Enhanced short and longer term network performance prediction capabilities through data-driven analytics and simulation:

Implementing Multi-Zone Perimeter Controls on Perth's Road Network

Submitted to	Main Roads Western Australia & iMOVE CRC
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Project details	iMOVE ITS Project 1-003, Sub-project 1 (Part 2), in part-fulfilment of Milestone 4
Date	16 January 2020
Version	Final

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EXECUTIVE SUMMARY

Perth's first Smart Freeway project is expected to bring significant improvement to Kwinana Northbound traffic operations by utilising a range of intelligent transport systems. Ramp metering is one of the cornerstone solutions, which in simple terms means regulating traffic inflow at on-ramps to prevent flow breakdowns on the freeway so it can remain reliable while delivering higher throughput. This iMOVE subproject investigates the possibility of applying perimeter control that is based on a similar idea but expands it to the whole network.

Perimeter control (also known as gating) works by dividing the network into multiple zones and regulating their flow exchange at the boundaries. It aims at load-balancing between zones across the network to achieve a stable and optimum operation at the global level. Controllers prevent overflow of traffic into busy zones by leveraging spare capacities in less busy zones as temporary storage space. This contrasts with local congestion relief strategies that focus on individual pinch points, which can result in pushing too much traffic downstream and creating another bottleneck.

By keeping the whole network at a steady state, gating has the potential benefit of maximising the total productivity and reducing the need for local capacity expansions. However, its effective implementation requires a good understanding of the behaviour of each zone. Macroscopic Fundamental Diagrams (MFDs) are commonly used for such purposes. They describe underlying relationships between a zone's speed, flow and density at the aggregate level. The accurate measurement of MFDs has become possible in recent years with the advent of 'big data'. As Main Roads' Network Operations Directorate is making rapid progress in this zone, the feasibility of implementing perimeter control becomes increasing likely.

The significant findings of this research are:

- The four Main Roads' metropolitan network performance sub areas (quadrants) have clear MFDs but their MFDs do not ever reach critical density (the maximum vehicles/lane-km before congestion happens). It is primarily because these large regions seldom enter a congested state as a whole. Therefore, they needed to be subdivided into smaller zones for perimeter control.
- We adopted a top-down approach by bisecting the four network performance sub areas until desired MFDs with low scatter and clearly defined critical density were found. The end results are 38 zones across the whole metro network (Section 4.1). Zones with high traffic demand tend to have more usable and well-behaved MFDs that clearly indicate a critical density or 'tipping point' while still having low scatter. Conversely, zones with low traffic demand tend to have less-than-ideal MFDs with higher scatter and no clear indication of critical density, these zones would derive less benefit from the implementation of perimeter control.

- We have also simulated the performance of MFD-based perimeter control using mathematical models (Section 5.2). The results show the control strategy, regulating traffic flows at boundaries by means of signalling, can avoid flow breakdown of the congested zones. Although the traffic was slowed in zones that act as the buffer, the whole network performed substantially better. Travel time for completed trips decreased by 12% in the twelve-zone model (Table 2). *However, the numbers should not be taken literally since the models are hypothetical and include many assumptions. They are only intended to illustrate the potential of benefit of gating.*

Although much more research needs to be done to operationalise this concept, it is a potential paradigm change for network operations. If successful, it can maximise the productivity and reliability of the whole network by utilising spare capacity in zones with low demand-to-capacity ratio to alleviate stress for those under high demand. The productivity gain and avoidable cost of unnecessary road expansions could generate significant social, economic and environmental benefits.

The research presented in this report delivers on Subproject 1 (Part 2) of a larger research project comprising two sub-projects:

- **Subproject 1:** Data-driven empirical models for short-term traffic prediction (Part 1) & **non-route-based area optimisation of network productivity (Part 2)**
- Subproject 2: Simulating the traffic impact of AVs and CAVs to Perth’s freeways and arterial roads

This research is funded by PATREC and the iMOVE CRC and supported by the Cooperative Research Centres program, an Australian Government initiative. The contribution of the steering committee throughout the project, in guiding, monitoring and review, is gratefully acknowledged.

1 INTRODUCTION

1.1 BACKGROUND

The iMOVE project 1-003, *Enhanced short and longer term network performance prediction capabilities through data-driven analytics and simulation,* was co-funded by the following organisations:

- Planning and Transport Research Centre (PATREC)
- Main Roads Western Australia (Main Roads)
- iMOVE CRC
- The University of Western Australia (UWA)

The project comprised two subprojects:

- Subproject 1: Data-driven empirical models for short-term traffic prediction (Part 1) & **non-route-based area optimisation of network productivity (Part 2)**
- Subproject 2: Simulating the traffic impact of AVs and CAVs to Perth's freeways and arterial roads

This report summarises the findings of Subproject 1 (Part 2) - the Perimeter Control component.

The kick-off meeting was held on 12 February 2018 during which the project steering committee was formed:

- Kamal Weeratunga (Committee Chair) / Manager Network Performance (acting), Main Roads
- Graham Jacoby / Network Operations Analysis Manager, Main Roads
- Steve Atkinson / Principal Analyst Strategic Planning, Main Roads
- Chao Sun / Research Follow (Project Leader), UWA

The committee met monthly with other invitees to discuss the progress and make decisions. The project started officially in March 2018.

1.2 PROJECT BRIEF

This work investigates the feasibility of a paradigm shift from the conventional route-focused operations to network-wide perimeter controls with multiple zones. It utilises so-called macroscopic fundamental diagrams (MFDs), which describe the relationship between speed, flow and density of a given zone. The aim is to control the flow exchanges between different zones so that the performance of the whole network can be maximised.

