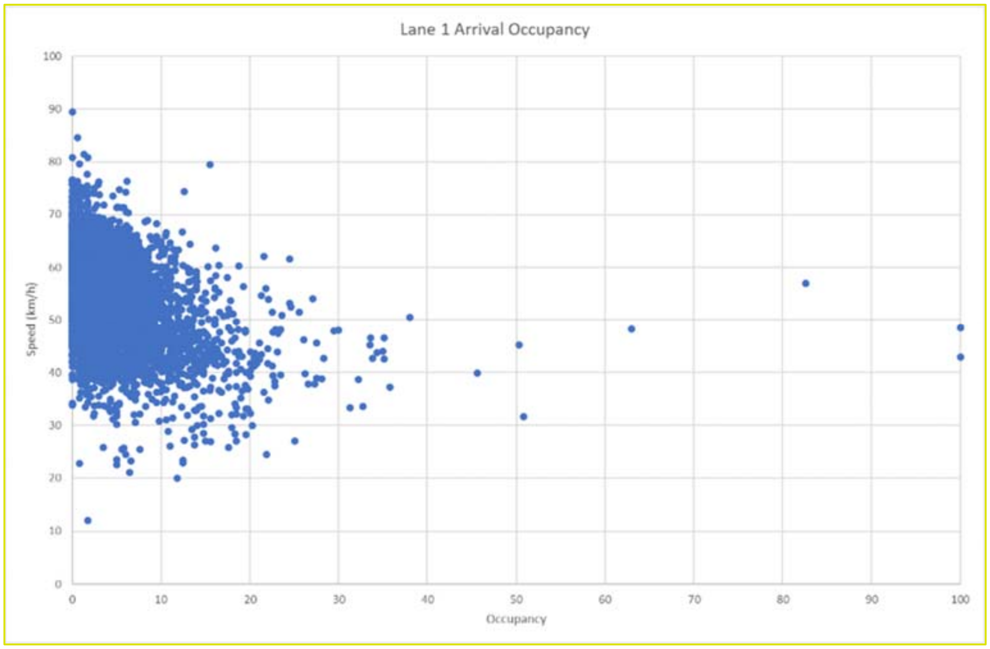


Figure 3.24 Speed vs Arrival Occupancy - M5538 EB - Lane 2

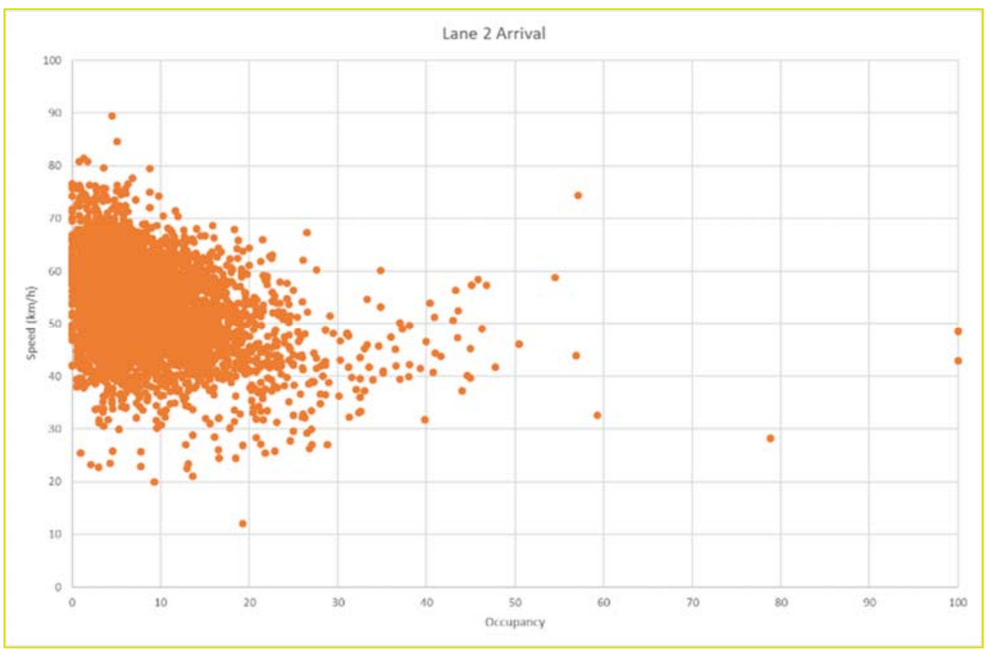
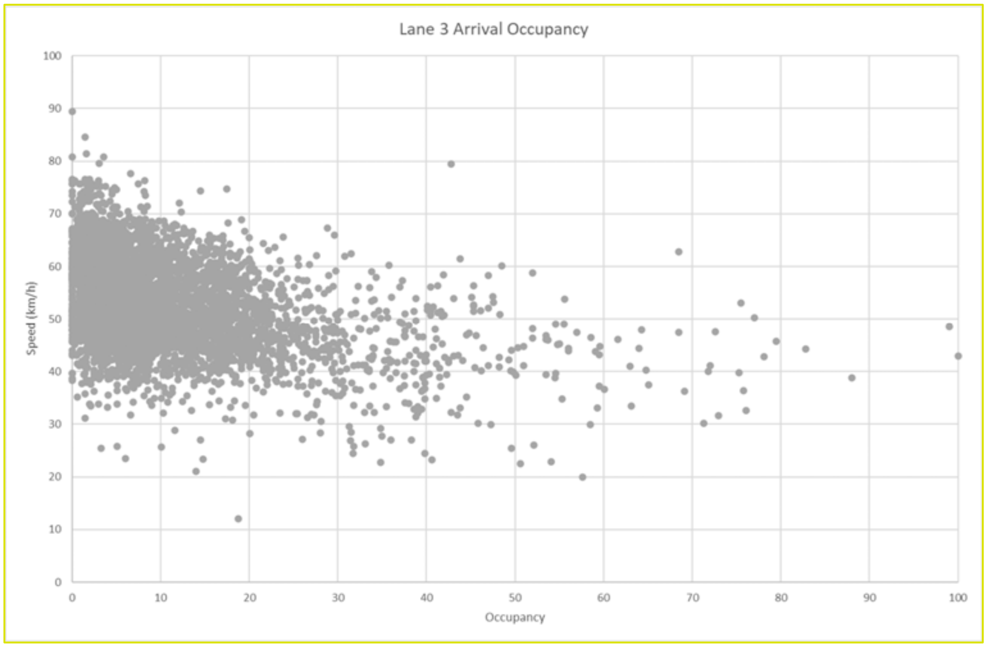


Figure 3.25 Speed vs Arrival Occupancy - M5538 EB - Lane 3



Speed versus Departure Occupancy

This section looks at the lane level speed versus departure occupancy. Figure 3.26 shows the relationship on the Lane 1, Figure 3.27 shows the relationship on the Lane 2 and Figure 3.28 shows the relationship on the Lane 3. The trend of the data is consistent with what is expected, in that occupancy increases as speed reduces. Similar to the arrival occupancy, the departure occupancy tends to increase from the outer to the inner lanes. This is likely due to a higher volume of vehicles getting through. Similar to the arrival occupancy, the points with a departure occupancy greater than 30% appear to be outliers. This may be due to the data having different granularity, with the occupancy data being 1-minute intervals while the speed data is 5-minute intervals.

Figure 3.26 Speed vs Departure Occupancy - M5538 EB - Lane 1

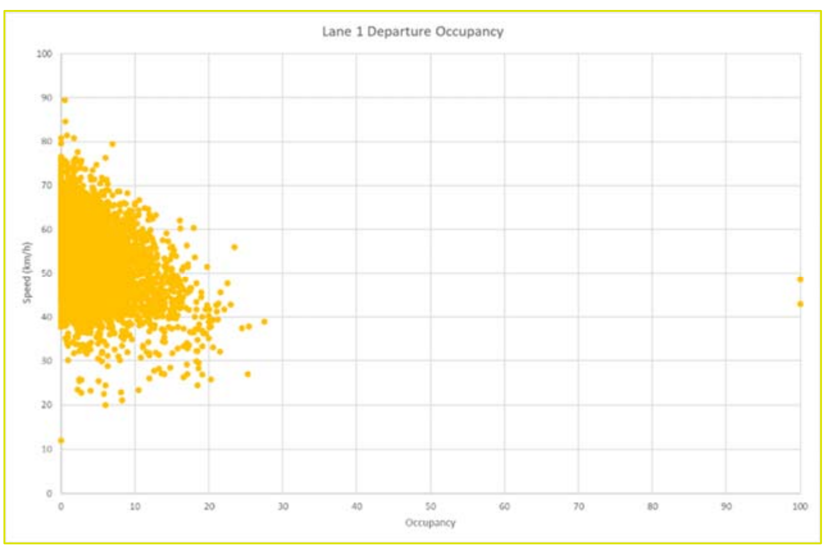


Figure 3.27 Speed vs Departure Occupancy - M5538 EB - Lane 2

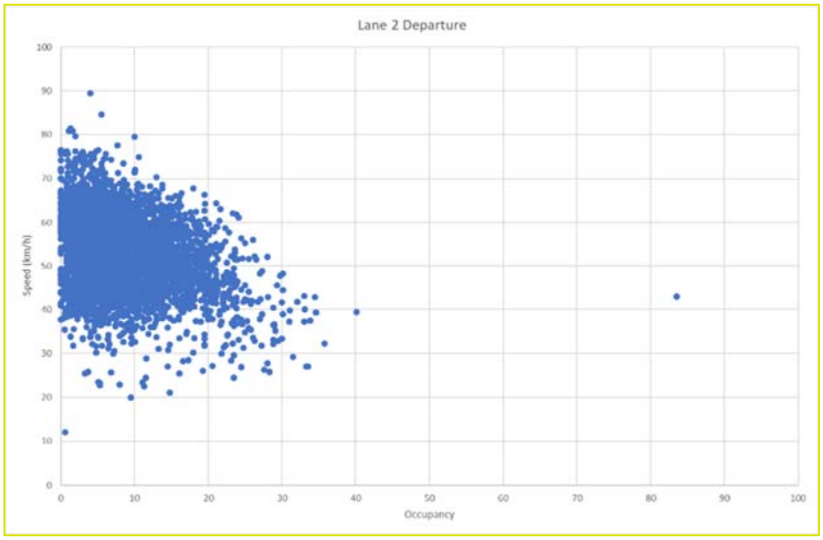
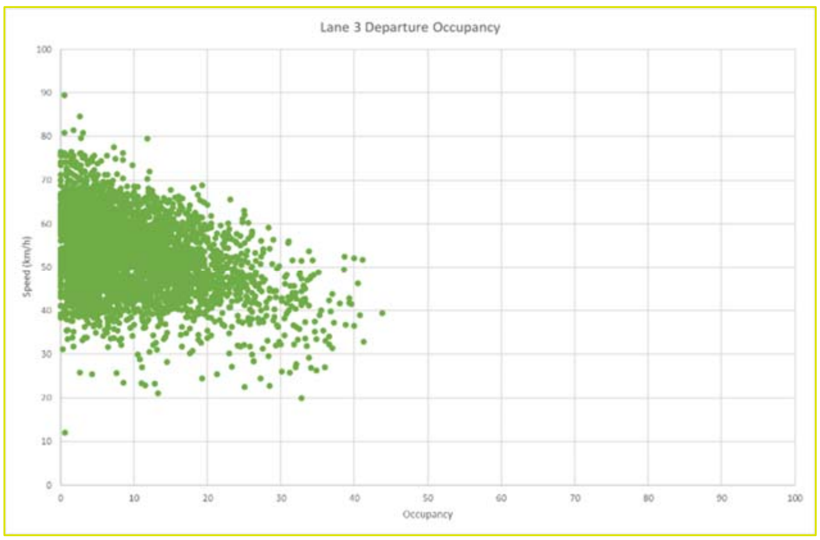


Figure 3.28 Speed vs Departure Occupancy - M5538 EB - Lane 3



Speed versus Occupancy Line of Best Fit

Figure 3.29 shows the line of best fit for the speed versus occupancy graphs, based on Figure 3.22 to Figure 3.28 using a polynomial of 2. These figures show that there is a tight cluster of points until approximately 30% occupancy, after which there are minimal speed and occupancy points. It is noted that speed and NPI occupancy have a good relationship, which may be due to the similarities of the data (i.e. both are presented at the approach level instead of lane by lane and having similar time frequencies). Figure 3.30 shows the line of best fit for the same graphs, with the occupancy values not in the cluster removed. This was generally when the occupancy was greater than 30%. It is noted that the line of best fit for two of the arrival lanes did not follow the relationship of the first principles. This includes some of the curves with an upward trend. This is likely due to the occupancy including red time and the speed data being of different granularity to the occupancy data and speed outliers.

Figure 3.29 Speed vs Occupancy - M5538 EB - Line of Best Fit (x^2)

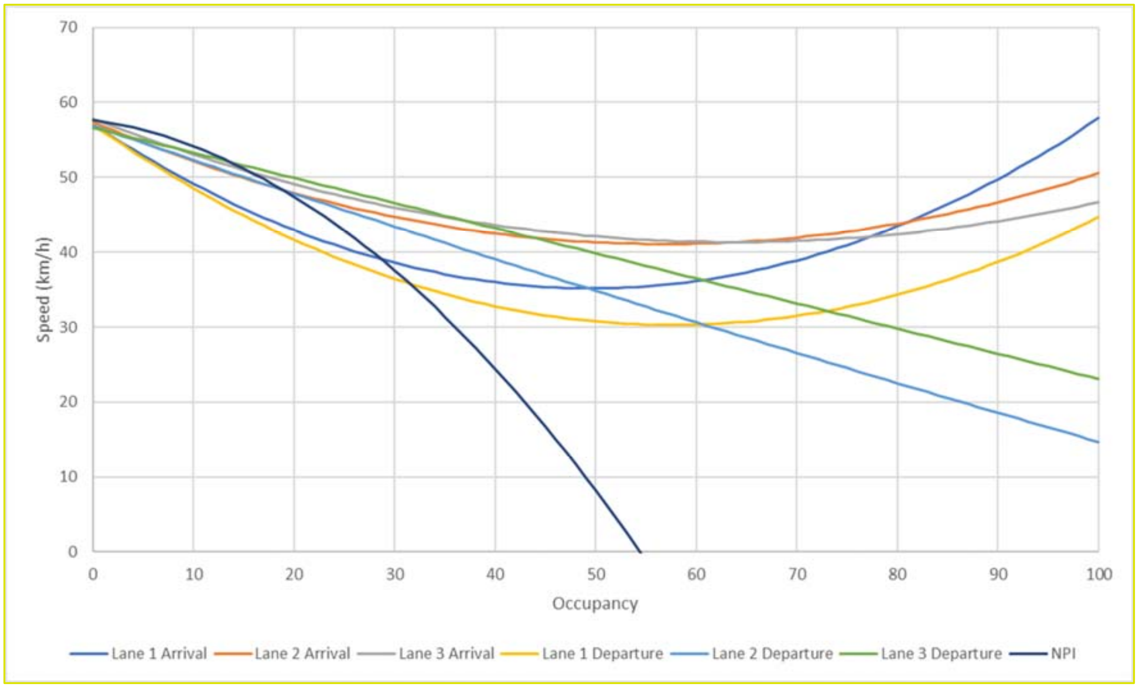
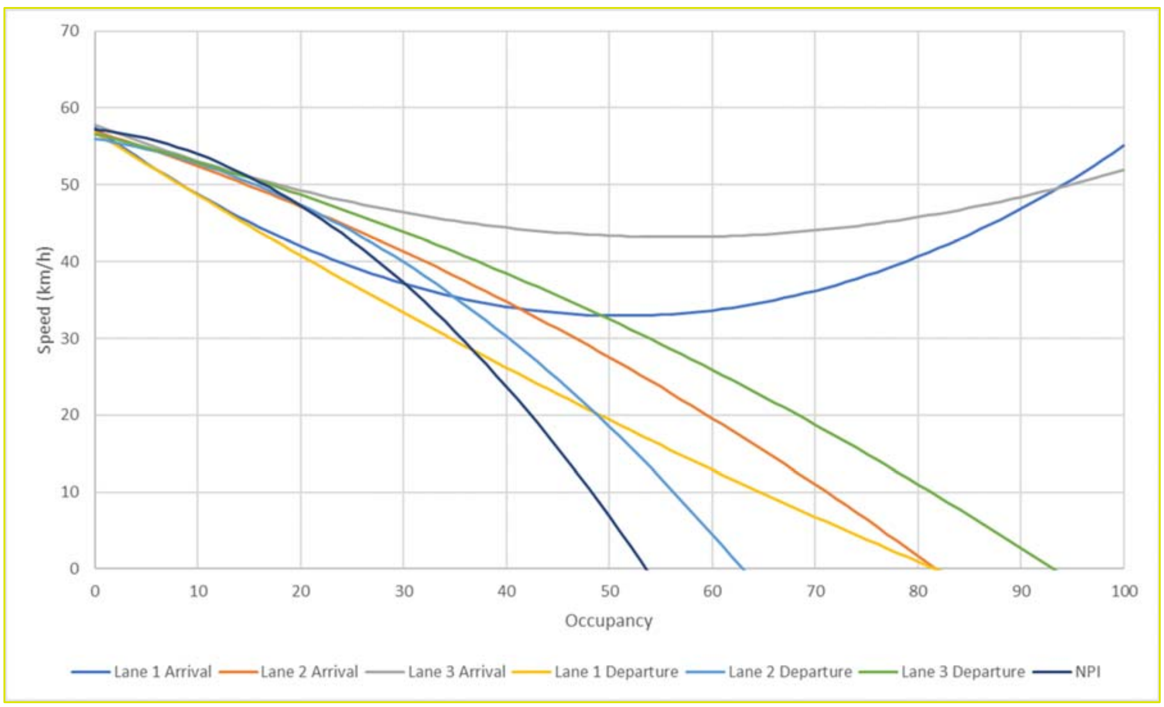


Figure 3.30 Speed vs Occupancy - M5538 EB - Line of Best Fit (x^2) - outliers removed



3.3.3 DESIGN CAPACITY

To get an indication of the design capacity for a road, the Highway Capacity Manual (HCM, Transportation Research Board 2016) and Austroads Guide to Traffic Management (2017) were referenced. Once it is determined whether the road is saturated or undersaturated, the design capacity can be used as a baseline to determine if there is spare capacity on the road, compared to the realised flow of traffic. If the road is saturated, this will mean that the operational capacity is the realised flow of traffic, with no spare capacity. If the road is undersaturated, then the design capacity can be compared with the realised flow to determine the magnitude of spare capacity.

Highway Capacity Manual

A review of the *Highway Capacity Manual* (2016) indicates that capacity is based on the saturation flow rate, the percentage cycle time and number of lanes. This is then adjusted based on factors such as the lane width, approach grade, vehicle types and parking. The formula for capacity is shown in equation (**1**):

$$c = Nsg/C \quad \textbf{1}$$

where

c	=	the capacity, in vehicles per hour
N	=	number of lanes
s	=	the saturation flow rate, in vehicles per hour
g	=	the effective green time per cycle that is available for the movement, in seconds
C	=	the cycle time, in seconds

The base saturation flow in pc/h/ln is 1,900 for metropolitan area with population ≥ 250,000, otherwise pc/h/ln is 1,750.

Base saturation flow must be adjusted for various factors, which is shown in equation (**2**):

$$s = s_o f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} \quad \textbf{2}$$

where

s	=	the estimated saturation flow in vehicles per hour
s_o	=	the base saturation flow in pc/h/ln
f_w	=	lane width factor
f_{HV}	=	heavy vehicle factor
f_g	=	gradient factor
f_p	=	parking lane factor
f_{bb}	=	bus blocking effect factor
f_a	=	area type factor
f_{LU}	=	lane utilisation factor
f_{LT}	=	left turn factor
f_{RT}	=	right turn factor
f_{Lpb}	=	pedestrian for left-turns factor
f_{Rpb}	=	pedestrian-bicycle for right-turn factor

The factors used as part of the calculation for base saturation flow provides an in-depth calibration of the estimated saturated flow. In practice, the factors are based on the judgement of the practitioner, which can lead to different capacities for the same intersection. Simplistically, the capacity for an intersection is based on the saturation flow, the number of lanes and the percent of effective green time.

Austroads

The method for determining capacity for an intersection was undertaken using Austroads literature. A review of *Austroads Guide to Traffic Management, Part 3: Traffic Studies and Analysis* (Austroads 2017) in the section regarding interrupted traffic flows at signalised intersections found that the method undertaken by Austroads is similar to that of the HCM, which is a saturation flow rate with adjustment factors.

Equations (**3**) and (**4**) show the capacity formulae based on Austroads (2017).

$$C=Sg/c \qquad (3)$$

where

C	=	the capacity, in vehicles per hour
S	=	the saturation flow rate, in vehicles per hour
g	=	the effective green time per cycle that is available for the movement, in seconds
c	=	the cycle time, in seconds

The base saturation flow in through-car units per hour (tcu/h) is 1850 for through lanes, 1810 for mixed through and turning.

Adjustment base saturation flow must be adjusted for various factors as shown in equation (**4**):

$$C = f_w f_g S_b (g/c)/f_c \qquad (4)$$

where

S_b	=	the base saturation flow in tcu/ln
f_w	=	lane width factor
f_g	=	gradient factor
f_c	=	traffic composition factor

The lane width factor, w, is as follows:

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

For a varying lane width, use the width at the narrowest point within 30 m of the stop line. The exit lane must be at least as wide as the approach lane – if it is narrower use its width.

The gradient factor is given by equation (**5**):

$$f_g = 1 \pm 0.5(per\ cent\ gradient)100 \qquad (5)$$

with + being for a down grade, and – for an upgrade.

The traffic composition factor is given by equation (**6**):

$$f_c = \sum e_i Q_i / Q \qquad (6)$$

where

Q_i	=	flow in vehicles per hour per vehicle type and movement
Q	=	total movement flow in vehicles per hour
e_i	=	through-car equivalent of vehicle traffic and movement (1 for cars, 2 for heavy vehicles)

Using site 5538 as an example and a green to cycle ratio of 0.85, the capacity can be calculated as shown in equation (**7**).

$$C = (f_w f_g S_b / f_c) 0.85 \qquad \mathbf{7}$$

where

f_w	=	0.83 + 0.05*4 = 1.03
f_g	=	1 (assume 0 grade)
S_b	=	1850
f_c		1 (assumption)
C		1905 tcu/h * 0.85 = 1619 tcu/h

It is noted that the saturation flow rate of 1850 tcu/h is slightly higher than that suggested in Stage 1 (Espada 2019), which was 1,700 veh/h per lane.

Simplistically, a saturation flow rate with the percentage green time can be used to identify the design capacity of an intersection.

3.3.4 TIME SERIES ANALYSIS

Using the thresholds gained from the occupancy versus volume, this section looks at the time-series for site M5538, identifying where the thresholds have been exceeded for a single day. The day used in the analysis is 14 March 2019. This section looks at time-series using different time intervals of data. This includes:

- 1-minute frequency
- Average of 5-minute frequency
- 1-minute frequency with rolling average of 5-minutes.

1-minute frequency

Figure 3.31 shows the time-series graph for the Lane 3. Lane 2 and Lane 1 show similar trends and are provided in Appendix C.1. Figure 3.32 shows the time-series graph with the volume and speed.

Each graph shows:

- NPI average occupancy (%, per cycle)
- arrival occupancy (%, per minute)
- departure occupancy (%, per minute)
- arrival volume (vehicle, per minute)
- speed (km/h, per 5-minutes)
- NPI occupancy maximum threshold (%)
- arrival occupancy maximum threshold (%)
- departure occupancy maximum threshold (%).

The morning time period was highlighted to allow for easier review, as it was noted to generally have higher volume and occupancy during this period. The graphs show that the speed drops at around 8:30 am. At the same point in time, the NPI average occupancy exceeds the maximum threshold for an extended period of time. The arrival occupancy threshold is exceeded in this same time period for lane 3, but not for a sustained period. Figure 3.32 shows the speed and volume for the same time period. This shows that there is no identifiable decrease in volume at the time period in which the speed drops. Review of video data may be required to determine whether saturation occurred during these time periods. Reading the time-series with 1-minute intervals can be hard due to the high variability of the granular data. A sustained average of data may give a better indication. It is noted that the maximum threshold was used, more time periods would be saturated using the critical threshold.

Figure 3.31 Time series analysis - M5538 EB - Lane 3 - 1-Minute

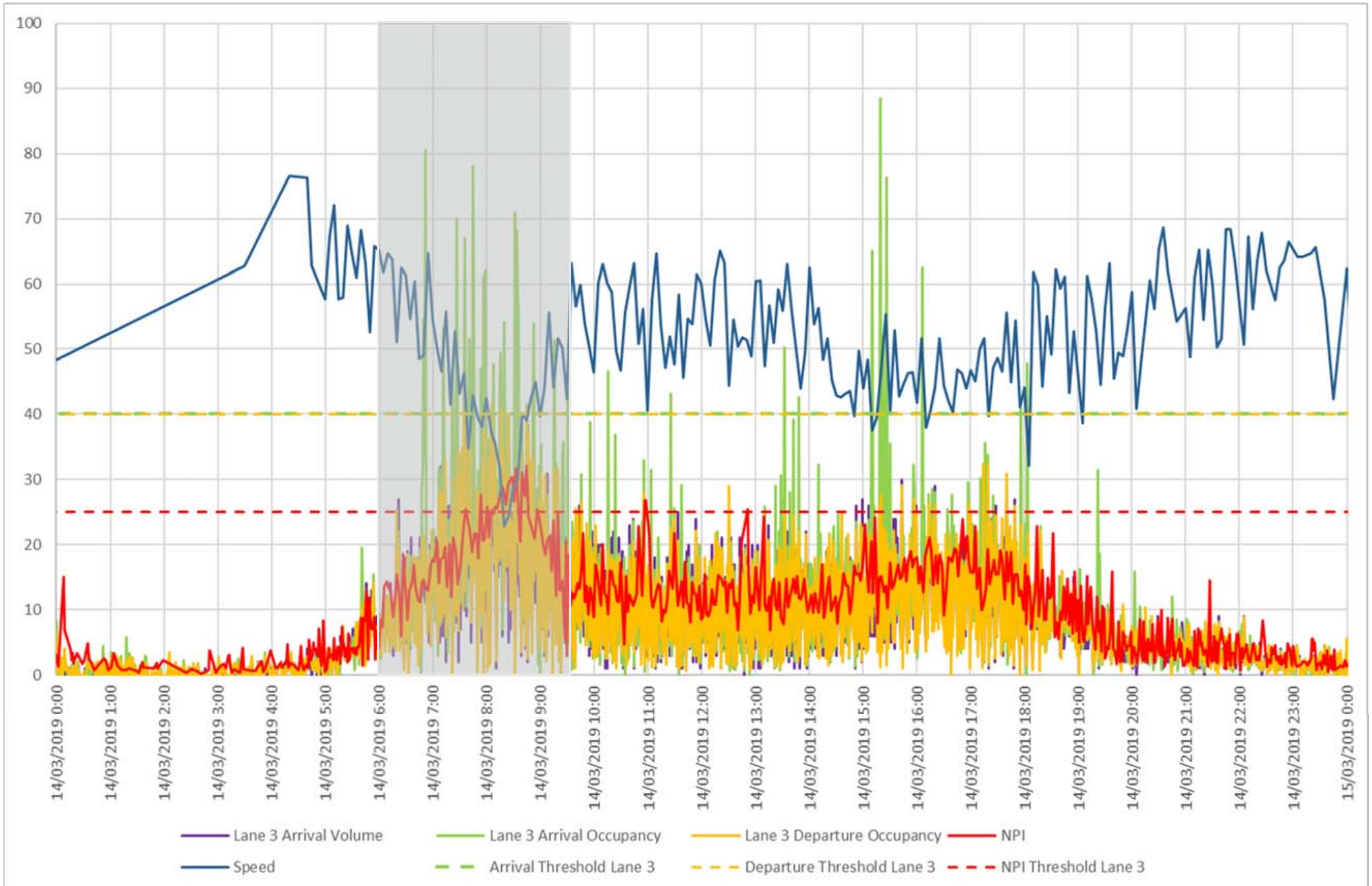


Figure 3.32 Time series analysis - M5538 EB - Lane 3 - 1-Minute - Speed and Volume

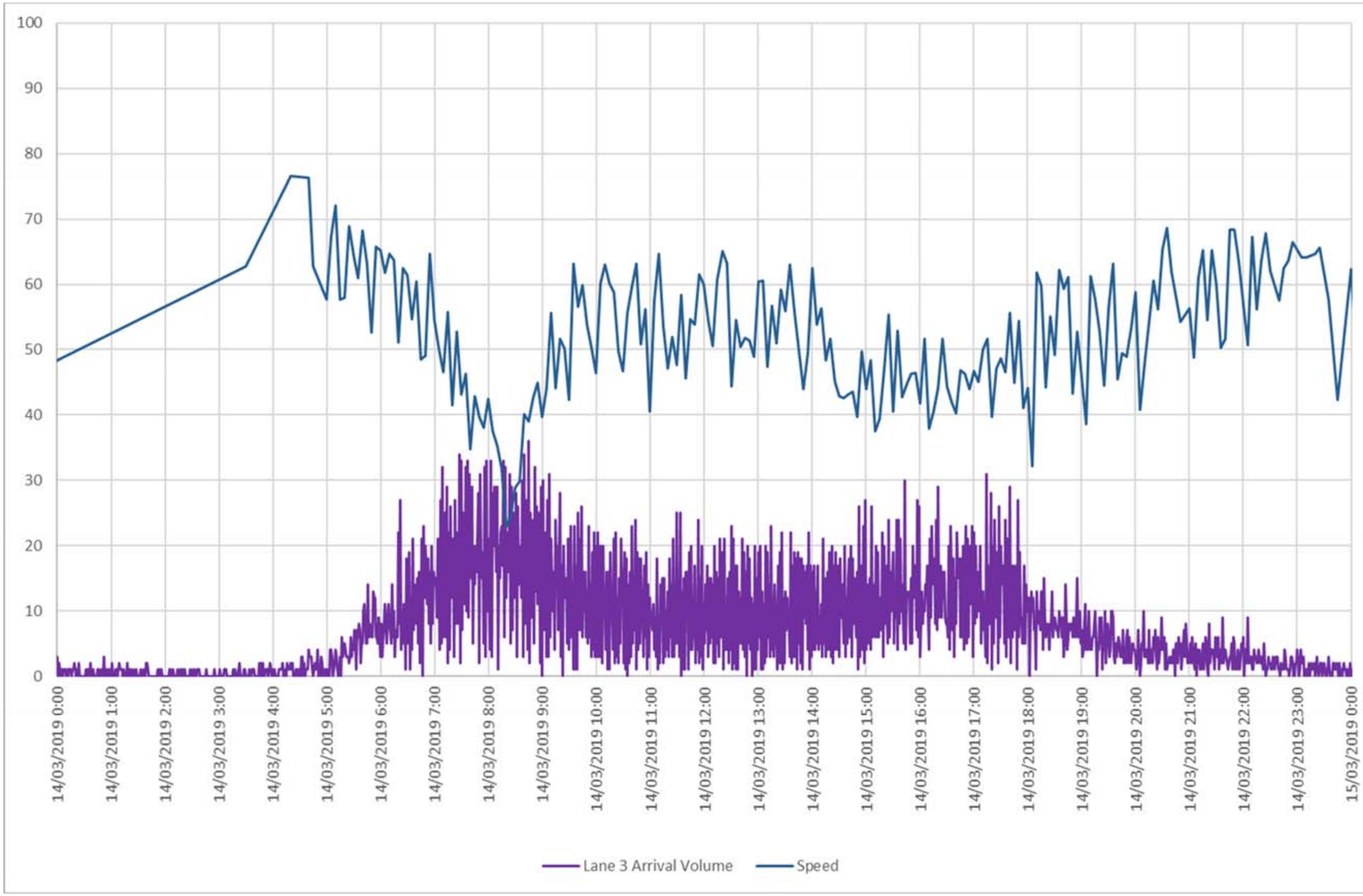


Figure 3.33 shows the 1-minute interval time-series for the volume and occupancy for lane 3, as shown in Figure 3.31, during the morning intersection plan (between 6am and 9:30am). Figure 3.34 to Figure 3.36 provides a time-step of the volume versus occupancy for the morning peak period. The NPI Occupancy does not clearly show a relationship between the excessive occupancy and volume. The arrival and departure occupancy give a clearer indication, with the volume decreasing as the occupancy exceeds the threshold. It is noted that there is not a clear indication of whether the site is fully saturated, as the saturation clears within a few minutes. This may indicate that the site is not fully saturated. The graphs for lane 2 and lane 1 are shown in Appendix C.4.

Figure 3.33 Time series analysis - M5538 EB - Lane 3 - 1-Minute - Morning Peak

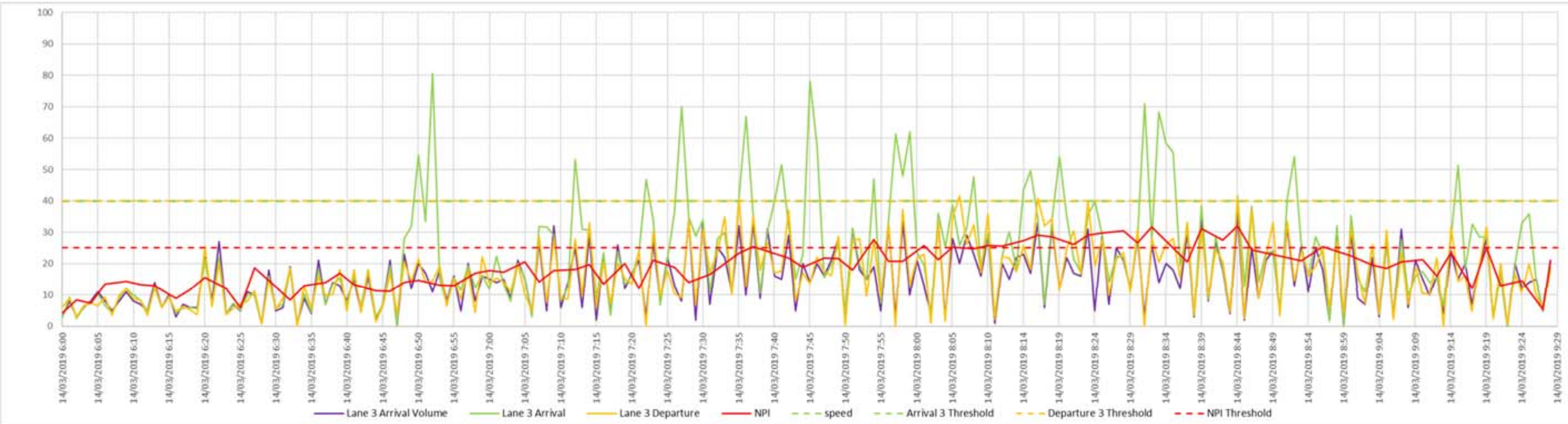


Figure 3.34 Arrival volume vs NPI Average Occupancy - M5538 EB - Lane 3 - Morning Peak Time Step

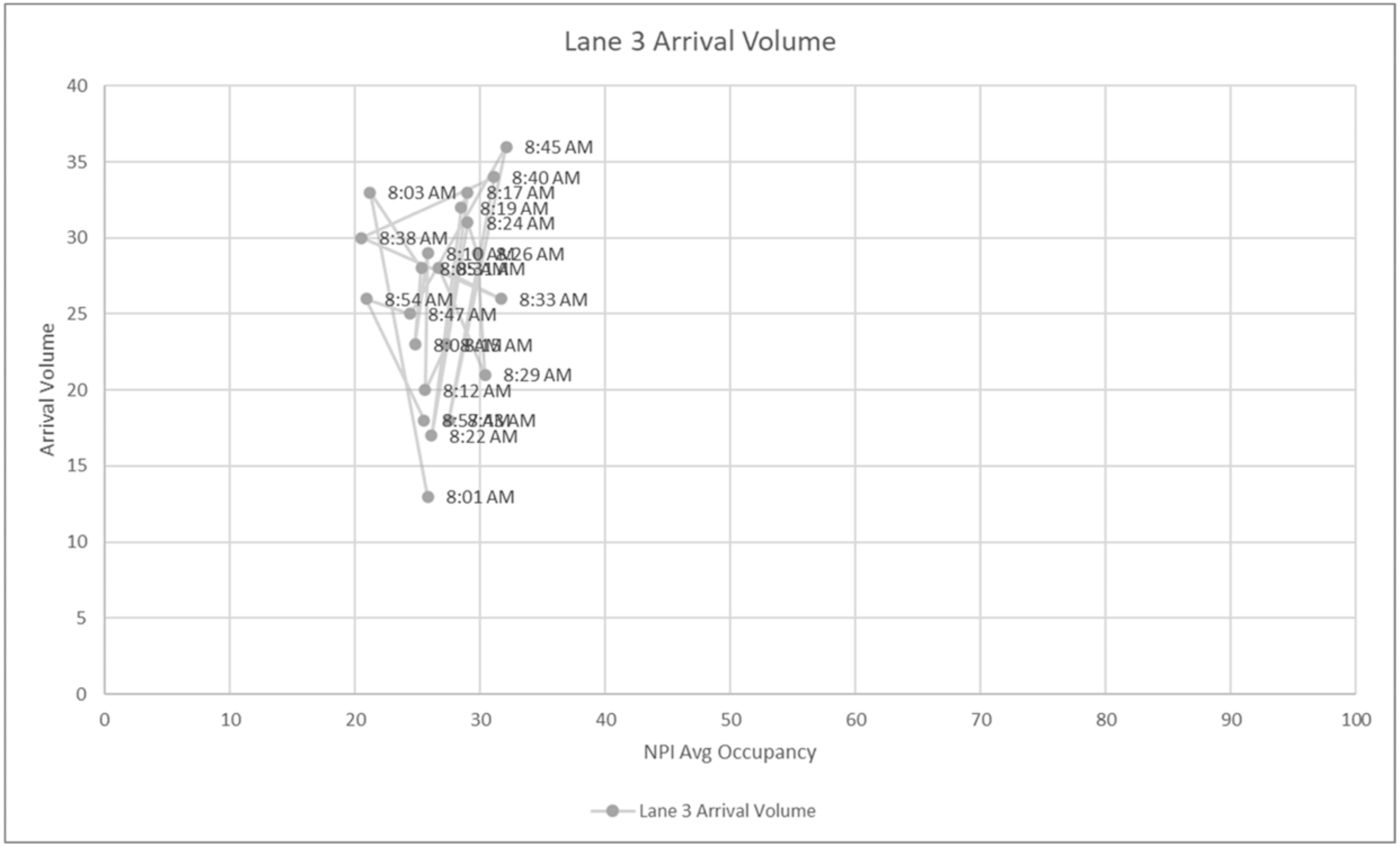


Figure 3.35 Arrival volume vs Arrival Occupancy - M5538 EB - Lane 3 - Morning Peak Time Step

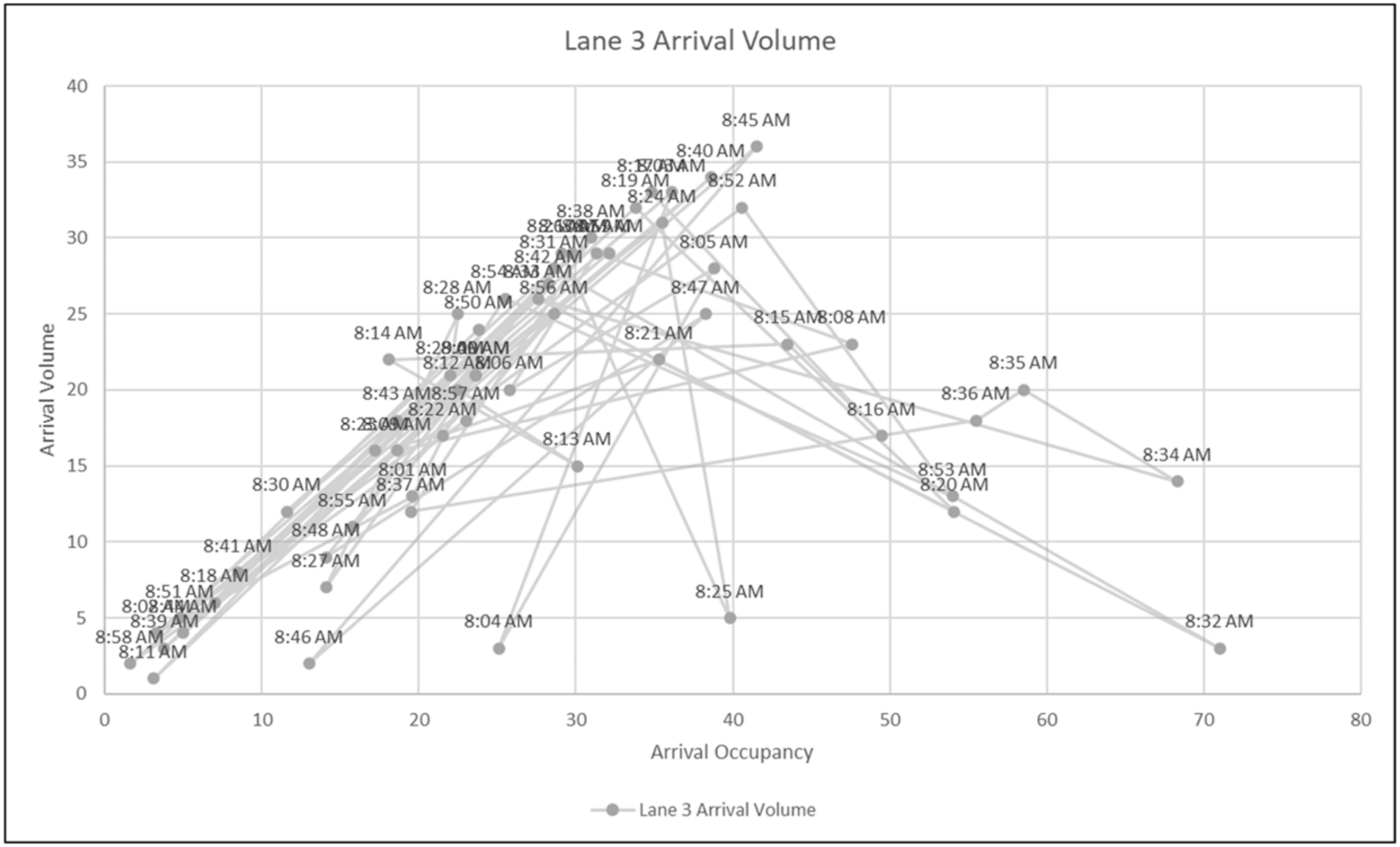
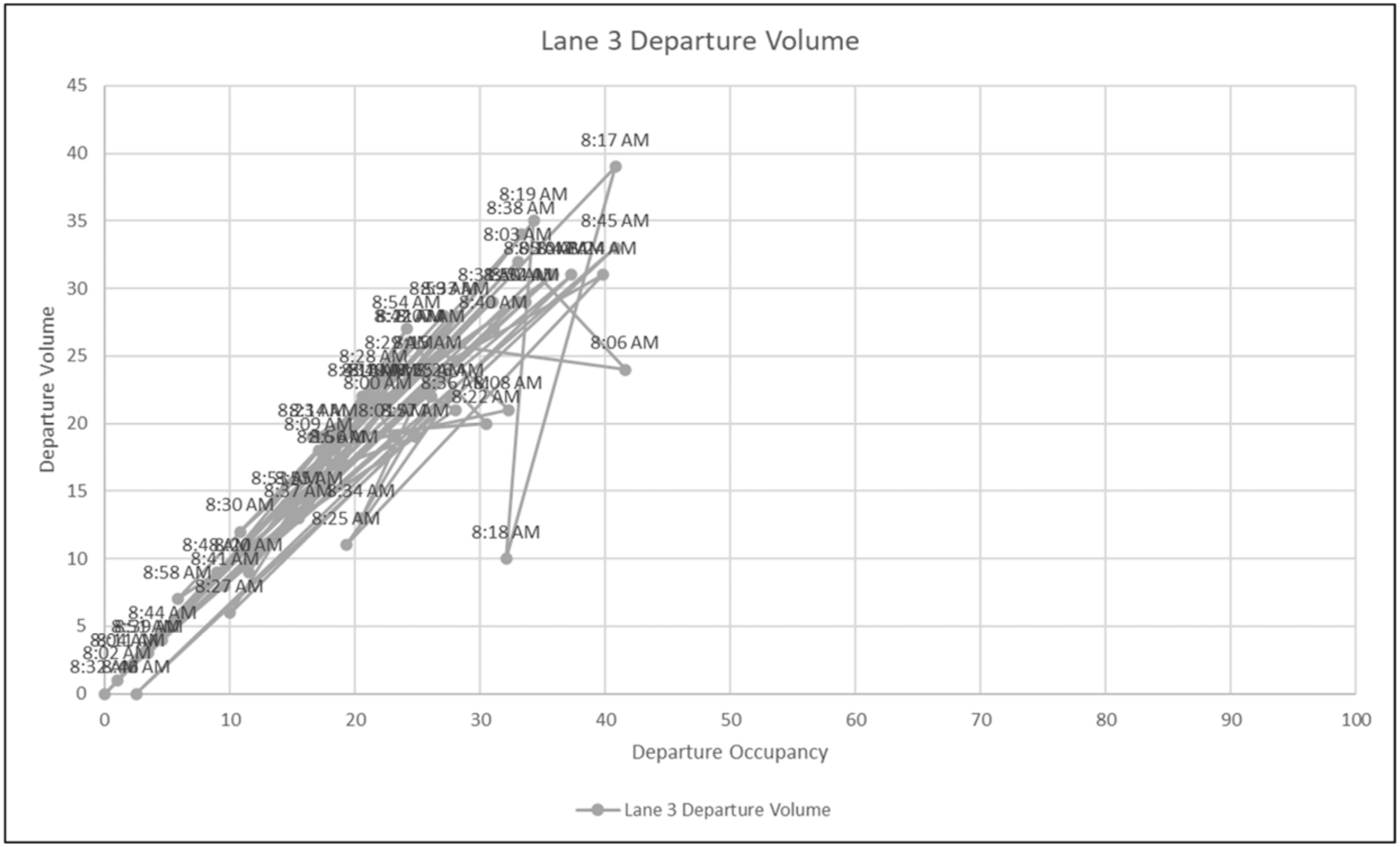


Figure 3.36 Departure volume vs Departure Occupancy - M5538 EB - Lane 3 - Morning Peak Time Step



Average of 5-minute frequency

Due to data changing minute by minute, the 5-minute data was reviewed for the same date range. Figure 3.37 shows the time-series graph for the Lane 3. Lane 2 and Lane 1 show similar trends and are provided in Appendix C.2.

