TE MANATŪ WAKA
MINISTRY OF TRANSPORT

Domestic Transport Costs and Charges Study

Working Paper D2
Road Congestion Costs

Prepared for Te Manatū Waka Ministry of Transport (NZ)
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The Research, Economics and Evaluation team operates within the System Performance and Governance Group of Te Manatū Waka Ministry of Transport. The team supports the Ministry's policy teams by providing the evidence base at each stage of the policy development.

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- Providing sector direction on the establishment and use of the Transport Evidence Base (see below) – including the collection, use, and sharing of data, research and analytics across the transport sector and fostering the development of sector research capabilities and ideas.
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The Domestic Transport Costs and Charges study aims to fill some of the research gaps identified in the 2016 Transport Domain Plan (Recommendation R6.2), which forms part of the Transport Evidence Base.

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For more information

For more information about this project and associated report, please contact: info@transport.govt.nz.

Executive Summary

Overview

The Domestic Transport Costs and Charges (DTCC) study aims to identify all the costs imposed by the domestic transport system on the wider New Zealand economy including costs (financial and non-financial) and charges borne by the transport user.

This Working Paper deals with road congestion costs that arise due to the interaction between vehicles using a road. This cost is addressed in three main ways: at the local level, traffic speed and density observations are used at a number of sites across New Zealand to determine the relationship between traffic speed, density and flow; data from the Auckland, Wellington and Christchurch regional models are used to estimate the average cost of congestion in those cities[1]; and road construction costs from recent road capacity expansion works are used to estimate the cost of increasing the capacity of a road to cater for increases in demand.

The basic principles underlying traffic congestion, including an understanding of the fundamental diagram of traffic whereby too many vehicles attempting to use a road actually reduce its carrying capacity, have been known for many years (e.g., Greenshields 1935). There is a large volume of literature on the subject, mostly in terms of optimum congestion charging. The economist’s rule for pricing is to price equal to the externality. This is a short run marginal cost concept – it varies by time of day and its purpose is to ensure that the existing infrastructure is used efficiently. The long run marginal cost is the cost of expanding the road to cater for the marginal vehicle. The investment rule is to increase capacity if the long run cost is less than the short run cost. This is mathematically the same as saying invest if the benefit: cost ratio exceeds 1.0. Note that the costs and benefits are very site specific – while the long and short run costs estimated in this study are indicative, any actual road improvement would require a full cost: benefit analysis.

Methodology

It is possible to derive the social marginal cost on a road section by using the travel time and the free flow time to calculate the elasticity of speed with respect to traffic density (Yang et al 2019). Previous analysis of congestion in New Zealand (Wallis and Lupton 2013) suggested that the relationship between travel time and demand could be represent by a BPR function[2]. We therefore used data on traffic volumes and speeds collected on a number of urban roads across both islands to see if we could fit a BPR function to the data. This would enable us to estimate the congestion externality by time of day. Only sites that are perceived to become congested during a typical day were studied.

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[1] These models are not ideal. There is some concern that the Household Travel Survey data underpinning these models is very old and the strategic models use simplistic volume-delay curves that generally do not account for intersection delay. The delay induced by ramp metering and onramp merges will also be missing. Alternate data sources are discussed in Section 0.

[2] This relationship was originally proposed by the US Bureau of Public Roads (BPR 1964).

In most cases, a BPR function (interpreted as described in Appendix 4) provides a satisfactory fit to the observed data and related traffic speeds to vehicle density on the road. In some lower traffic urban situations, the observed trips formed a completely different pattern and a hyperbolic shaped function was required to fit the data. It would appear that the hyperbolic function arises due to the effect of side friction and delay at signalised intersections, in which case, the relationship is probably not strictly causal, rather, higher levels of pedestrian and other activities coincide with periods of higher traffic.