The specific objectives are to:

- Test the existence of MFDs within Perth's road network
- Explore how to divide the network into smaller zones with well-behaved MFDs
- Investigate the potential benefit of perimeter control based on their MFDs

To accomplish these objectives, the following tasks have been undertaken:

- *Task 1*: Data cleaning, pre-processing and aggregation using Main Roads' NetPReS (Network Performance Reporting System) datasets (Section 3.2)
    - Exploration and cleaning of the multiple data sources available for speed, density and flow for each road section (referred to as *M-Links* in NetPReS);
    - Development of an appropriate method for aggregating M-Link (road section) level data to that of zones.
- *Task 2*: Confirm the existence of MFDs and define the MFD zones (Section 4.1)
  Confirm the existence of MFDs within the Perth road network and develop techniques to divide the metro network into MFD zones to ensure each of them has well-behaved MFDs.
- *Task 3*: Simulate the effect of MFD-based perimeter controllers (Section 5.2 & 5.3)
  Control theory utilising MFDs was applied in simulations. Its effectiveness was compared to the 'no-controller' (which applies no restriction to the traffic flow) scenario and the greedy control algorithm (which restricts the traffic flow only based on the current status) scenario.

2 MFD OVERVIEW

2.1 TRADITIONAL FUNDAMENTAL DIAGRAMS

Since the early days of traffic engineering, Fundamental Diagrams (FDs) have been used to study the relationships between a single road section’s speed, flow and density. The FDs are governed by the fundamental relationship flow = density * speed. Figure 1 presents idealised examples that illustrate how they relate to each other. The actual shapes of FDs for individual road segments vary depending on multiple factors so field observations are required. Theoretically, knowing characteristics of FDs could help traffic engineers gauge the current traffic state and prevent it from going beyond capacity that will result in congestion (marked by the red dashed lines in Figure 1).

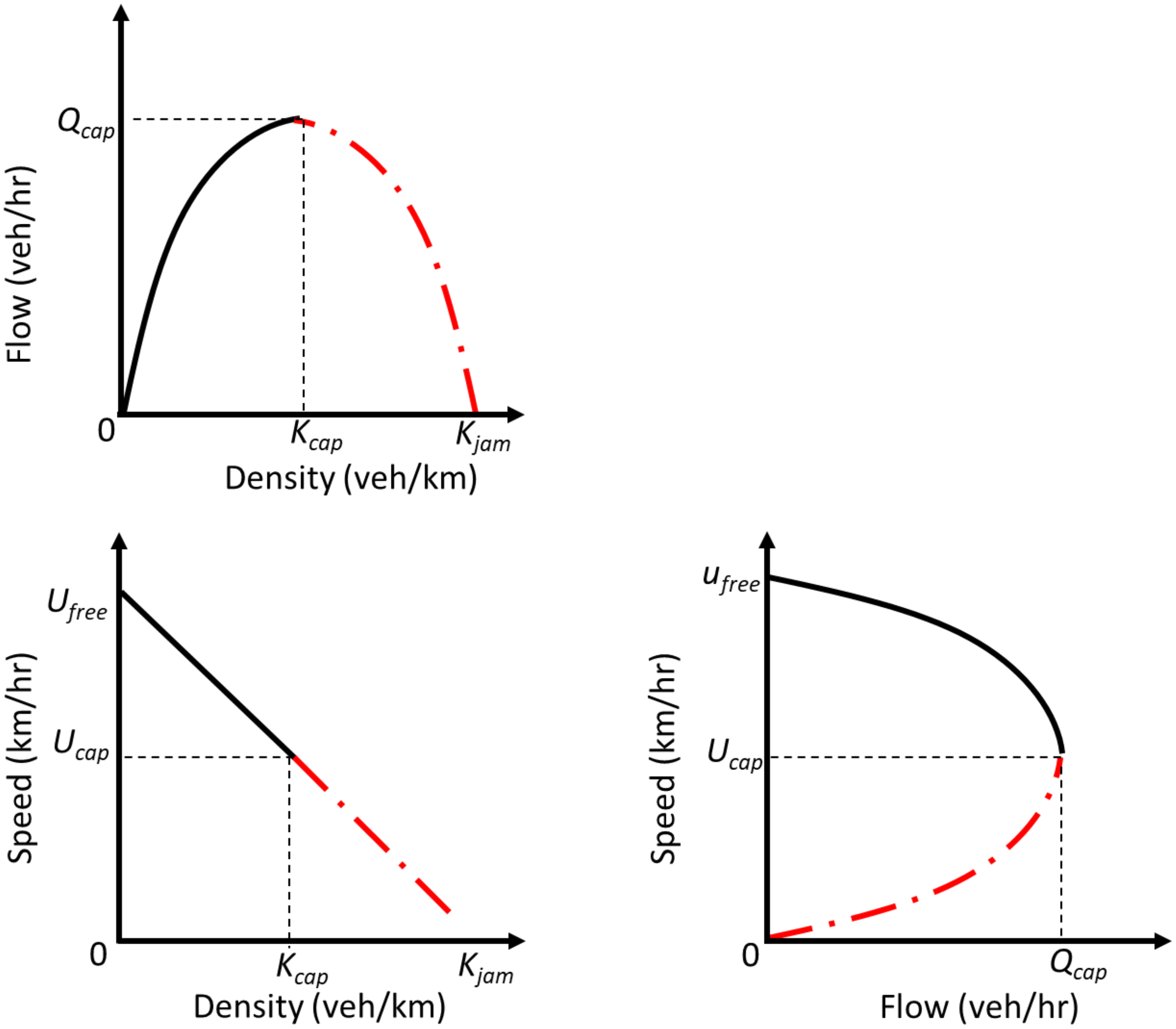


Figure 1 Idealised Fundamental Diagrams of a single road section (adopted from Figure 5.3 & 5.4 of Mannering, Washburn & Kilareski 2009 with modifications)*