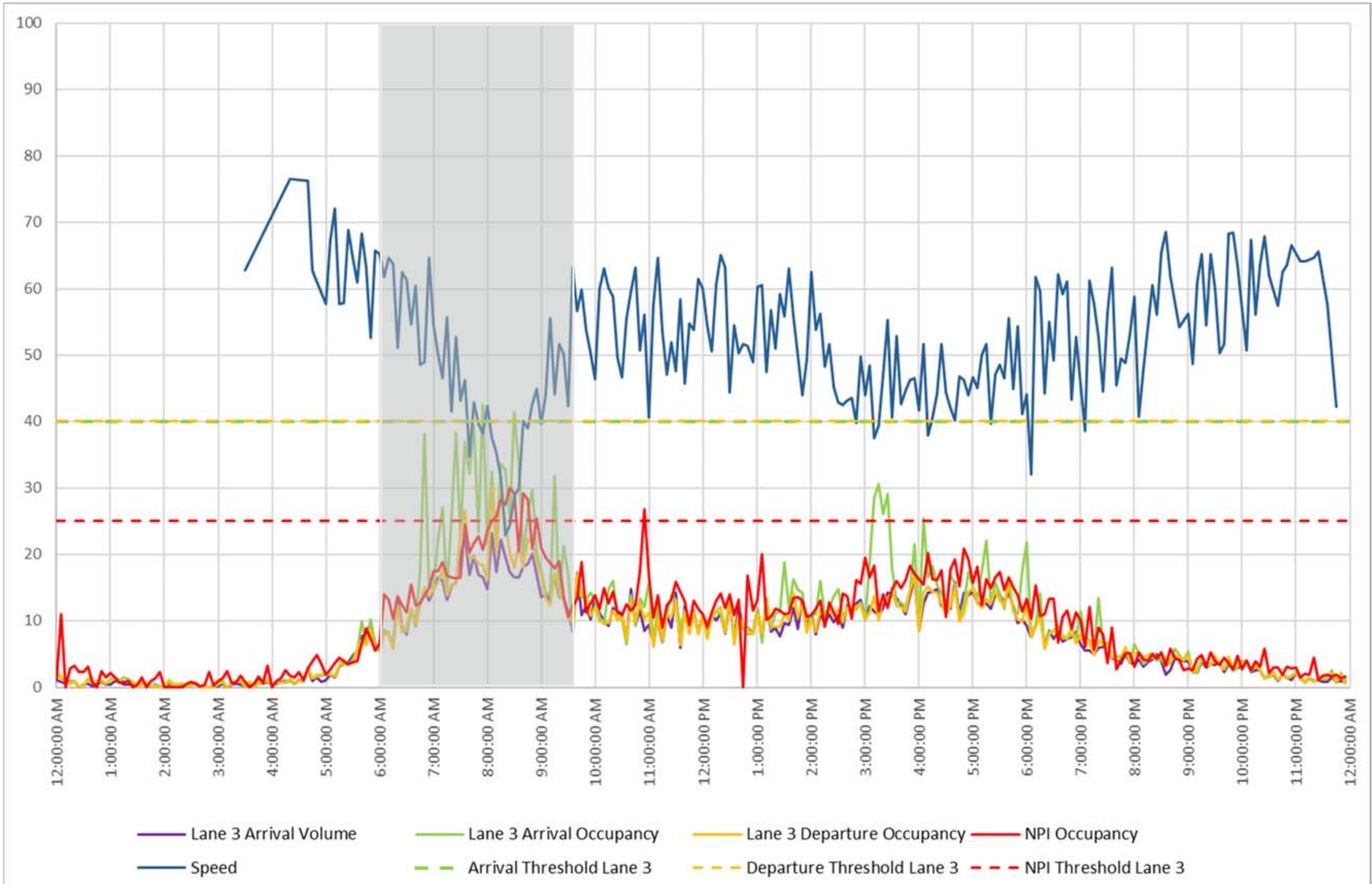
Each graph shows:

- NPI average occupancy (%, average of 5-minutes)*
- arrival occupancy (%, average of 5-minutes)
- departure occupancy (%, average of 5-minutes)
- arrival volume (vehicle per minute, average of 5-minutes)
- speed (km/h, per 5-minutes)
- NPI occupancy maximum threshold (%)
- arrival occupancy maximum threshold (%)
- departure occupancy maximum threshold (%).

* Note: NPI average occupancy is based on the average of the values that occur during the relevant time intervals.

Reviewing the data based on the average of 5-minutes provides a cleaner view, enabling a better understanding of what is happening at the intersection. Averaging the data to every 5-minutes means that the short-term peaks that occur in a 1-minute period are smoothed. This enables a view of the sustained saturation events, which will allow for better identification. In terms of operation, if the data refreshes every 5-minutes, then this will not enable real-time analysis. This should be reviewed using a moving 5-minute average. It is noted that the maximum threshold was used, more time periods would be saturated using the critical threshold.

Figure 3.37 Time series analysis - M5538 EB - Lane 3 - 5-Minute



1-minute frequency with moving average of 5 minutes

The moving 5-minute average data was reviewed for the same date range. Figure 3.38 shows the time-series graph for the Lane 3. Lane 2 and Lane 1 show similar trends and are provided in Appendix C.3.

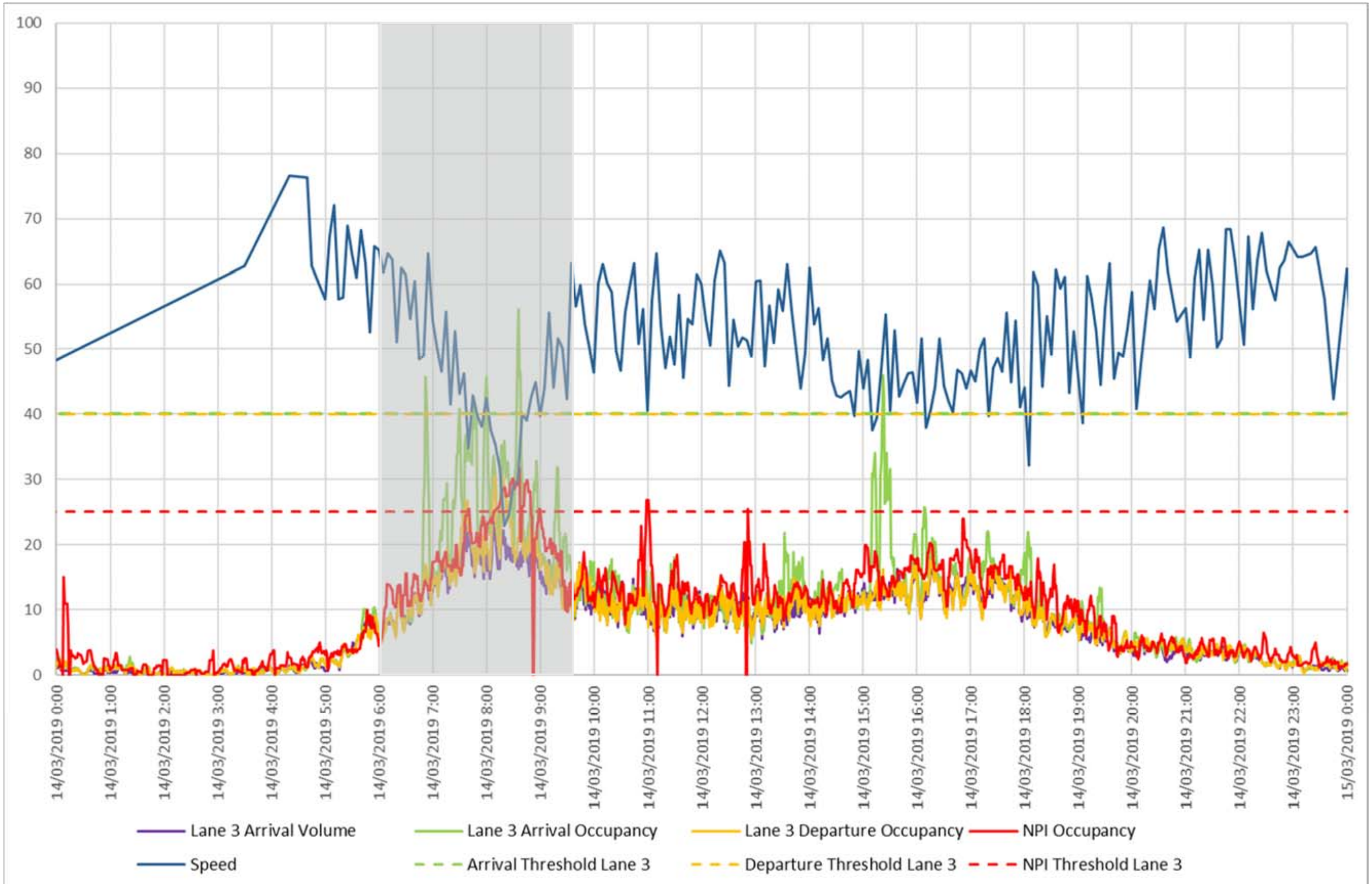
Each graph shows:

- NPI average occupancy (%, 1-minute moving average of 5-minutes)*
- arrival occupancy (%, 1-minute moving average of 5-minutes)
- departure occupancy (%, 1-minute moving average of 5-minutes)
- arrival volume (vehicle per minute, 1-minute moving average of 5-minutes)
- speed (km/h, per 5-minutes)
- NPI occupancy maximum threshold (%)
- arrival occupancy maximum threshold (%)
- departure occupancy maximum threshold (%).

* Note: NPI average occupancy is based on the average of the values that occur during the relevant time intervals.

The moving 5-minte average data is the average of 5-minutes every minute. This is similar to the 5-minute average data, but with the average occurring every minute. The results of the moving average data are similar to the 5-minute data but allow for near real-time view of what is happening with the traffic. It is noted that the maximum threshold was used, more time periods would be saturated using the critical threshold.

Figure 3.38 Time series analysis - M5538 EB - Lane 3 - 5-Minute moving average



3.3.5 DISCUSSION

An intersection was reviewed using first principles, to get an indication of when saturation occurs. This involved graphing the occupancy versus volume relationship to determine the occupancy when saturation occurs. Based on 90% of maximum volume, the critical occupancy was determined as shown in Table 3.5. It is noted that defining the curve of the envelope of the volume versus occupancy scatter plot by sight is subjective. This has been undertaken for the algorithm development as a proof of concept. The prototype should use these values for the first iteration, with the aim of finetuning and automating the process in future years.

While reviewing the occupancy, it was found that the occupancy for lane 3 (closest to the median strip) is generally higher than lane 2 and lane 1 (kerbside lane). This could be due to influences such as the road rules, which dictate that you keep left unless overtaking. This could also be due to lane 1 being under-utilised due to merging and destination choice downstream. This means that slower vehicles tend to stay in the left lane while faster vehicles are in the right lane. The higher volume in lane 3 is consistent with the higher occupancy. The NPI average occupancy tends to be lower than the arrival and departure occupancy, which is consistent with other sites (refer Appendix B). This is likely to be because NPI average occupancy is during the green time only, while arrival and departure occupancy is during green and red time, so some extreme values were observed. Another consideration is that NPI average occupancy is the average occupancy at the arrival side for all the lanes, while the arrival and departure occupancy are lane level occupancy. It is noted that the critical occupancy for NPI was found to be in line with the transition value for NPI saturation as found by Luk (2008). Unsurprisingly, the arrival occupancy tends to be higher than the departure occupancy. This is considered normal as vehicles must remain stationary at red lights, and when the lights change to green have to pick up speed. The departure side detector on the other hand is at a distance which the vehicles may have reached a steady speed, unless traffic is backed up to a point that there is a traffic jam. When reviewing the relationships between occupancy and volume, it was found that the departure occupancy and volume thresholds are similar to the arrival thresholds. The departure occupancy was also assessed using arrival volume. This was assessed to determine the suitability. However, this was deemed unusable due to the arrival and departure detectors being 25m away from the intersection, respectively. The results of the departure occupancy using arrival volume were provided to be indicative only. Based on the review of data, it is believed that the departure occupancy is the most reliable source, noting that departure detectors are not common. The arrival detector is the next most reliable source.

Table 3.5: Volume vs Occupancy - M5538 EB Threshold Summary

Lane	Parameter	Maximum flow (vehicles per minute)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 1	NPI average occupancy vs arrival volume	28	25	20
	Arrival occupancy vs arrival volume	30	27	24
	Departure occupancy vs arrival volume	30	27	23
	Departure occupancy vs departure volume	30	27	23
Lane 2	NPI average occupancy vs arrival volume	32	29	20
	Arrival occupancy vs arrival volume	33	30	27
	Departure occupancy vs arrival volume	33	30	26
	Departure occupancy vs departure volume	41	37	27
Lane 3	NPI average occupancy vs arrival volume	41	37	20
	Arrival occupancy vs arrival volume	40	36	30
	Departure occupancy vs arrival volume	40	36	28
	Departure occupancy vs departure volume	40	36	32

As the occupancy is to be used to determine whether a site is saturated or undersaturated, the lane level thresholds were compared to get an indication of when there may be conflicting information and why the information may be conflicting. It was found that most of the time the data was below the determined lane level threshold. During the morning peak period, the NPI average occupancy can exceed the threshold while the arrival and departure occupancy is under the threshold. This is likely to be due to the NPI average occupancy occurring per cycle while the arrival and departure occupancy is per minute. The misalignment meant that the peaks could occur, but at different times.

The speed versus occupancy generally follows the relationship of the first principles, which is when the speed decreases, the occupancy increases. While the sites generally follow this relationship, it is noted that there are several outliers for the arrival and departure graphs. This may occur due to the different granularity of the data (i.e. the occupancy being 1-minute intervals, while the speed data is 5-minute intervals). Another reason this may be happening is due to the data utilising the red time as well as the green time.

Review of design capacity shows that capacity can be subjective, as practitioners can chose different values based on what they believe are correct. The methods undertaken for design capacity for signalised intersections on arterial roads are similar between the HCM and Austroads method, in that they have a base saturation flow which is calibrated based on multipliers and percent effective green time. For the algorithm it is believed that a simpler base saturation flow value of 1,800 veh/h/lane should be used in the first instance of the algorithm. The base saturation flow would then be multiplied by the green split to derive the design capacity for each lane for each minute while in operation. After the system is known to be working, the base saturation flow should be calibrated for each lane at each intersection. Calibration should focus on the key intersections and corridors first. This will allow for an appreciation of the operation of the corridors without going into the level of detail required to determine a site-specific design capacity for the whole network. The volume and occupancy charts should be reviewed in conjunction with the design capacity when calibrating the capacity, reviewing whether there are any site-specific issues. This will help to identify if the theoretical capacity is achievable. If not properly calibrated, this could result in the algorithm determining there is spare capacity when there is none.

Review of the time-series analysis found that 1-minute data is too noisy/volatile for use in operations. Using a 5-minute data aggregation is still variable but smooths out the short term high/low values. Locations which may be congested in the 1-minute data are not considered to be congested for the 5-minute data. While 5-minute data gives a good indication of what is going on, it is believed that an update every 5 minutes is not acceptable for operational purposes. It is believed that a mixture of the two should be used, aggregating 5-minutes of data per minute. It is noted that this is not a perfect option, however it is a good compromise allowing for near real time information for TMC operators who may need to review or make decisions based on real-time events. It is worth considering in the next stage whether a site should be considered saturated after it has multiple saturated events consecutively. Another consideration is the use of an aging factor in the averaging for the next stage, where the data point of the instantaneous minute weighs more than the previous minutes. An example is provided in Table 3.6.

Table 3.6: Example instantaneous minute weighting

Time, t (sec)	Weighting
0	0.4
-1	0.2
-2	0.2
-3	0.1
-4	0.1

Looking at the results of the time-series analysis found that not all the occupancy measures indicate that the site is congested. While the critical threshold wasn't used for the time-series, it is noted that this would be the best tool for operators to use as this indicates when the site is unstable. The maximum occupancy was used, to get an indication of whether the site was saturated. Three of the indicators (speed, NPI occupancy and volume) show that at site M5538 in the eastbound direction between 8 am and 9 am on 14 March 2019, the site is saturated, thus has no spare capacity. The NPI average occupancy is generally higher than both the arrival and departure occupancy for this site during the morning peak. Looking at the time-step diagrams of volume and occupancy, it is believed that arrival and departure occupancy may provide a better indication of saturation than NPI average occupancy, as the volume drops when the occupancy threshold has been exceeded. While the occupancy is exceeded at times, it is noted that it is for a short duration, which indicates that the site may not be fully saturated for the day assessed. Based on the time-series graph, it appears that NPI average occupancy follows similar trends to the arrival and departure occupancy and provides a representative indication of what is occurring on the site, however, a better representation may be given if the units for volume were comparable to the NPI average occupancy (i.e. average volume per cycle per minute per site). It is believed that initially, saturation should be based on the departure occupancy and flow. If departure occupancy is not available, the arrival occupancy and flow should be used and validated with speed data.

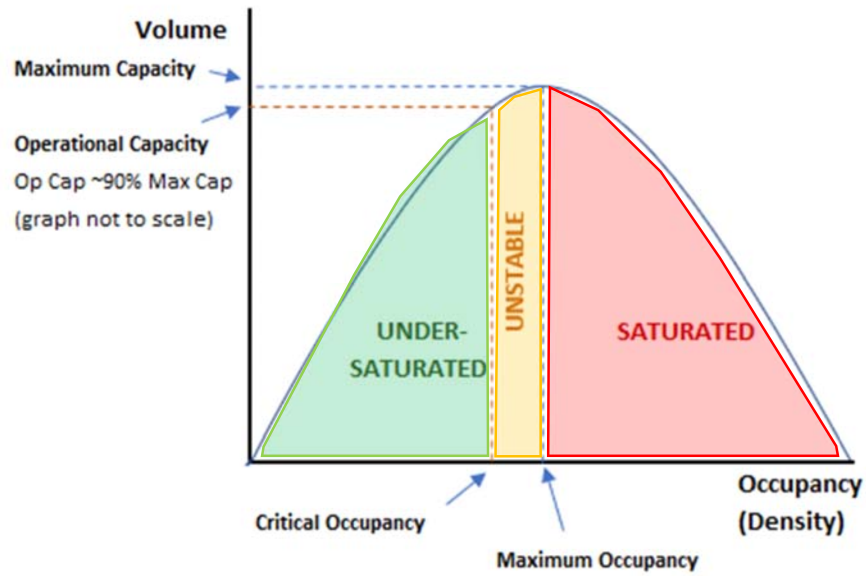
This shows that, as a proof of concept, the methodology for determining operational capacity is promising. The method shall be validated with the provision of a case study. As part of the case study, if a major incident occurs during the assessed period, it should be reviewed. This shall determine whether the method is able to identify a major incident, which is likely to cause a breakdown of flow. This should be confirmed visually using CCTV footage captured at the point of breakdown.

4 ALGORITHM

Based on the learnings of Stage 1 (Espada 2019), the review of the data (Section 3.2) and the thresholds analysis (Section 3.3), this section forms the development of the algorithm as defined in Task 2.3.

As traffic becomes unstable prior to saturation, the threshold analysis looked at the maximum occupancy and critical occupancy. (Refer to Figure 4.1.) The critical occupancy can be derived from the maximum occupancy based on business rules, a value below the maximum at which the site may be saturated. This was undertaken using the volume versus occupancy graphs (e.g. determine critical occupancy based on 0.9 x maximum capacity).

Figure 4.1 Occupancy vs volume - critical occupancy



To determine whether a site is saturated, three scenarios have been identified to take into consideration when there is conflicting information or missing data. Refer Figure 4.2 for an overview of the scenarios.

The situational scenarios for the data are:

1. If flow and departure occupancy agree there is sufficient evidence for verdict
2. If don't have departure occupancy, arrival occupancy next best data source. In this case, flow, arrival occupancy and speed must all agree to reach a verdict.
3. If don't have departure occupancy and arrival occupancy does not agree, check NPI Ave occupancy. In this case, flow, NPI Ave occupancy and speed must all agree to reach a verdict.

All other scenarios are to be considered inconclusive. Such inconclusive scenarios should be rare, but if they do occur, the same condition as the previous minute should be adopted. Figure 4.3 provides the verdict for saturation based on scenarios 1 to 3.

Task 2.5 (case study, calibration and validation) identified some shortfalls of the arrival detector data, therefore the business rules have been revised, refer to the Year 3 (Stage 2 Year 2) report for changes.

Figure 4.2 Situational rules for determining saturation - minimum evidence scenarios

Scenario	FLOW	DEP. OCC	ARR. OCC	NPI OCC	SPEED *
1					
2					
3					

Legend:	
	Data sources agree on verdict; be it saturated or undersaturated.
	Data not required. Will likely agree but accept blue data sources as sufficient evidence to support verdict.
	Missing data
	Not agreeing data

** Speed measure must be for the immediate downstream segment only for its 'above' or 'below' critical speed assessment to be accepted.*

Figure 4.3 Situational rules for determining saturation

Scenario	FLOW	DEP. OCC	ARR. OCC	NPI OCC	SPEED	Verdict
1	At capacity	Near critical	Ignore	Ignore	Ignore	Saturated
	Below	Above	Ignore	Ignore	Ignore	Saturated
	Below	Below	Ignore	Ignore	Ignore	Undersaturated
2	At capacity	Missing	Near critical	Ignore	Near critical	Saturated
	Below	Missing	Above	Ignore	Below	Saturated
	Below	Missing	Below	Ignore	Above	Undersaturated
3	At capacity	Missing	Well below	Near critical	Near critical	Saturated
	Below	Missing	Below	Above	Below	Saturated
	Below	Missing	Above	Below	Above	Undersaturated

The definitions for the terms used in the situational rules are:

- At capacity - considers flows just below capacity as effectively 'at capacity'. In some cases, flow may be measured as slightly above capacity, but this will not last long. Equate as being 'at capacity'.
- Near Critical – considers the measured speed or occupancy just above or just below the critical threshold. Either indicates flow is at or close to capacity, provided they are near their critical value.

The situational rules for determining saturation are at a lane level. A link is then considered saturated if >= 50% of the lanes are determined to be saturated. Thus, the following applies:

- 2-lane carriageway saturated if 1 or more lanes saturated
- 3-lane carriageway saturated if 2 or more lanes saturated
- 4-lane carriageway saturated if 2 or more lanes saturated
- 5-lane carriageway saturated if 3 or more lanes saturated.

Figure 4.4 provides a flowchart of the algorithm for an intersection, in relevant swim lanes, based on the learnings of this project. Note that it assesses minute-by-minute, lane-by-lane. Each lane's flow per minute is assessed against design capacity. If at design capacity, flow is fully utilised and at saturation flow. If flow is below design capacity, then departure occupancy, arrival occupancy and NPI average occupancy are checked against their critical values for saturation. Low occupancy with low flow means low demands, whereas high occupancy with low flow means flow is constrained due to downstream spillback such that the high demands are not being serviced. Finally, the current minute's speed is assessed against the critical speed. Speeds below critical are also an indication of constrained flow due to saturated conditions. For each lane, each flow, occupancy and speed assessment results in their own verdicts of whether the lane is saturated or undersaturated. With multiple verdicts, the rules shown in Figure 4.3 are then applied to determine if the lane is either saturated or undersaturated.

Figure 4.4 Algorithm for operational capacity from intersection

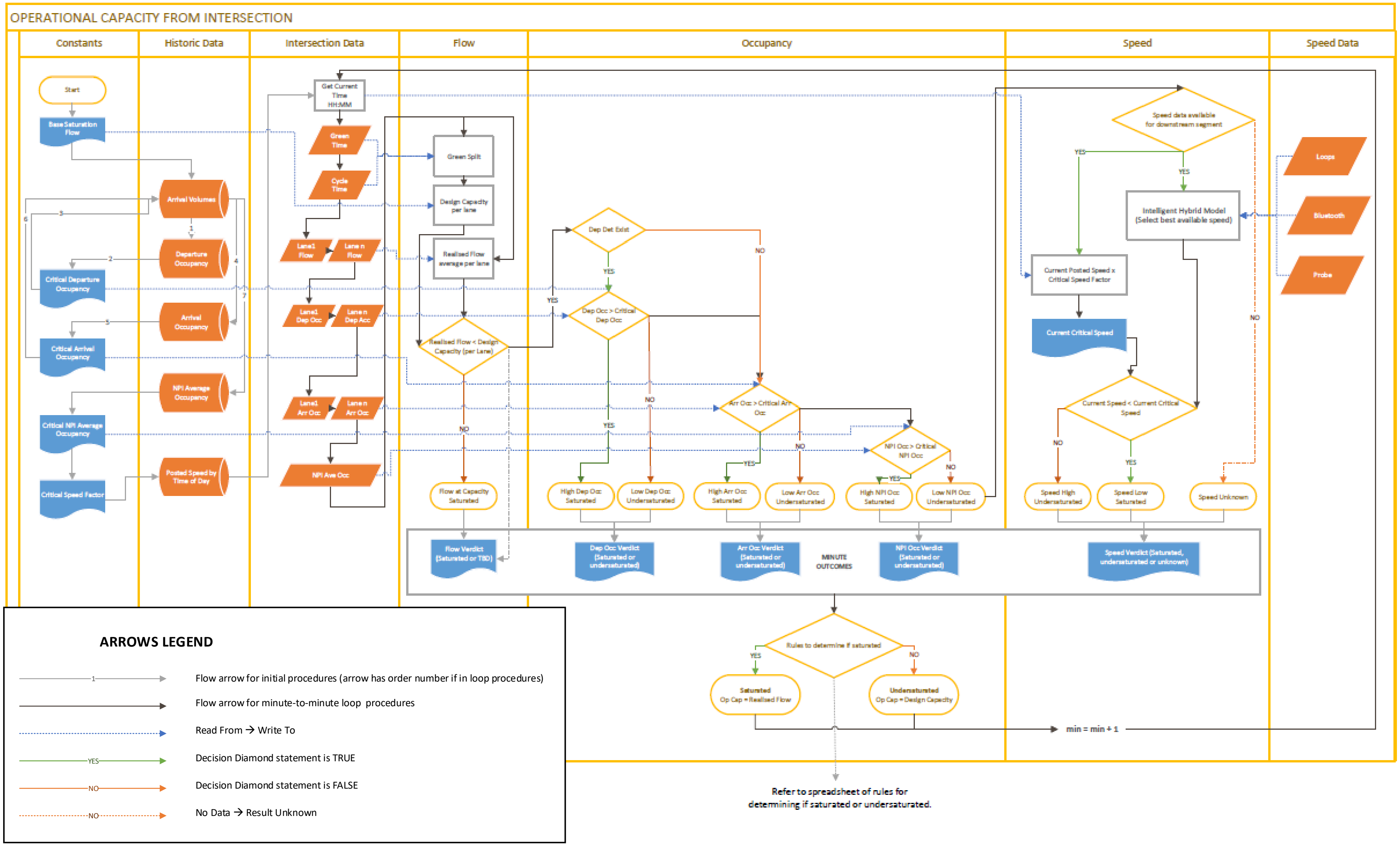


Figure 4.5 provides a flowchart for the determination of the operational capacity of a segment.

For each intersection, the operational capacity is the design capacity if undersaturated. Otherwise, if saturated, the operational capacity is the realised flow.

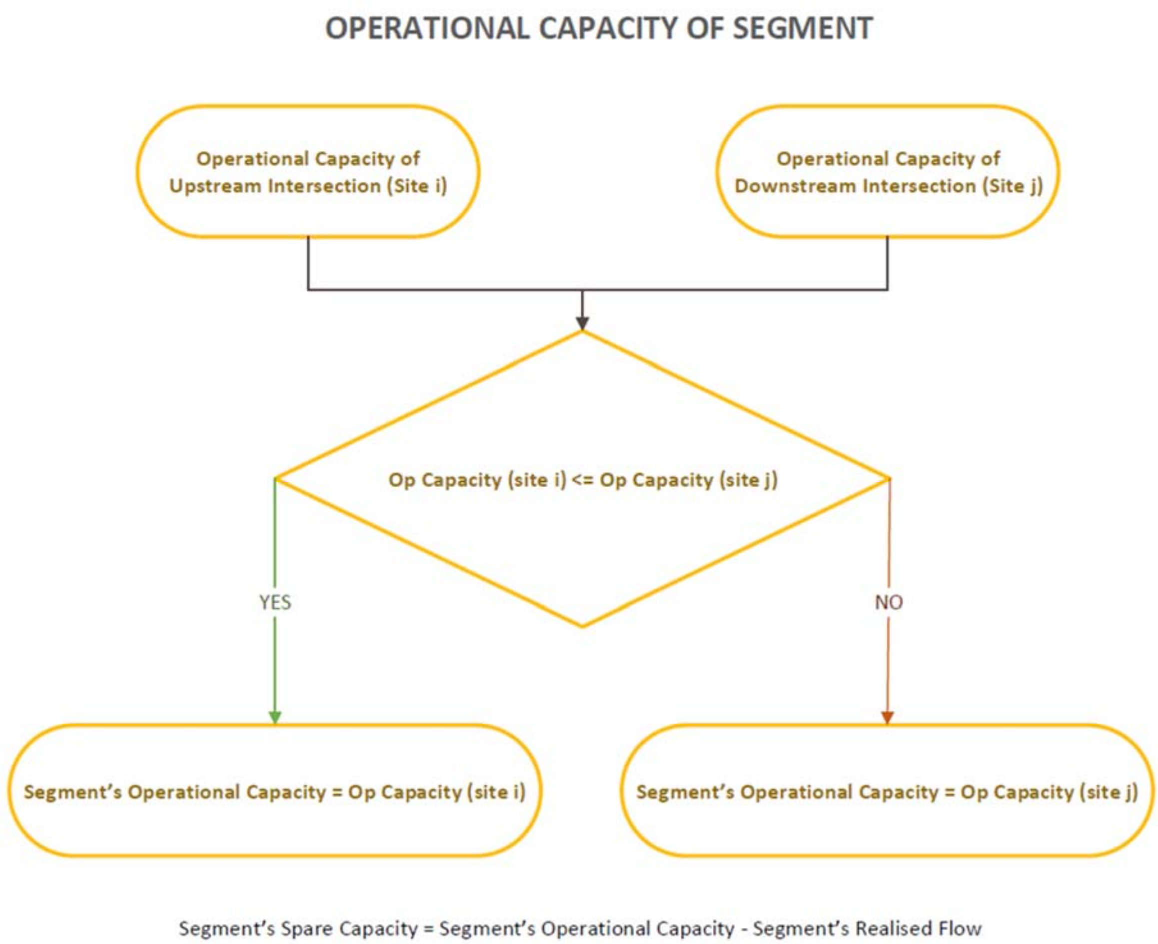
A ‘segment’ is defined as a section of road between an upstream intersection and a downstream intersection and can also be referred to as a mid-block or link.

The operational capacity of a segment is equal to the effective capacity of its upstream intersection.

If the upstream intersection’s operational capacity is greater than the downstream intersection’s operational capacity, then the upstream’s effective capacity is constrained to that of the downstream intersection’s capacity. This is because flows into the segment cannot be greater than flows out of the segment.

However, if the upstream intersection’s operational capacity is less than the downstream intersection’s operational capacity, then the upstream’s effective capacity is its full operational capacity. This is because the downstream flows out of the segment are higher than the upstream demands such that upstream flows into the segment are not constrained by limited outflow and the upstream operational capacity can therefore be fully utilised.

Figure 4.5 Algorithm for operational capacity of segment



5 PROTOTYPE DEVELOPMENT

A prototype of the algorithm was developed, as defined in Task 2.4, using the data provided by TMR and the process described in Section 4.

The process involved in integrating the raw data is provided in Figure 5.1. Refer to Section 3.2 for a sample of the relevant input data. The volume, occupancy and speed data are run through an R script which imports the data and formats it into 1-minute intervals, as shown in Figure 5.2. This is then put through a python script which gap fills based on previous time periods and appends the green time information to the data and outputs the data into an integrated data file, as shown in Figure 5.3.

Figure 5.1 Process for integrating raw data

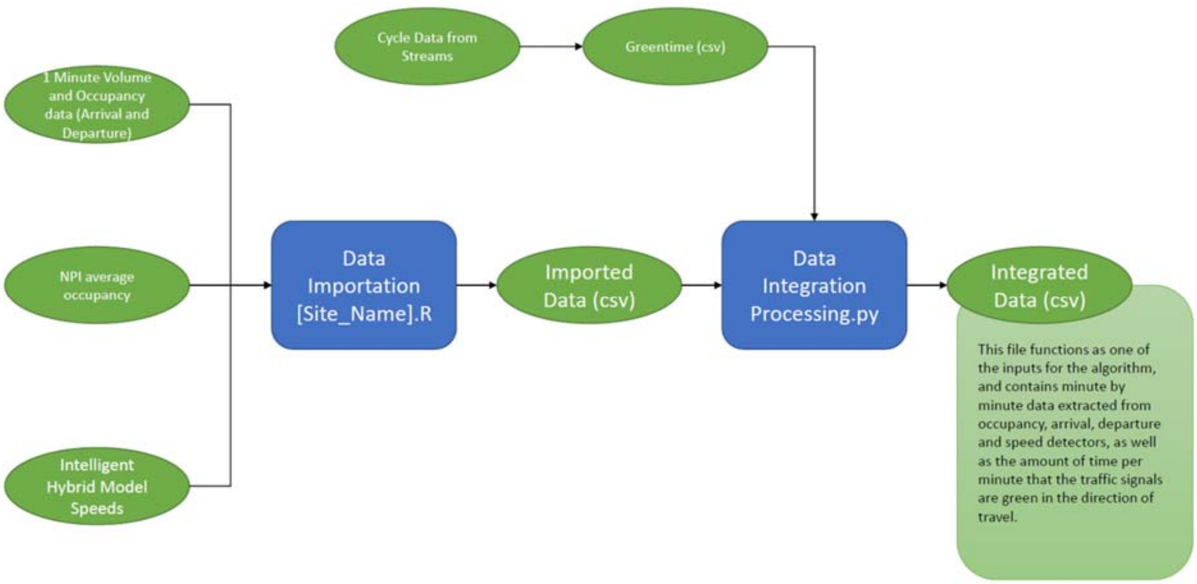


Figure 5.2 Imported data sample

Date	Hour	Minute	Time	Occa1	Vola1	Occa2	Vola2	Occa3	Vola3	Occd1	Vold1	Occd2	Vold2	Occd3	Vold3	NPIoccupa	NPIcycle	NPIgreen	BTvolt	BTspet
11/03/2019	0	0	0:00	48	2	54	2	43	1	50	2	62	3	41	1	NA	NA	NA	NA	NA
11/03/2019	0	1	0:01	10	1	10	1	0	0	15	2	10	1	0	0	NA	NA	NA	NA	NA
11/03/2019	0	2	0:02	6	0	10	1	0	0	8	1	10	0	0	0	NA	NA	NA	NA	NA
11/03/2019	0	3	0:03	0	0	0	0	0	0	0	0	0	0	0	0	NA	NA	NA	NA	NA
11/03/2019	0	4	0:04	0	0	0	0	0	0	0	0	0	0	0	0	NA	NA	NA	NA	NA
11/03/2019	0	5	0:05	20	1	8	1	6	1	6	1	13	2	8	1	NA	NA	NA	NA	NA
11/03/2019	0	6	0:06	18	2	11	1	0	0	28	3	11	1	0	0	NA	NA	NA	NA	NA
11/03/2019	0	7	0:07	13	2	10	1	10	1	15	2	13	2	8	1	NA	NA	NA	NA	NA
11/03/2019	0	8	0:08	8	1	0	0	0	0	0	0	0	0	0	0	NA	NA	NA	NA	NA
11/03/2019	0	9	0:09	6	1	13	2	0	0	16	2	11	2	0	0	NA	NA	NA	NA	NA
11/03/2019	0	10	0:10	54	3	50	1	35	0	53	3	53	2	35	0	NA	NA	NA	NA	NA
11/03/2019	0	11	0:11	5	0	8	1	0	0	11	1	10	1	0	0	NA	NA	NA	NA	NA
11/03/2019	0	12	0:12	16	0	25	1	16	0	16	0	26	1	16	0	NA	NA	NA	NA	NA
11/03/2019	0	13	0:13	15	2	0	0	0	0	13	2	0	0	0	0	NA	NA	NA	NA	NA
11/03/2019	0	14	0:14	27	1	18	0	17	0	28	1	17	0	18	0	NA	NA	NA	NA	NA
11/03/2019	0	15	0:15	0	0	28	3	0	0	0	0	25	2	0	0	NA	NA	NA	NA	NA
11/03/2019	0	16	0:16	28	3	8	1	0	0	16	2	8	1	0	0	NA	NA	NA	NA	NA
11/03/2019	0	17	0:17	0	0	10	1	0	0	8	1	10	0	0	0	NA	NA	NA	NA	NA
11/03/2019	0	18	0:18	20	2	8	1	10	1	10	1	11	1	8	0	NA	NA	NA	NA	NA
11/03/2019	0	19	0:19	10	1	10	1	0	0	16	2	11	1	0	0	NA	NA	NA	NA	NA
11/03/2019	0	20	0:20	8	1	15	1	21	1	6	1	16	1	20	1	NA	NA	NA	3	66.50814
11/03/2019	0	21	0:21	0	0	6	1	3	1	0	0	6	1	0	0	NA	NA	NA	NA	NA
11/03/2019	0	22	0:22	0	0	10	1	5	1	5	0	10	1	0	0	NA	NA	NA	NA	NA

Figure 5.3 Integrated data sample

Date	Hour	Minute	Time	Occa1	Vola1	Occa2	Vola2	Occa3	Vola3	Occd1	Vold1	Occd2	Vold2	Occd3	Vold3	NPIoccupa	NPIcycle	NPIgreen	BTvolt	BTspet	time_green
11/03/2019	0	0	0:00	4.8	2	5.4	2	4.3	1	5	2	6.2	3	4.1	1	0	20	4	3	66.50814	60
11/03/2019	0	1	0:01	1	1	1	1	0	0	1.5	2	1	1	0	0	0	20	4	3	66.50814	60
11/03/2019	0	2	0:02	0.6	0	1	1	0	0	0.8	1	1	0	0	0	0	20	4	3	66.50814	60
11/03/2019	0	3	0:03	0	0	0	0	0	0	0	0	0	0	0	0	0	20	4	3	66.50814	60
11/03/2019	0	4	0:04	0	0	0	0	0	0	0	0	0	0	0	0	0	20	4	3	66.50814	60

As part of the integration process, the green time is determined. The raw phase cycle data provides the start time and duration of each phase. After determining the relevant phases for the through movement, the start and end of each green period are calculated and put into a csv file that contains the start and end phases. This was undertaken through the function “Greentime read to dict”. This function takes phase changes and turns them into start/end event entries in a dictionary. (In python this is essentially a hash table data structure). Figure 5.4 provides the explanatory text of the function.

Figure 5.4 Function - greentime start/end

```
# Input : The filename of a .csv containing the start and end times of green cycles in minutes from the start of the
# Input : period to be examined, along with a separate entries wor seconds past the minute at which the
# Input : cycle end/cycle start occurs.
# Output : A dictionary of lists of dictionaries of the form
# Output :      {'type' : |start or end|, 'seconds': |seconds past the minute in which the green phase starts or ends|}
# Output : Where the minutes past the beginning of the period to be examined are used as keys for each entry in
# Output : the overall dictionary. Thus the output is a dictionary callable by minutes past beginning of 'epoch'
# Output : that will return a list of start/end events for the given minute.
def greentime_read_to_dict(filename):
```

After determining the start and end times, the function “Add greentimes” takes the greentime dictionary and calculates the time spent green each minute and appends this information to the main dataset. The explanatory text for the appending of the green time to the imported data is shown in Figure 5.5. Both “Greentime read to dict” and “add greentimes” are part of the “Data Integration Processing” box.