The main source of data used was GPS data from vehicle navigation systems. More than 10 years of speed data on roads throughout New Zealand are available. These data were used to provide speed and number of probes (GPS units from which data are collected) by time period for fifteen roads. Most locations provided data for three separate points on the road in each direction. Data were extracted for a ten-week period during the third school term of 2019. The data were plotted and a curve that best fitted in terms of maximum speed and maximum flow was fitted in each case.

In order to get some measure of the overall average cost of congestion we need to look at entire journeys at a network level. Data from the Auckland, Wellington and Christchurch transport models were used to estimate the total cost and the average cost per kilometre in the three main urban areas. The results for Auckland were compared with those calculated in previous studies.

Cities tend to form around a city centre as this maximises accessibility of people to employment, business and commerce. The effect of congestion is to increase the cost of travel – in particular the cost to the centre and this warps the time vs distance plane increasing the relative attractiveness of non-central locations. We ranked the zones in each city both under free-flow and congested speeds and plotted the difference to show the impact of congestion on location attractiveness. This is most noticeable for Auckland where the effect is to move the centre of attractiveness southward, but is also present for Wellington and Christchurch.

Congestion is a short run cost. The long run marginal cost is the cost of increasing the capacity of the road by one unit. Road construction involves lumpy investments so this concept has practical issues. The New Zealand Transport Agency (Waka Kotahi) provided data on recent road capacity increases: this was divided by the expected increase in peak period capacity in order to provide an estimated marginal cost. Details of a sample of in the order of 15 -20 NZ state highway schemes that were completed within the last 10 years or so, or that are under construction or in an advanced state of planning, were requested from Waka Kotahi. An average lane capacity was used to estimate the cost per additional passenger car unit (pcu) of capacity[3].

Results

The results from the individual road sections are very site specific, with the short run marginal cost ranging from zero (Waimakariri bridge northbound) to $1.85/km (Dominion Road northbound) and the implied cost of congestion ranging up to $7 million per year per kilometre and averaging $1m per kilometre over the chosen sites.

Some of the results may appear a little surprising - for example the low congestion externality attributed to State Highway 1 between Pukerua Bay and Paekakariki (Now SH59). This is likely

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[3] The analysis was undertaken in terms of passenger car units rather than passengers. However, the time costs of other users took account of average occupancy.

due to bottlenecks that restrict the traffic each end of this stretch and the 80km/h speed limit which means the free flow speed and the speed at capacity are virtually the same, while the demand is never able to exceed capacity.

While some urban streets exhibit BPR-type congestion[4], others exhibit a hyperbolic relationship where speeds appear to be constrained by side friction and signalised junctions. While it would be possible to estimate the underlying relationship, it is probably not causal. The SRMC will only be significant towards the tail of the distribution where the road is approaching capacity.

The average congestion cost per kilometre faced by motorists in the three largest urban areas were estimated using the respective transport planning models as shown in Table ES.1. It is a limitation of the approach that the transport models used effectively assume a uniform ‘peak’ demand over a two-hour period. This may underestimate the actual delays. The average delay costs during the AM peak period vary from $0.08 per kilometre for Christchurch to $0.31 per kilometre for Auckland, while the long run marginal cost based on recent projects in each centre was a factor of 10 higher, at $0.80 per pcu-km in Christchurch, $3.20 in Wellington and $3.10 in Auckland. The total delay per AM peak period for Auckland is $1.7 million, equivalent to $850 million per year, while the ‘avoidable’ cost of congestion[5] is $400 million per year. This compares with the figure of $145 million calculated by Wallis and Lupton in 2013 that is equal to $155 million in current (i.e. 2019) prices.

Table ES. 1 Average delays and costs

	AM peak trips	Free flow time (minutes)	Actual time (minutes)	Distance vehicle km	Delay per AM peak	Delay cost per kilometre	Annual Cost of Congestion
Auckland	543,500	6,164,000	9,366,500	5,776,000	$1,730,000	$0.31	$400 million
Wellington	182,700	1,738,000	2,189,000	1,178,000	$243,000	$0.21	$39 million
Christchurch	226,000	2,260,000	2,723,000	1,810,000	$250,000	$0.14	$4 million

Source: consultant estimates.