*Notes:
U_{free} – free flow speed
U_{cap} – speed at capacity
Q_{cap} – flow at capacity
K_{cap} – density at capacity, also known as critical density
K_{jam} – jam density, at which traffic flow totally stops

2.2 MACROSCOPIC FUNDAMENTAL DIAGRAMS

Although the theory of fundamental diagrams for individual road segments has been well established, the road network is not a simple summation of its parts. Optimising traffic operations based on FDs will not necessarily add up to the optimisation of the entire network. The action of improving single segments or routes could produce sub-optimum solutions by pushing too much traffic downstream and worsen its bottlenecks.

In order to optimise operations of the whole network, it is critical to establish traffic flow theory on an aggregate level. Although various theories have been proposed since 1960s, the empirical evidence could not be obtained until the dawn of 'big data'. Using data gathered from fixed detectors and taxi GPS logs, Geroliminis & Daganzo (2008) have shown the existence of fundamental diagrams for downtown Yokohama, Japan. The diagrams have similar characteristics to conventional FDs but they are commonly named as Macroscopic Fundamental Diagrams (MFDs) to reflect the fact that they apply to zones rather than individual roads. MFDs can help estimate the capacity of the zone, that is, the maximum density it can support, and hence its maximum flow, before entering a congested state.

Since Geroliminis & Daganzo's (2008) seminal paper, the greater availability of high-resolution traffic data in recent years has seen burgeoning research into MFDs, especially their applications in perimeter control (also known as gating) strategies. MFD-based perimeter control involves dividing the network into operational zones and controlling the flow exchange between them. Controllers optimise the productivity of the entire network by spreading out traffic more evenly to prevent the flow collapse of a particular zone. It is an attractive concept because controllers do not require the complex modelling of individual roads.

Nevertheless, the existence of MFDs requires certain conditions to be satisfied so not every arbitrary zone will have clear MFDs. Therefore Task 2 (Section 1.2) focused on confirming the existence of MFDs within the Perth road network and then explore how the whole network can be partitioned in such a way that each zone contains well-defined MFDs with low scatter. For the purpose of this research, we focus on the flow-density diagram.

3 DATA PRE-PROCESSING AND AGGREGATION

3.1 DATASETS AND TERMINOLOGIES

The following data sources have been used by the project team:

- Vehicle Detection Stations: loop detectors on Perth freeways that can gather speed, flow and density data
- Intelematics: a third-party supplier that provides vehicle speed estimated from GPS probes
- AddInsight: Main Roads' system that can estimate vehicle speed from anonymised Bluetooth data
- SCATS: Main Roads' traffic control system that has loop detectors at intersections that can estimate vehicle flow
- IRIS: Main Roads' corporate Integrated Road Information System from which the M-Link (road section) definitions are drawn

The TomTom GPS data was not available at the time of analysis due to technical issues.

3.2 DATA CLEANING

NetPReS data points were modified in the following cases:

- If SCATS_VolumeQuality = 0 – Data point was removed as the volume quality was deemed to be too low.
- If NumberOfLanes = na – Data point was replaced with 1.

Other data points were removed in the following cases:

- If the date was a weekend or public holiday.
- If speed is not displayed as a number – Density cannot be calculated.
- If speed is 0 km/h – Detector limitation.
- If flow is 0 volume/(h*lane) and speed > 0 km/h – Faulty detector.
- If density > 200 volume/(km*lane) – Theoretical maximum density breached (Figure 1 & Figure 2)