Figure 5.5 Function - append greentime to integrated data

```
# Input 1 : A dictionary of dictionaries, wherein each dictionary contains one minute of sensor data from a given
# Input 1 : intersection and direction of travel, and the key for each dictionary is the number of minutes elapsed
# Input 1 : since the beginning of the period to be examined.
# Input 2 : A dictionary of lists of dictionaries of the form
# Input 2 :      {'type' : |start or end|, 'seconds': |seconds past the minute in which the green phase starts or ends|}
# Input 2 : Where the minutes past the beginning of the periods to be examined are used as keys for each entry in
# Input 2 : the overall dictionary
# Output : The dictionary of dictionaries described in Input 1, but with each minute having a 'time_green' entry
# Output : indicating the number of seconds of that particular minute were green in that direction fo travel
def add_greentimes(dict, green_source):
```

Figure 5.6 provides the inputs and process for determining the lane, and subsequently the site status. The critical values used in the algorithm were the values determined in this report (Refer Table 3.5, Table B.1, Table B.2, Table B.3), which are considered to be subjective. It is believed that future iterations of the prototype should have an additional process which determines the critical values based on the envelope of historical data. This process imports the data and checks the lane status to identify the site status. The lane status in undertaken through the function “lane algorithm” (the yellow box in Figure 5.6). The explanatory text for the “lane algorithm” function is shown in Figure 5.7. The lane function is part of the “site algorithm”, which calls the “lane algorithm” for each lane to determine the site status. The site status is shown as the blue boxes in both Figure 5.6 and Figure 5.9.

Figure 5.6 Process for determining site status

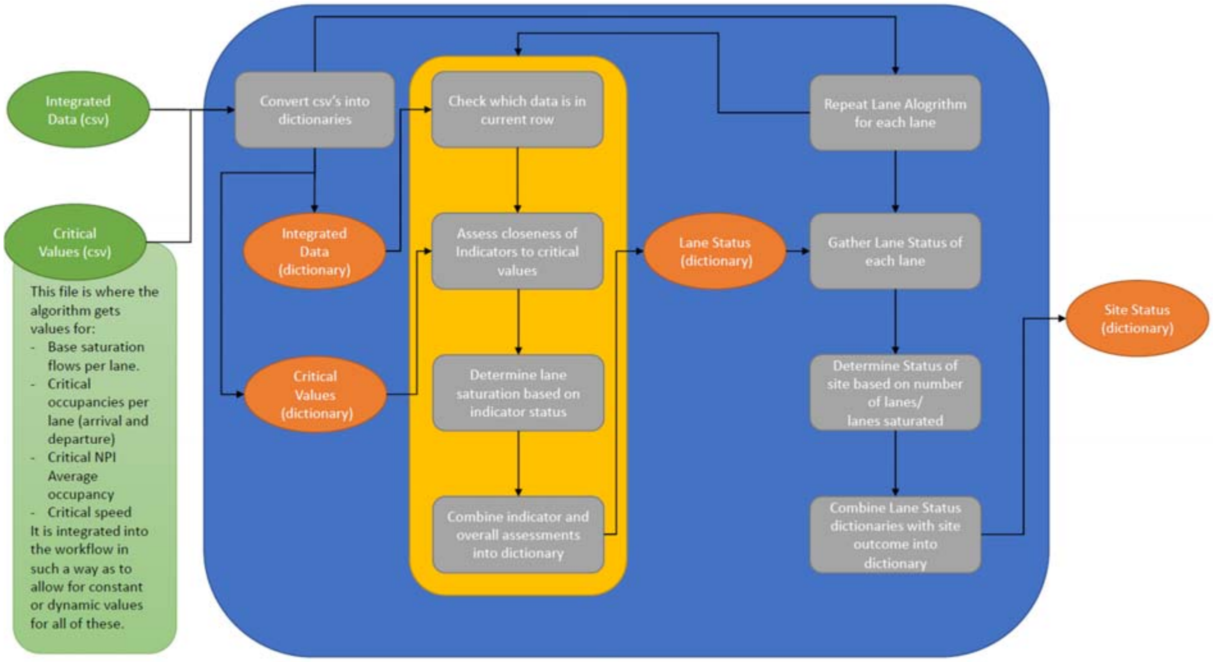


Figure 5.7 Function - determine whether lane is saturated

```
# Input 1 : a dictionary with the sensor data for the current time, site
# Input 2 : a dictionary with historically derived critical values for the current site
# Input 3 : an integer specifying the lane to be assessed (starting from 1)
# Output : a dictionary of the outcomes of key indicators, the overall assessment of whether the lane is
# Output : saturated or unsaturated
def v4_lane_algorithm(current_row, hist_data, lane):
```

Figure 5.8 Function - site status

```
# Input 1 : a dictionary with the sensor data for the current time, site
# Input 2 : a dictionary with historically derived critical values for the current site
# Output : a dictionary containing the site outcome and a dictionary of the outcomes of each lance and the indicators
# Output : within each lane formatted as follows:
# Output :      {site_outcome : (saturated/unsaturated), lane_outcomes : { lane_dict }
# Output : where lane_dict is of the form :
# Output :      {lane_number :
# Output :      {outcome : (saturated/unsaturated),
# Output :      'flow': ('below cap'/'above cap'),
# Output :      'departure': ('below cap'/'above cap'/'near cap'),
# Output :      'arrival': ('below cap'/'above cap'/'near cap'/'well below'),
# Output :      'NPI': ('below cap'/'above cap'/'near cap'),
# Output :      'speed': ('above'/'below'/'critical'/'near critical')
# Output :      }
# Output :      *as above for each lane examined at the site*
# Output :      }
def v4_site_algorithm(current_row, hist_data):
```

Based on the site status, the operational capacity is determined. The process the prototype uses for determining the spare capacity is shown in Figure 5.9. The process builds upon the process in Figure 5.6 and shows how the prototype determines the operational capacity for a link. This is done through the function “over algorithm”, which calls the site algorithm for all the sites specified and returns the site status of the route and the links therein. The explanatory text for the “over algorithm” is shown in Figure 5.10. The “over algorithm” does the tasks shown in the red box in Figure 5.9. The data is output every minute, with an output every 6 seconds for the prototype to simulate real-time reporting. A sample output of the real-time operational capacity for a link is shown in Figure 5.11. This shows the realised flow and design capacity for each site on a route per minute per lane. The operational capacity shown for the intersection is compared against the upstream and downstream intersection, the operational capacity used is the value between the intersection, as per the process shown in Figure 5.9.

Figure 5.9 Process for determining operational capacity for link

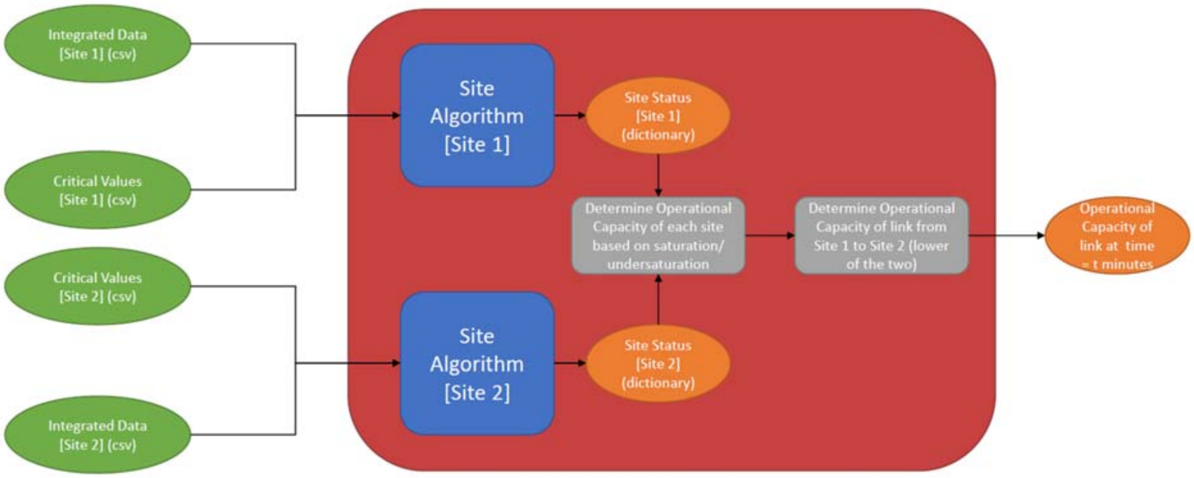


Figure 5.10 Function - comparrison of site status

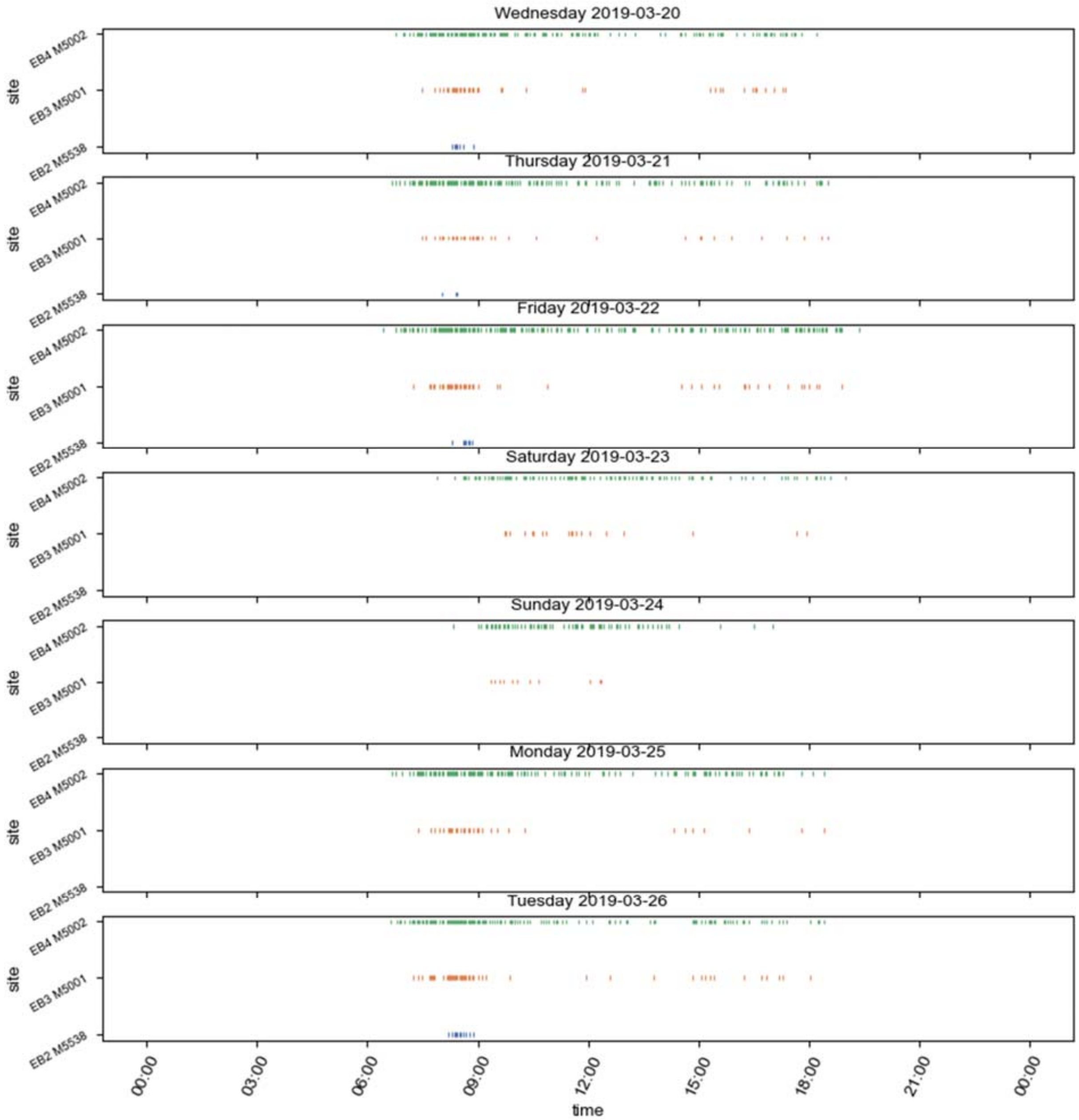
```
# Input 1 : The list of site names
# Input 2 : A dictionary of site data dictionaries
# Input 3 : The time on which the calculation is focused
# Output : A set of dictionaries that contains all the information about each indicator for each lane of each site
# Output : as well as operational capacities of each site and of links between sites where appropriate
def over_alg(site_names, site_dicts, time):
```

Figure 5.11 Real-time output for route

```
2019-03-16_12-51
Route capacity = 760 (veh/hour/lane)
Site Name                    EB2 M5538         EB3 M5001         EB4 M5002
Design Capacity (v/h/l)      920               760               1760
Realised Flow (v/h/l)        240               400               860
Operational Capacity (v/h/l) 920       760     760       760     860
```

The prototype also provides a daily overview of when saturation occurs. This is visualised using a graph showing the links on a route, with a point added for the minutes in which saturation occurs. Refer to Figure 5.12 for a sample of multiple daily saturation graphs. This is provided to allow the operator to see if there is single saturation event or if it is a trend on the network. Looking at the graphs there are time periods between the saturated points where there is not saturation. As part of the calibration process, this should look at whether the saturation occurs for consecutive periods. The graph also shows where there are congested conditions along the corridor. Around 8 am to 9 am on Monday to Friday shows congestion at all 3 sites indicating there are bottleneck conditions. Of the sites shown, M5002 appears to be the cause. This may not be the case depending on the analysis of the whole route.

Figure 5.12 Occurrence of intersections operating in oversaturated conditions



6 NEXT STEPS

This Stage 2 Year 2 report outlines the process for the development of the prototype program which determines spare capacity using historical data. It was identified by the stakeholders, and in the analysis, that determining spare capacity is a challenging task.

As it was identified that site-specific calibration will be required during the case study, some of the tasks from year 2 will be achieved in year 3. As part of the calibration process, variations in traffic conditions shall be reviewed, taking into consideration high pedestrian activity, lane drops, side street movements and when signal plan changes occur. Year 3 will achieve the following:

- Case study using the prototype algorithm to assess case study corridor, which will be Smith Street Motorway and North Street in both directions. The prototype will input traffic data from the case study corridor and apply the methodology developed as part of this report. The prototype will output estimates of operational capacity, which will be validated against video data captured during the same period as the input traffic data. Where needed, the algorithms within the prototype will be calibrated to improve the estimates of real-time operational capacity.
- Final Report summarising the learnings of Stage 2, identifying the tasks undertaken and providing conclusions and recommendations.

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APPENDIX A MEETING MINUTES

A.1 QUEENSLAND TRANSPORT AND MAIN ROADS

Meeting Name:	*Real-time Operational Capacity Estimation – TMR*		
Meeting Date: 21 November 2019	**Location:** Skype		
Time: 15:30 AEDT	**Duration:** 1 hour		
Meeting Chair: Paul Bennett	**Minutes By:** Kenneth Lewis		

Attendance	Yes
Paul Bennett	Y
Kenneth Lewis	Y
David Stewart	Y
Kelvin Marrett	Y
Mark Jones	Y
Merle Wood	Y
David Johnston	Y

item	Subject
1.	**Background** Provided the background of the project, indicating the aim is to estimate the effective operational capacity across the network in real-time, identifying whether links are saturated or undersaturated. Spare capacity would be identified on undersaturated links, being the difference between their design capacity and current flow. The use case would be to enable TMC operators to reroute traffic where possible from congested areas of the network to alternative routes with spare capacity. Real-time measures of spare capacity could also be used in the routing algorithms of TMR's QLDTraffic app. This would improve network operations as it would reroute once spare capacity is utilised. It was raised that TMC may not be able to use this to divert motorists if it was in operation. However, it may be useful for CAVI to allow for roads to not exceed operational capacity. If there was near real-time data interchanges with the navigation providers, they could create an algorithm to balance the network.
2.	**Discussion** Currently spare capacity is assumed based on travel speeds. Adelaide currently uses travel speed from the Bluetooth data to help inform the operators. It is believed that this is not perfect, but with operational experience it may be fine-tuned locally. Colour-coding the map in STREAMS Explorer by spare capacity (percentage or actual number) could lead to other strategies available inside of STREAMS or other automated procedures. David Johnston presented 'Calculating spare capacity: What STREAMS does, current issues & identified fixes' which provides a snapshot of what was implemented in STREAMS previously in regards with spare capacity. It was tweaked for the Commonwealth Games, of which David Johnston was not part of the project, so some of the issues encountered may have been fixed. STREAMS currently determines 'capacity' based on the highest observed 'maximum' (1-min) flow and highest observed sustainable (15-min average) flow. It remembers these two points on the volume-occupancy curve. Assumed capacity is said to be the sustainable (15 min) flow plus 40% of the difference between the sustainable flow and maximum flow.

item	Subject
	Problems with STREAMS: • Bad data could be learnt as good data. All subsequent data monitoring accepts bad data and may reject good data. Needs a set of first pass sanity checks. • Currently processes at the detector site level and assumes standard vol-occ behaviour from the aggregated lane volume data. However, behaviour should be assessed at the individual lane level. Resultant maximum and sustainable flows at site level can be 'crazy' when one lane detector fails or one lane breaks down. • If a site never reaches capacity, then you will never know the true capacity. A separate calculation, like the HCM theoretical capacity, should be included to work out what the true capacity should be for roads that never reach full capacity. Capacity is dictated by green time for arterials, which will be harder to measure than for freeways. This is a very hard/long calculation in the HCM. If a factor in the HCM is wrong this needs to be able to be challenged by the learnt data. The HCM value may change if the speed or number of operable lanes changes. Needs to be a combination of a learnt value and a theoretical value. Need to make sure this is immune to once off events (i.e. 60 motorbikes in 1 minute) and the faults of the system (i.e. a chattering detector). An issue for consideration is when the different lanes have different levels of service (i.e. L1 LOSA, L2 LOSF), is the LOS the worst LOS or LOS of 2 lanes etc. This could be site dependant (i.e. 3 lane road where left turning lane gets a lot of turning traffic instead of vehicles going straight). This is not as simple as using the highest or choosing if 2 lanes have the same LOS. David Johnston believes that for arterial roads, the capacity is more based on delay than density. Delay can be calculated from NPI speed converted into travel time, which can be compared against the flow. David Johnston believes motorways should be tackled first as they are easier to implement than the arterials. In Queensland, the issue is they do not have an established motorway management system, which means that vehicles are sent onto the arterials when there is no capacity. Previous work undertaken for real-time capacity has not looked at design capacity – may need to investigate design capacity. Need to be aware of where the data can lead you astray. Capacity can change based on the traffic plans Real-time system would need to take into consideration weather (i.e. value for dry weather and wet weather or adverse weather). Information on how people chose their route could point to the most effective target for routing (i.e. VMS and/or navigation devices). M1 programs are looking at using VMS at decision points on the arterials. Another way of looking into this is through a virtual VMS through TomTom or SUNA etc. (i.e. where the road authority will want people to go) Data 61 wrote and presented a paper on interface into a simulator to look at AI learning algorithms in relation to traffic controllers alongside RMS at ITSWC – TMR to send these documents.

A.2 VICTORIAN DEPARTMENT OF TRANSPORT

A.2.1 VIC DOT MEETING 1

Meeting Name:	*Real-time Operational Capacity Estimation – DoT – Meeting 1*			
Meeting Date:	2 December 2019	**Location:**	Skype	
Time:	14:00 AEDT	**Duration:**	1 hour	
Meeting Chair:	Paul Bennett	**Minutes By:**	Kenneth Lewis	

Attendance	Yes
Paul Bennett	Y
Kenneth Lewis	Y
Tony Fitts – Department of Transport	Y

item	Subject
1.	**Background** Provided the background of the project, indicating the aim is to predict the real-time capacity. The current stage is to look at the operational capacity.
2.	**Discussion**

Currently Department of Transport use SCATS degree of saturation for real time capacity. This uses occupancy and the number of vehicles, considering the length of the vehicle. This means that there may be more occupancy due to the length of the vehicle. Tony indicated that he would send through some examples of calculating degree of saturation for different length vehicles.

$$\mathbf{DS} = \frac{\textbf{Effectively Utilised Green Time}}{\textbf{Total Available Green Time}}$$

$$\mathbf{DS} = \frac{[g_m - (T - n.t)]}{g_m + g_u}$$

where:

g_m	=	measured green time
g_u	=	unused green time (gap)
T	=	total space during the measured green time
n	=	number of spaces (i.e. vehicles measured this green)
t	=	average space per vehicle recorded at previous maximum flow (i.e. space which is unavoidably associated with each vehicle)

Explanation of Formula

The various parts of the formula have the following "consequence":

- Product **n.t** is the total space time that would occur if **n** vehicles cross the stop line at saturation (MF) i.e. space which is not a "waste" of green time because it must occur at saturation flow
- Difference **(T – n.t)** is the space which is a "waste" of green time because it is the total space less the "non-waste" time.
- Hence $[g_m - (T - n.t)]$ is the amount of green needed to pass **n** vehicles without any "waste"

Usually there is tidal flow. It is useful to measure whether there is spare capacity for the counter-peak direction. If there is spare capacity the following actions can be undertaken:

item	Subject
	• Repeat right turn lagging phases to be included in the phase sequence when the opposing through movement has spare capacity or low DS. • Allow the main road through phase to gap out or terminate early if the DS is low. • If there are opportunities to run other movements, Department of Transport are not looking at the phase control, but to utilise the signal group control. If the volumes are low, consideration is given to break co-ordination between intersections to allow for intersections to operate independent cycle times. A traffic volume threshold only is adopted for this type of operation. The operation is dependent on green time. The critical operation would be the ratio of green time to the cycle time, which is in line with the degree of saturation calculation. VR83, the SCATS routine for congestion, is based on Vk/Vo being high, high occupancy with low flow. This indicates a congested network with spillback. There are no departure side detectors in SCATS. Mid-block detectors are not practical to use due to the cost associated with setup and maintenance. It is believed that data such as AddInsight or probe vehicle data would be more helpful. Some people use the decision tree in STREAMS to make decisions in SCASTS. Bluetooth could help to control the phase splits, to identify where bottlenecks are located. Delays on approaches and travel time would help to setup operations. There is an opportunity to provide more data. Bluetooth data is getting better, currently for the Melbourne networks it is setup for the main roads. However, there are no links for turning movement. Do not know if this is possible to get this information. However, this would be a complex task if can get the information, plus it would be site specific. Department of Transport tend to use Bluetooth mainly for historical purposes to make comparisons. If Bluetooth were used for real-time operations, there would have to be minimal latency of the data. However, unsure of the latency of the data. It is noted that HERE are looking at a measure of ride along flow, which indicates the number of stops under 10 km/h. It is noted that the arterial network has other modes, so spare capacity may be re-allocated to support these modes. i.e. public transport priority. It is believed that redirecting vehicles from one corridor to another would be hard to undertake once people are already travelling. The best time to get people to consider changing their route would be at the start of the journey. Advising which routes are quicker may be more useful. Tony will review slides and provide comments such as whether critical occupancy is feasible.

A.2.2 VIC DOT MEETING 2

Meeting Name:	*Real-time Operational Capacity Estimation – DoT – Meeting 2*		
Meeting Date:	3 December 2019	**Location:**	Department of Transport, Kew
Time:	11:00 AEDT	**Duration:**	1 hour
Meeting Chair:	Paul Bennett	**Minutes By:**	Kenneth Lewis

Attendance	Yes
Paul Bennett	Y
Kenneth Lewis	Y
Matthew Hall – Department of Transport	Y
John Gaffney – Department of Transport	Y
Chris Harper – Department of Transport	Y

item	Subject
1.	**Background** Provided the background of the project, indicating the aim is to predict the real-time capacity. The current stage is to look at the operational capacity.
2.	**Discussion** Similar issues for freeways and arterials. In terms of the thresholds for occupancy, it is believed that 25% occupancy for a 4-lane freeway is too much. Department of Transport generally use an occupancy of 12-14% for the freeway (for the carriageway). This depends on the number of lanes and the speed limit. It also depends on what you are wanting to look at. Are you wanting to have the capacity or maximum sustainable flow? Occupancy is different based on the detector used. i.e. studs, loops etc. Need to be careful, there is a difference in terms of per lane occupancy and carriageway occupancy. To calculate it properly, the total time occupied divided by the number of lanes. Do not weight the occupancy by volume. What is operating speed? Breakdown for freeways is generally at around 64km/h. As a generalised rule 80% of the speed limit is not bad. It is believed that a threshold of the maximum flow may be a better indicator than occupancy. The underlying problem is the issues of bottlenecks. Downstream or upstream of the bottleneck you never reach the threshold values. Downstream of a bottleneck has spare capacity, so if you can identify and release the bottleneck this can be helpful. The methodology shown is alright. However, the values for the thresholds are the main issue. Rather than capacity, Department of Transport look at utilisation. i.e. time that is effectively used, time that is unused and total time. The challenge for arterials is to balance the competing demands. Capacity is when you cannot service more traffic. The network is very fluid. Increase delay for a movement and demand moves elsewhere, which increases capacity at the intersection. Demands and patterns for the arterials are unknown. To be able to optimise to move everything in real-time is hard as the demands are variable i.e. There may have been only 1 right turn vehicle in previous cycle, but this then becomes 10 vehicles in next cycle. With managed motorways the network is known, which means that you can control the entry into the system based on the current demand. Currently Department of Transport uses dynamic demand for the managed motorways and understand demand at the 20 second frequency. Most people pick their route before they get into the car. If you have a different trip purpose or a trip change would be when you are looking into how to get somewhere.

item	Subject
	Capacity for an intersection is not a fixed field. This can be done on a cycle by cycle basis. Low cycle and low demand periods to improve the efficiency of the intersection may have a much lower capacity on the off-peak. The work that Department of Transport have undertaken in the capacity guide of managed motorways may be useful. The vehicle mix and the O-D pattern changes per day. The detectors are never in the perfect location. You need a statistical model to work out the probability percent flow breakdown. For design, a probability of 1% may be used, but in operation a probability of 0.1% is used. It is based on looking at a whole suite of fundamental diagrams and the relations change daily. For a freeway, the operational flow is not necessarily the flow breakdown volume. For motorways you avoid flow breakdown to avoid the loss when the network is saturated. i.e. maximum flow of 1800, but1400 when flow is broken down. If you manage to maintain the flow then you have the operational capacity. If the flow has broken down, you stop traffic coming near so it can recover. 1550 vehicles per lane per hour is a sustainable volume for unmanaged motorways. 1800 vehicles per hour per lane is what can be sustained for managed motorways. It must be a system treatment, not a local treatment. If you let too many vehicles in upstream when there is a bottleneck it will extend the bottleneck. Department of Transport believe you need to work in minute or sub-minute for operation. John and Matt will be publishing something soon which would be good for discussion in this space. Techniques like perimeter control and mid-block feedback sensors to get stable networks could be more valuable. Need to be careful how spare capacity is phrased as it could easily be misconstrued out of context. i.e. 40% of the network is underutilised 100% of the time does not mean that there is any spare capacity. A review of tolling tags by time of day showed that at the same time the same tags are not active, meaning there are no daily patterns beyond that there is a large volume at the same time every day. Capacity is only an issue when you have the demand. If you want to optimise a network, you may need to compromise some nodes. Need to be careful about utilisation as this is site specific. E.g. If there is parking just before an intersection, vehicles wanting to get into the left lane may not fully utilise the lane due to the parked cars, which may affect the utilisation. i.e. there may be 70% utilisation, but it is fully saturated. The key question is what do TMR want to do with this knowledge? i.e. What is the purpose of real-time operation? Bluetooth data gets dropped after 20 minutes, which means if there is excessive delay this will not get picked up. Also need to be confident that this is just the cars and not pedestrians or cyclists or turning movements. Need to consider the impacts of speed limits, as the slower the speed limit is the closer the following is. The faster the speed limit the lower the expected occupancy is.

A.3 TRANSPORT FOR NEW SOUTH WALES

Meeting Name:	*Real-time Operational Capacity Estimation – TfNSW*		
Meeting Date: 10 December 2019	**Location:** Skype		
Time: 11:00 AEDT	**Duration:** 1 hour		
Meeting Chair: Paul Bennett	**Minutes By:** Kenneth Lewis		

Attendance	Yes
Paul Bennett	Y
Kenneth Lewis	Y
Christian Chong-White – Transport for New South Whales	Y
Merle Wood – Queensland Department of Transport and Main Roads	Y

item	Subject
1.	**Background** Provided the background of the project, indicating the aim is to predict the real-time capacity. The current stage is to look at the operational capacity.
2.	**Discussion** The fundamental methodology seems reasonable. It is believed that a site-specific calibrated value should be used instead of a static threshold for the network. Currently calibrate each site using SCATS and use relative values. If already have observed capacity, why do you need a design capacity? The reason is due to arterial roads operational capacity not being able to utilise design capacity. Why wouldn't Bluetooth give you enough speed resolution? Queensland do not have Bluetooth at every major intersection. Cannot assume the same speed from 1 observation over multiple lengths. Have TfNSW/RMS attempted to do this or something similar in the past? SCATS calibrates the capacity, but only uses it for optimising the signal controllers. This is done at a site level, not for a corridor. It is believed that re-routing road users based on spare capacity is good thinking. SCATS calibrates the maximum flow of every detector. It is noted that every vehicle movement has different characteristics. It is believed that instead of using a static threshold, each detector should be calibrated due to every site and detector being different. It would be interesting to see if the occupancy for different sites have different occupancy thresholds. It is noted that current work has been looking at calibrating sites, looking at density. It was noted that there has not been much research into the calibration variations due to seasonal changes. You can infer traffic jam from stop-line detectors. You do not have to have a departure side detector to do this. A departure side detector shall give you the same information just in a different way. This means that if you tie yourself to assumptions, it may be harder to use for arrival side detectors. SCATS, when the light goes green, the flow becomes the maximum. Any deviation from this is considered to be congestion. This is based on data calibrated from the previous day. Are the calibration values good? The calibrated data is good but suffers from situations such as inside lanes that are underutilised due to lane drop or parking, leading to vehicles not using the inside lane. This causes alarms in SCATS indicating that the lane is not calibrated properly, although it usually is. The calibration effects the usability of the lane. SCATS learns and uses it. The values don't change much day by day for each site, but the values change site to site.

item	Subject
	Do you have concerns about if the methodology were applied, would this compromise the current signal controllers? Yes, unless it would add value. How would this deviate from the current operation? Bus priority, you deviate from the current operation of the intersection, you must have good justification of why it deviates. i.e. struggle to see how another route has capacity but is not married to the solution. If you guide people to an alternative route and manage to do this, it could be a win-win. Like the idea of determining if have spare capacity and giving users better information to make decisions. The real-time operation of this is more of a stretch. It is believed that this should be done retrospectively first and then draw out the real-time aspects. This could help to identify where there are static issues. In SCATS, some of these can probably be implemented in real-time. The delay is relatively known (speed), but not the operational utilisation such as network level decisions. Degree of Saturation is relative to capacity. Cycle time is an indication of capacity. These measures can give false negatives, so this should be considered when investigating – i.e. side roads are seen as having no capacity, but this is false as there is capacity, but capacity is not given based on the signal logic. A good example is you could use something like SCATSSIM or Aimsun to look at how this could improve the network. This would be a costly exercise. To summarise, should go towards detector-based calibration instead of a static general threshold.

A.4 MAIN ROADS WESTERN AUSTRALIA

Meeting Name:	*Real-time Operational Capacity Estimation – MRWA*		
Meeting Date: 10 December 2019	**Location:** Skype		
Time: 14:00 AEDT	**Duration:** 1 hour		
Meeting Chair: Paul Bennett	**Minutes By:** Kenneth Lewis		

Attendance	Yes
Paul Bennett	Y
Kenneth Lewis	Y
Kamal Weeratunga – Main Roads Western Australia	Y
Graham Jacoby – Main Roads Western Australia	Y
Merle Wood – Queensland Department of Transport and Main Roads	Y

item	Subject
1.	**Background** Provided the background of the project, indicating the aim is to predict the real-time capacity. The current stage is to look at the operational capacity.
2.	**Discussion** How are we getting occupancy on arterial roads? STREAMS, occupancy for arrival and departure detectors. Trying to work out how this could potentially be undertaken for Perth. SCATS, depends what mode the detector is in: • Detectors in presence mode can provide more data, fluid occupancy and speed. i.e. back of queue. • Detectors in passage mode essentially just determine the number of vehicles. i.e. stop line. STREAMS differ from SCATS by having detectors at 35m from intersection, except for turns which are located at stop line. MRWA believe the methodology is attractive at an initial look. Interested in getting more information on the findings of the project, especially at milestones. (Merle to check whether there is a problem to send a copy of the stage 1 report to Kamal and Graham, as they are interested in knowing a bit more from the report.) Believe this work would be able to close the loop by relaying information to map providers, to show where capacity is available. Unsure about would manage to close the loop, as have previously had trouble trying to get Google to make minor changes such as road closures. TMR may be able to undertake a workaround, as they have a navigation app which uses the Google navigation information for routing. MRWA primarily operate the arterial network with SCATS, but there is an interface to STREAMS in SCATS for the motorways. Merle indicated that when reach the stage of implementing, if implementing in Brisbane, would need to do in conjunction with BCC, as they own all the alternative routes. Unsure if lane-level data is available for SCATS. Need to check with the operators of SCATS. How would this be seen to work for Motorways? It would potentially allow for users to be directed onto the arterial road network if there is spare capacity when there is flow breakdown on the freeway.

item	Subject
	Flow breakdown is instantaneous for un-managed motorways but is a bit more predictable for a managed motorway. Some corridors break down every day in Queensland. It is just a matter of time. If the capacity can be distinguished and reported, this can help the users make an informed choice. Another piece of research could look at what would motivate people to change their route.

APPENDIX B OCCUPANCY VERSUS VOLUME

B.1 M5001

Figure B.1 Intersection Signal Drawing - Site M5001

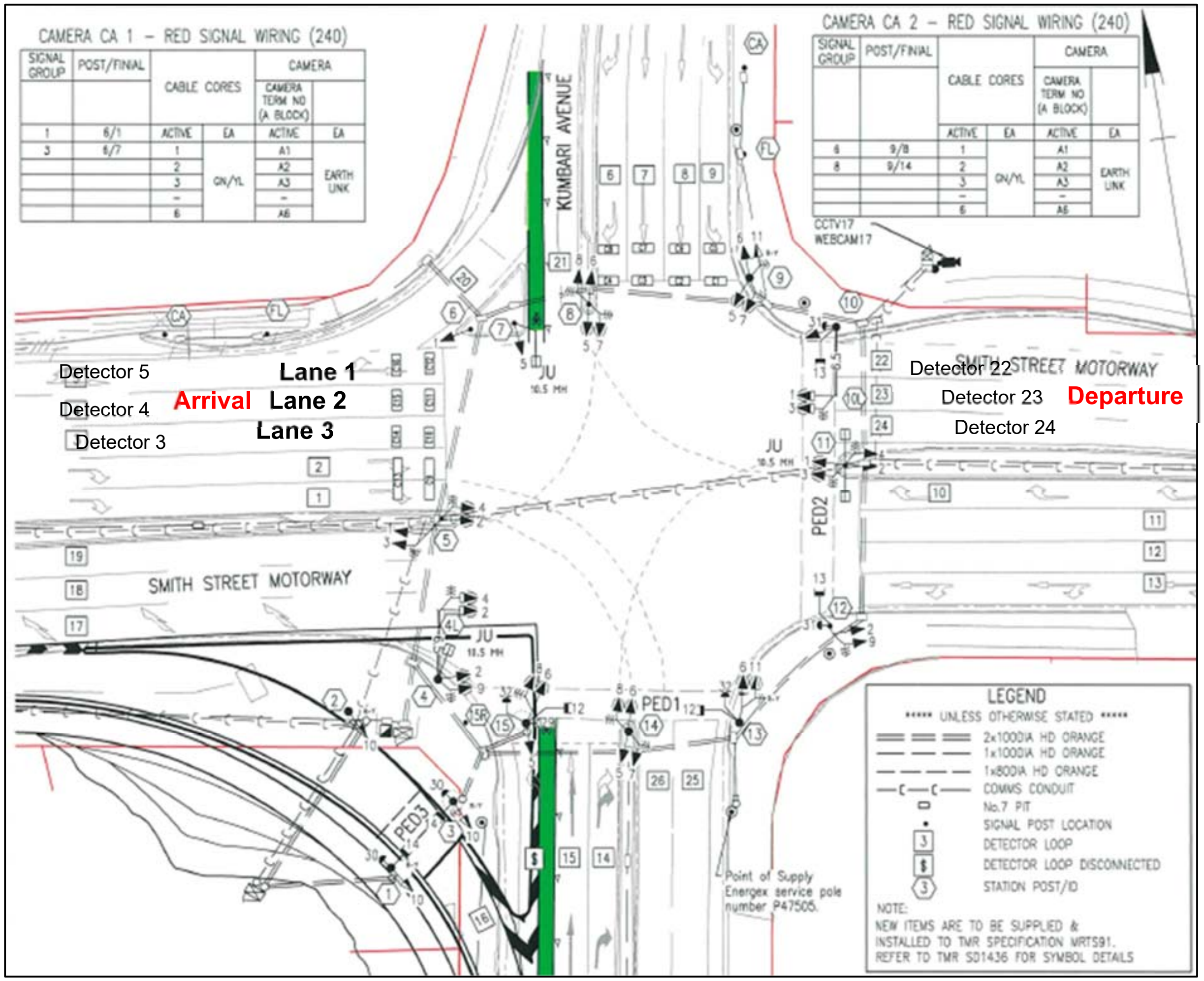


Table B.1: Volume vs Occupancy - M5001 Threshold Summary

Lane	Parameter	Maximum flow (vehicles per minute)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 1	NPI average occupancy vs arrival volume	25	23	21
	Arrival occupancy vs arrival volume	30	27	28
	Departure occupancy vs arrival volume	30	27	20
	Departure occupancy vs departure volume	26	23	22
Lane 2	NPI average occupancy vs arrival volume	25	23	20
	Arrival occupancy vs arrival volume	30	27	27
	Departure occupancy vs arrival volume	30	27	23
	Departure occupancy vs departure volume	29	26	24
Lane 3	NPI average occupancy vs arrival volume	25	23	20
	Arrival occupancy vs arrival volume	30	27	26
	Departure occupancy vs arrival volume	30	27	27
	Departure occupancy vs departure volume	33	30	30