The average delay cost per kilometre is not very helpful as the cost varies so significantly across the network. However, it is useful to inform travel demand policies such as congestion pricing. For example, “The Congestion Question” (TCQ) report considered a cordon charge for entering the Auckland CBD. When designing a congestion charging scheme, the ability to initially achieve an optimum charge will be influenced by the need to make trade-offs, including managing equity concerns and the costs associated with more sophisticated charging mechanisms. Recognising these trade-offs, TCQ proposes an initial flat rate access charge, but does not rule out variable pricing in the future. Using results from this working paper, we calculate that about 5% of all AM peak trips responsible for 14% of the congestion delays currently cross this cordon. The average delay for these trips is 15 minutes and the short run marginal cost is $33 per trip. This means that the marginal vehicle dissuaded from travelling at the peak would initially reduce total delay costs by

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[4] Ie with delays that increase rapidly as demand approaches and exceeds capacity. This leads to the classic ‘backward bending’ speed-flow curve. This is discussed in detail later in this paper.

[5] Ie comparing with the speed at capacity rather than the speed at free-flow.

$33. The equilibrium SRMC that would result in the peak demand for travel just equalling the road capacity across the cordon would be $7.70 per trip. Note however that the COVID situation and post-COVID adjustments may reduce the demand – and hence the SRMC - for CBD-oriented trips, at least in the shorter term.

Limitations, future updates and potential additional areas of work

The site-specific nature of congestion means that any estimates need to be used with care. In particular identifying whether the congestion is due to interaction between vehicles or whether it can mainly be ascribed to side friction. The observed behaviour may reflect bottlenecks before or after the observed location rather than the characteristics of the chapter itself: Whether this is important or not depends on the use to which the data will be put.

Transport models provide an easy-to-use source of network data, but again this needs to be interpreted with care – these data already incorporate assumptions about the behaviour of traffic. As an alternative to using model data, we did consider using mobile phone network data to track the movement of vehicles through the day. This could be used to record the average travel times between pairs of zones in the network by time of day in a similar way to the use of Tom Tom data and would enable the free-flow, peak flow and congested flow times to be determined accurately including the pattern of demand within and on the shoulders of the peak periods This approach should be investigated further in the future.

Glossary of terms and abbreviations

Term	Description
BPR	Bureau of Public Roads (USA)
CBD	Central business district
DTCC	Domestic Transport Costs and Charges Study
EEM	Economic evaluation manual, NZ Transport Agency (Now Monetised Benefits and Costs Manual, MBCM)
GPS	Global positioning system
Hyper-congestion	When demand exceeds the capacity of the road and additional demand results in the flow decreasing.
LRMC	Long run marginal costs
MBCM	Monetised Benefits and Costs Manual (Waka Kotahi, 2020)
Normal congestion	Where additional demand slows all other traffic but the total flow is nevertheless increasing.
pcu	Passenger car unit
SMC	Social marginal cost
SRMC	Short run marginal costs
TCi	Transport Congestion Info (company supplying data)
TOF	Transport Outcomes Framework

Chapter 1 Introduction

1.1 Study scope and overview

The Domestic Transport Costs and Charges (DTCC) study aims to identify all the costs imposed by the domestic transport system on the wider New Zealand economy including costs (financial and non-financial) and charges borne by the transport user.

The Study is an important input to achieving a quality transport system for New Zealand that improves wellbeing and liveability. Its outputs will improve our understanding of the economic, environmental and social costs imposed by different transport modes - including road, rail, coastal shipping and domestic passenger aviation - and the extent to which those costs are currently offset by charges paid by transport users.