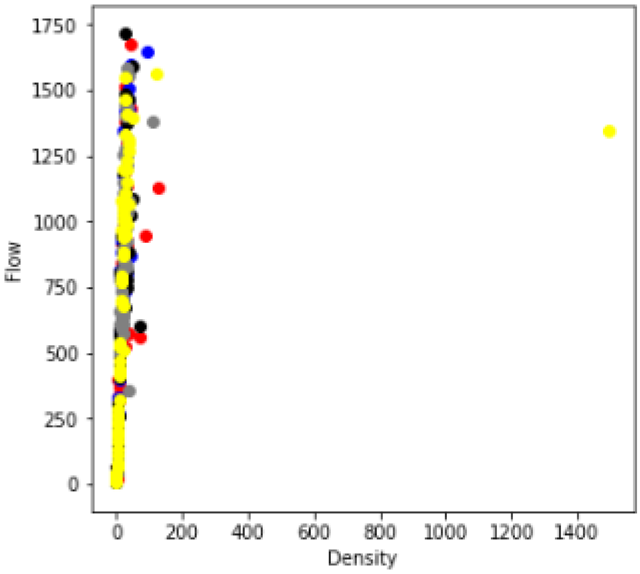


Figure 2 Example density breach

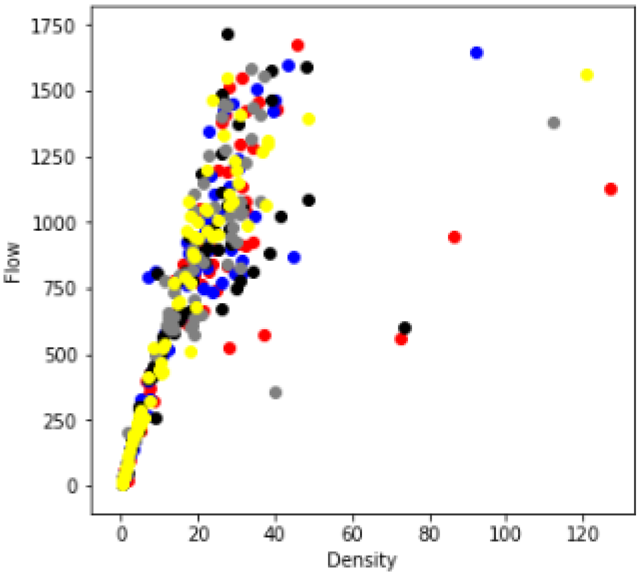


Figure 3 After removing the density breach

4 DEFINING THE MFD ZONES

4.1 THE BISECTION METHOD

The bisection method starts from the four Main Roads network performance sub areas (Figure 4) before repeatedly subdividing laterally and horizontally using each M-Links' (road section) latitude and longitude of its starting position (while