Figure B.2 Arrival volume vs NPI Average Occupancy - M5001 - Lane 1

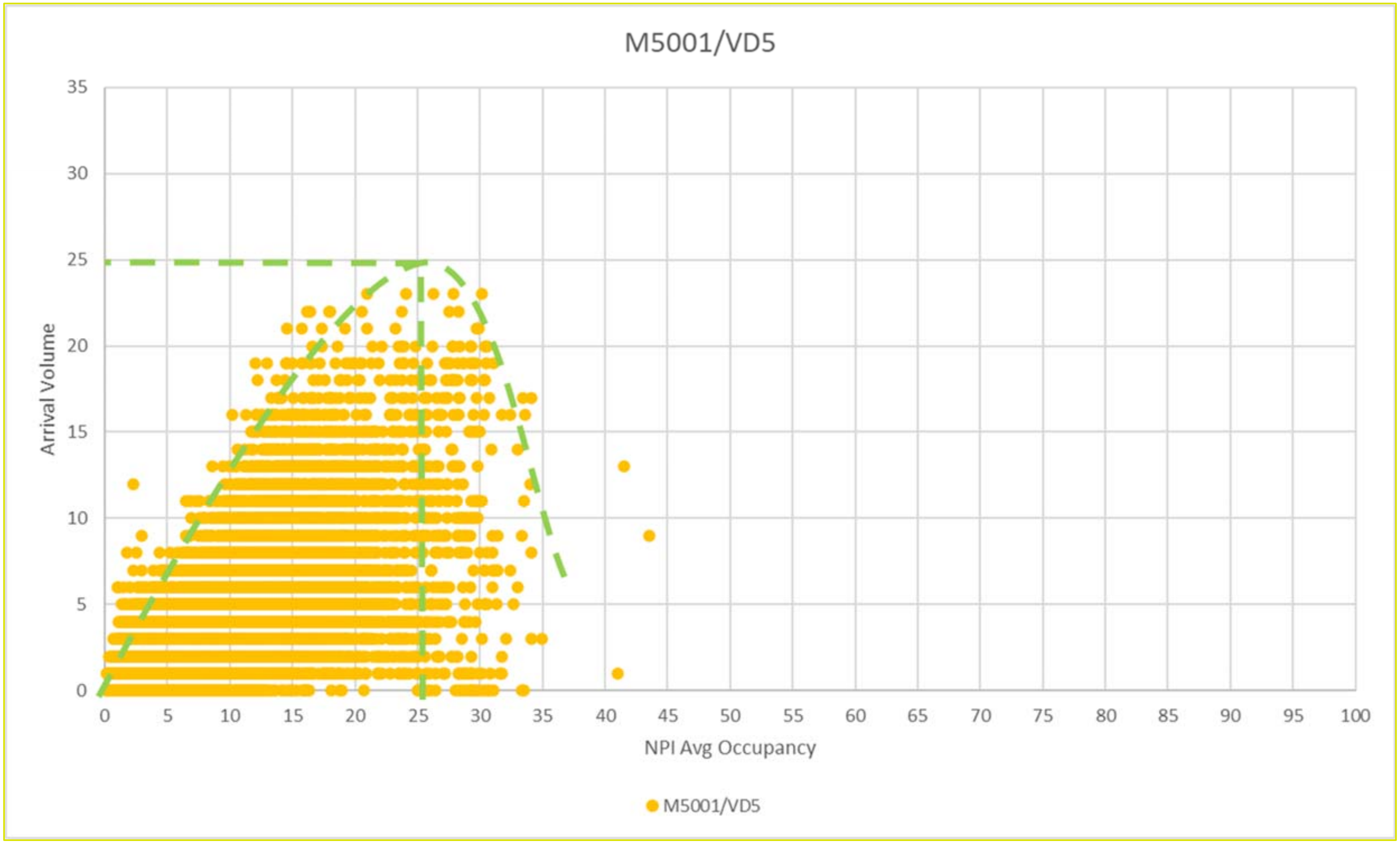


Figure B.3 Arrival volume vs NPI Average Occupancy - M5001 - Lane 2

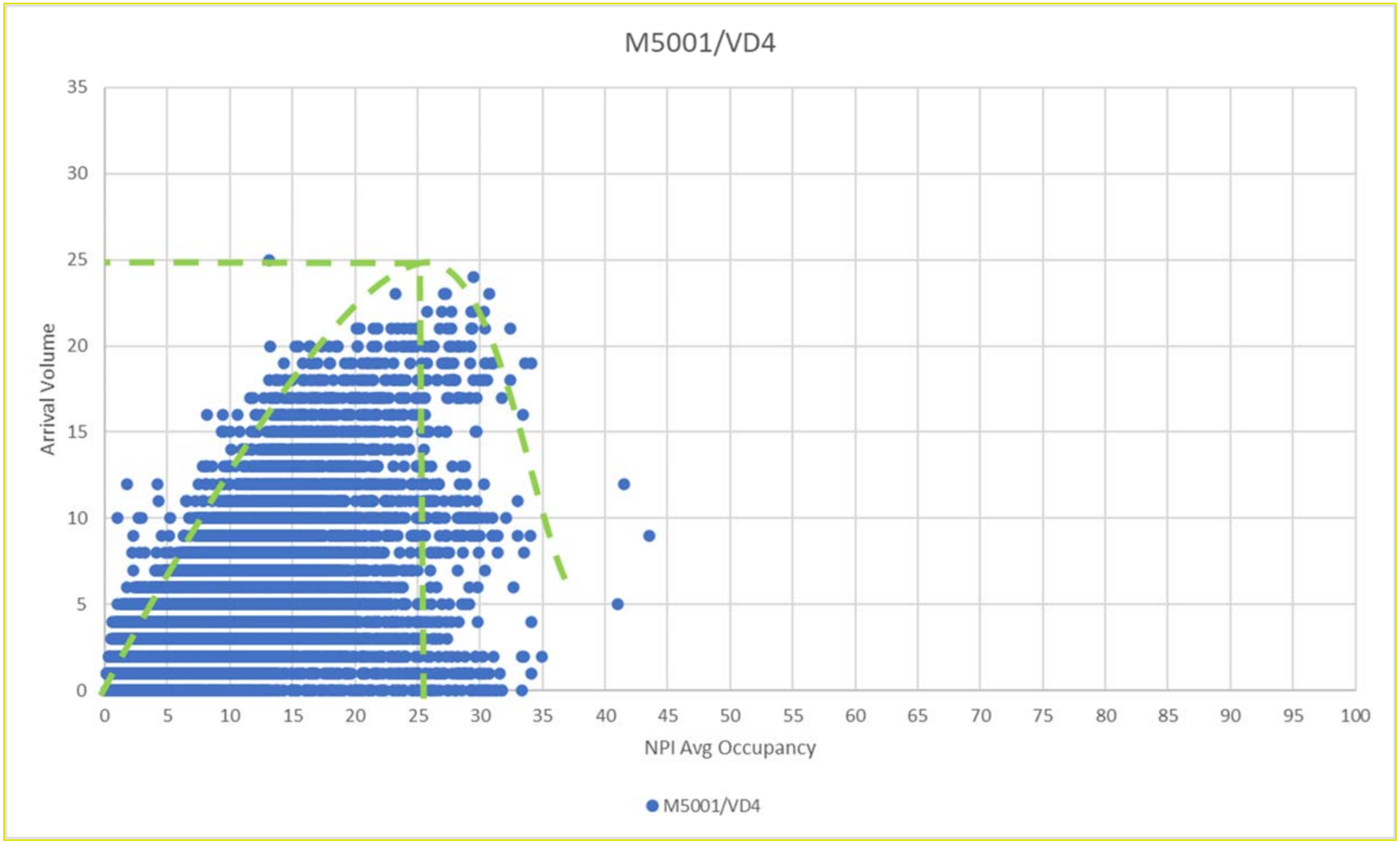


Figure B.4 Arrival volume vs NPI Average Occupancy - M5001 - Lane 3

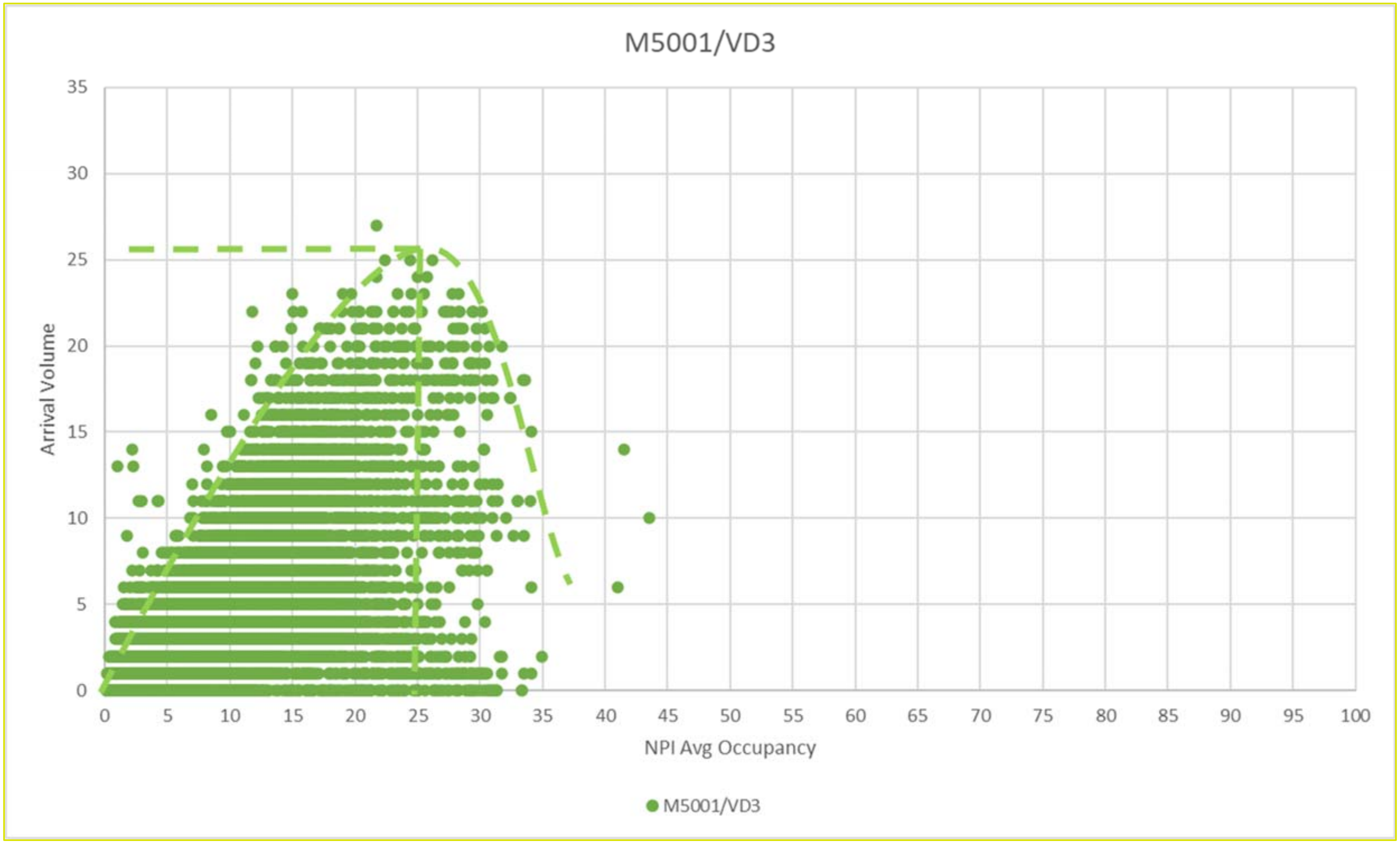


Figure B.5 Arrival volume vs Arrival Occupancy - M5001 - Lane 1

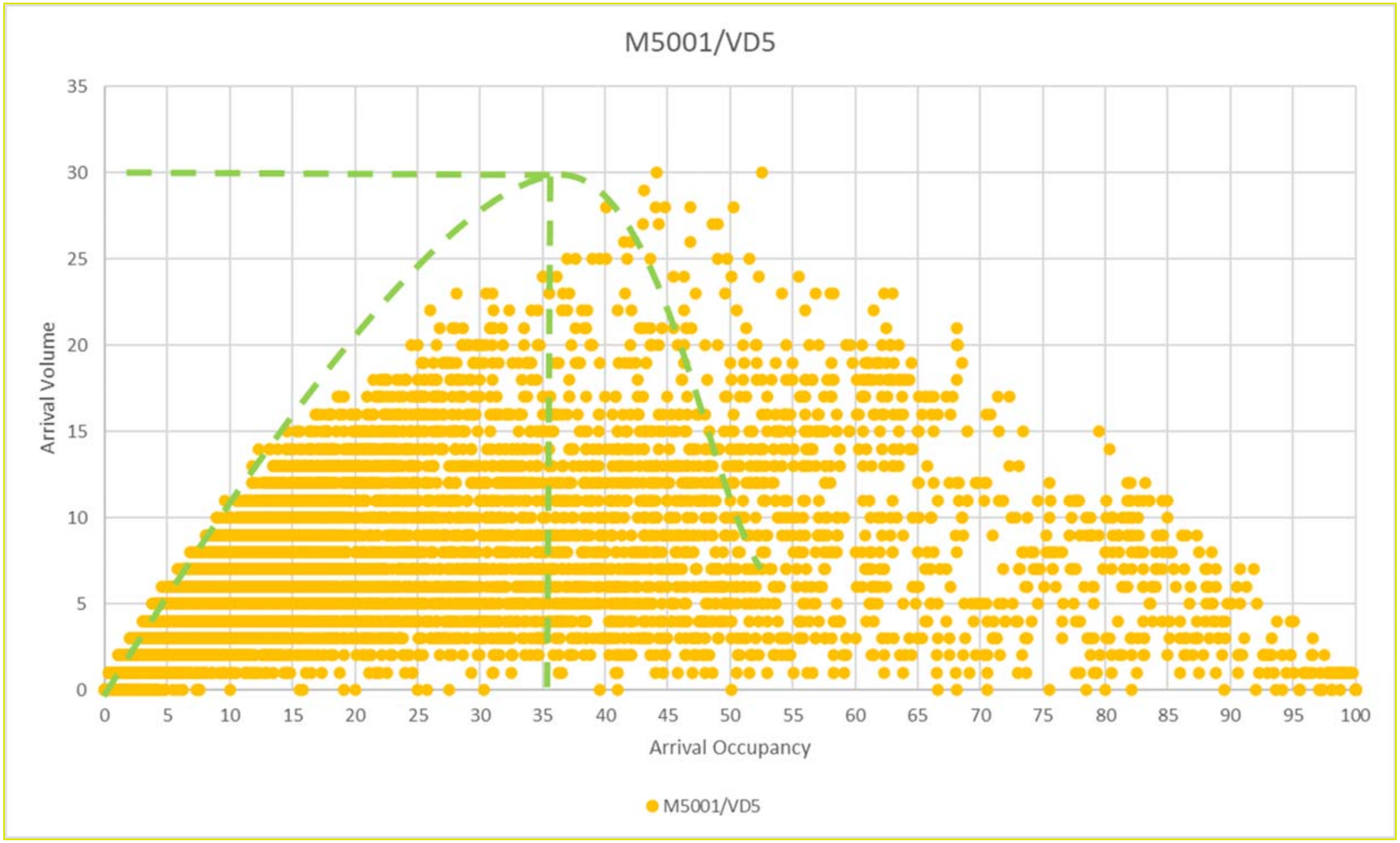


Figure B.6 Arrival volume vs Arrival Occupancy - M5001 - Lane 2

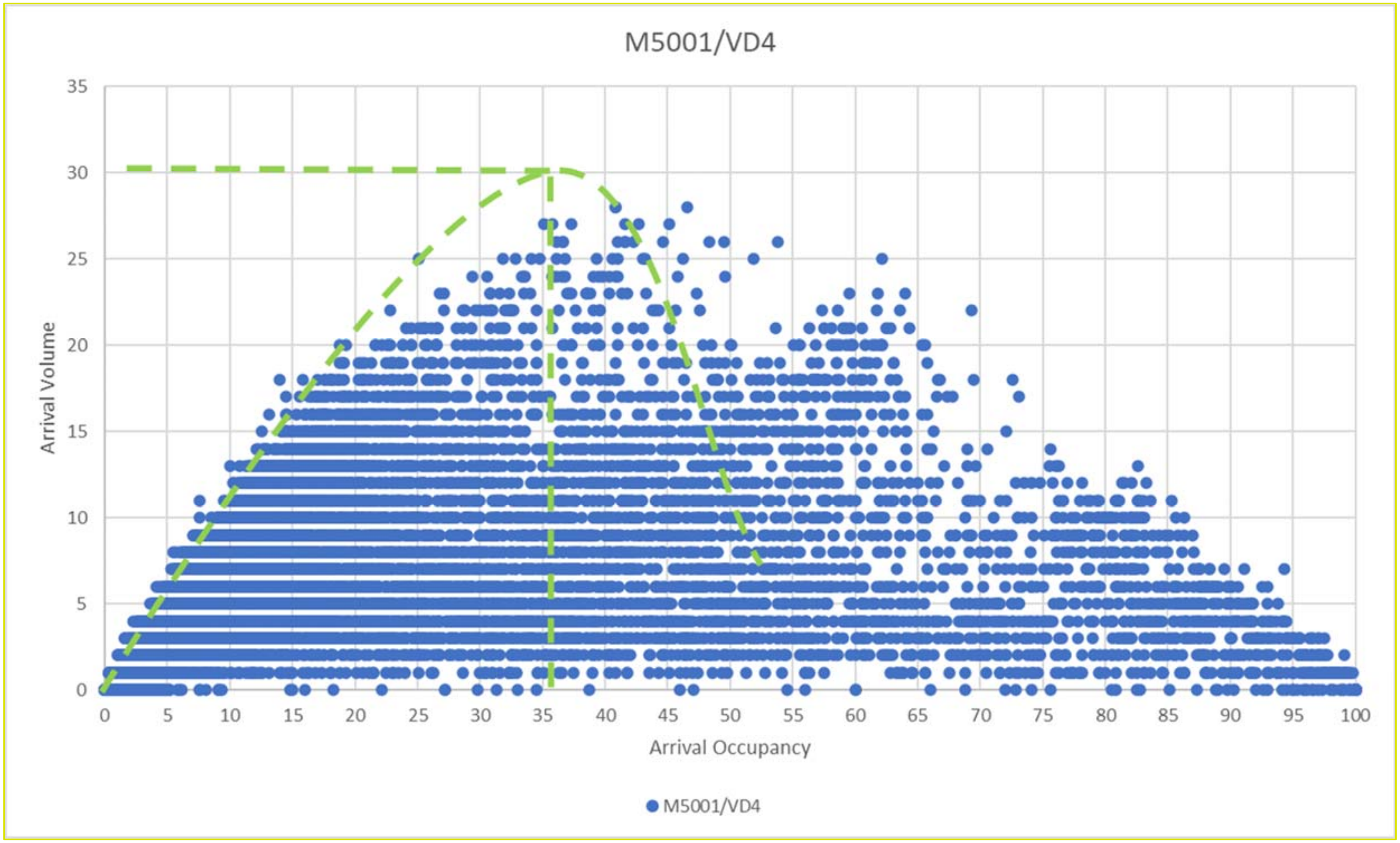


Figure B.7 Arrival volume vs Arrival Occupancy - M5001 - Lane 3

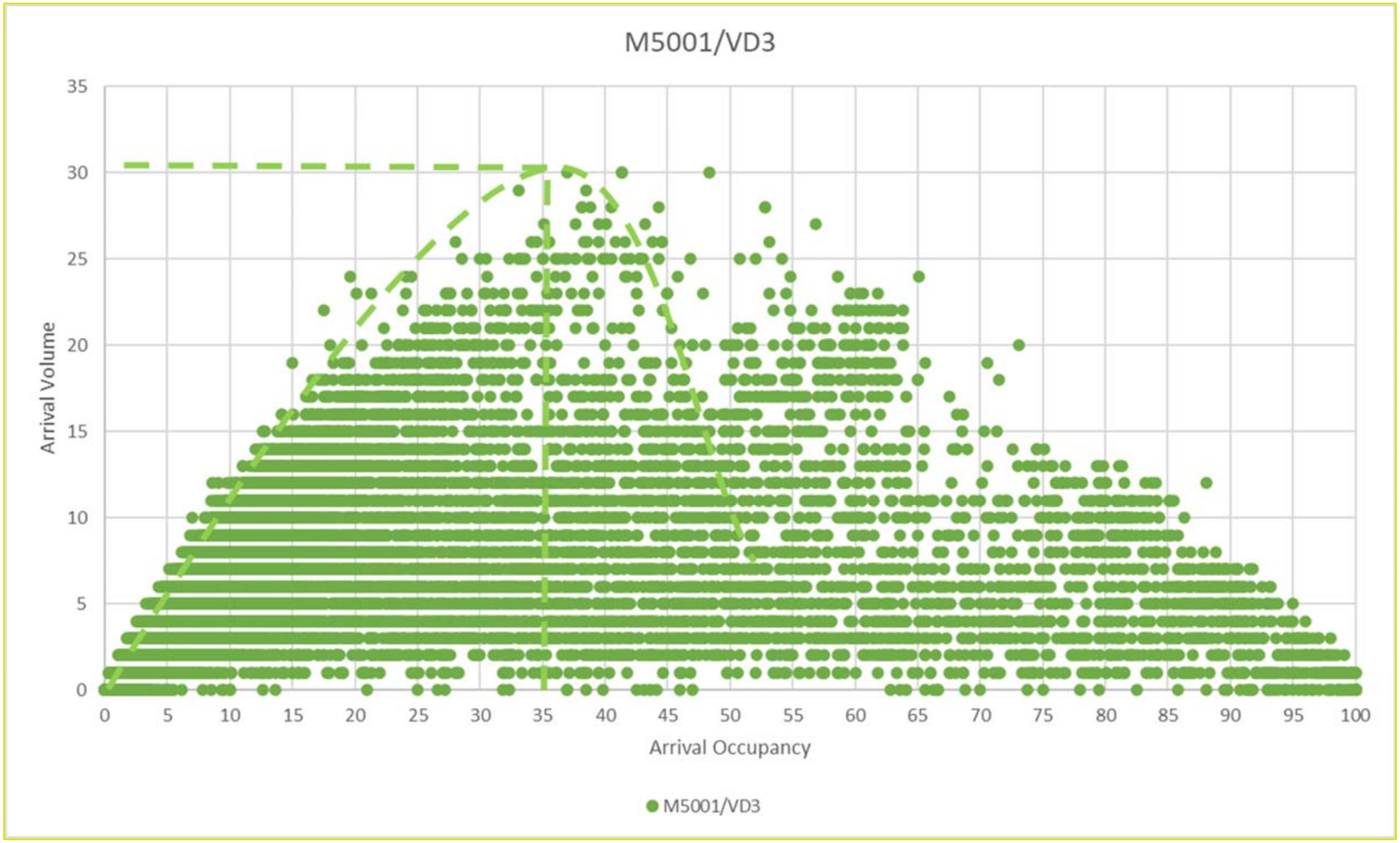


Figure B.8 Arrival volume vs Departure Occupancy - M5001 - Lane 1

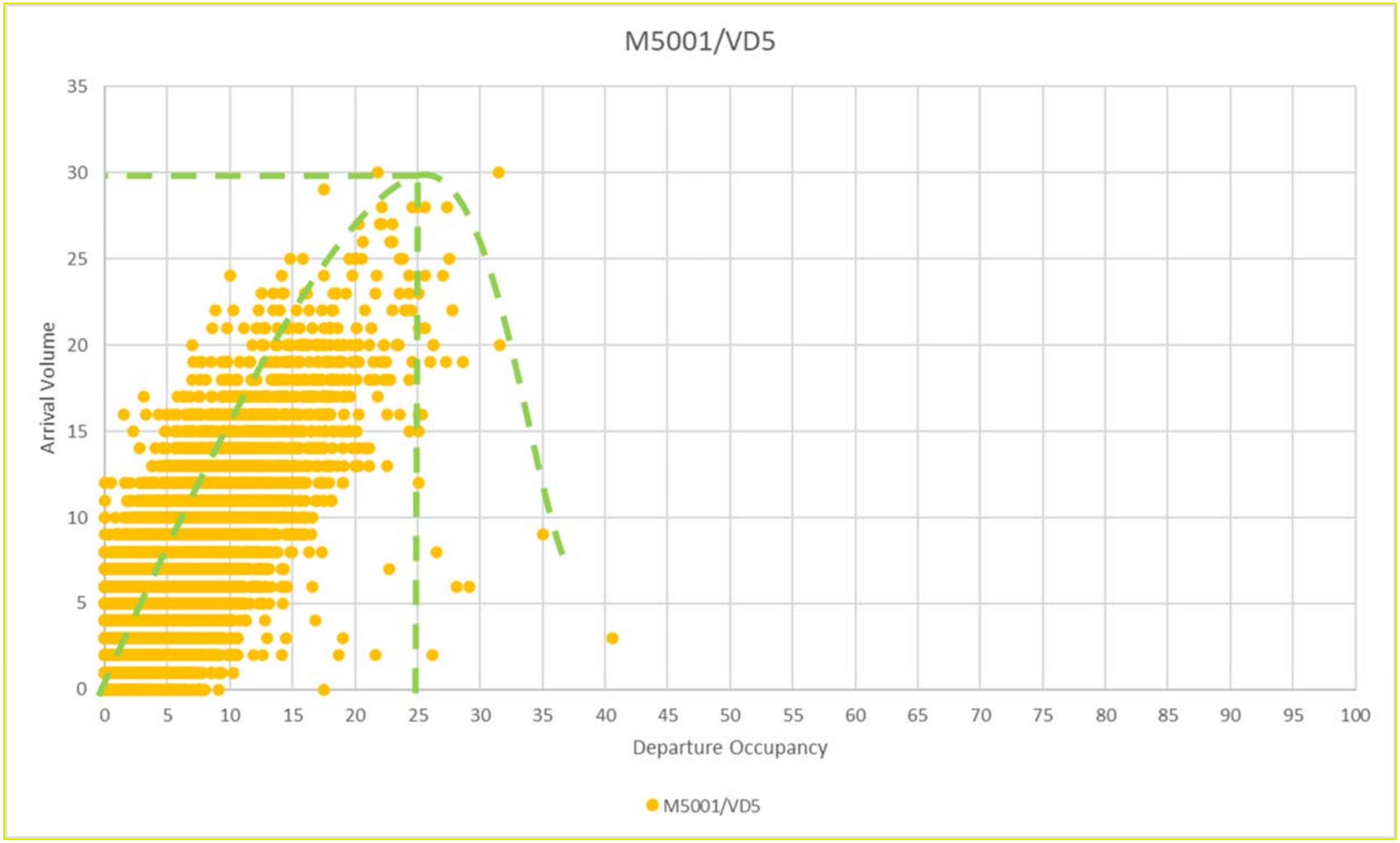


Figure B.9 Arrival volume vs Departure Occupancy - M5001 - Lane 2

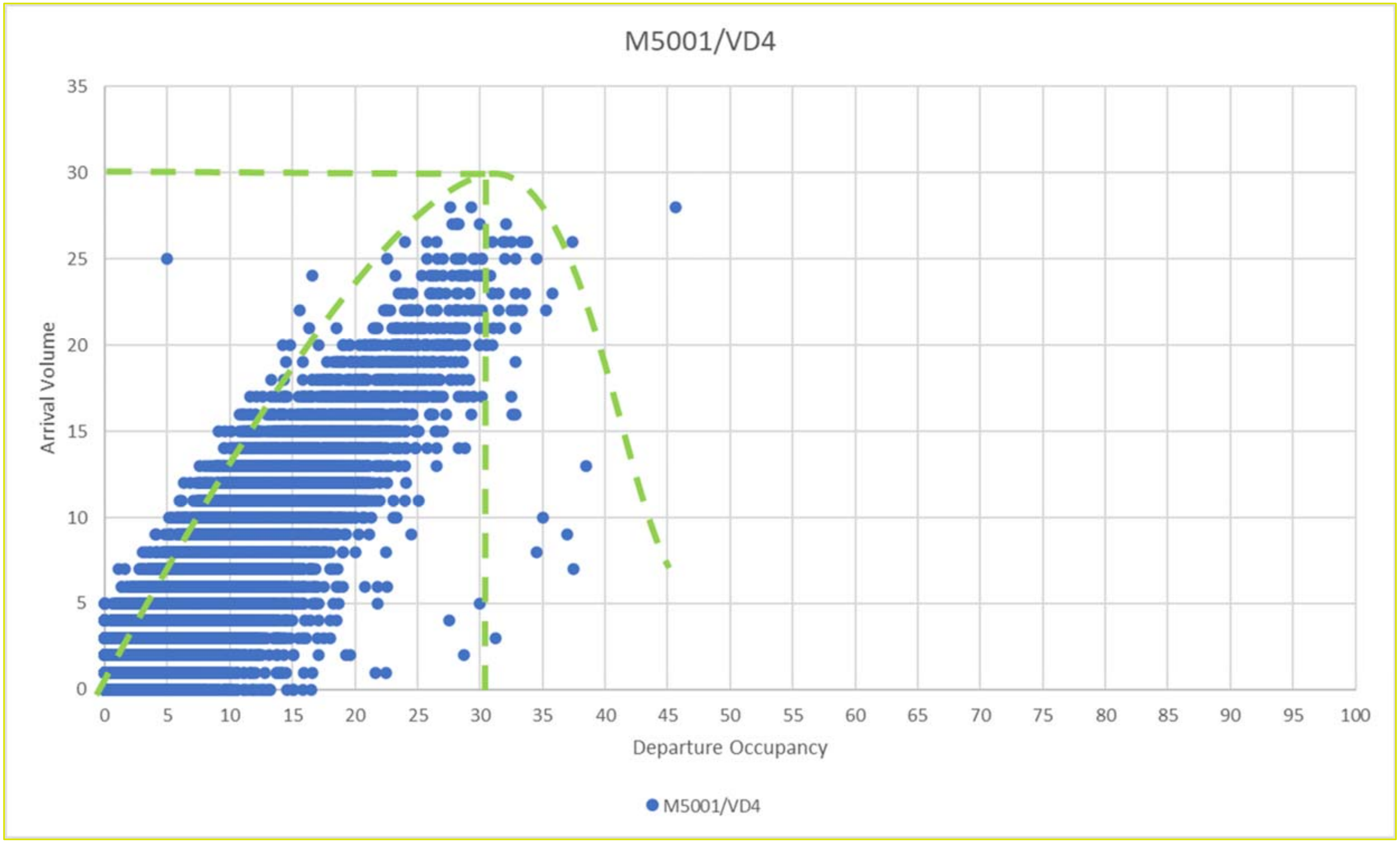


Figure B.10 Arrival volume vs Departure Occupancy - M5001 - Lane 3

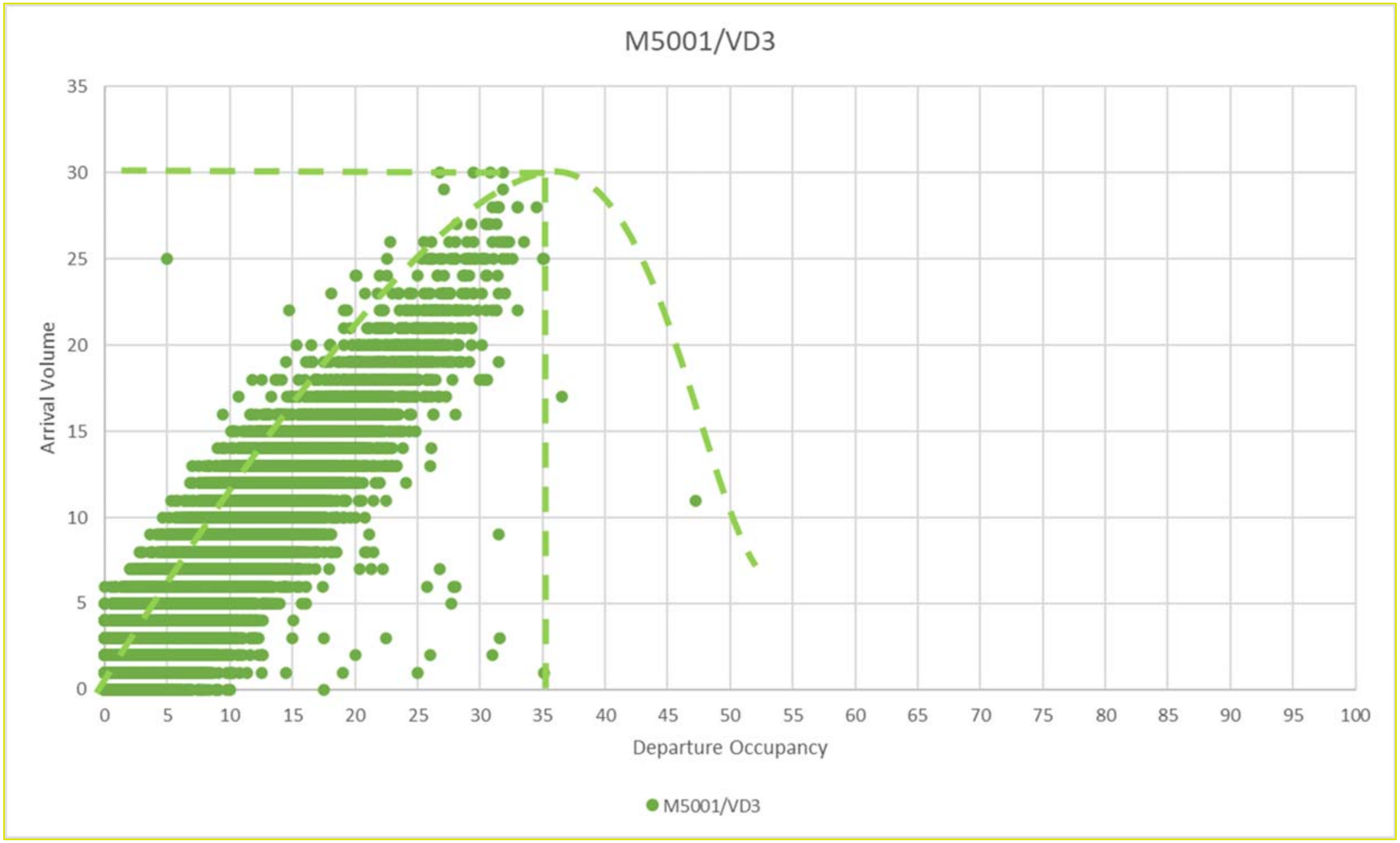


Figure B.11 Departure volume vs Departure Occupancy - M5001 - Lane 1

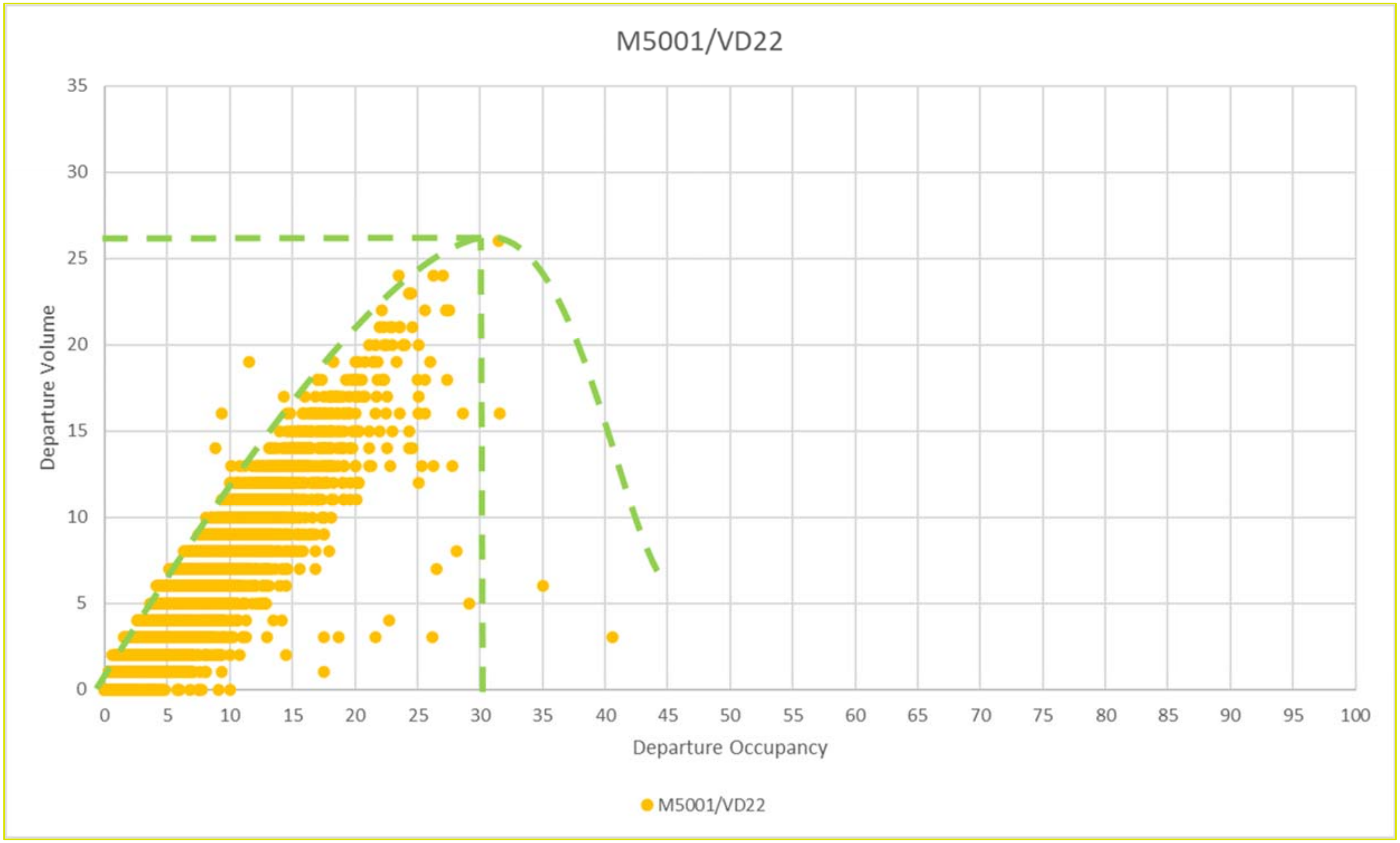


Figure B.12 Departure volume vs Departure Occupancy - M5001 - Lane 2

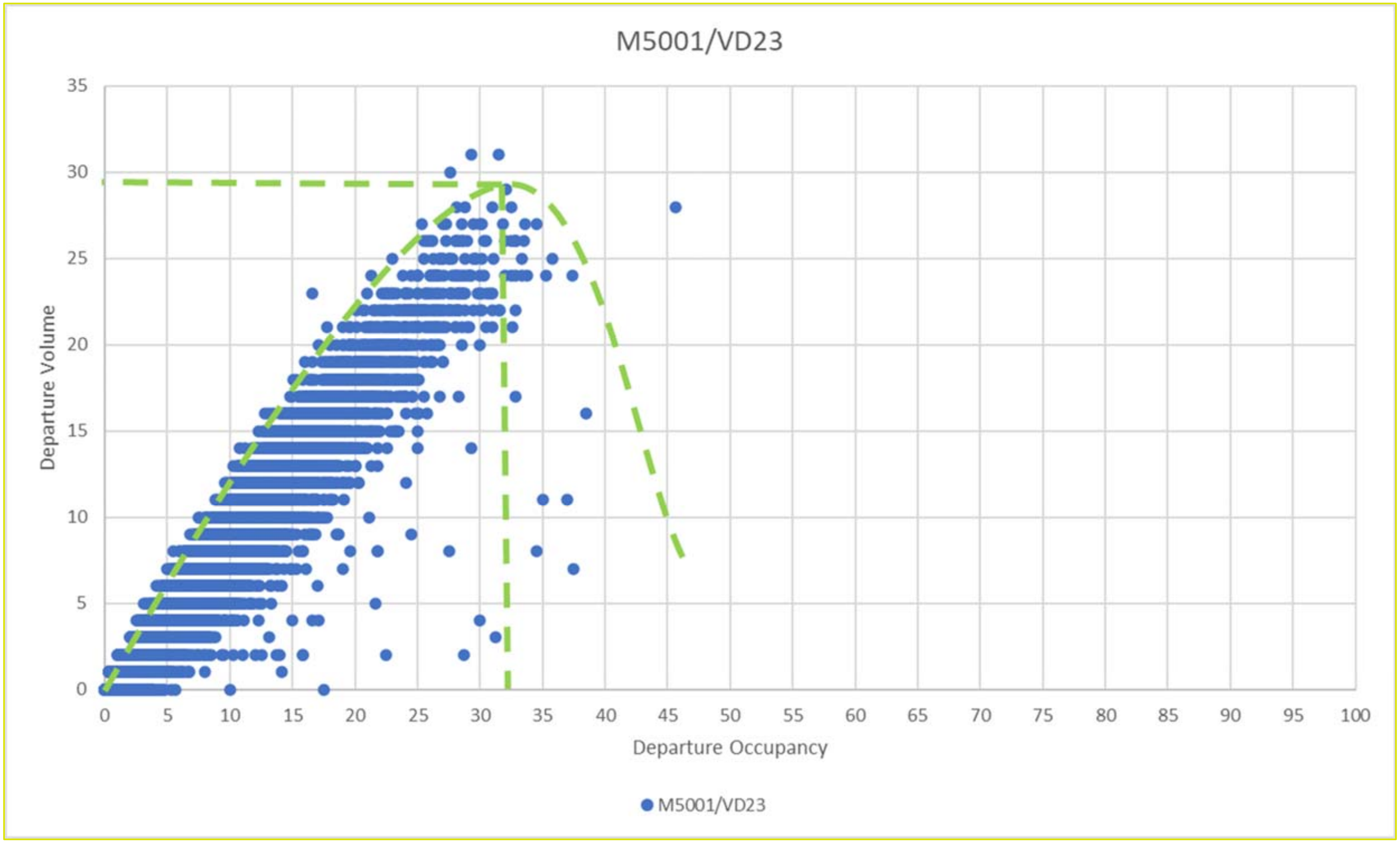
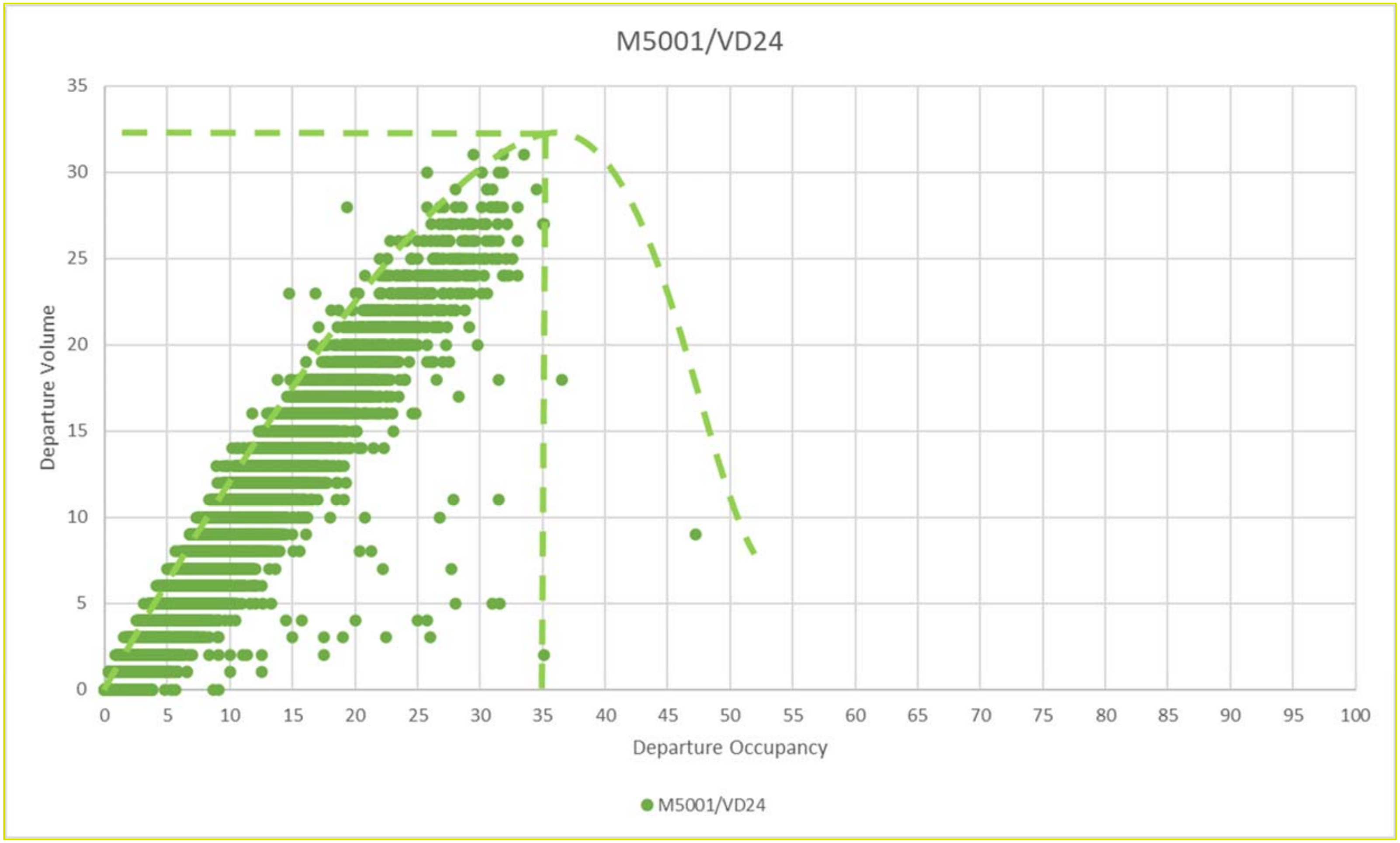


Figure B.13 Departure volume vs Departure Occupancy - M5001 - Lane 3



B.2 M5002

Figure B.14 Intersection Signal Drawing - Site M5002

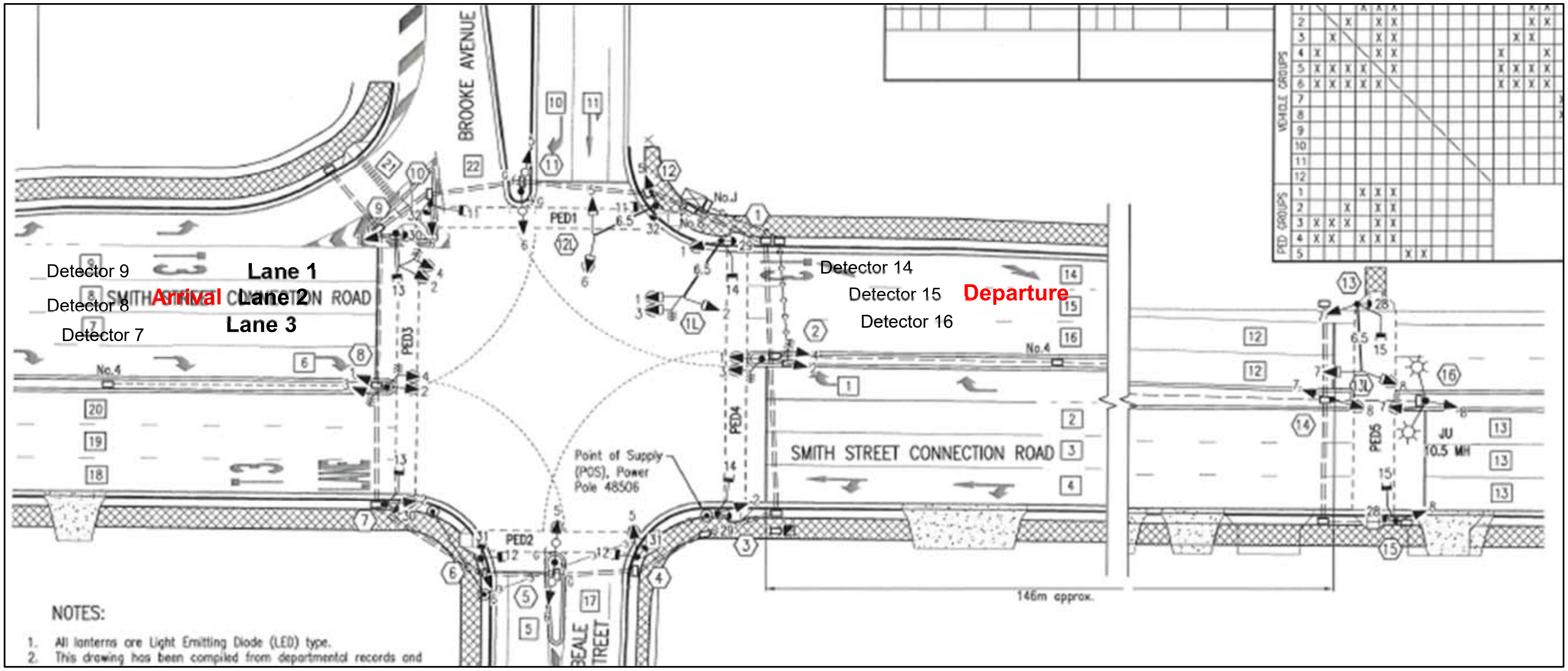


Table B.2: Volume vs Occupancy - M5002 Threshold Summary

Lane*	Parameter	Maximum flow (vehicles per minute)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 1	NPI average occupancy vs arrival volume	18	16	20
	Arrival occupancy vs arrival volume	25	23	22
	Departure occupancy vs arrival volume	22	20	29
	Departure occupancy vs departure volume	41	37	32

Lane*	Parameter	Maximum flow (vehicles per minute)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 2	NPI average occupancy vs arrival volume	27	24	20
	Arrival occupancy vs arrival volume	30	27	26
	Departure occupancy vs arrival volume	30	27	35
	Departure occupancy vs departure volume	43	39	34
Lane 3	NPI average occupancy vs arrival volume	30	27	20
	Arrival occupancy vs arrival volume	31	28	28
	Departure occupancy vs arrival volume	31	28	10
	Departure occupancy vs departure volume	40	36	23

*Note: Lane 1 is a merge lane, this will affect the occupancy and volume. The presence of the pedestrian crossing located near the intersection will also influence the occupancy and volume.