The DTCC is intended to support the MOT's wider policy framework, especially the Transport Outcomes Framework (TOF). The TOF seeks to make clear what government wants to achieve through the transport system under five outcome areas:

- Inclusive access,
- Economic prosperity,
- Healthy and safe people,
- Environmental sustainability, and
- Resilience and security.

Underpinning outcomes in these areas is the guiding principle of mode neutrality. In general, outputs of the DTCC study will contribute to the TOF by providing consistent methods for (1) estimating and reporting economic costs and financial charges and (2) understanding how these costs and charges vary across dimensions that are relevant to policy, such as location, mode, and trip type.

Robust information on transport costs and charges is critical to establishing a sound transport policy framework. The Study itself does not address future transport policy options; but the study outputs will help inform important policy development including areas such as charging and revenue management, internalising externalities, and travel demand management.

The Study is being undertaken for the Ministry of Transport by a consultant consortium headed by Ian Wallis Associates. The Study has been divided into a number of topic areas, some of which relate to different transport modes (including road, rail, urban public transport, aviation, and coastal shipping), and others to impacts or externalities (including crashes, congestion, public health, emissions, noise, biodiversity and biosecurity).

Working papers are being prepared for each of the topic areas. The topic areas and specialist authors are listed in Appendix 2.

1.2 Costing practices

The focus of DTCC is on NZ transport operations, economic costs, financial costs and charges for the year ending 30 June 2019 (FY 2018/19). Consistent with this focus, all economic and financial cost figures are given in NZ$2018/19 (average for the 12-month period) unless otherwise specified.

All financial costs include any taxes and charges (but exclude GST); while economic costs exclude all taxes and charges.

The DTCC economic and financial analyses comprise essentially single-year assessments of transport sector costs and charges for FY 2018/19. Capital charges have been included in these assessments, with annualised costs based on typical market depreciation rates plus an annualised charge (derived as 4% pa of the optimised replacement costs of the assets involved).

1.3 Analytical approach and coverage

Unless otherwise noted, the analysis in in this paper is based on the following:

- ***Base price period.*** All prices are expressed in NZ$2018/19 (i.e. prices typical of or averaged over the 12 months ending 30 June 19).
- ***Pricing in real terms.*** All prices are expressed in constant real $ terms, i.e. excluding any inflationary components.
- ***GST.*** All costs (prices) are expressed **excluding** any GST component.
- ***Other taxes and duties.*** Economic analyses are concerned with resource costs rather than financial costs, so any specific taxes or duties have been excluded from the prices of goods and services for the purpose of any economic analyses; but retained in any analyses of travel behaviour (e.g. choices between alternative travel modes), which would be based on financial cost to the traveller.

1.4 Paper scope and structure

This Working Paper deals with road congestion costs that arise due to the interaction between vehicles using a road. This cost is addressed in three main ways: at the local level, traffic speed and density observations are used at a number of sites across New Zealand to determine the relationship between traffic speed, density and flow; the conclusions from this work are used in conjunction with data from the Auckland, Wellington and Christchurch regional models to estimate the average cost of congestion in those cities; and road construction costs from recent road capacity expansion works are used to estimate the cost of increasing the capacity of a road to cater for increases in demand.

While we have addressed congestion as an external impact, it is in fact one component of the marginal cost of road transport alongside the road wear cost, which is covered in a separate paper.

In their paper “Costs of Congestion Reappraised” Wallis and Lupton estimated the costs associated with trip re-timing and calculated these to be 60-70% of the direct delay costs. Similarly, a recent NZIER (NZIER 2017) study identified the cost of congestion as including many costs consequential upon congestion of the road network. We have not attempted to calculate these consequential costs, interpreting the scope of this paper as relating to the direct costs only.

1.5 Relationship to Transport Outcomes Framework

The purpose of the Transport Outcomes Framework (TOF) is to make it clear what government is aiming to achieve through the transport system. It identifies five outcome areas - Inclusive access, economic prosperity, healthy and safe people, environmental sustainability, and resilience and security – and a guiding principle of mode neutrality.