keeping the number of M-Links in each division as close as possible) until neat MFDs are produced. The M-Links normally end at major intersections or ramps so the boundaries drawn this way ensure a good chance of implementing traffic control strategies through existing traffic lights or ramp meters (assuming wider roll-out of smart freeways) so that cost can be minimised.

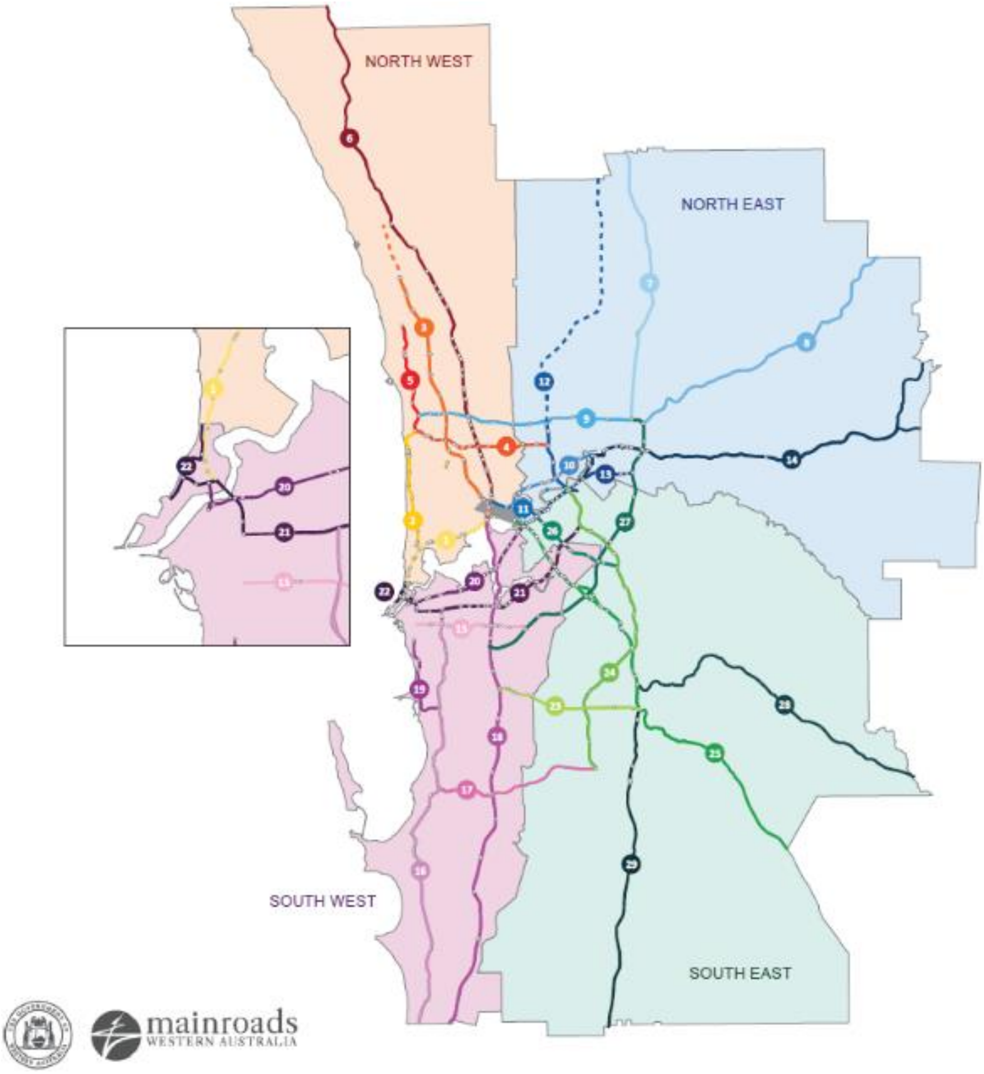
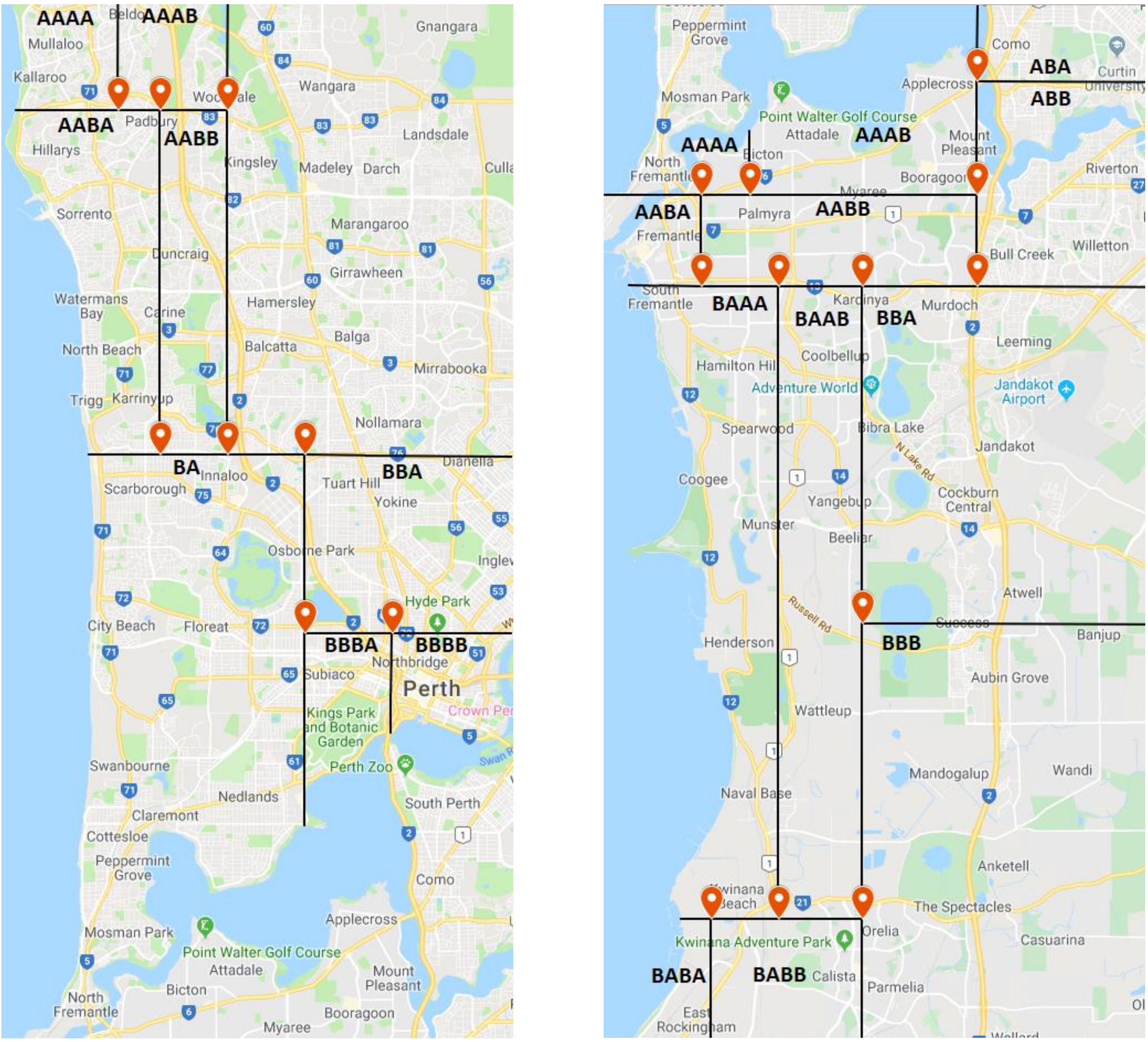