Figure B.15 Arrival volume vs NPI Average Occupancy - M5002 - Lane 1

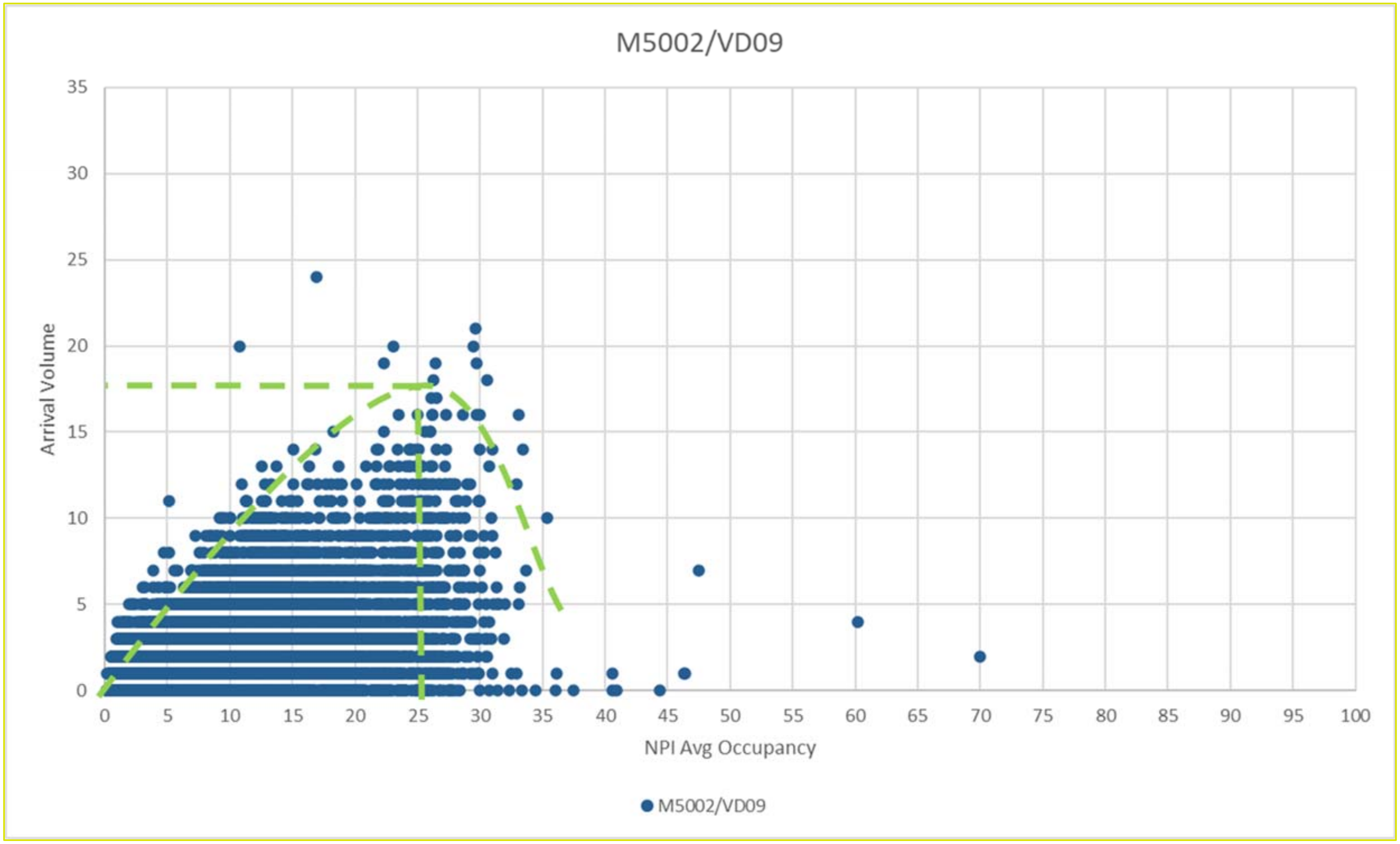


Figure B.16 Arrival volume vs NPI Average Occupancy - M5002 - Lane 2

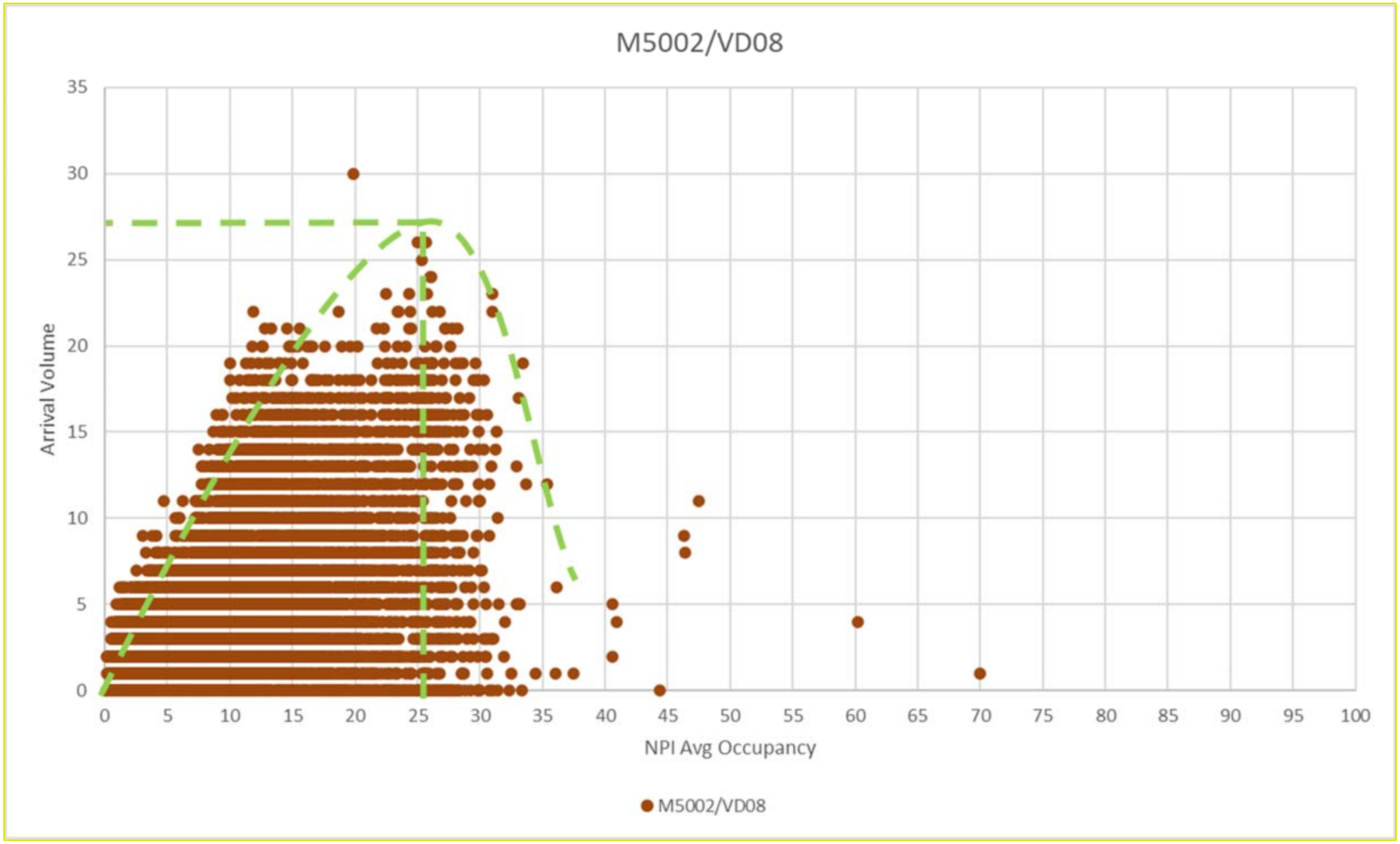


Figure B.17 Arrival volume vs NPI Average Occupancy - M5002 - Lane 3

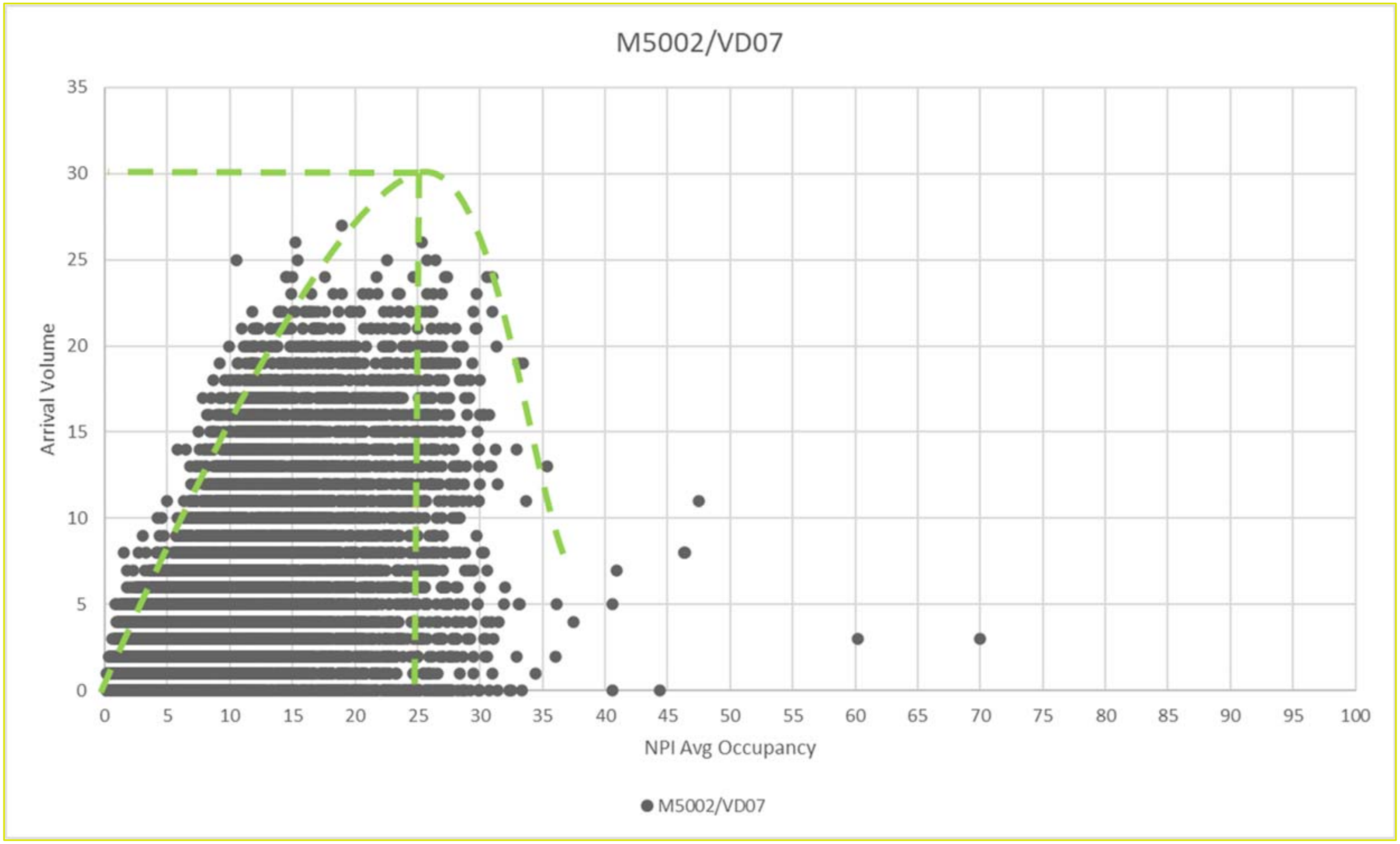


Figure B.18 Arrival volume vs Arrival Occupancy - M5002 - Lane 1

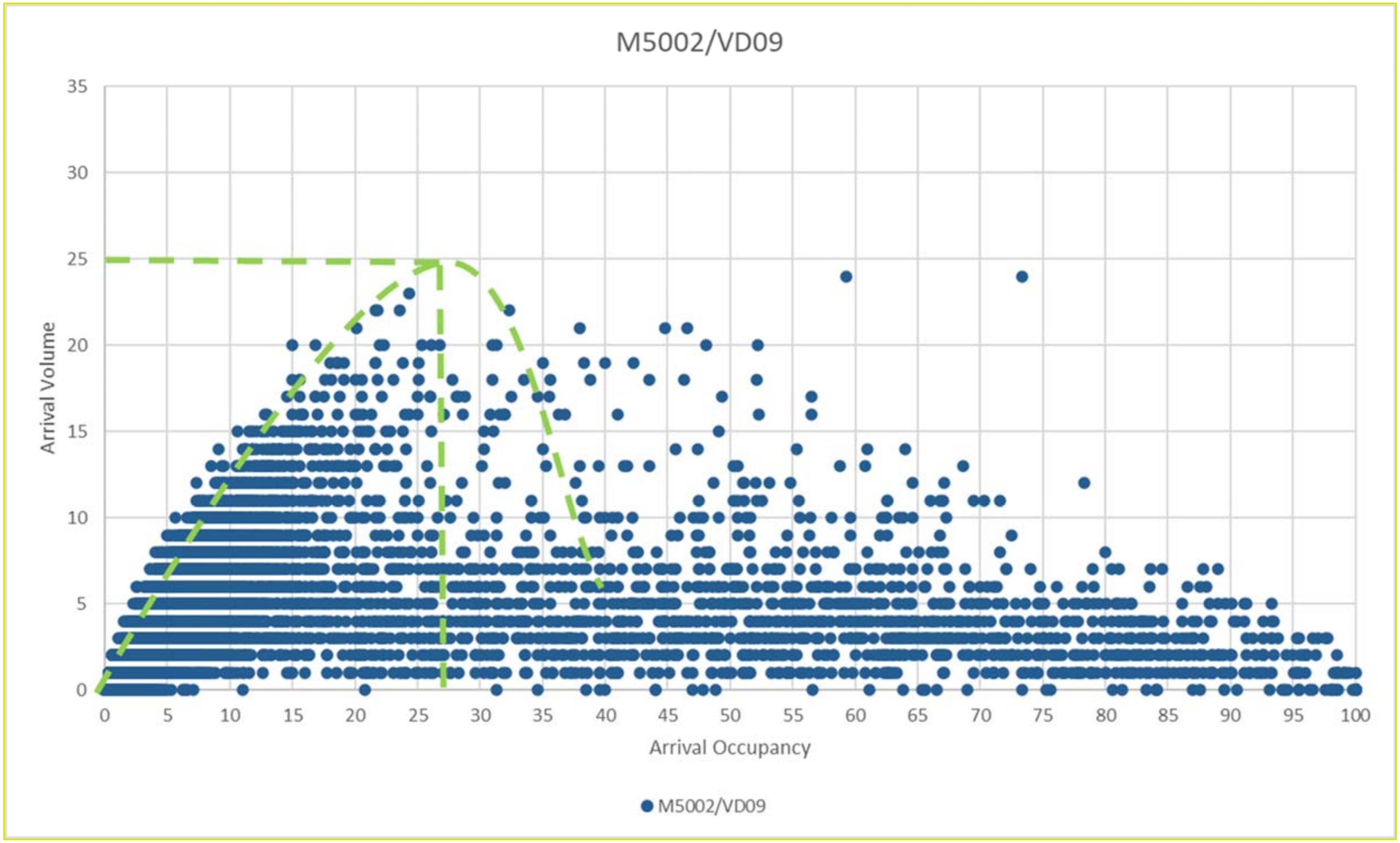


Figure B.19 Arrival volume vs Arrival Occupancy - M5002 - Lane 2

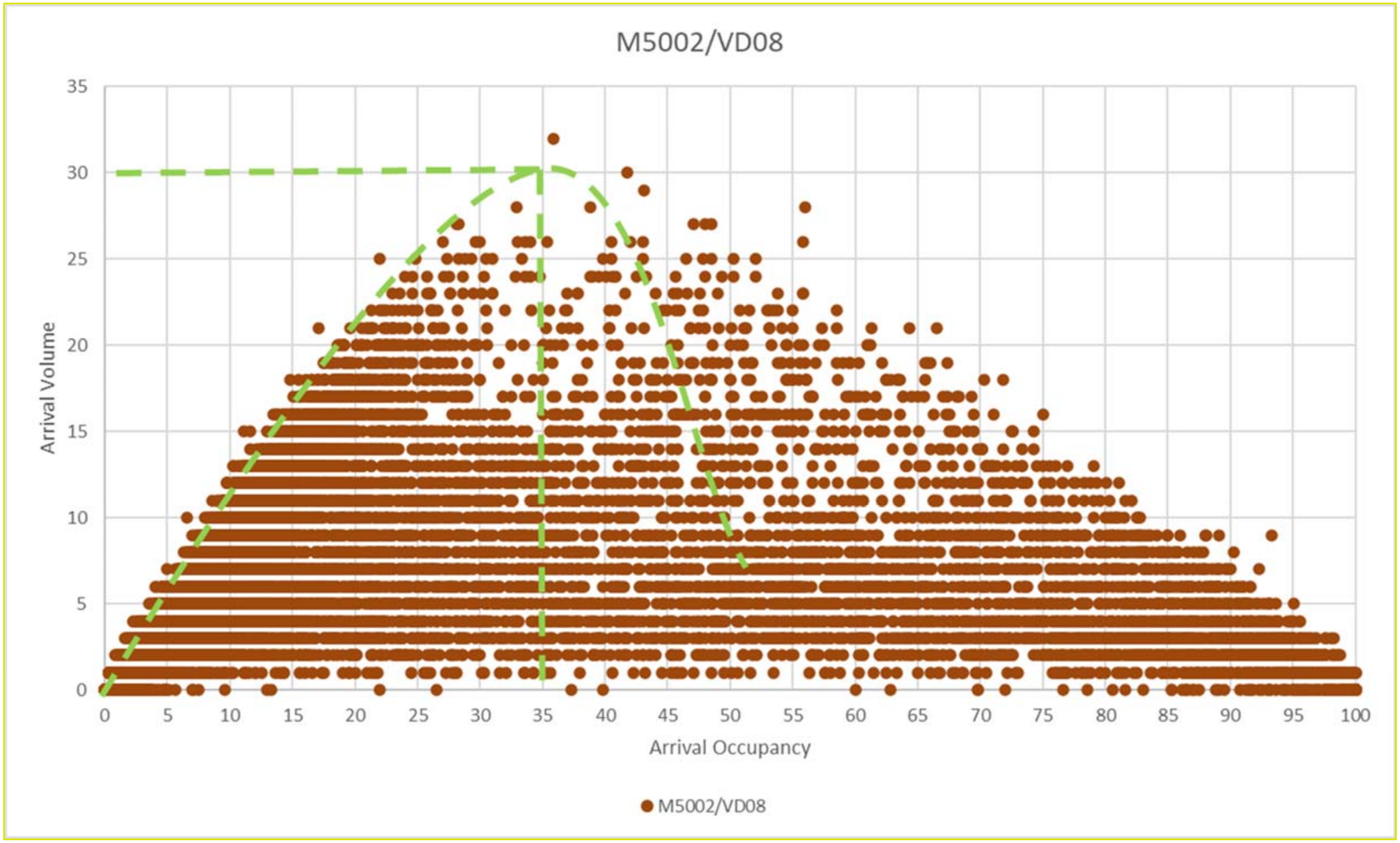


Figure B.20 Arrival volume vs Arrival Occupancy - M5002 - Lane 3

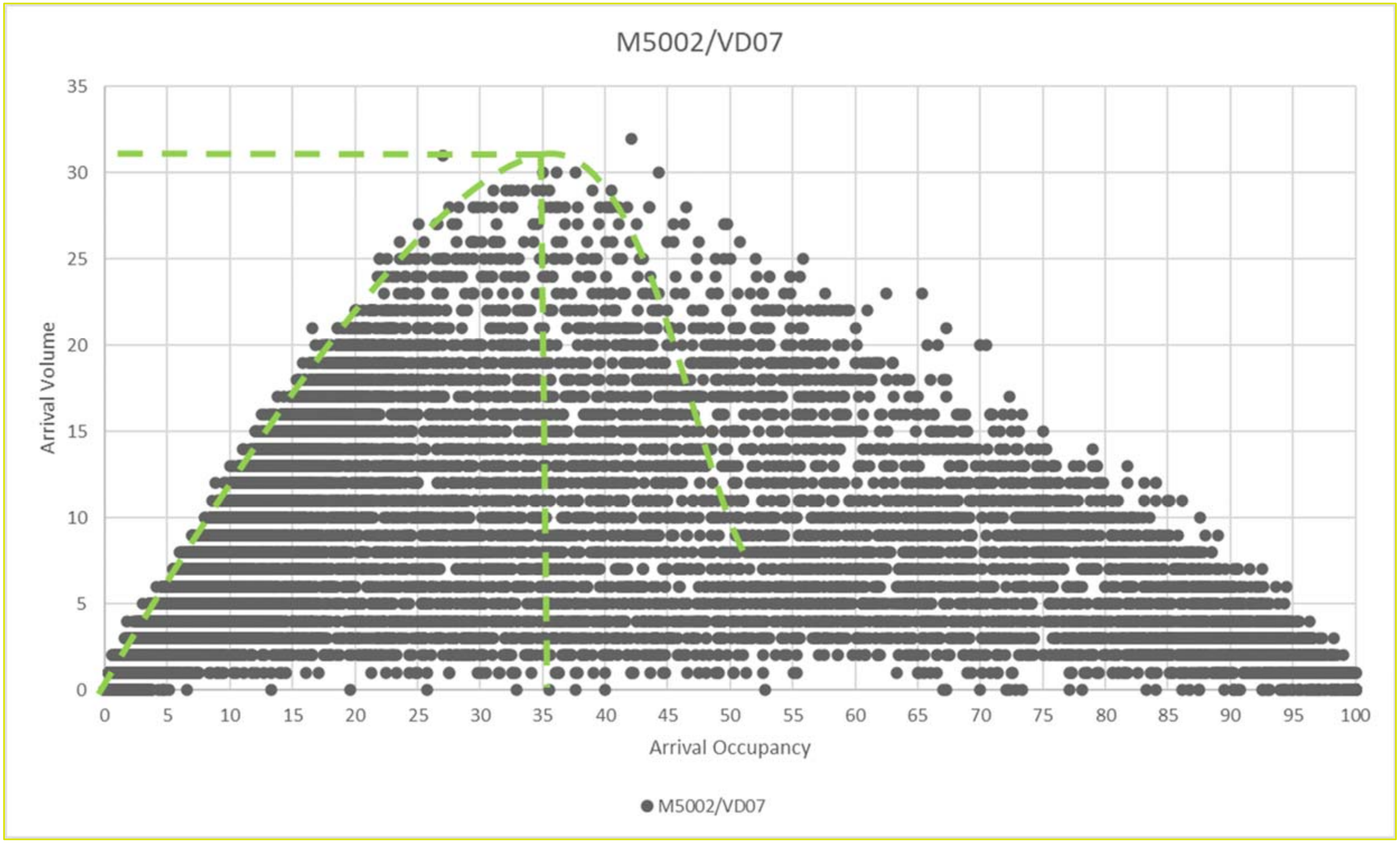


Figure B.21 Arrival volume vs Departure Occupancy - M5002 - Lane 1

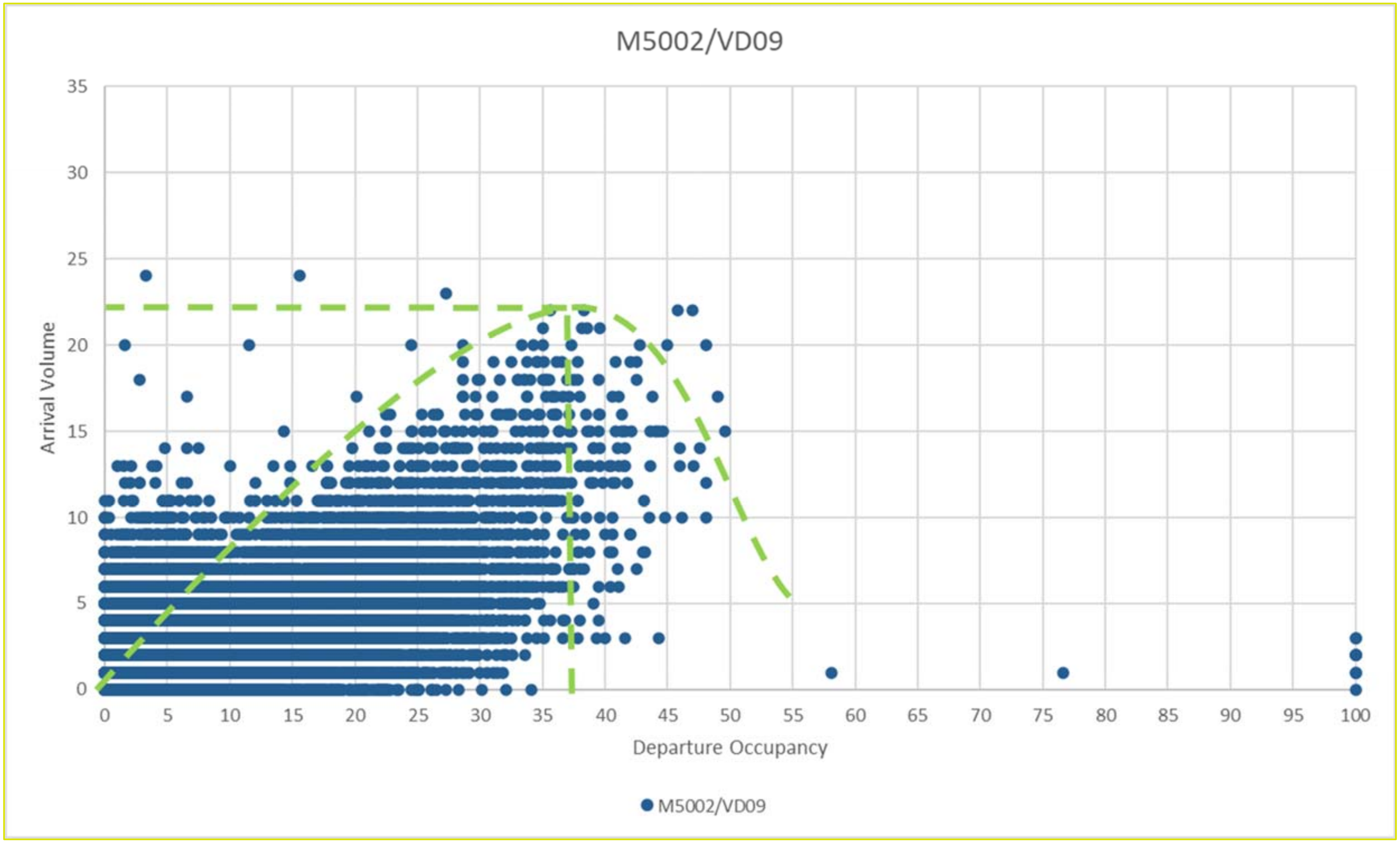


Figure B.22 Arrival volume vs Departure Occupancy - M5002 - Lane 2

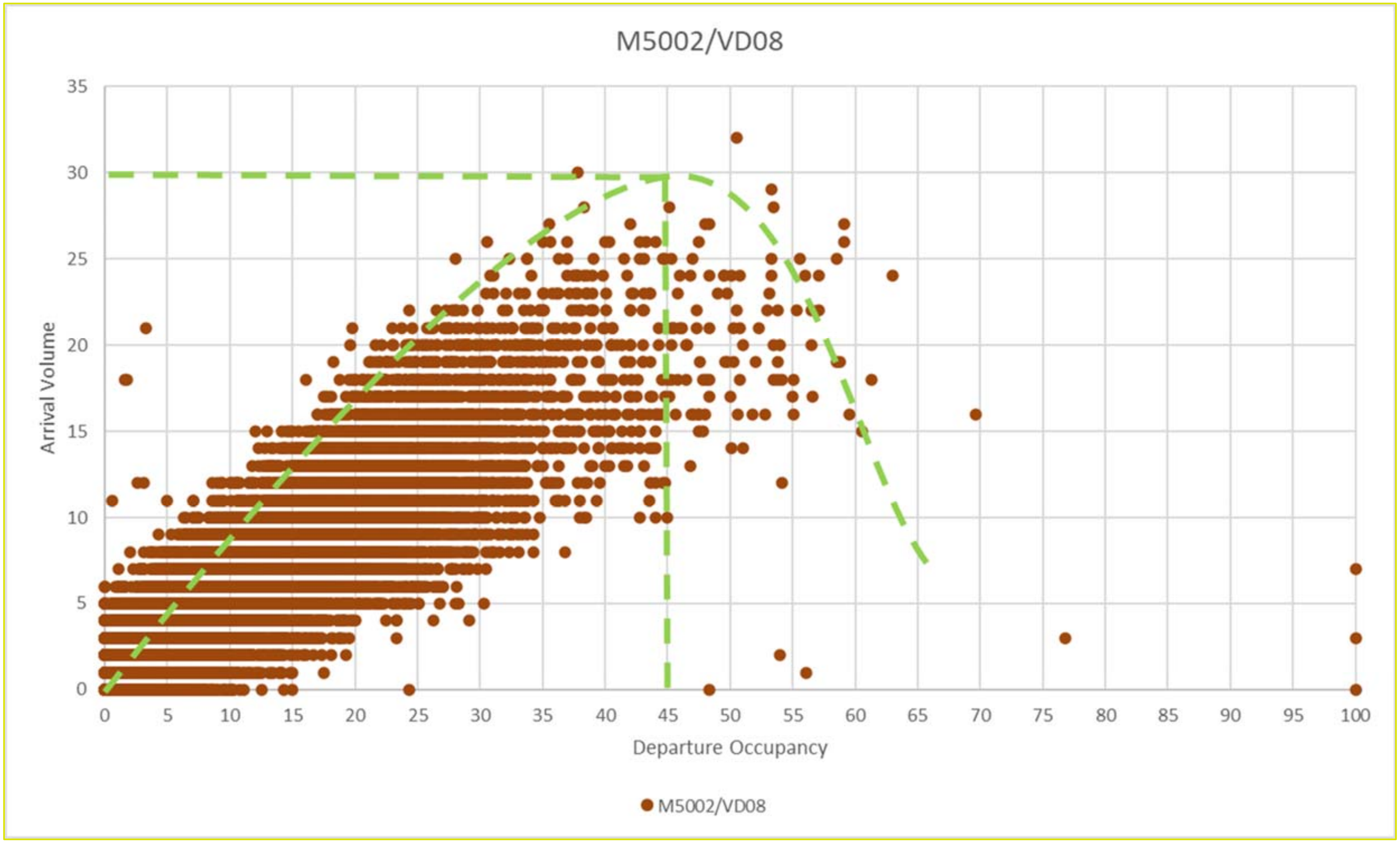


Figure B.23 Arrival volume vs Departure Occupancy - M5002 - Lane 3

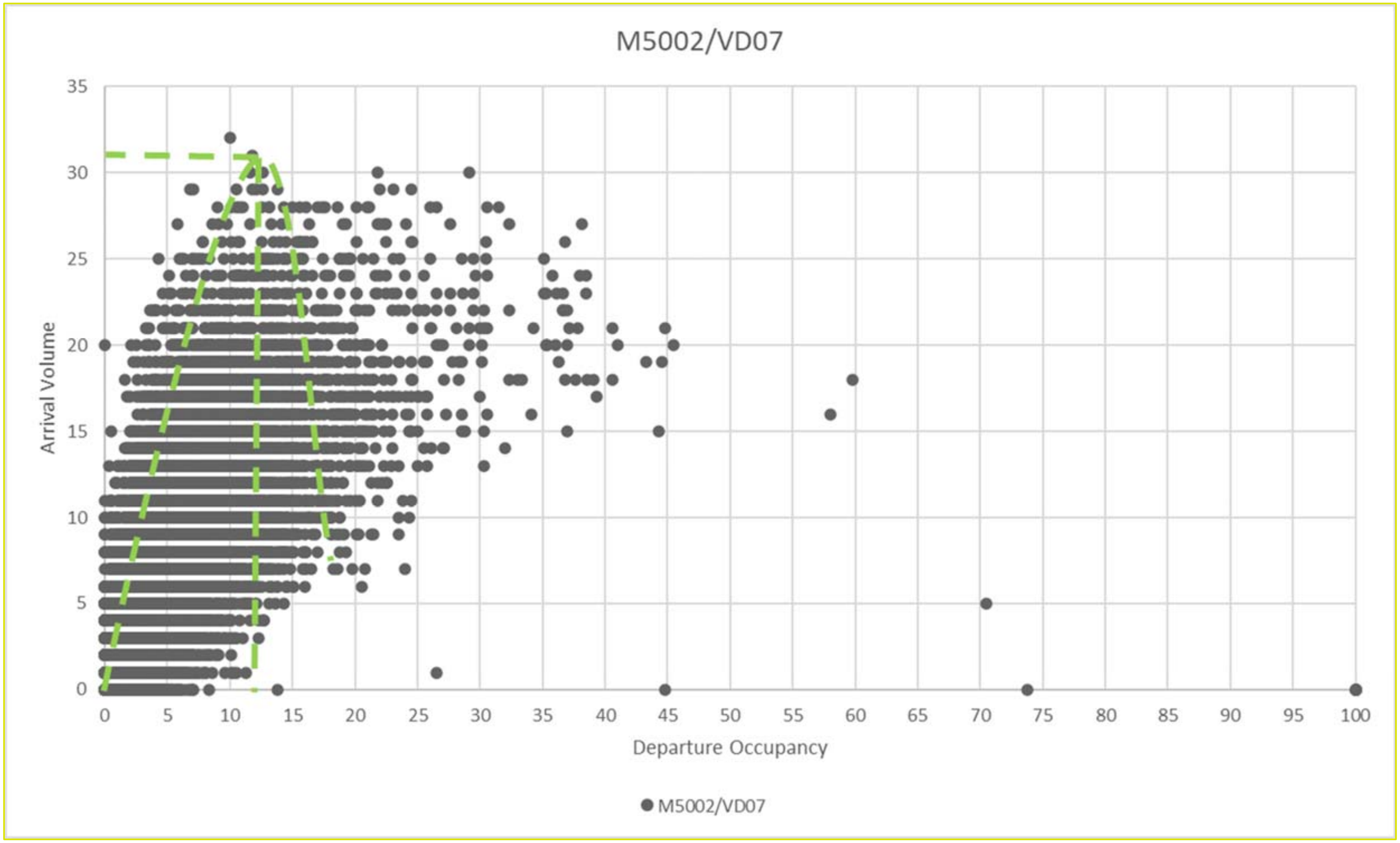


Figure B.24 Departure volume vs Departure Occupancy - M5002 - Lane 1

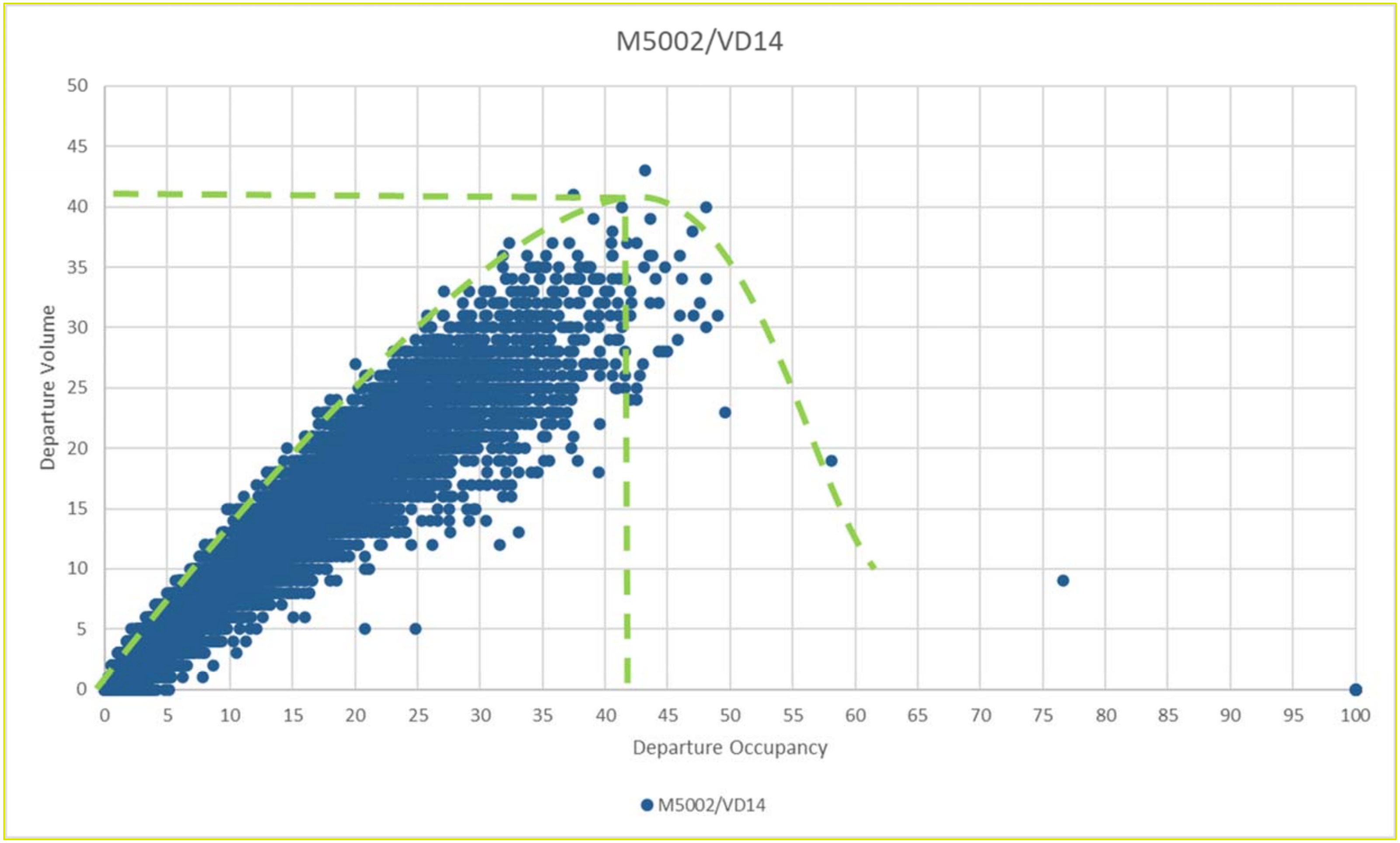


Figure B.25 Departure volume vs Departure Occupancy - M5002 - Lane 2

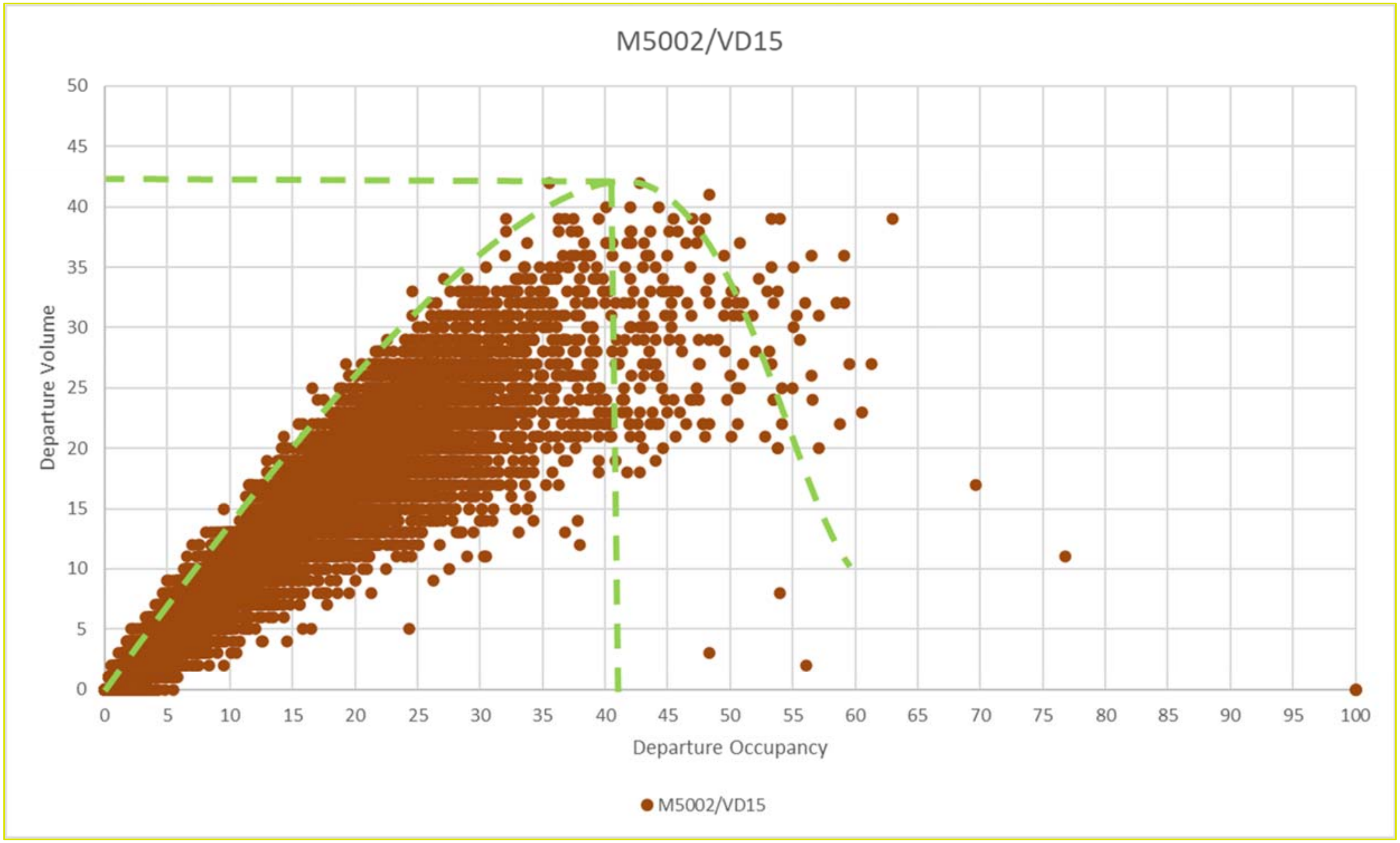
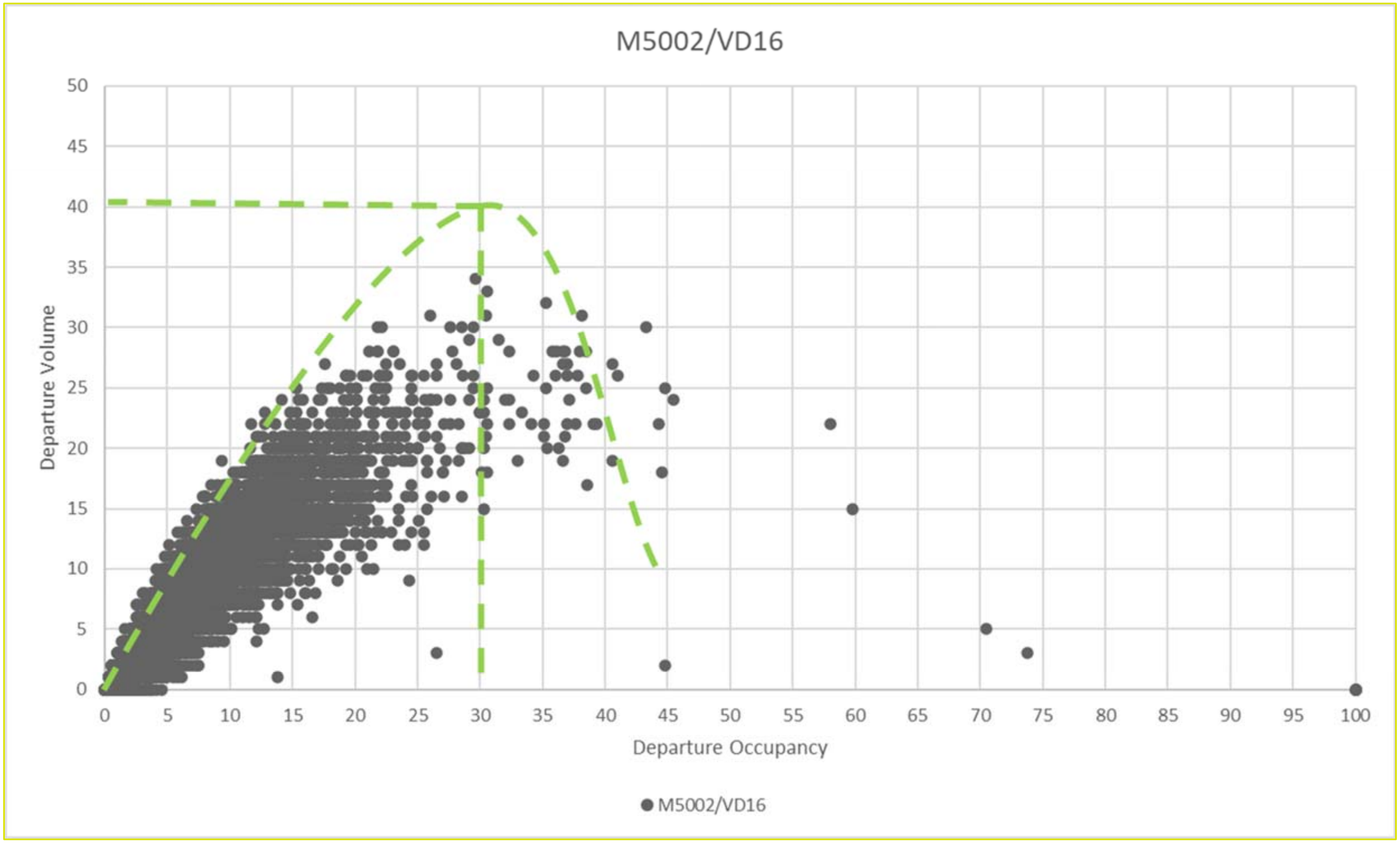