The DTCC outputs will contribute to the TOF primarily by providing a consistent method for estimating and reporting financial and economic costs and impacts by different modes and user types.

Working Paper B1 provides an overview of the TOF and how the DTCC topics are expected to contribute. The two TOF outcomes most impacted by congestion are: **Economic prosperity (***Supporting economic activity via local, regional and international connections, with efficient movements of people and products); and* **Inclusive access** *(Enabling all people to participate in society through access to social and economic opportunities, such as work, education and healthcare)*

Chapter 2 Methodology

2.1 Approach

Road congestion is a phenomenon where the demand for road infrastructure exceeds its capacity. Similar situations occur for other modes of transport and are dealt with in various ways (e.g. with high peak and discounted off-peak fares for airlines). These are discussed in other technical papers as appropriate. Road congestion is different, at least in New Zealand, in that no pricing mechanism is currently used to manage demand. Motorists in New Zealand make no monetary payment for their travel's contribution to road congestion and there is no clearly defined financial 'cost'. However, the cost to society (including the user) created by use of a congested road is readily discernible in the form of lengthened travel times. The short run marginal cost is thus the externality – increased travel times – due to the marginal vehicle - referred to in the literature as the social marginal cost (SMC)[6].

The long-term effect of increasing demand on an already congested road is the cost to the road agency of increasing capacity either by road widening, building new roads in the corridor or by providing subsidised alternatives.

It is possible to derive the social marginal cost on a road section by using the travel time and the free flow time to calculate the elasticity of speed with respect to traffic density[7] (Yang et al 2019). The general result is:

$E = \mu\varepsilon t$

where E is the congestion externality

t = travel time
ε = travel time elasticity
μ = value of time.

The elasticity ε can be approximated by

$$\varepsilon = t_c / \mathrm{t} . (\mathrm{t} - t_f / (t_c - \mathrm{t})$$

t_f = free-flow travel time
t_c = travel time when the road is at capacity.

While the formulation in terms of elasticity provides a suitable theoretical framework, estimation of the elasticity requires knowledge of the underlying relationships between travel demand, density and speeds. Previous analysis of congestion in New Zealand (Wallis and Lupton 2013, Wallis et al 2014) suggested that it should be possible to represent the relationship between travel time and demand by a BPR function[8]. In this case the elasticity can be calculated as

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[6] The SMC is often defined to include the travel time of the marginal vehicle. In this analysis we are only interested in the externality – the cost imposed on others.

[7] Sometimes incorrectly called the elasticity with respect to flow. The elasticity with respect to density is a useful concept even when demand exceeds capacity and thus the flow is decreasing

[8] Bureau of Public Roads (1964)

$$\varepsilon = \beta (t - t_f) / t$$

where t and t_f are as before and β is the power coefficient of the BPR function. The properties of the BPR function are discussed in Appendix 4.

We therefore proposed to use data on traffic volumes and speeds collected on a number of urban roads across both islands to see if we could fit a BPR function to the data. This would enable us to estimate the congestion externality by time of day by location.

The shape of the speed v flow curve reflects the behaviour of motorists. There are a number of formulae that attempt to explain the relationship, but the reality will always differ from the formula due to random events (a motorist getting distracted, a learner driver driving too slowly, etc). Provided the formula used replicates the shape of the observed pattern of behaviour it should be able to be used to estimate the typical impact on traffic speeds of a change in demand and thus estimate the congestion externality due to the marginal vehicle.

In most cases, a BPR function (interpreted as described in Appendix 4) provides a satisfactory fit to the observed data and relates traffic speeds to vehicle density on the road. In some low traffic urban situations, the observed trips formed a completely different pattern and a hyperbolic shaped function was required to fit the data. It would appear that the hyperbolic function arises due to the effect of side friction and delay at signalised intersections, in which case, the relationship is probably not strictly causal, rather that the higher levels of pedestrian and other activities coincide with periods of higher traffic.