Figure 4 The Main Roads four network performance sub areas (Main Roads 2018)



a.) Northwest b.) Southwest

Figure 5 MFD zones for Northwest and Southwest (maps have been rescaled to align with each other)

Figure 5 shows the final layout of MFD subdivisions for Perth's two busiest Main Roads network performance sub areas. In total, the whole network is divided into 38 MFD zones (Table 1), which is deemed to be a reasonable number for Main Roads to manage.

Table 1 Number of MFD zones for each Main Roads network performance sub area

Network performance sub area	Number of MFD zones
Northwest	9
Northeast	7
Southwest	12
Southeast	10
Total	38

In general, zones surrounding the CBD such as Northwest Zone BBBB (Figure 6) and Southwest Zone ABA (Figure 7) are more likely to exhibit well-behaved MFDs, which have less scatter and clear indication of critical density (beyond which congestion is likely to occur) of the zone. This is essential for implementing the controllers described in Section 5.

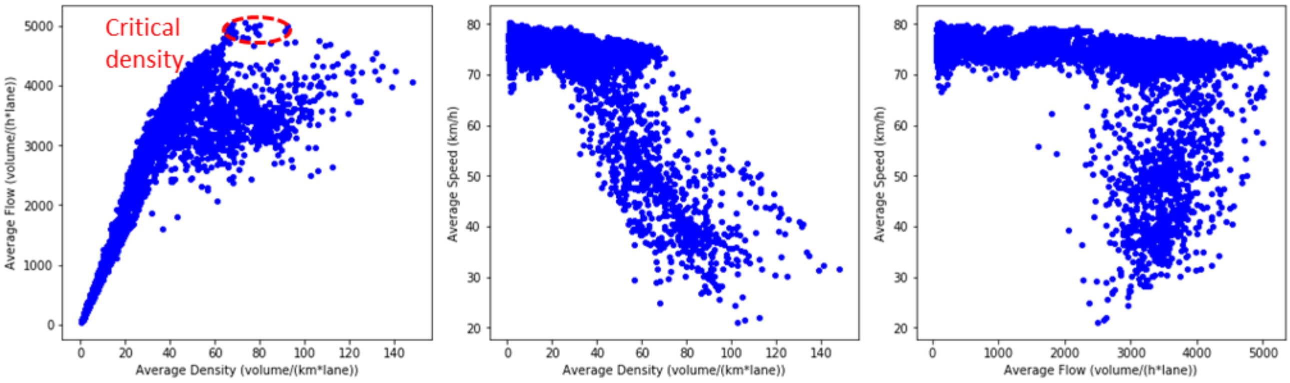


Figure 6 Northwest Zone BBBB

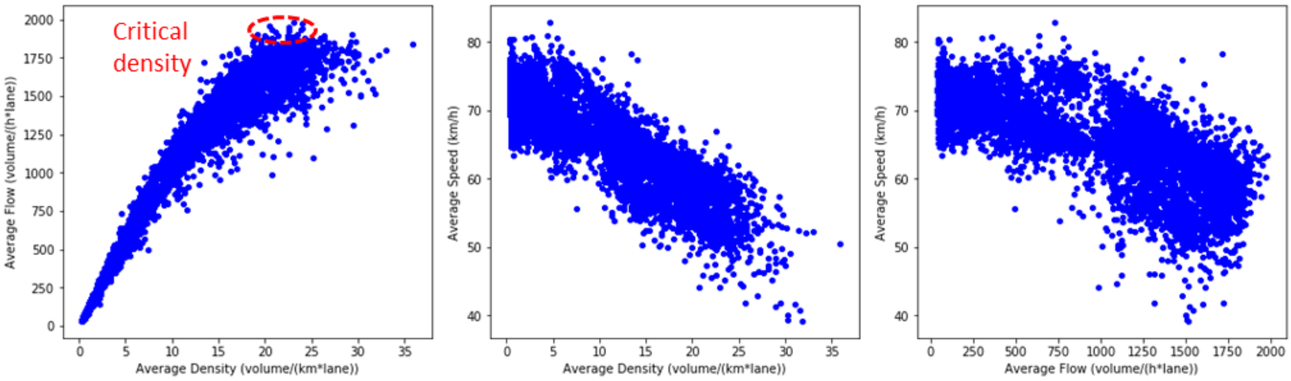


Figure 7 MFDs for Southwest Zone ABA

Zones with low traffic, especially some in northeast and southeast tend not to have well behaved MFDs (e.g. Figure 8). They have high scatter and provide no clear indication of where the maximum density lies.

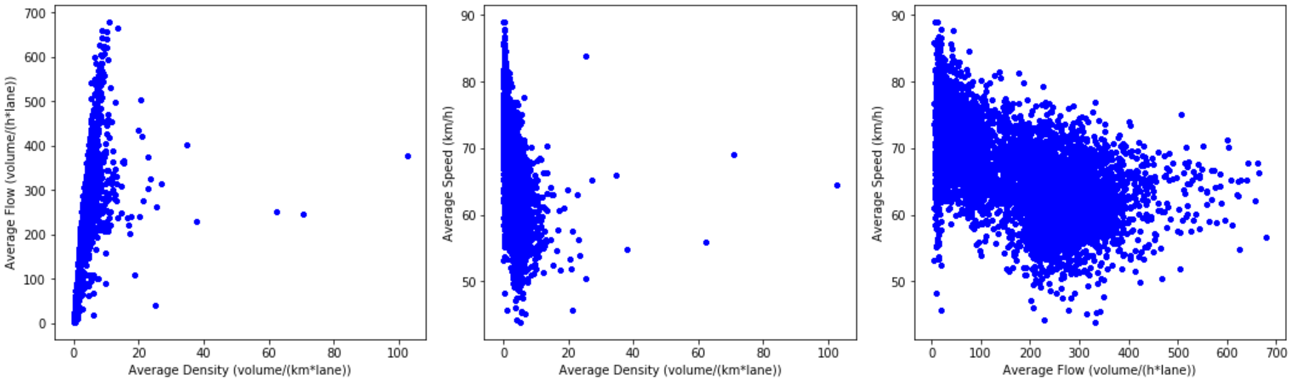


Figure 8 An example of not well defined MFDs in the Southeast Region

5 SIMULATING THE PERFORMANCE OF MFD-BASED CONTROLLERS

5.1 A BRIEF EXPLANATION OF CONTROL THEORY

As mentioned previously, there is growing interest and research in applying MFDs to perimeter control of traffic. The existing traffic control system SCATS relies on fixed location sensors, mostly inductive loops at stop lines, to maximise the utilisation of road capacity by maintaining the desired Degree of Saturation (DS) of critical movements. The focus is more on keep the traffic moving. On the other hand, perimeter control aims at load-balancing between zones to avoid situations in which improved operation of certain road sections simply pushes bottlenecks downstream. Instead of aiming for maintaining high utilisation, this could mean restricting flows. It is analogous to applying ramp metering to the whole network.

Given that this is an early stage feasibility study, we simulated the performance in hypothetical scenarios. We consider the case of implementing a perimeter control strategy to regulate the flow between zones with defined MFDs. The goal is to maximize the total production of the network by reducing the inflow from less congested zones into more congested ones. We assume a flow controller exists between every pair of adjacent zones. It can regulate the exchange of vehicular flows between them, e.g. it can speed up the flow from Zone *i* to Zone *j* and slow down the other direction if *i* is approaching critical density and *j* still has spare capacity.

In reality, the control will be achieved by changing the traffic light settings such as cycle time and phase split. This has to be done subtly on multiple signals through the existing traffic control systems (i.e. SCATS in Main Roads' case) so the complexity is not to be underestimated. However, for an initial feasibility study it is sufficient to assume the controllers can regulate the traffic flows.