Figure B.26 Departure volume vs Departure Occupancy - M5002 - Lane 3



B.3 M5491

Figure B.27 Intersection Signal Drawing - Site M5491

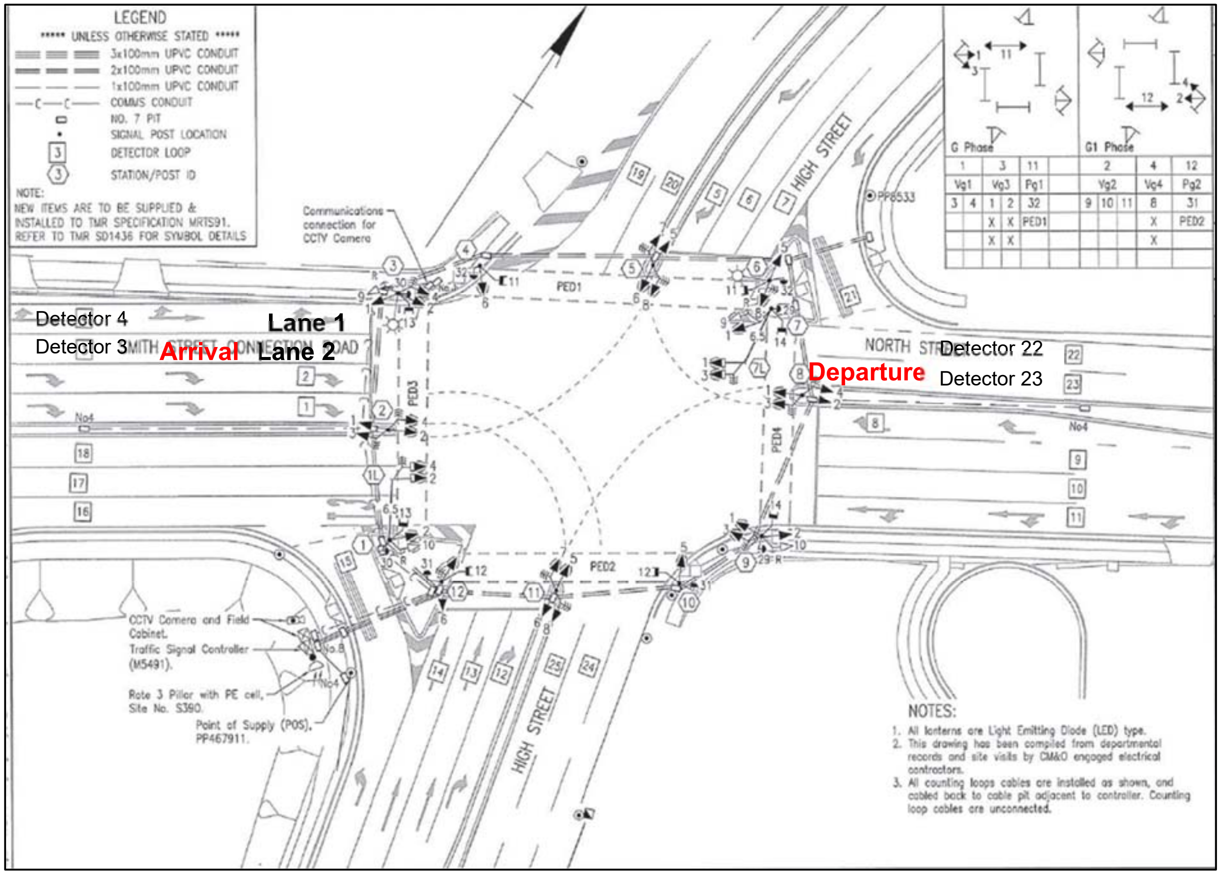


Table B.3: Volume vs Occupancy - M5491 Threshold Summary

Lane	Parameter	Maximum flow (vehicles per minute)	Maximum sustainable flow (vehicles per minute)	Critical occupancy (%)
Lane 1	NPI average occupancy vs arrival volume	25	23	22
	Arrival occupancy vs arrival volume	26	23	23
	Departure occupancy vs arrival volume	27	24	23
	Departure occupancy vs departure volume	33	30	28
Lane 2	NPI average occupancy vs arrival volume	28	25	20
	Arrival occupancy vs arrival volume	29	26	26
	Departure occupancy vs arrival volume	29	26	23
	Departure occupancy vs departure volume	25	23	26

Figure B.28 Arrival volume vs NPI Average Occupancy - M5491 - Lane 1

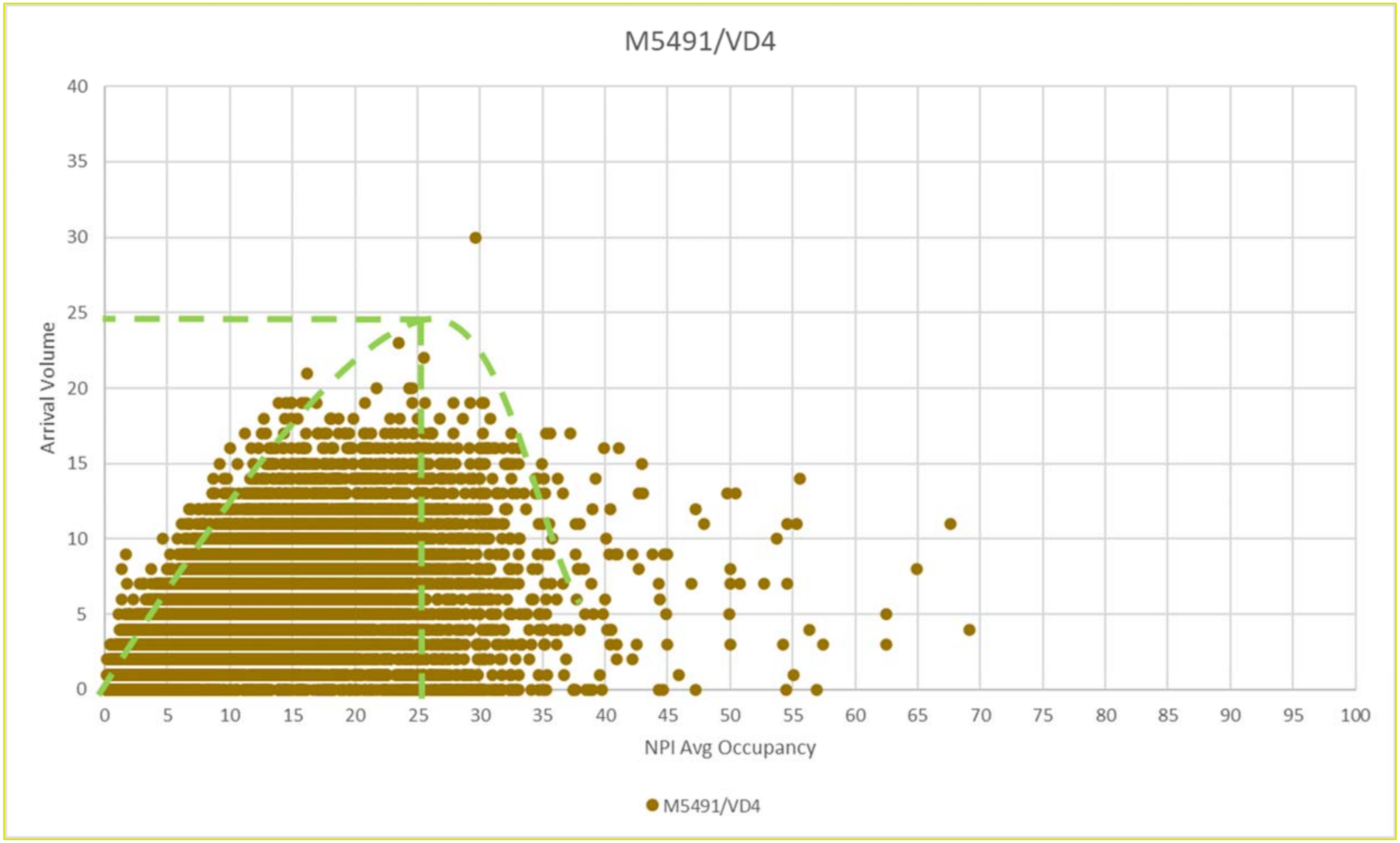


Figure B.29 Arrival volume vs NPI Average Occupancy - M5491 - Lane 2

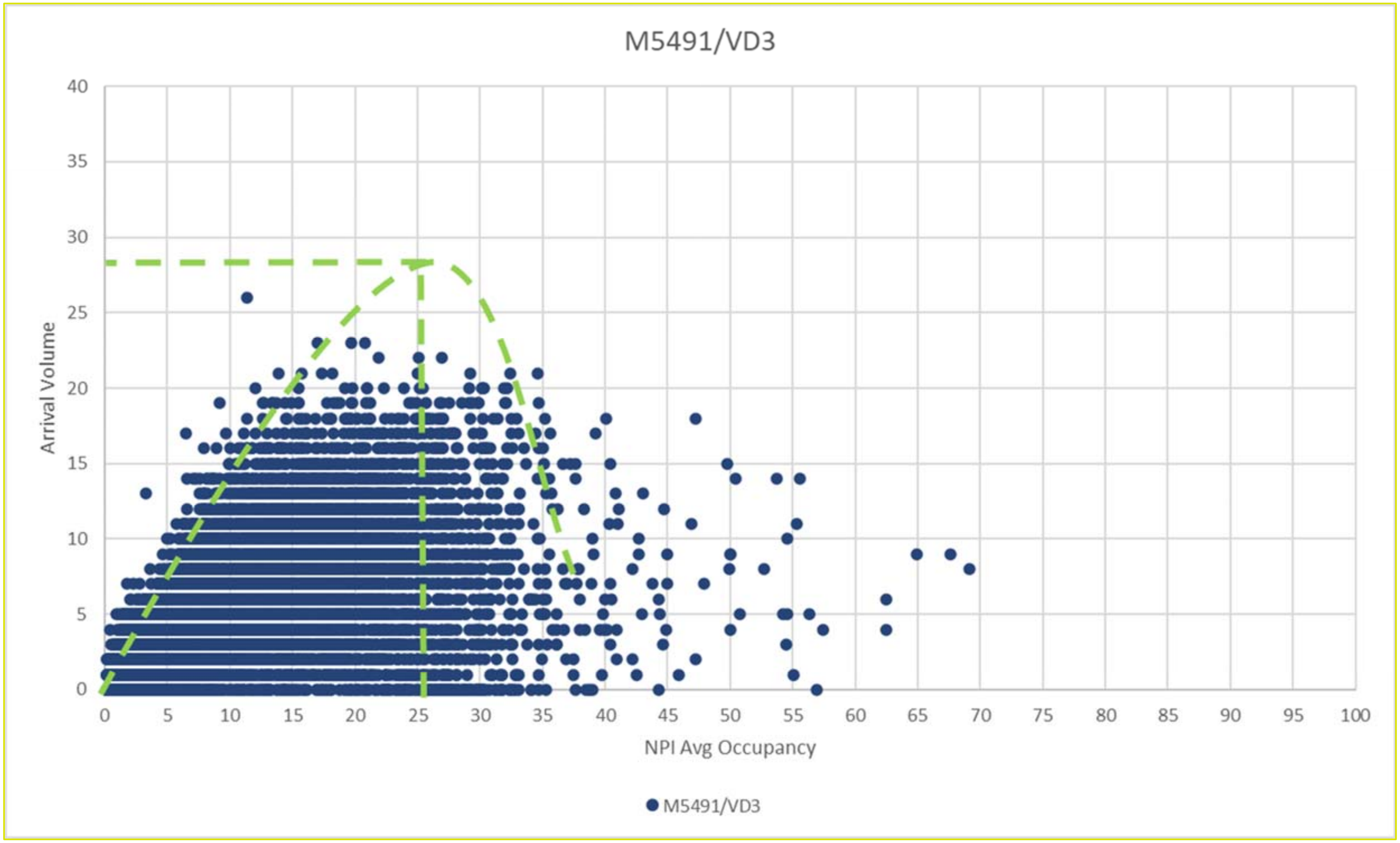


Figure B.30 Arrival volume vs Arrival Occupancy - M5491 - Lane 1

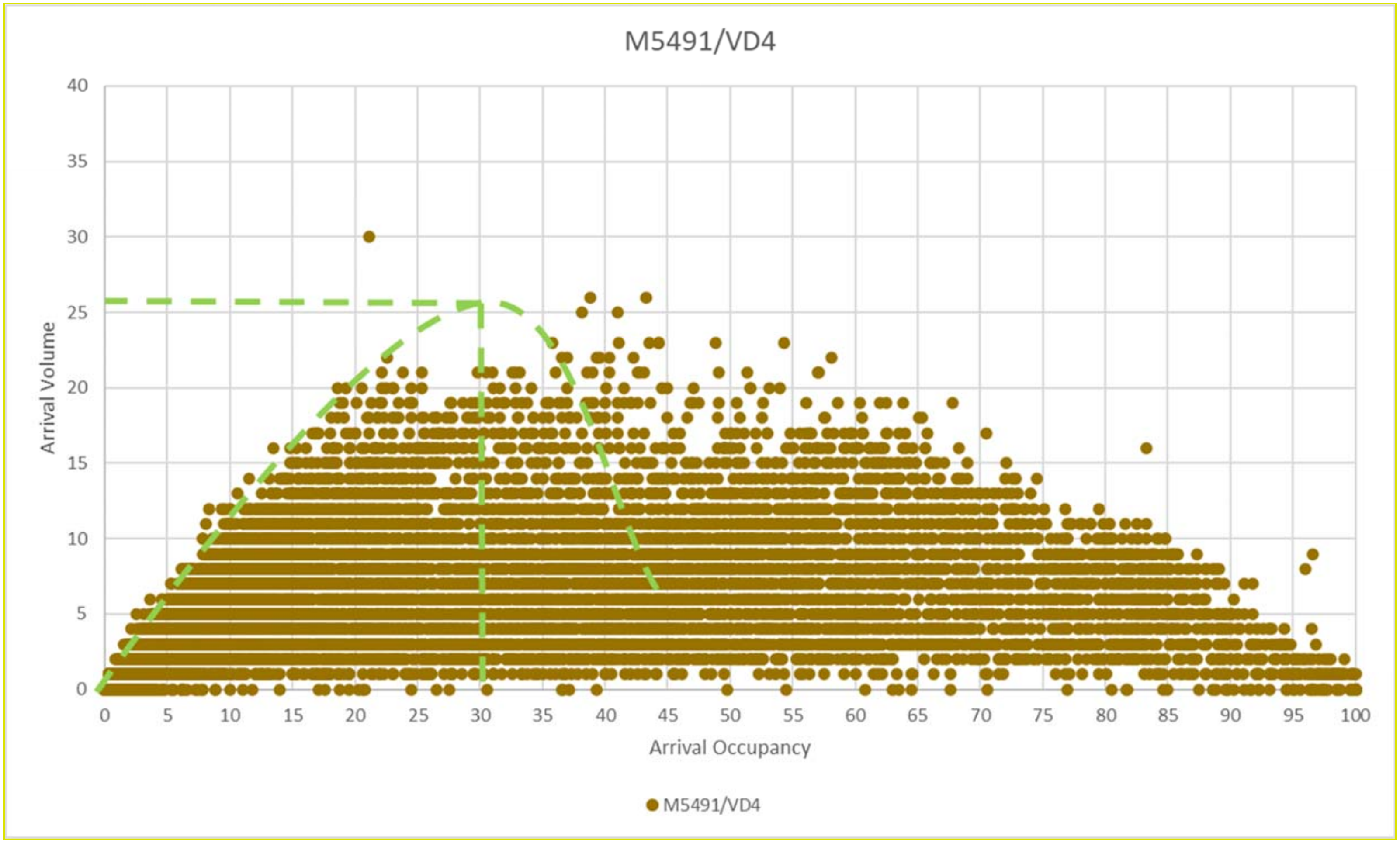


Figure B.31 Arrival volume vs Arrival Occupancy - M5491 - Lane 2

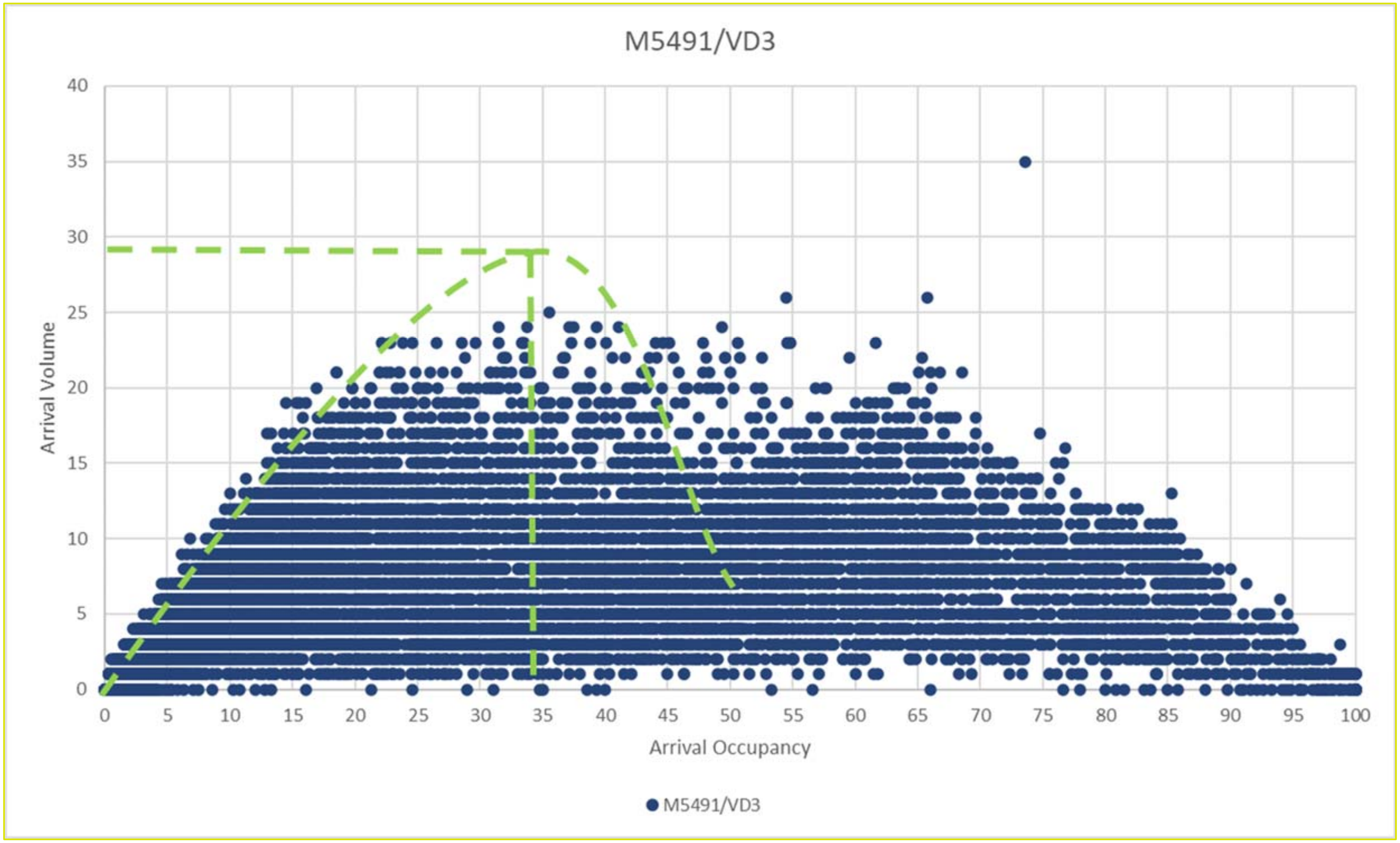


Figure B.32 Arrival volume vs Departure Occupancy - M5491 - Lane 1

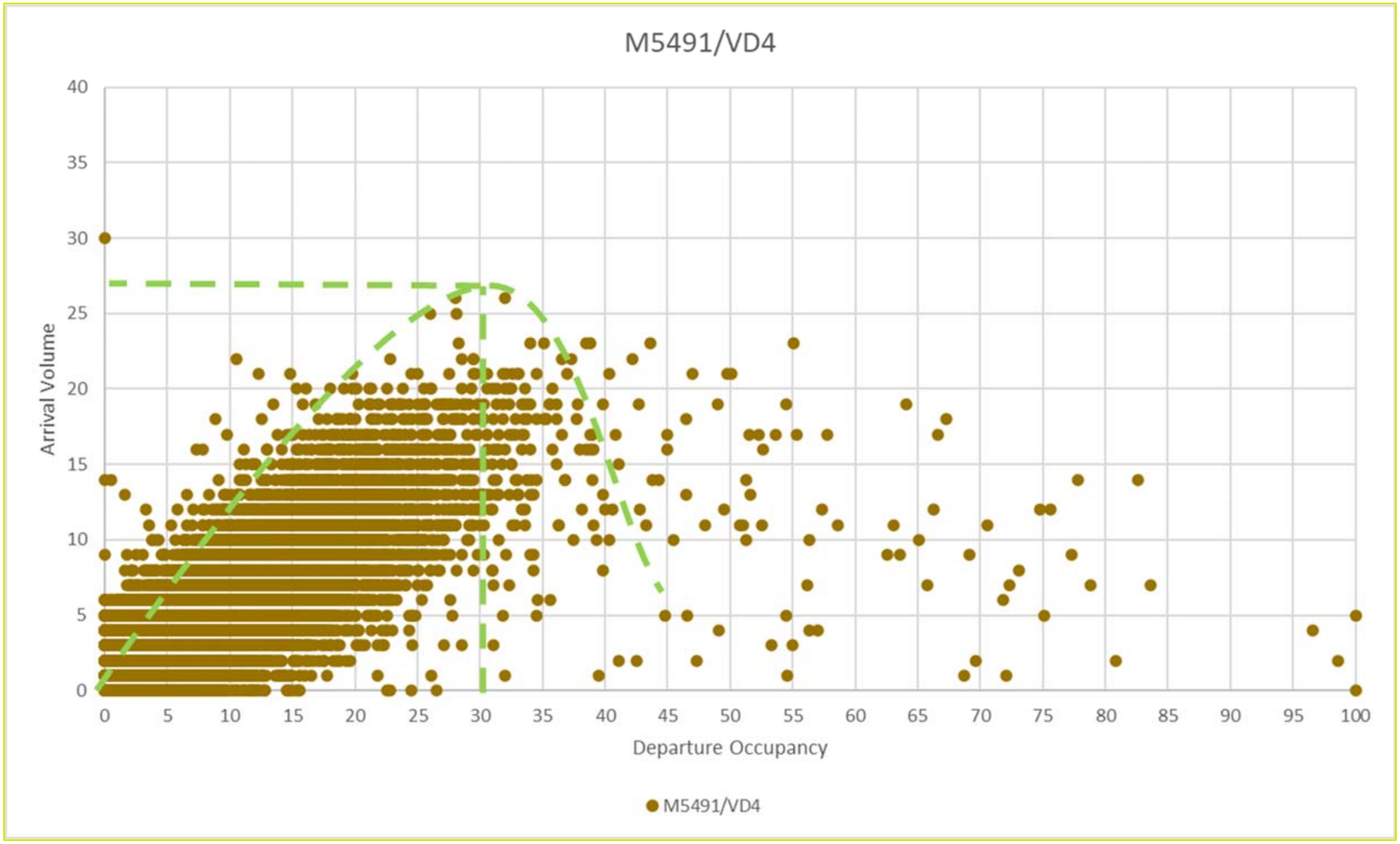


Figure B.33 Arrival volume vs Departure Occupancy - M5491 - Lane 2

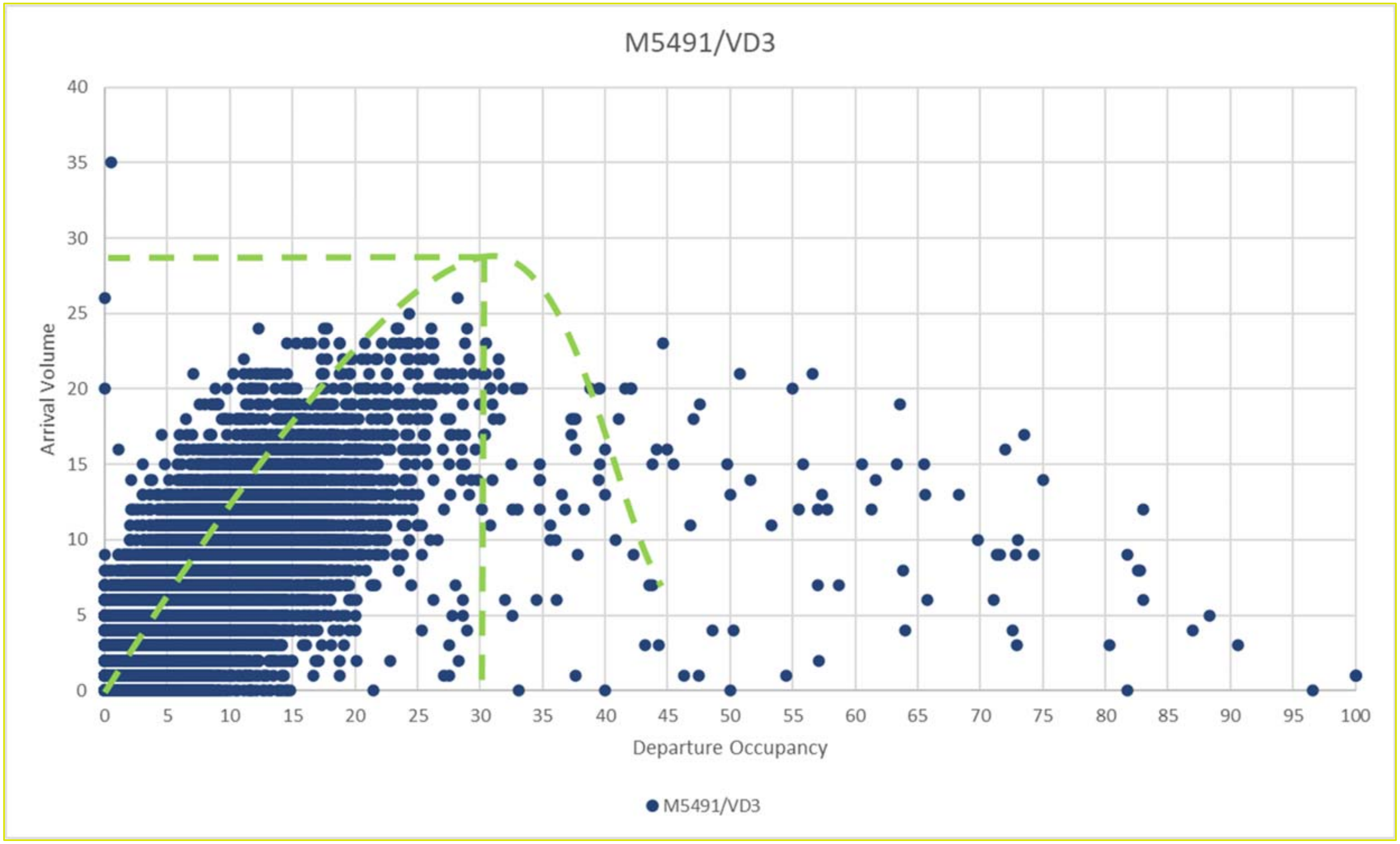


Figure B.34 Departure volume vs Departure Occupancy - M5491 - Lane 1

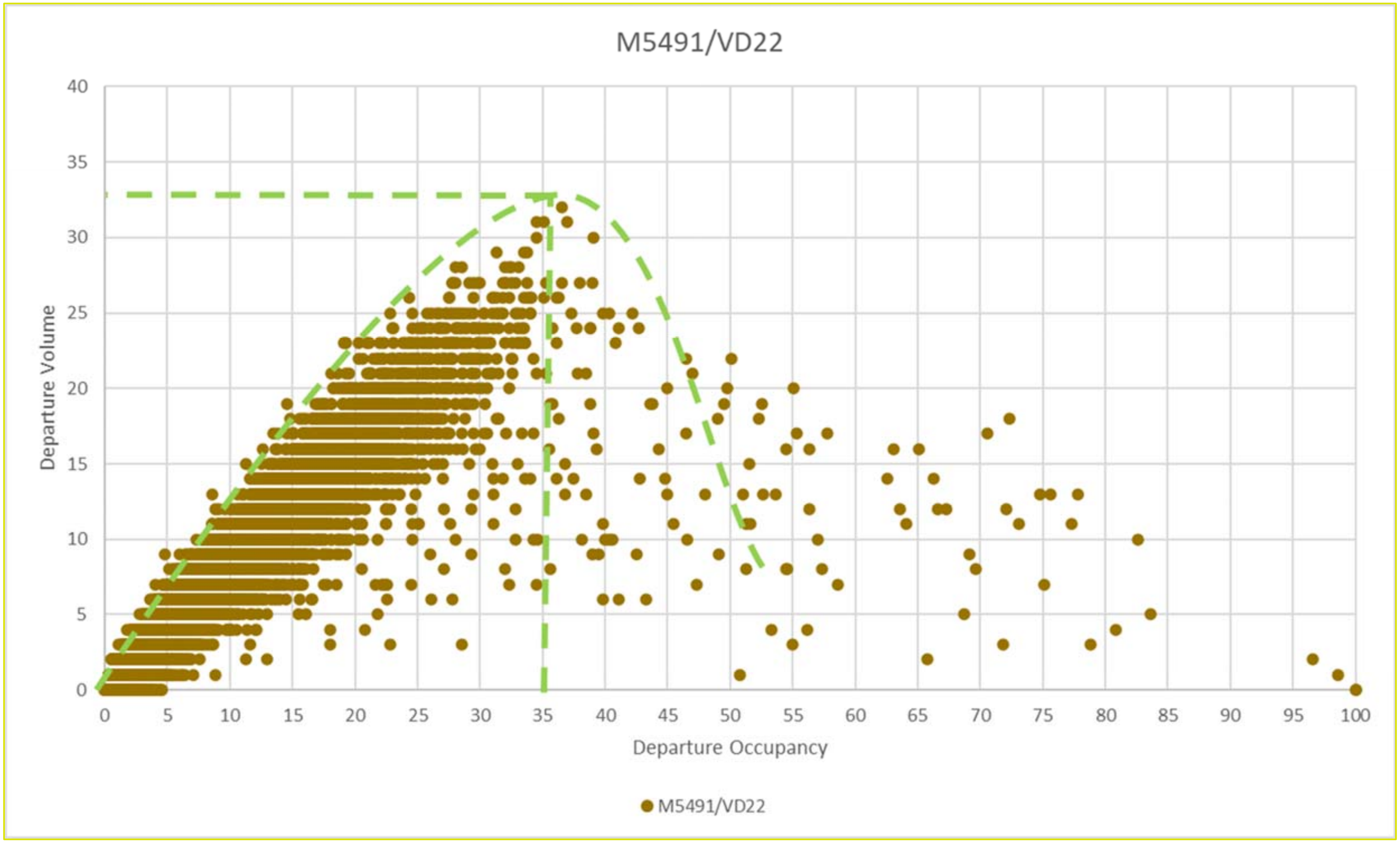
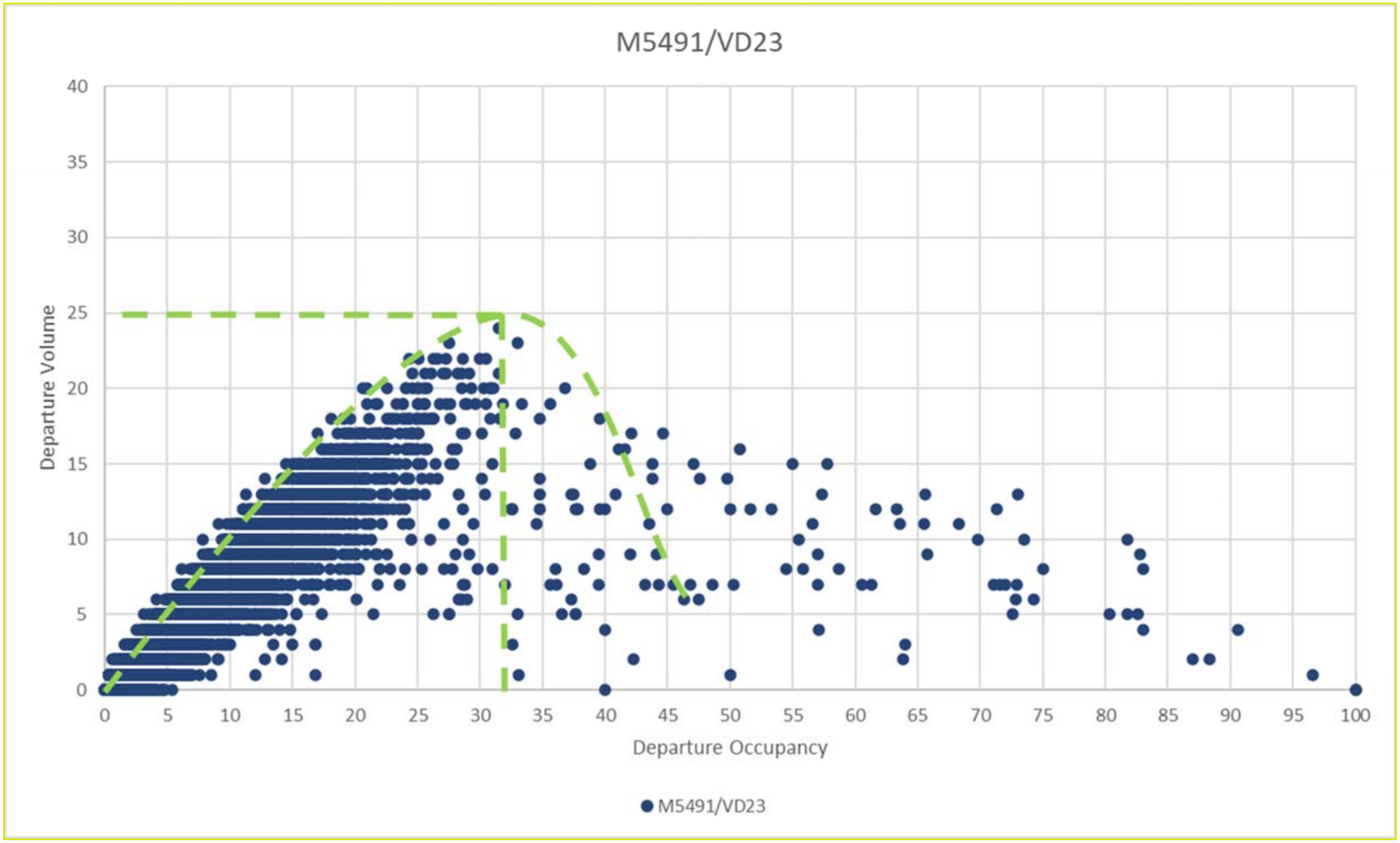


Figure B.35 Departure volume vs Departure Occupancy - M5491 - Lane 2



APPENDIX C TIME SERIES ANALYSIS

C.1 1-MINUTE FREQUENCY

Figure C.1 Time series analysis - M5538 EB - Lane 2 - 1-Minute

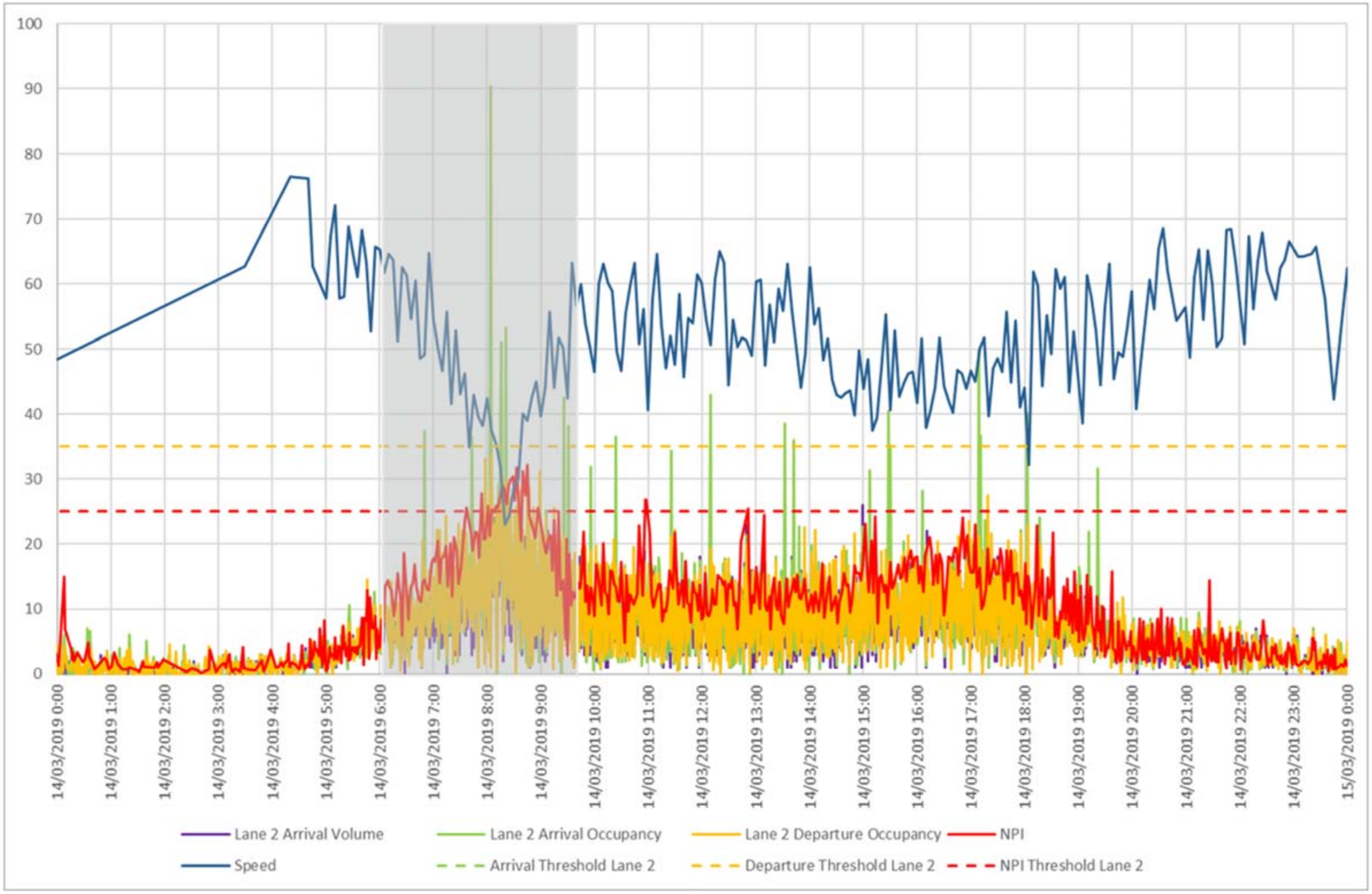


Figure C.2 Time series analysis - M5538 EB - Lane 2 - 1-Minute - volume and speed