The marginal cost of congestion is highly site and time specific: the approach was to determine the methodology, but this does not give a single answer. However, having established the relationship between travel times and the congestion externality at the local level, it is possible to apply this relationship across a network to determine the average cost of congestion. Data from the Auckland, Wellington and Christchurch transport models was used to estimate the total cost and the average cost per kilometre in the three main urban areas. The results for Auckland were compared with those calculated in previous studies.

The congestion cost is a short run cost. The long run marginal cost is the cost of increasing the capacity of the road by one unit. Road construction involves lumpy investments so this concept has practical issues. Waka Kotahi provided data on the capital costs of recent road capacity increases: this was divided by the expected increase in peak period capacity in order to provide an estimated marginal cost.

2.2 Data sources and literature

Data Sources

Two sources of data were investigated for the road specific analysis: The main source of data used was GPS data available through Traffic-Congestion-info (TCi)[9]. TCi is collaborating with TomTom, a global leader in navigation, to make speed and travel time data available to New Zealand road authorities and their consultants. TomTom now has more than 10 years of speed

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[9] https://www.traffic-congestion-info.com/

data on roads throughout New Zealand. The TCi data provided speed and number of probes (GPS units from which data are collected) by time period for fifteen roads. Each location provided data for three separate points on the road in each direction. Data was extracted for a ten-week period during the third school term of 2019.

Only a relatively small proportion of vehicles have GPS software installed and operating. While the TCi data provides good information on vehicle speeds and sufficient data to derive t_c and t_f and thus calculate the congestion externality by location and time period, they do not provide the actual traffic volume.

Waka Kotahi collects traffic volume data at a large number of locations but only collect speed data at a small subset of these. Waka Kotahi counts were compared with the number of probes counted in the TCi data, enabling us to convert the speed vs #probes result to speed vs volume. The comparison of Waka Kotahi traffic count to #probes was able to be made at four locations and is reported in Annex F. In almost all cases the relationship between the two measures is basically linear, confirming that the percentage of vehicles with GPS does not vary significantly by time of day. The only exceptions were the results for the Queenstown-Frankton road in the vicinity of Queenstown where the ‘scatter’ of the points is more marked. It is likely that this is due to a varying proportion of tourist vehicles in the traffic stream throughout the day.

For the cost of congestion analysis, we used data from the Auckland, Wellington and Christchurch transport models. Matrices for peak travel times distances and volumes were provided along with a matrix of travel times obtained by assigning only 5% of the peak traffic. These data enable two measures to be calculated: the average congestion externality cost, which is calculated by comparing the total travel time in congested conditions with the total travel time in free-flow conditions and the cost of congestion which is calculated by comparing the cost in congested conditions with the cost when the network is operating at capacity.

Another approach we considered was to use mobile phone network data to track trips through an urban network to develop a fine-grained map of where congestion is occurring and relate this to the number of vehicles attempting to travel at that time. This option would have provided a more accurate measure of the actual times and volumes but was not pursued due to the high cost of the data. It has potential for future work particularly if the transport planning agencies in each centre purchase the data for their own planning purposes.

Long run marginal costs were based on data from Waka Kotahi/NZ Transport Agency for recent capacity enhancements in the main cities.

In all cases we estimated the costs in relation to vehicle-kilometres. The reason for this is that most policy questions revolve around the impact of more or less vehicles on the road. Costs per person-kilometre can be derived using average occupancy but often the policy seeks to change this (e.g. ride sharing) so that an assumed occupancy would be unhelpful.