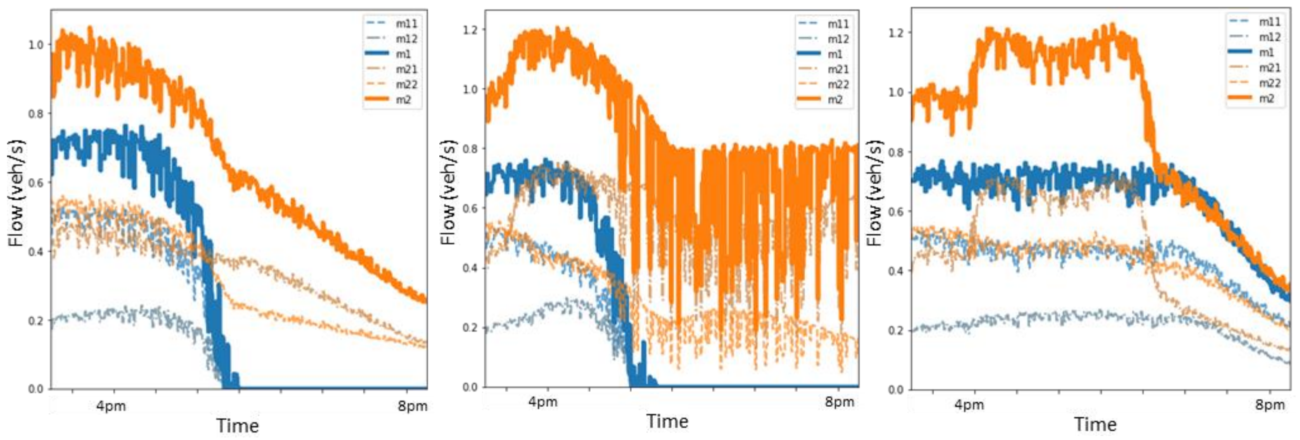
The implemented control strategy is the Model Predictive Control (MPC), described in Geroliminis, Haddad & Ramezani (2013). It works by iteratively optimizing the system in discrete time intervals (e.g. 1 minute). During each optimization step, the flow control parameters are calculated so that the predicted objective function is maximized at a defined time horizon (e.g. 20 minutes) in the future. Note that the time horizon is longer than the time step. At the next interval, the actual states of the two zones are compared with the predicted states and new control parameters will be adjusted based on the differences. The procedure then repeats. This step-wise 'states update' accounts for errors in the model and steers the system towards the desired performance.

The MPC controller is benchmarked against a Greedy Controller strategy (GC) (Geroliminis, Haddad & Ramezani 2013). The GC strategy works by the following simple policy: If no zone is congested, set both boundary controllers to their maximum value, i.e. no cap on the flow exchange in either direction. If one zone is congested and the other is not, set the inflow perimeter controller of the congested zone to the minimum possible value and the other one to the maximum. If both zones are congested, treat the least congested zone as not congested and execute the policy described above.

5.2 SIMULATION RESULTS OF TWO MFD ZONES

Due to the limited scope of this project, two abstract simulations were conducted to test the performance of the MPC strategy. Data is based on Zones Northwest BBBB and Southwest ABA (Figure 5). The flow-accumulation relationship is modelled based on their observed data. Demand has been estimated using observed data for the peak evening hour, but the initial state of both zones has been set to a highly congested situation. The simulation comprises 5 hours of traffic in the afternoon peak.

As Figure 9 shows, when no control is applied, Zone 1 surpasses its jam density and quickly enters a gridlock state. The GC fails to prevent the gridlock state of zone1 and causes significant oscillation to Zone 2 flows. The MPC effectively avoids the gridlock and maintains both zones near their optimal operation point by regulating the flow from Zone 2 into Zone1 (m21 in Figure 9 c).



a.) No Controller b.) Greedy Controller c.) MPC

*Figure 9 Results of the two-zone simulation**

*Notes:
m11 is the traffic flow starts from Zone 1 and Ends in Zone 1, i.e. its internal flow.
m12 is the traffic flow starts in Zone 1 but ends in Zone 2.
m1 is the total traffic flow of Zone 1, i.e. m1 = m11 + m12
The same applies to Zone 2

5.3 MULTIPLE MFD ZONES

The methodology can in theory be applied to any arbitrary disposition of zones with well-behaved MFDs. We simulated a hypothetical scenario with 12 MFD zones (Figure 10).