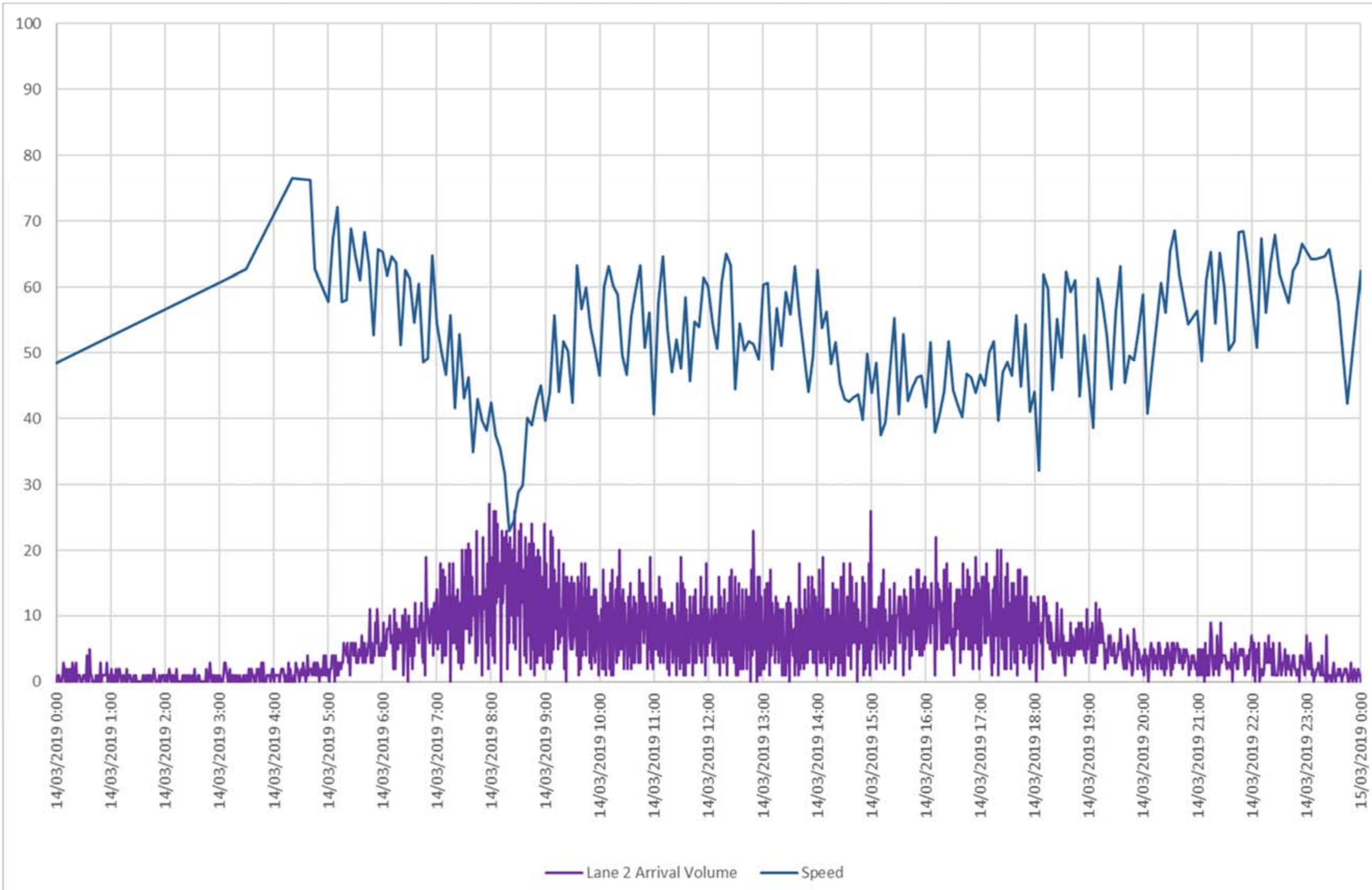


Figure C.3 Time series analysis - M5538 EB - Lane 1 - 1-Minute

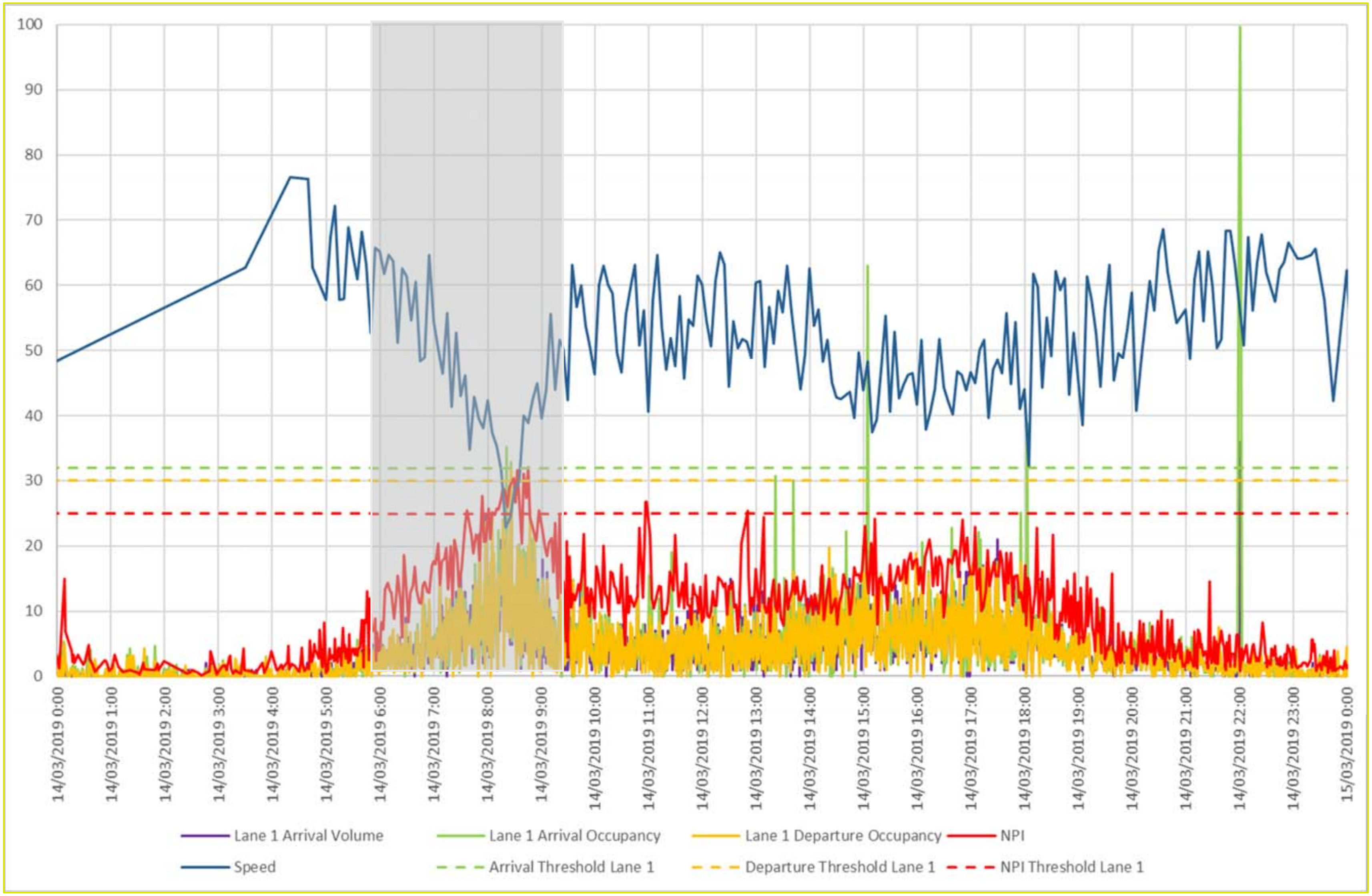
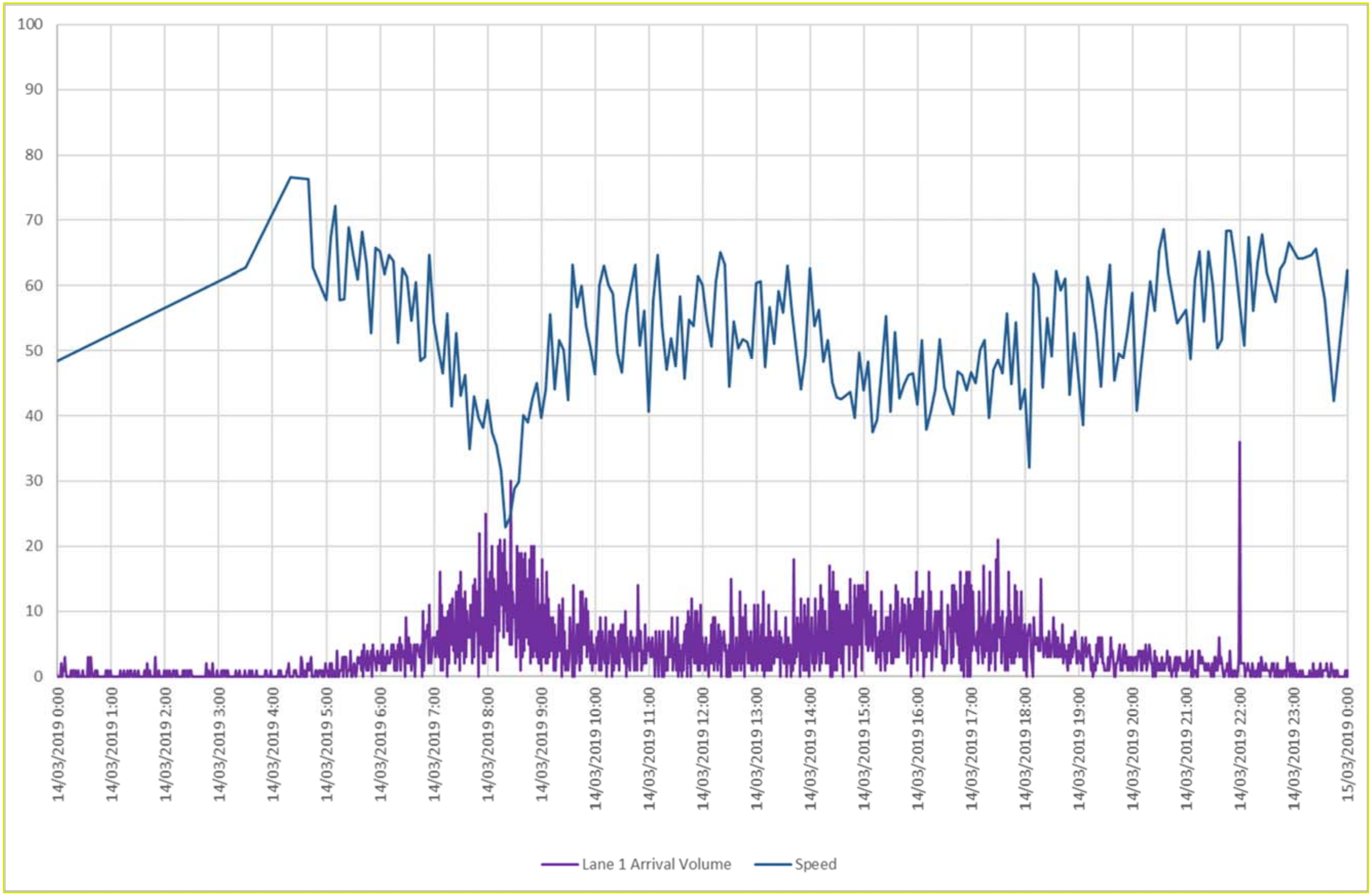


Figure C.4 Time series analysis - M5538 EB - Lane 1 - 1-Minute - volume and speed



C.2 AVERAGE OF 5-MINUTE FREQUENCY

Figure C.5 Time series analysis - M5538 EB - Lane 2 - 5-Minute

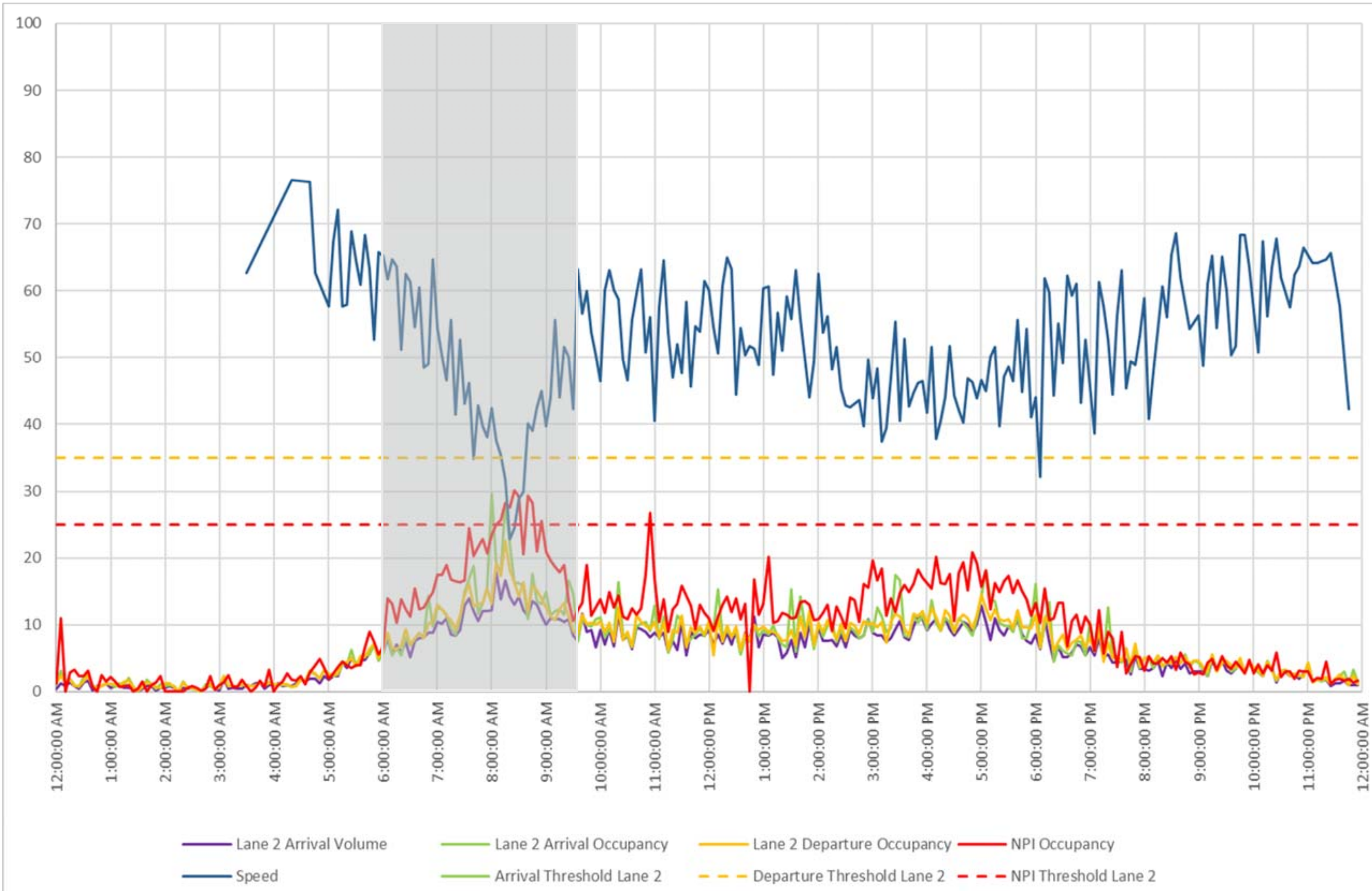
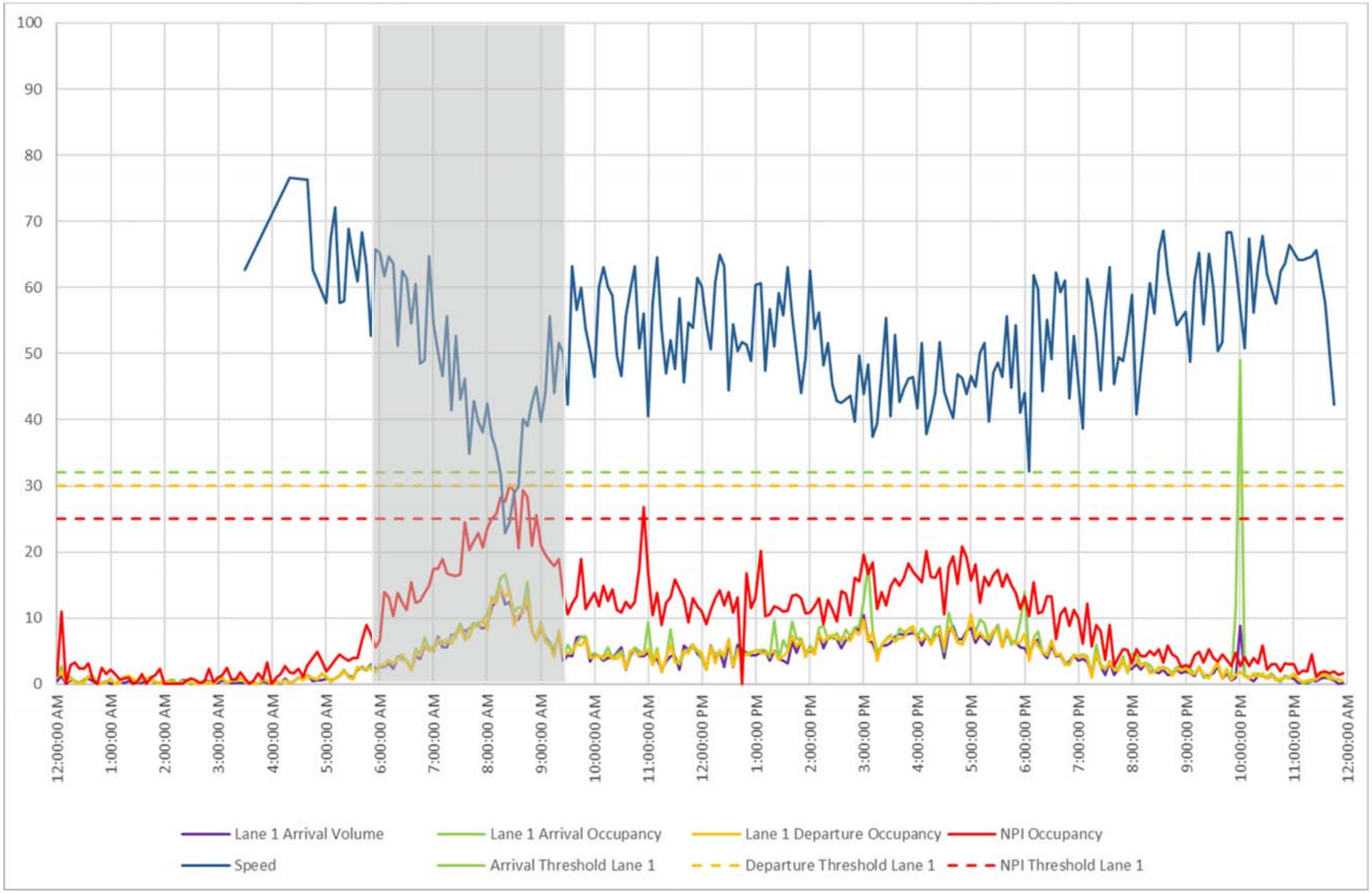


Figure C.6 Time series analysis - M5538 EB - Lane 1 - 5-Minute



C.3 1-MINUTE FREQUENCY WITH AVERAGE OF 5 MINUTES

Figure C.7 Time series analysis - M5538 EB - Lane 2 - 5-Minute moving average

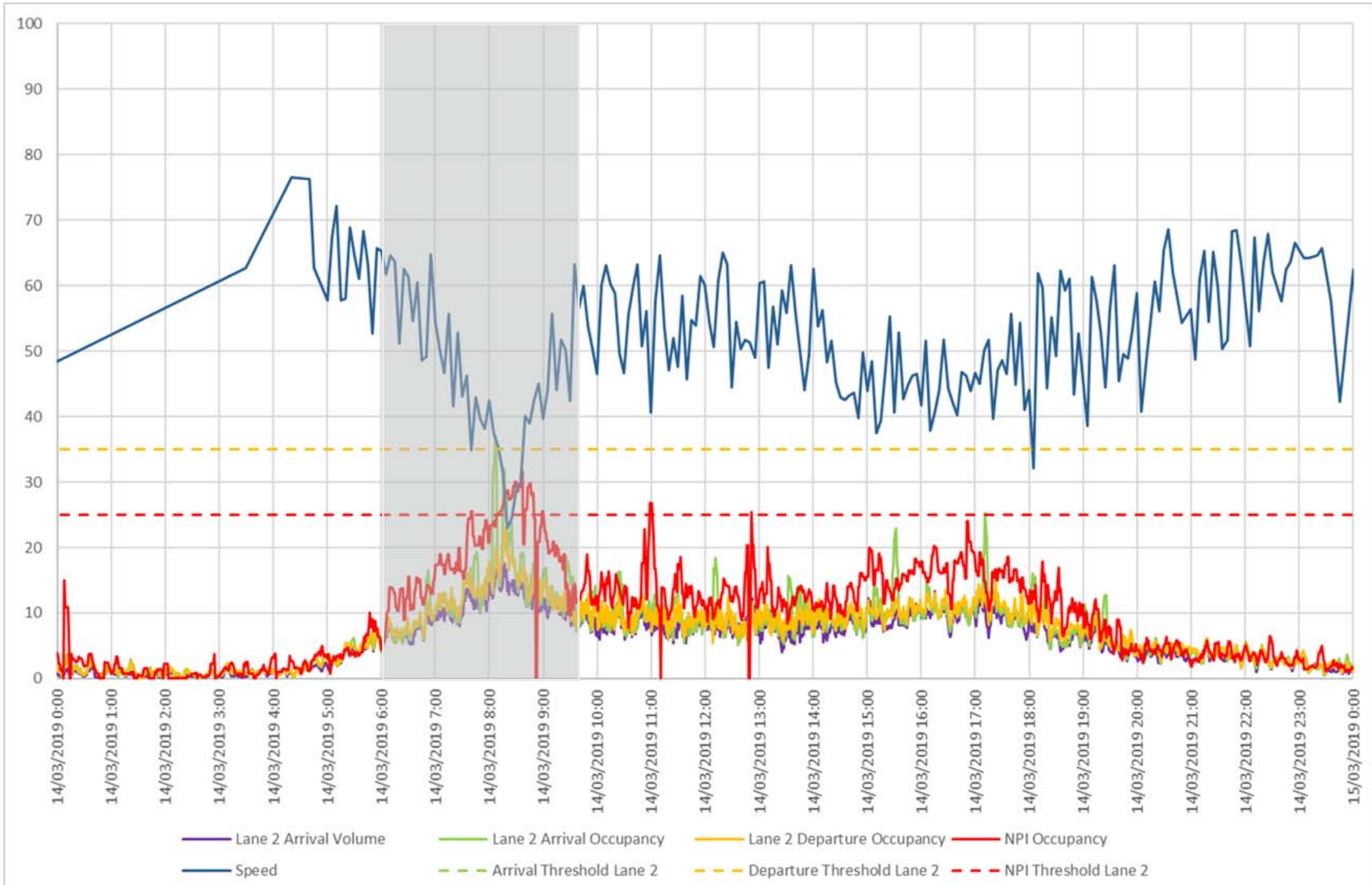
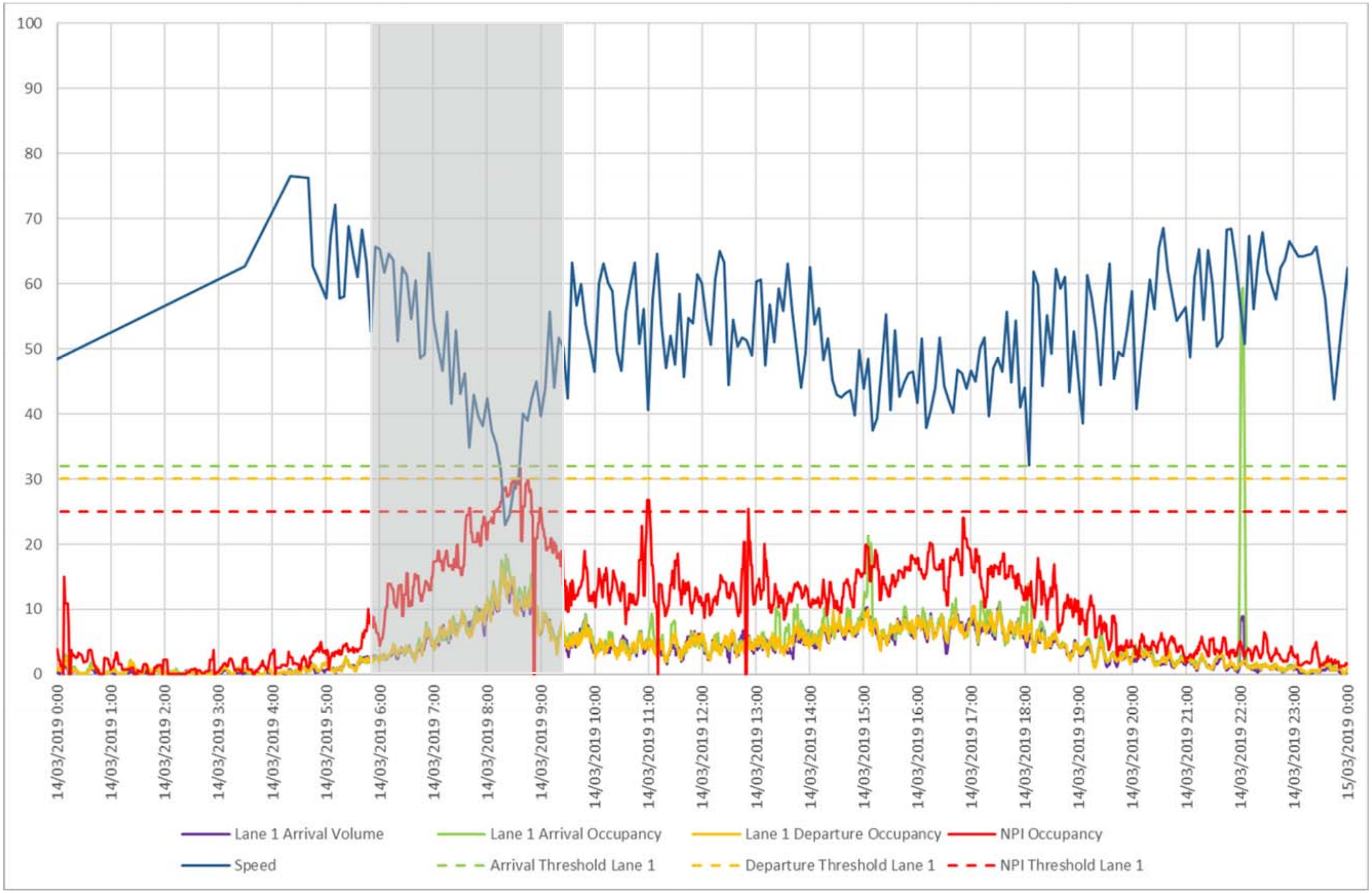


Figure C.8 Time series analysis - M5538 EB - Lane 1 - 5-Minute moving average



C.4 MORNING PEAK ANALYSIS

Figure C.9 Time series analysis - M5538 EB - Lane 2 - 1-Minute - Morning Peak

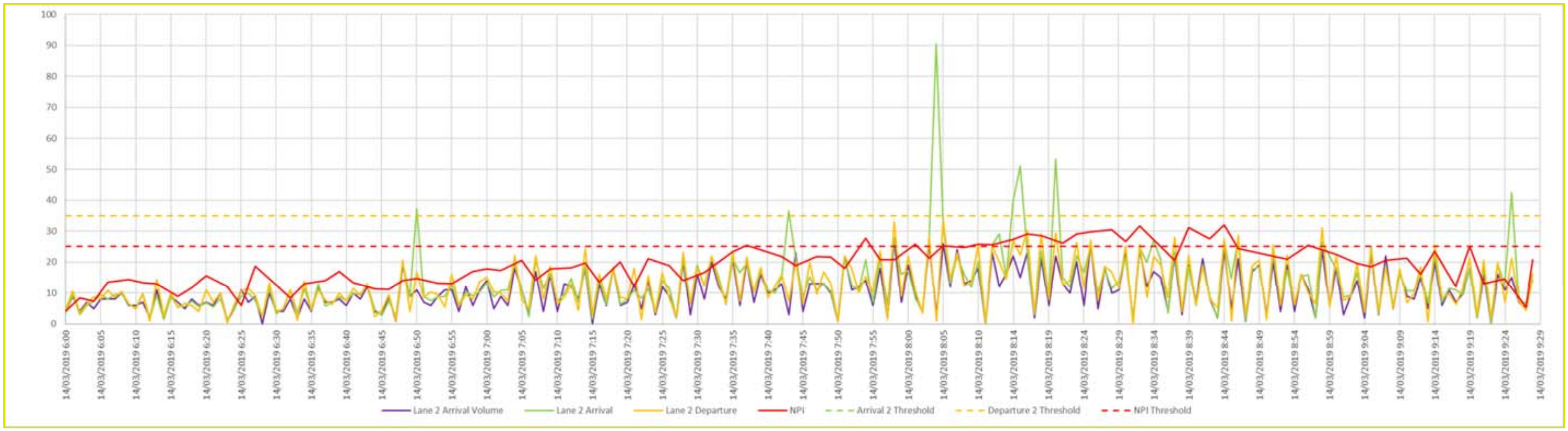


Figure C.10 Arrival volume vs NPI Average Occupancy - M5538 EB - Lane 2 - Morning Peak Time Step

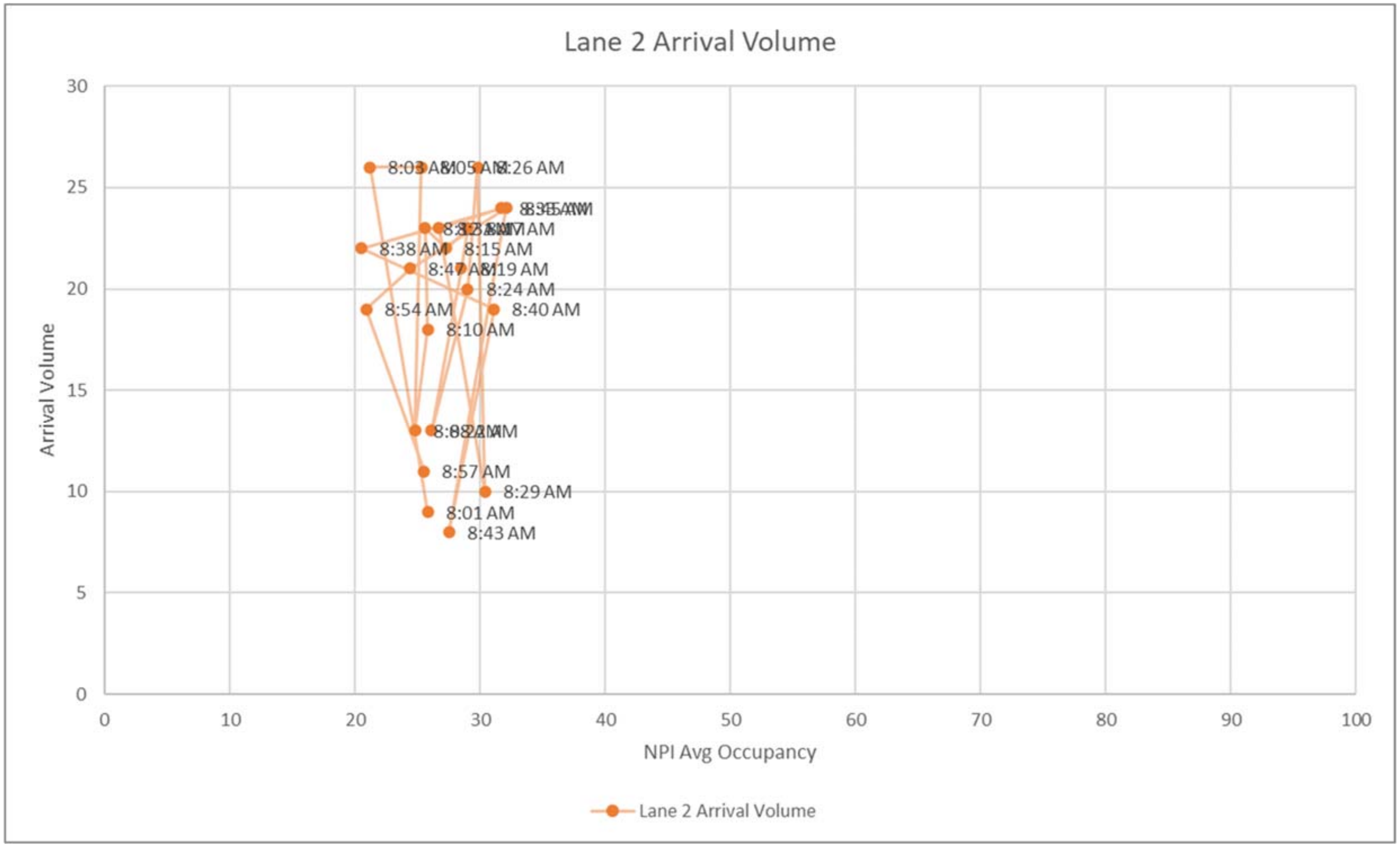


Figure C.11 Arrival volume vs Arrival Occupancy - M5538 EB - Lane 2 - Morning Peak Time Step

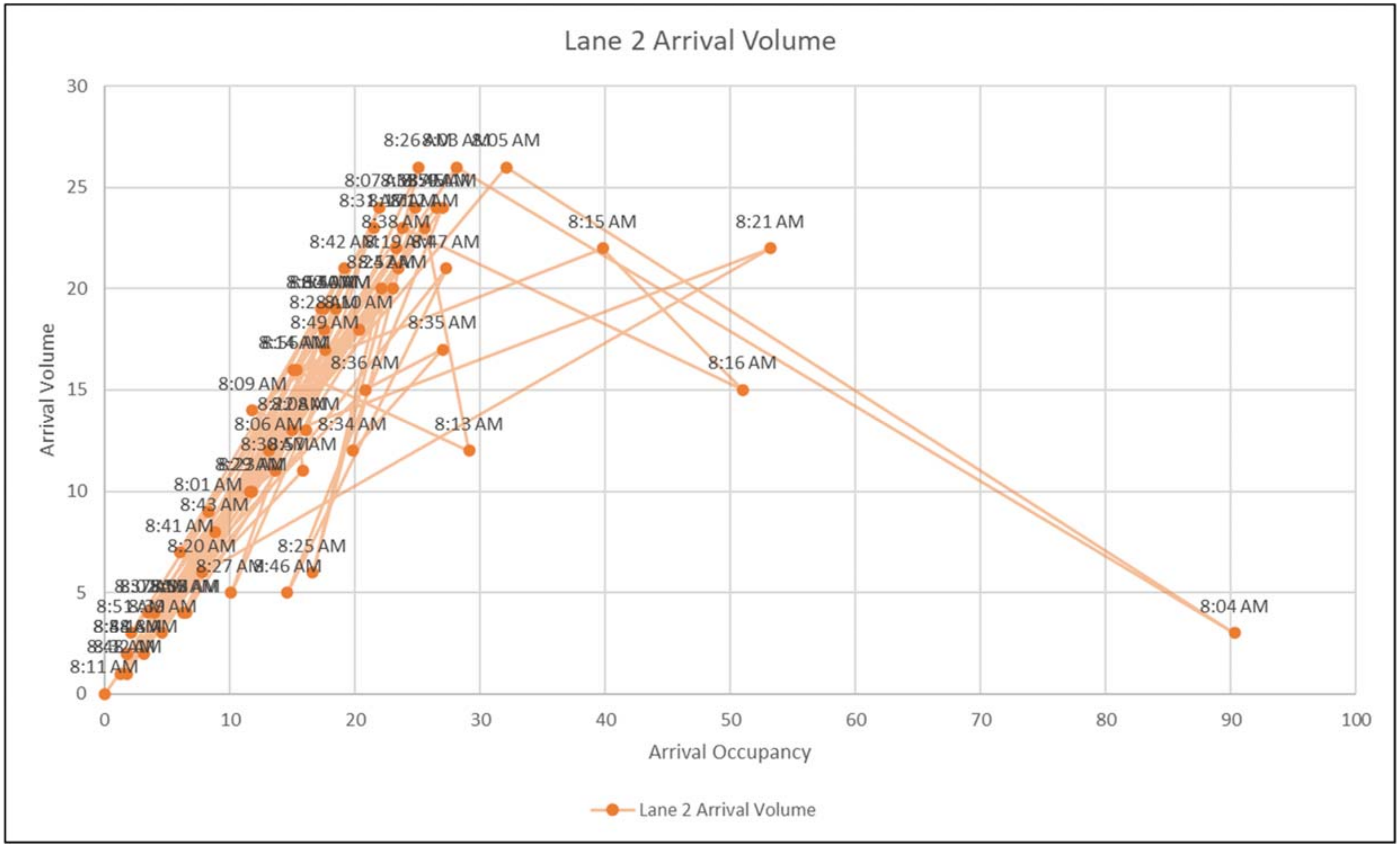


Figure C.12 Departure volume vs Deparute Occupancy - M5538 EB - Lane 2 - Morning Peak Time Step

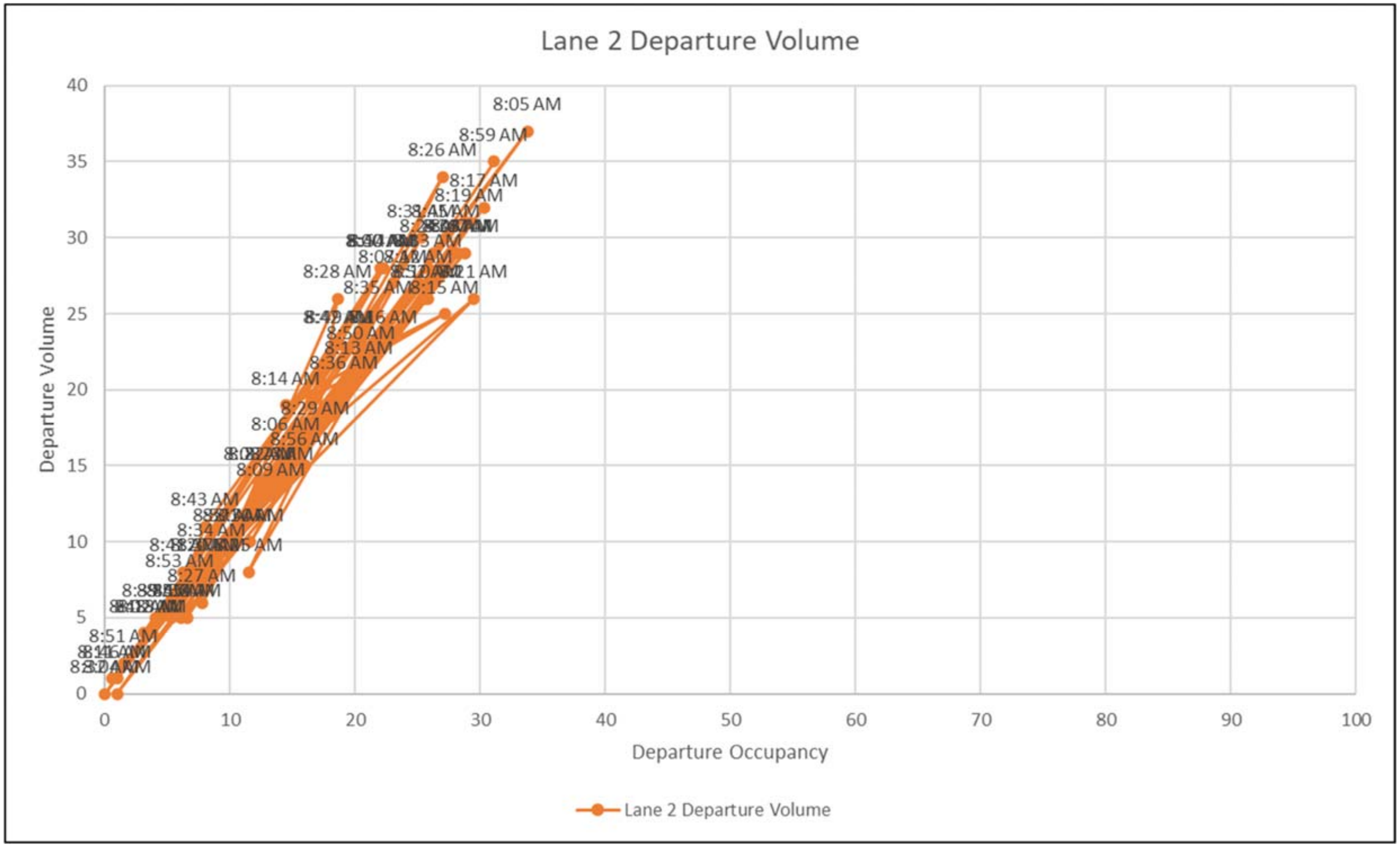


Figure C.13 Time series analysis - M5538 EB - Lane 1 - 1-Minute - Morning Peak

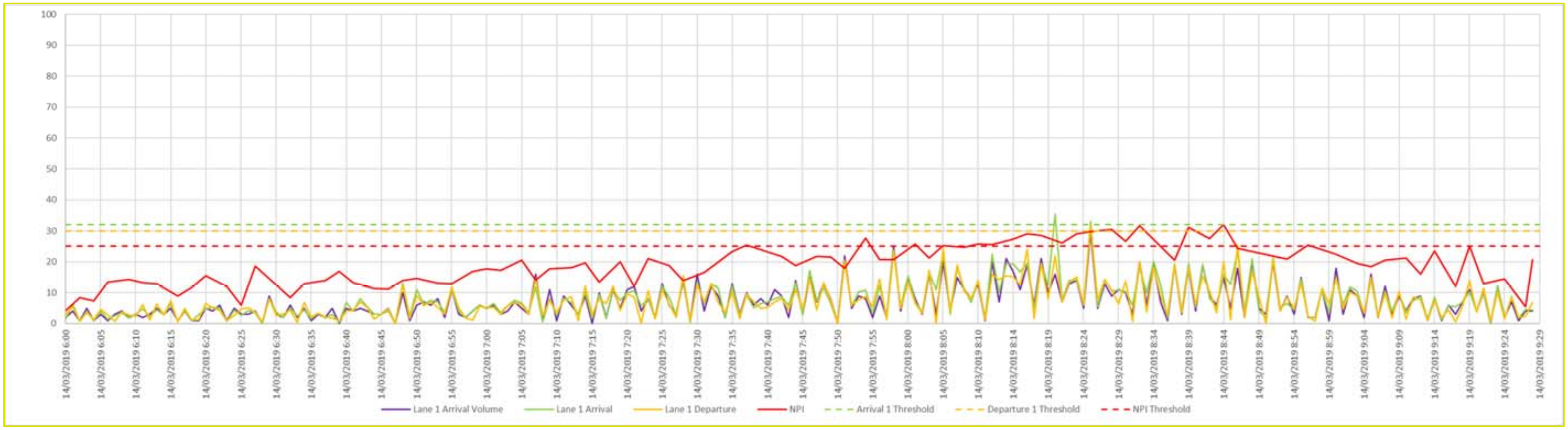


Figure C.14 Arrival volume vs NPI Average Occupancy - M5538 EB - Lane 1 - Morning Peak Time Step

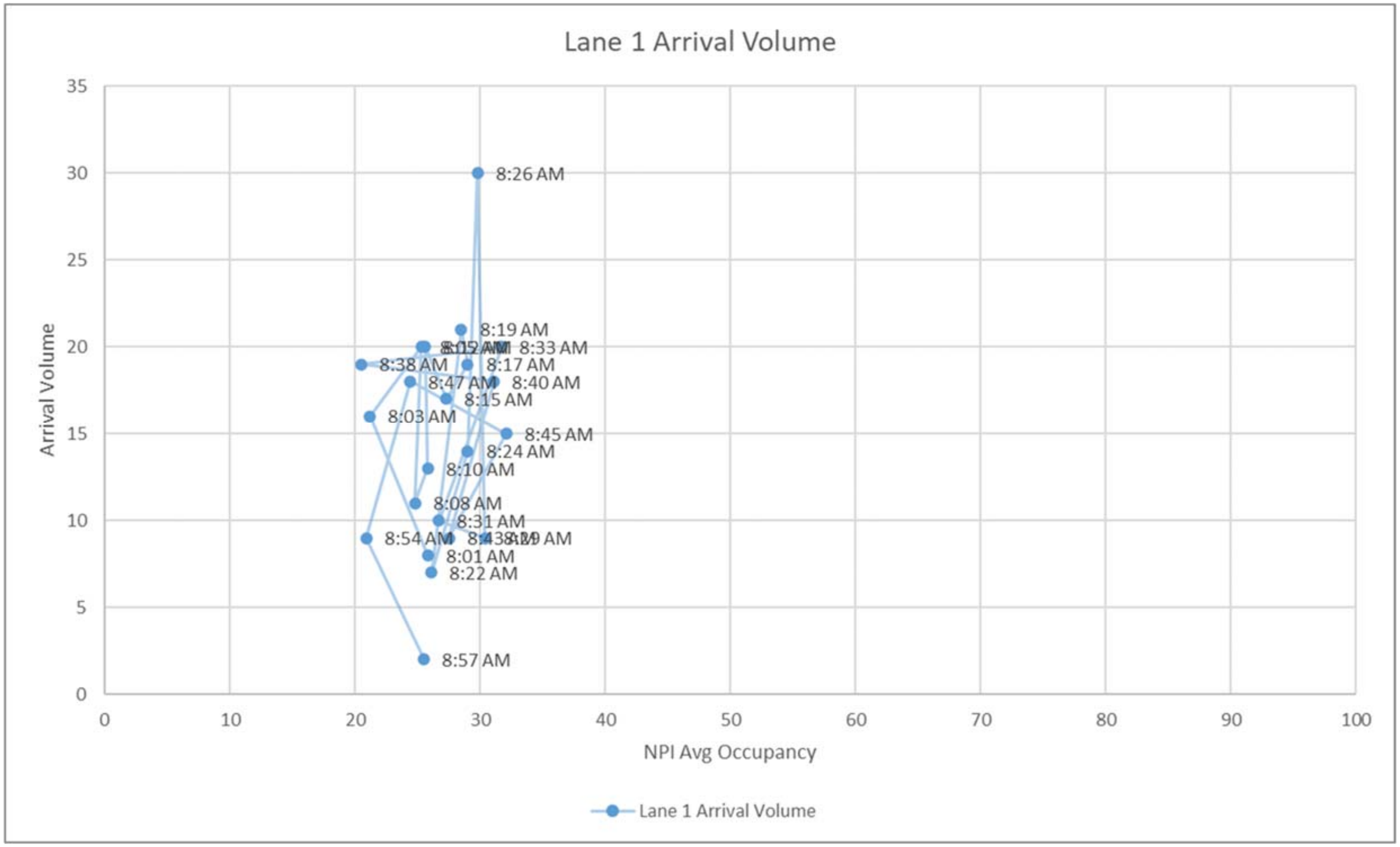


Figure C.15 Arrival volume vs Arrival Occupancy - M5538 EB - Lane 1 - Morning Peak Time Step

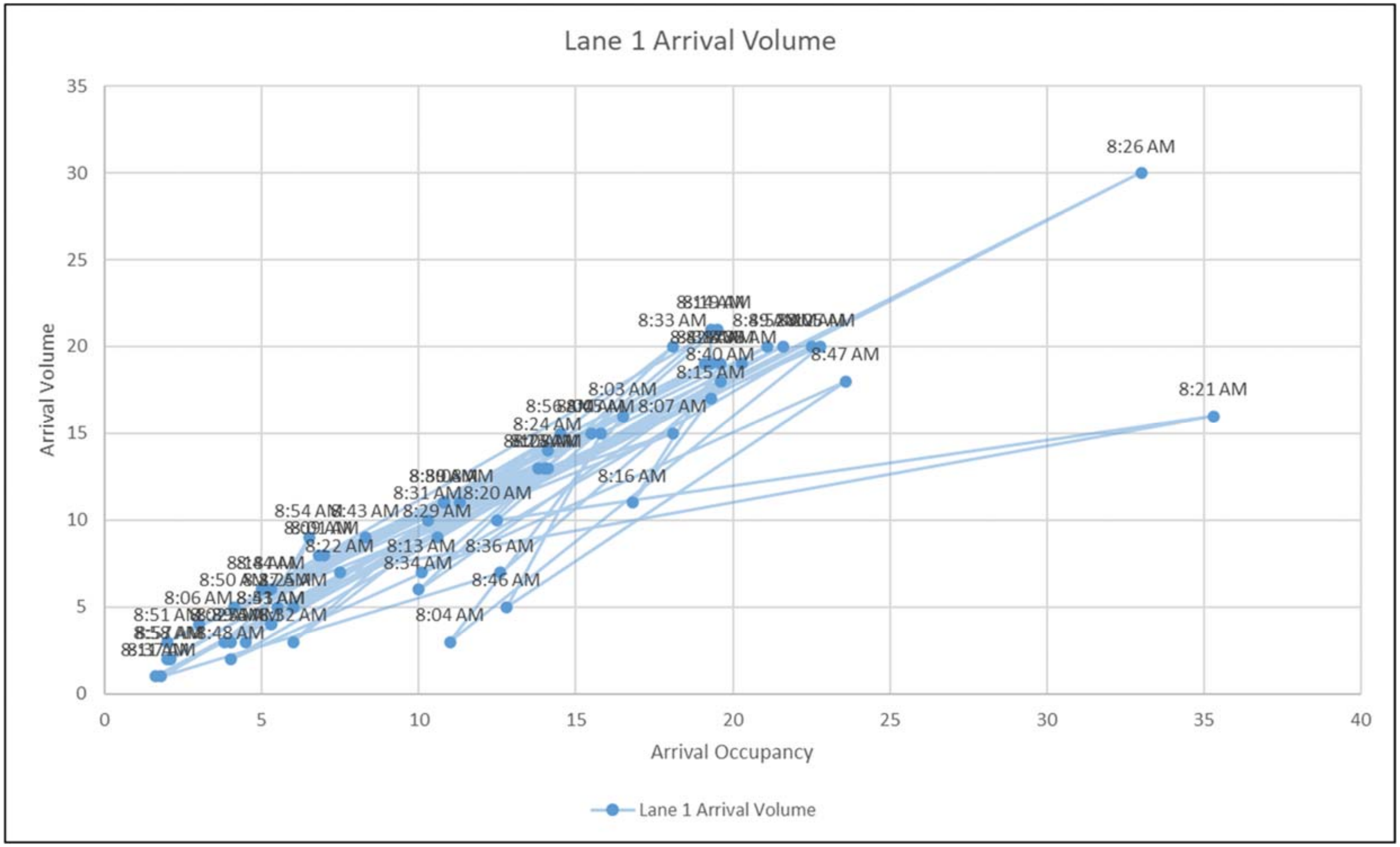
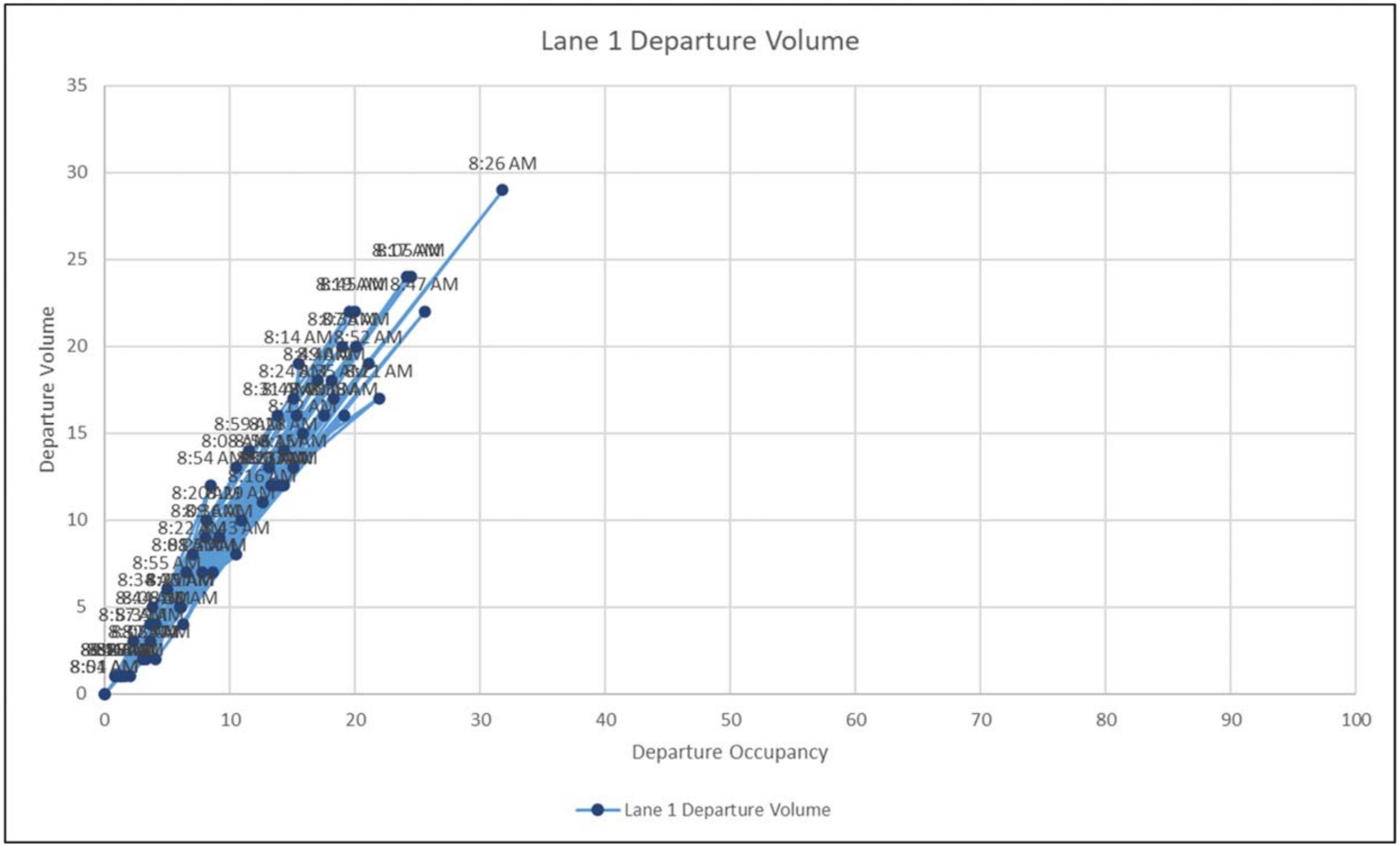


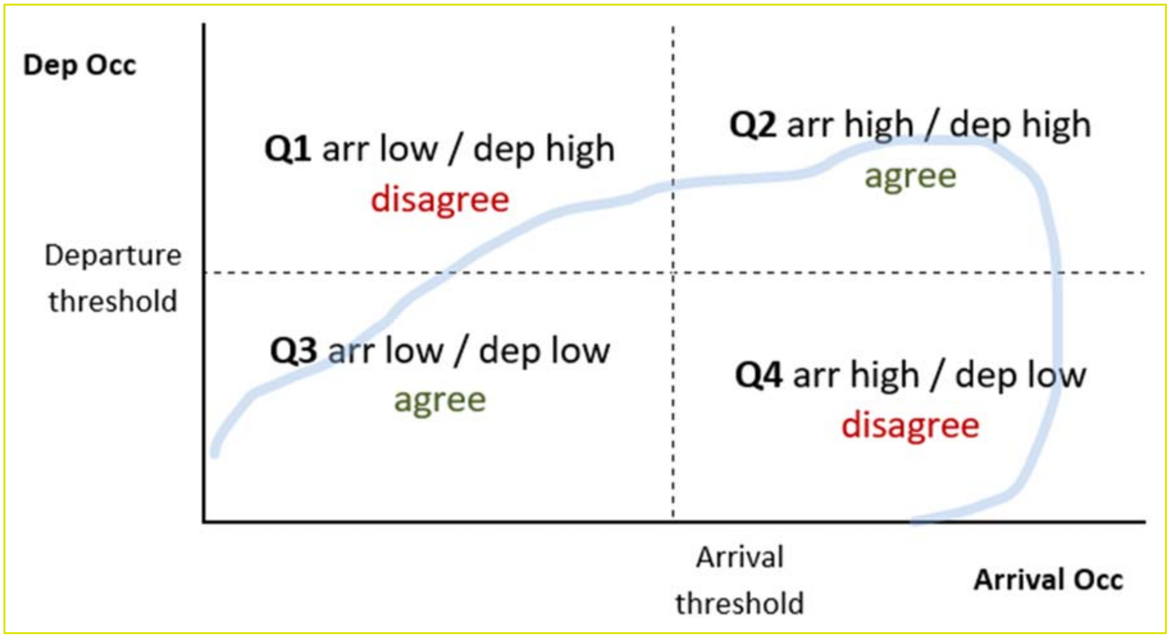
Figure C.16 Departure volume vs Deparute Occupancy - M5538 EB - Lane 1 - Morning Peak Time Step



APPENDIX D OCCUPANCY VERSUS OCCUPANCY

This section looks at the occupancy versus occupancy (i.e. departure occupancy versus NPI average occupancy, arrival occupancy versus NPI average occupancy and departure occupancy versus arrival occupancy). This shall look at the lane-level thresholds determined in the previous section and assess when the occupancy values do not align. Occupancy versus occupancy is reviewed to identify if there is a trend to when and why the thresholds disagree. Figure D.1 shows an example of how this shall be analysed, using departure occupancy and arrival occupancy as an example. The blue line marks the outline of a typical distribution of points in an arrival occupancy versus departure occupancy scatter plot.

Figure D.1 Occupancy vs occupancy - sample graph



Departure Occupancy Versus NPI Average Occupancy

This section looks at the departure occupancy and the NPI average occupancy based on position in the lane. Figure D.1 shows the Lane 1, Figure D.2 shows the Lane 2 and Figure D.3 shows the Lane 3. The values indicate the percentage of data points which are within the relevant quadrant. The quadrants are based on the thresholds from Table 3.1 and Table 3.4. A review of the quadrants in which the occupancy measures for saturation do not align were investigated. It was found that most of the points align in quadrant 3, which is when the vehicles are undersaturated based on the departure and NPI average occupancy. Approximately 2.26% to 2.33% of the points do not align (e.g. departure occupancy is high while NPI occupancy is low), when using the sum of quadrant 1 and quadrant 4. A review of these points found most reside in quadrant 4 and generally occur when the NPI average occupancy indicates the lane is saturated, but the lanes downstream of the intersection are still undersaturated. A review of when the misalignment occurs found that most of the points occur during the morning peak period, which is when the site has the highest volume. The cause of the misalignment could be due to several reasons. These include the two occupancy measures use different time measurements causing a misalignment in occupancy. Another reason may be due to the departure occupancy being during both green and red time, while the NPI average occupancy is during green time only. It is noted that there are points in which the departure occupancy reaches 100%, which would indicate that there is extreme congestion. A review of when this occurs found that it was for a 5-minute period, with a spike in occupancy for all the departure detectors. This may be due to an event which blocked traffic. Figure D.4 provides a snippet of the time-series for the departure detectors at the time of the event. The event appears to be in Lane 1, which has 100% occupancy, while lane 2 and lane 3 appear to have peaks in occupancy due to vehicles changing lanes to avoid being stuck in the lane with an incident. Figure D.5 shows a snippet of the time-series for the NPI average occupancy at the same time period. There is minimal change to the NPI average occupancy at the time of the event, which is likely due to NPI average occupancy being during green time for the whole site, which means that the values would be smoothed due to factors such as being during the red-light and being a lane specific event.

Figure D.1 Departure Occupancy vs NPI Average Occupancy - M5538 EB - Lane 1

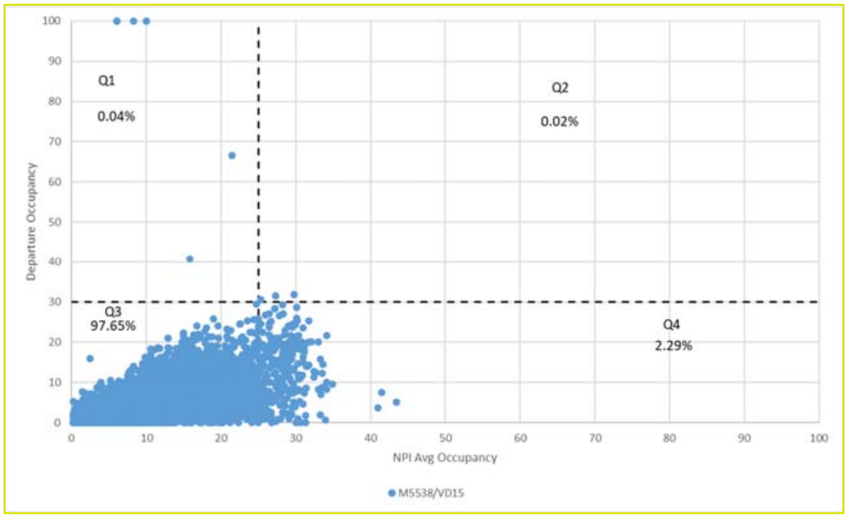


Figure D.2 Departure Occupancy vs NPI Average Occupancy - M5538 EB - Lane 2

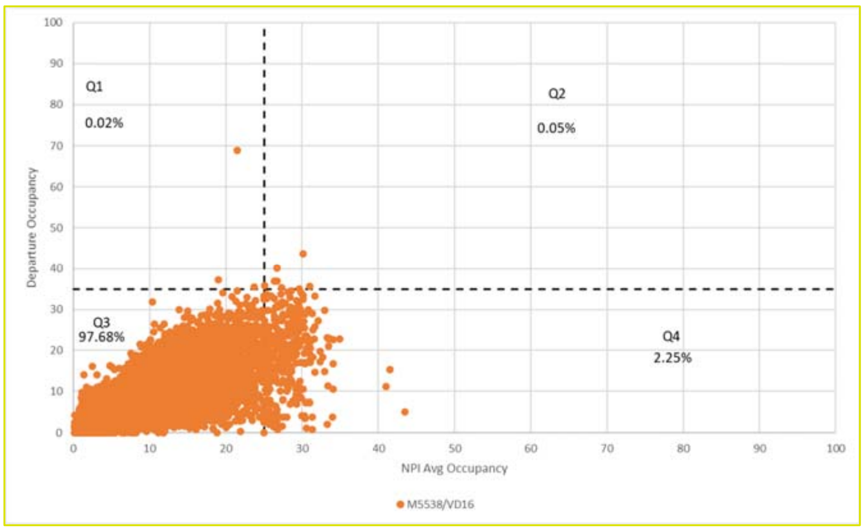


Figure D.3 Departure Occupancy vs NPI Average Occupancy - M5538 EB - Lane 3

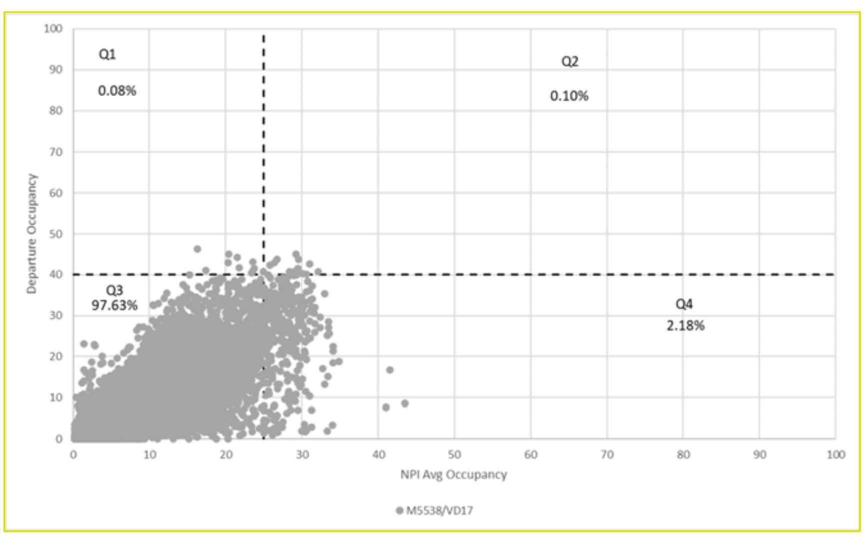


Figure D.4 Time series of peak departure occupancy - M5538 EB

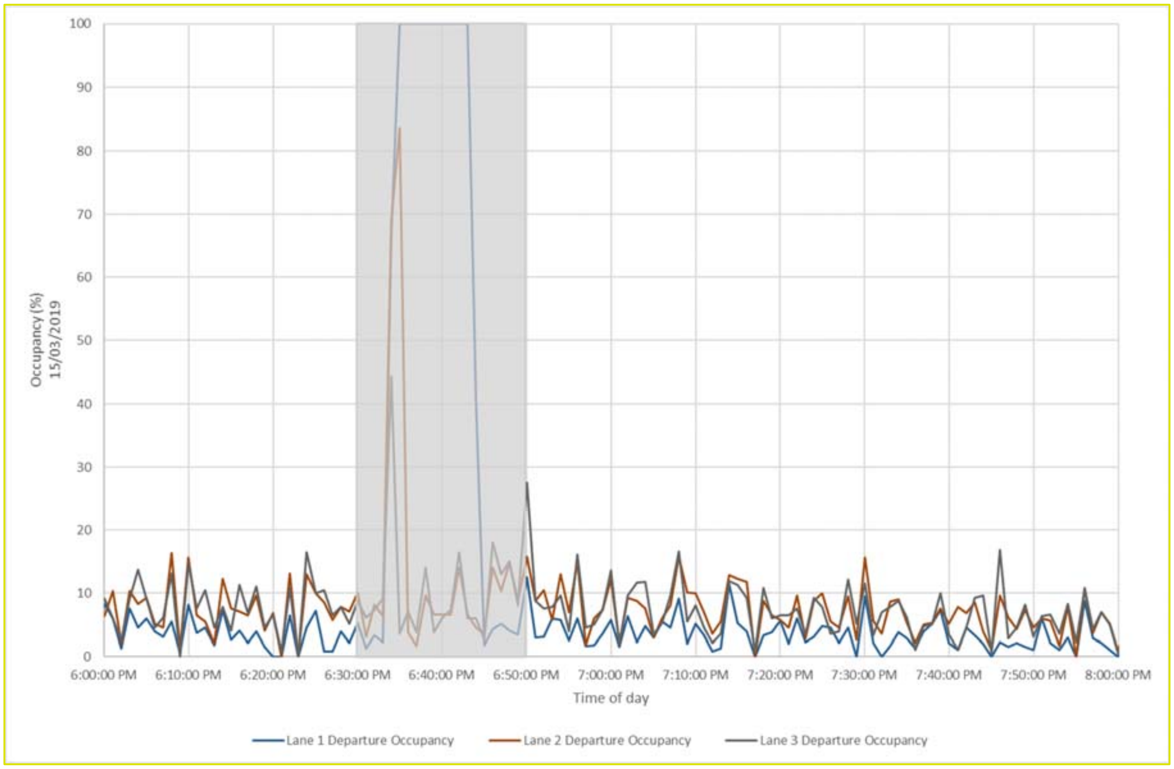
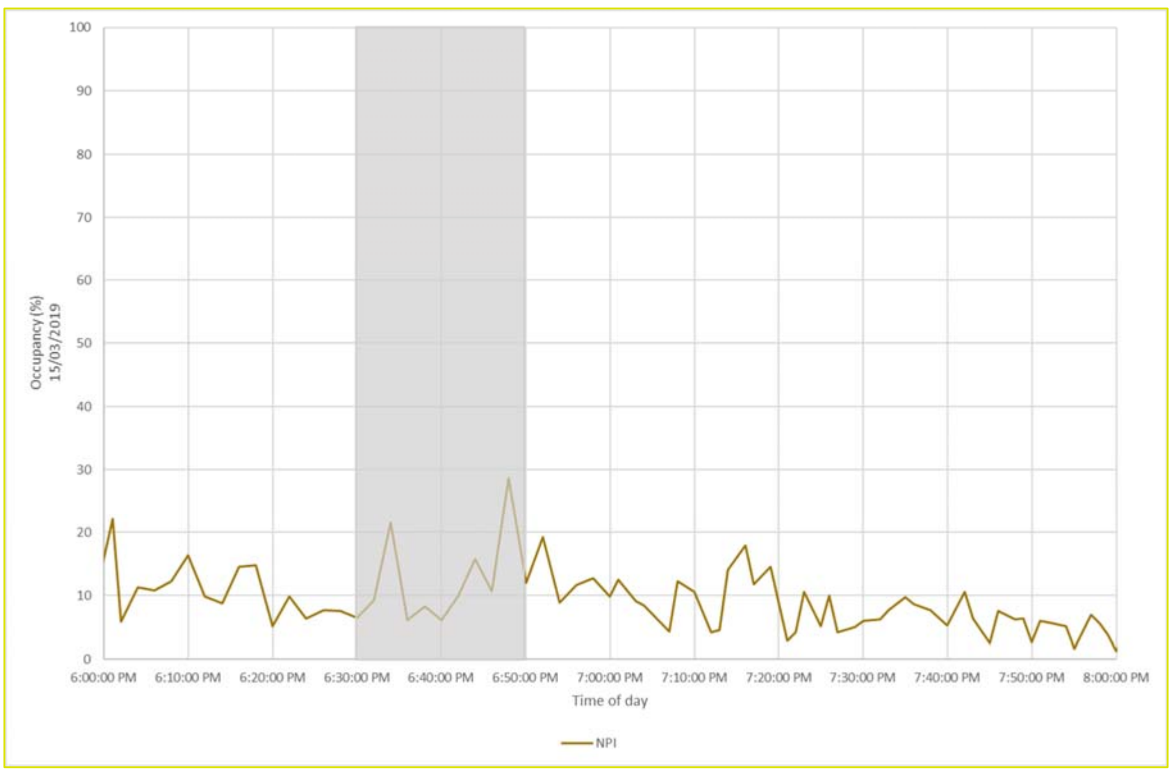


Figure D.5 Time series of NPI average occupancy - M5538 EB



Arrival Occupancy Versus NPI Average Occupancy

This section looks at the arrival occupancy and the NPI average occupancy based on position in the lane. Figure D.1 shows the Lane 1, Figure D.2 shows the Lane 2 and Figure D.3 shows the Lane 3. The values indicate the percentage of data points which are within the relevant quadrant. The quadrants are based on the thresholds from Table 3.1 and Table 3.2. A review of the quadrants of the graph in which the values for occupancy do not align were investigated. Most of the points align in quadrant 3, which is when the vehicles are undersaturated. Approximately 2.53% to 3.25% of the points do not align (e.g. arrival occupancy is high while NPI occupancy is low). A review of where the points do not align found that this generally occurs when the NPI average occupancy exceeds the threshold, but arrival occupancy does not. The morning peak is when the occupancy measures disagree, for both quadrant 1 and quadrant 4. This is consistent with the findings of the departure versus NPI average occupancy. Like the NPI average occupancy versus departure occupancy, the cause of the misalignment could be due to the different units of time for occupancy and the phasing in which the data is recorded. A review of the time-series may give a better indication of what is happening as more context can be given when comparing metrics, such as speed and volume. It is noted that there are points in which the arrival occupancy is 100%. A review of when this occurs found that it was for a 5-minute period, which occurred at the same time as the event noted for the departure occupancy versus NPI average occupancy. Figure D.4 provides a snippet of the time-series of the arrival detectors at the time of the event.

Figure D.1 Arrival Occupancy vs NPI Average Occupancy - M5538 EB - Lane 1

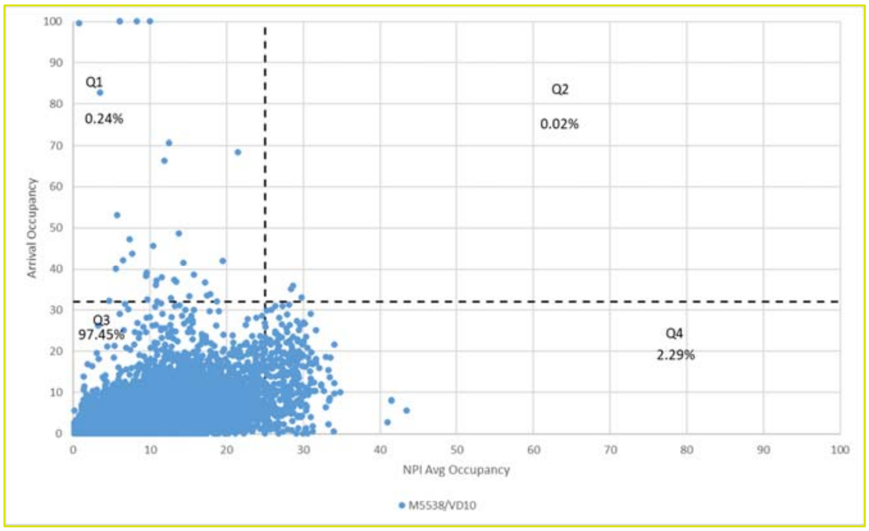


Figure D.2 Arrival Occupancy vs NPI Average Occupancy - M5538 EB - Lane 2

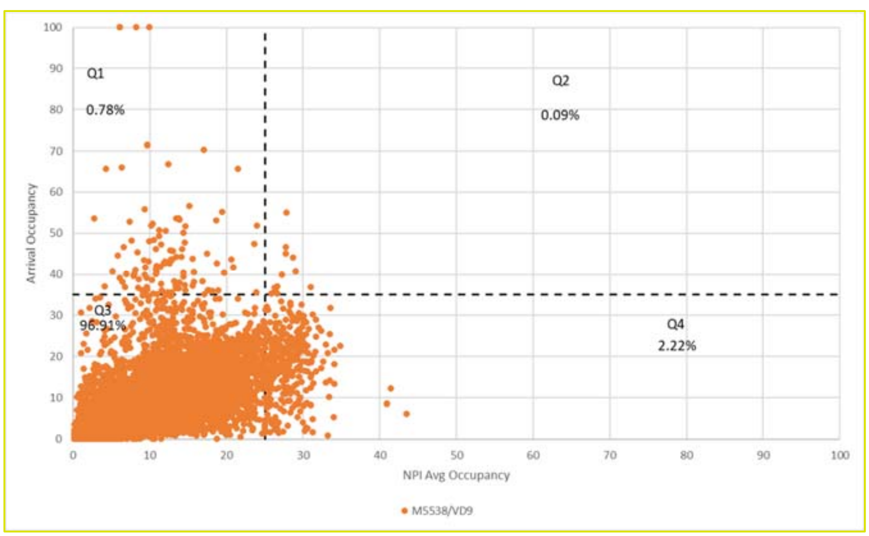


Figure D.3 Arrival Occupancy vs NPI Average Occupancy - M5538 EB - Lane 3

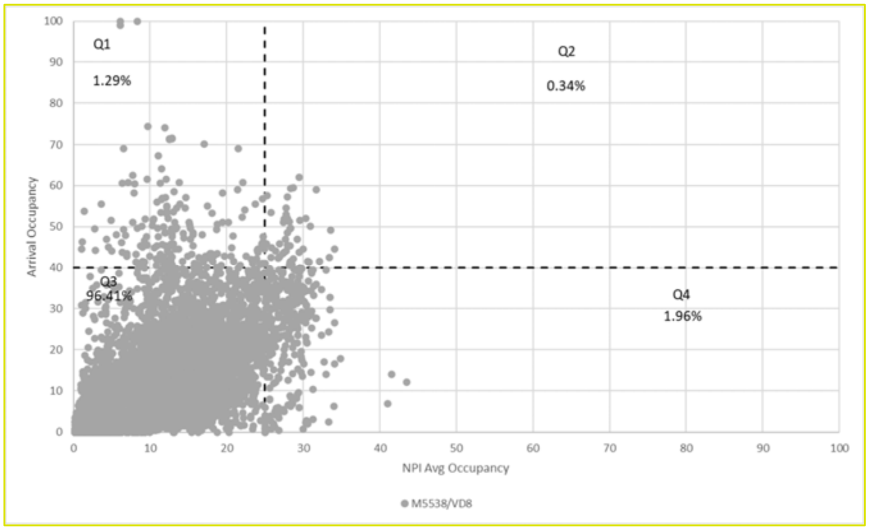
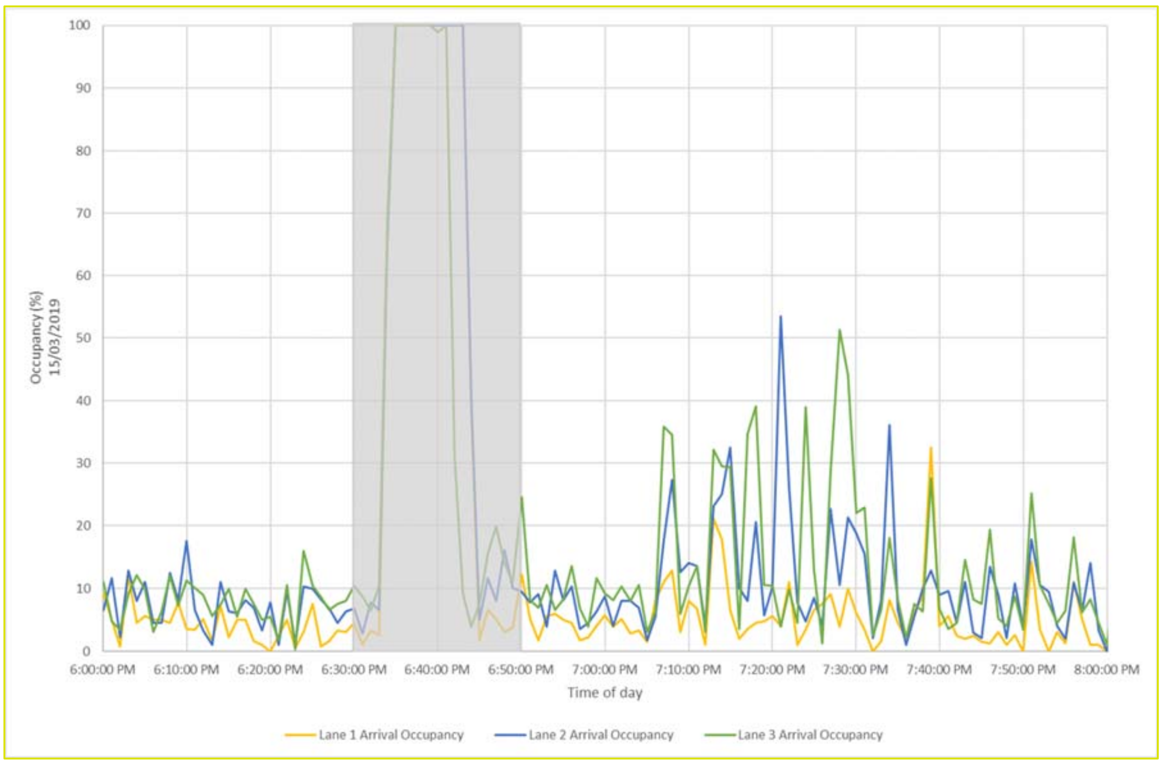


Figure D.4 Time series of peak arrival occupancy - M5538 EB



Departure Occupancy Versus Arrival Occupancy

This section looks at the arrival occupancy and the departure occupancy based on position in the lane. Figure D.1 shows the Lane 1, Figure D.2 shows the Lane 2 and Figure D.3 shows the Lane 3. The values indicate the percentage of data points which are within the relevant quadrant. The quadrants are based on the thresholds from Table 3.2 and Table 3.4. A review of the quadrants in which the occupancy measures for saturation do not align were investigated. It was found that most of the points align in quadrant 3, which is when the vehicles are undersaturated. Approximately 0.33% to 2.25% of the points do not align (e.g. departure occupancy is high while arrival occupancy is low). A review of where these points do not align found that this generally occurs when the arrival occupancy exceeds the threshold, but the departure occupancy has not (quadrant 4). A large proportion of the points that don't align are during the morning peak period, with a smaller amount during the afternoon peak period. The graphs show that the points are more misaligned on the inner lanes. The higher occupancy for arrival detectors is likely due to their positioning. The arrival detector will have high occupancy as vehicles will sit on the detector when the light is red, departure detectors will only have occupancy when a vehicle goes over the detector. When there is a red light, arrival detectors will still accumulate occupancy, due to vehicles sitting on the detector. The departure detector will also have occupancy during the red lights due to turning vehicles, but not as much.

Figure D.1 Departure Occupancy vs Arrival Occupancy - M5538 EB - Lane 1

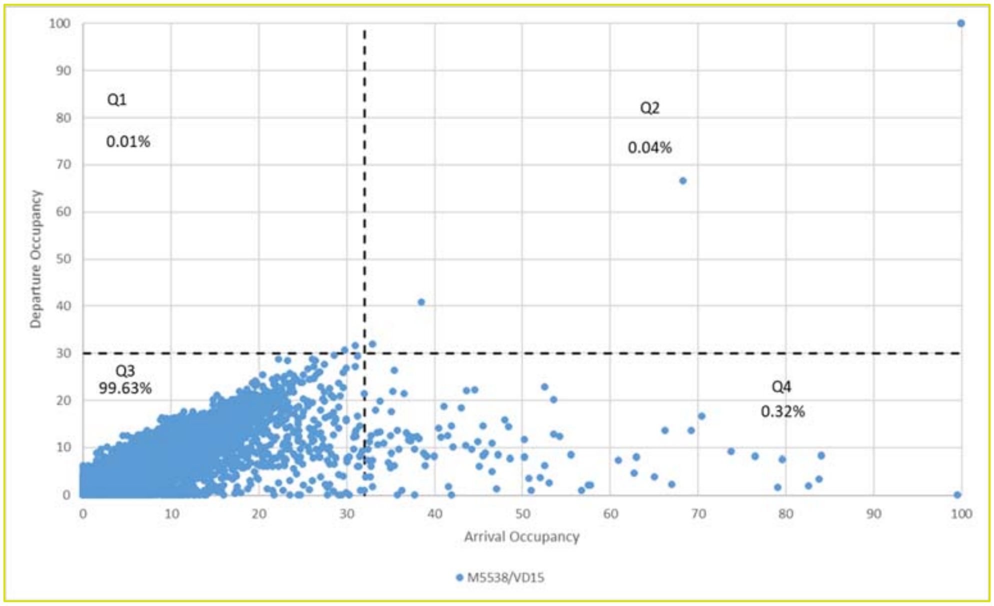


Figure D.2 Departure Occupancy vs Arrival Occupancy - M5538 EB - Lane 2

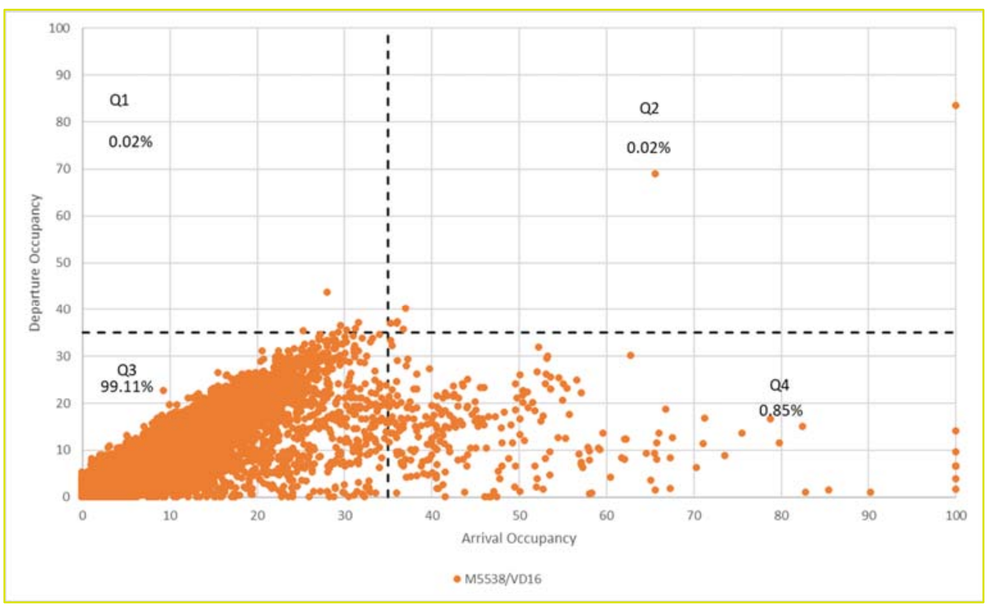


Figure D.3 Departure Occupancy vs Arrival Occupancy - M5538 EB - Lane 3