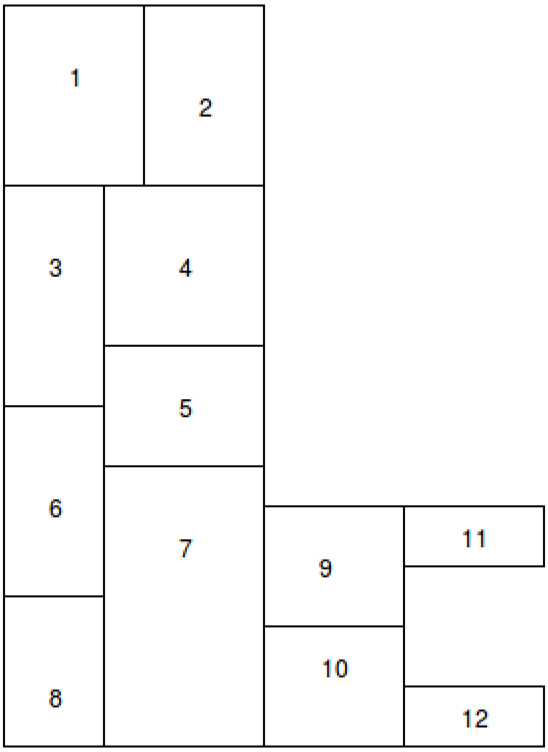
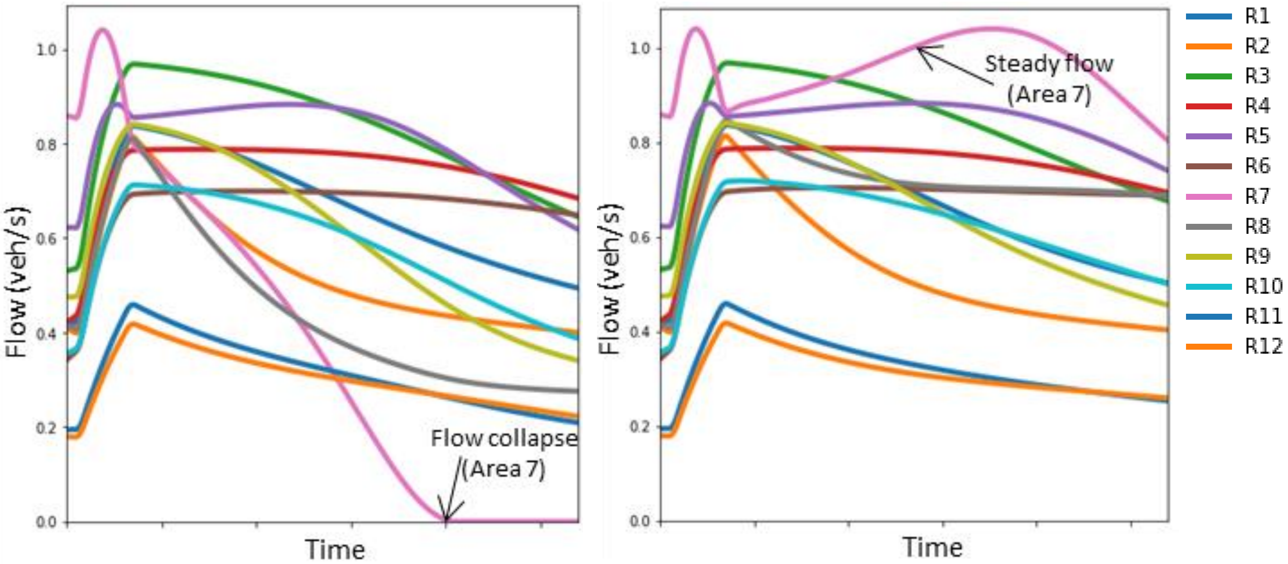


Figure 10 The layout of the 12 simulated MFD zones

All zones have an initial mid-level congestion and different MFDs. The traffic demands were set to peak simultaneously on all possible connections.

Figure 11 (a) shows that when no controller is used, Zone 7 gets over-congested and reaches a grid-lock state. This is determined by its key location in the network – it connects 5 different other zones, most of which are disconnected with each other. Figure 11 (b) shows that MPC effectively avoids the gridlock by reducing the inflow into Zone 7. The total productivity of the network also improves.



a.) No Controller b.) MPC

*Figure 11 Results of the twelve-zone simulation**

*Notes:

No units are shown in the horizontal axis since the actual time has no meaning in this hypothetical scenario

m11 is the traffic flow starts from Zone 1 and ends in Zone 1, i.e. its internal flow.

m12 is the traffic flow starts in Zone 1 but ends in Zone 2.

…

m17 is the traffic flow starts in Zone 1 but ends in Zone 7.

m1 is the total traffic flow of Zone 1, i.e. m1 = m11 + m12 + … + m17

The same applies to other zones

Table 2 MPC improvement relative to the base case with no controllers

Scenario	**Avg. Speed**	**Total Travelled Time**	**Total Completed Trips**	**Travelled Time per Completed Trip**	**Average Density**
2 Zones	247%	-44%	66%	-66%	-44%
12 Zones	18%	-3%	11%	-12%	-3%

In both simulations the MPC improved the performance of speed, travel time, trips completed and density, especially in the two-zone case scenario (Table 2). This was largely due to less complicated inter-zonal interactions *However, the numbers should not be taken literally since the models used are abstract with many assumptions including the demand used in the twelve-zone case* scenario.

6 CONCLUSIONS AND FUTURE RESEARCH

This research has demonstrated conceptually that MFDs can be applied to better manage Perth's road network. Although much more research needs to be done to operationalise MFD-based perimeter control, it is a potential paradigm change for network operations. If successful, it can maximise the productivity and reliability of the whole network by utilising spare capacity in zones with a low demand-to-capacity ratio to alleviate stress in those zones under high demand. The productivity gain and avoidable cost of unnecessary road expansions could generate significant social, economic and environmental benefits.

The priorities for future research are:

- The MPC used in this project requires reasonably accurate demand estimation. Estimated origin and destination matrices are also needed for managing multiple zones. However, both should be achievable using the Main Roads datasets.

- There are other controllers available that do not require demand data, but their performance needs to be compared against MPC.

- The current mathematical models are sufficient as proof-of-concept but more elaborate simulation models are needed to produce accurate results. There is also an opportunity to incorporate operational factors such as the delay between implementing the control and having an impact due to the time vehicles need to travel between points.

- Determining how such a strategy can be implemented with existing traffic control systems such as SCATS currently used by Main Roads.

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