2.3 Literature

Marginal costs and congestion charges

There is a large volume of literature on the subject of calculating the congestion externality, mostly in relation to optimum congestion charging. The economist’s rule for congestion pricing is to price equal to the externality. The basic principles, including an understanding of the fundamental diagram of traffic whereby too many vehicles attempting to use a road actually reduce it’s carrying capacity, have been known for many years (e.g., Greenshields 1935). This is a short run marginal cost concept – it varies by time of day and its purpose is to ensure that the existing infrastructure is used efficiently. Most transport economists, following Walters (1961), have approached determining the optimum from the point of view of the marginal social cost. Under this approach, the optimum price is achieved by setting the toll equal to the additional social cost due to the marginal vehicle. The optimum toll can thus be calculated as the equilibrium price where the demand curve meets the marginal social cost curve[10].

Papers on congestion pricing based on this idea include papers by Small (2001), Verhoef (1997), Hau (1972), and many others. These all are based on the same basic idea that the cost faced by the motorist should equal the social marginal cost. The problem has been how to calculate it and how to charge it. For example, de Palma and Lindsey (2009), list problems in determining the optimum charge including: *"… that traffic flows vary greatly by time of day, day of week, and season. Congestion tolls should therefore vary over time as well. Formulating a dynamic system optimum on a road network, deriving tolls that support the optimum, and solving the system of equations numerically remains a challenge despite many years of research* ".

Note on the BPR function

Li (2002) states that the BPR function is unsuitable for congestion analysis as it does not have the necessary backward-bending property. This is correct if one interprets the volume (Q) in the BPR function as the observed flow. If however, as proposed by Gwilliam[11], the underlying relationship is assumed to be between traffic density and speed, with the initial density assumed to be proportional to the exogenous demand, then the function has all the correct properties as identified by Li. Calculating the flow as Q. t_c/t where t_c is the travel time at capacity and plotting the curve in the time vs flow space gives the appropriate backward-bending function.

An alternative to the BPR formulation, quoted by Li (2002) as used in Singapore, is the generalised Drake model (Drake 1967) which can be written:

$q = K_c/t\ (\delta \ln(t/t_f))\hat{}(1/\delta)$

where q = flow, K_c = density at capacity, t=time and t_f is free flow time. δ is a parameter

It can be shown that by an appropriate selection of δ and β, the BPR and Drake functions give a similar fit over observed speeds and flows. The congestion externality based on Drake is $v\ t\ \delta\ (\ln(t) - \ln(t_f))$ where v is the value of time. This would be easy to implement technically but does not have the mathematical tractability and intuitive appeal of the BPR version. Since the degree of fit is similar, we have used BPR.

2.3 Measuring congestion on the road

Analysis of the data

In order to explore the relationship between speed and flow, data on traffic speeds and volume by time of day were obtained and plotted. To illustrate, we used data for Wellington's Petone

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[10] In theory the social cost could be interpreted to include carbon dioxide production, etc. but in this paper, we will only be concerned with the impact on travel times.

[11] Ken Gwilliam, private correspondence.

Esplanade (eastbound) in the following discussion. The analysis started with a download from Tom Tom for each of fifteen example roads. The download in each case was similar to Table 2.1.

Tom Tom data only include vehicles using the Tom Tom navigation software. Thus while the data provide a reliable measure of the traffic speeds, they are only a proxy for the actual volumes. The Tom Tom data used are for 10 weeks (weekday only) during term 3 of 2019. The figure '#probes" is the total number of devices tracked over the 10 week period, while the speed is the average speed in the time period during the 10 weeks. The speed limit in this case is 50km/h.

Table 2.1 Data for Petone Esplanade Eastbound. (Typical weekday during 10 weeks of Term 3, 2019)

	Te Puni St - Victoria St		near Buick St)		near Jessie St	
TIME interval	**Speed (km/h)**	**# probes**	**Speed (km/h)**	**# probes**	**Speed (km/h)**	**# probes**
0400-0500	50.0	113	50.0	103	49.7	101
0500-0600	50.0	246	50.0	223	48.9	233
0600-0630	49.1	326	48.9	303	47.3	310
0630-0700	46.9	563	47.3	575	45.5	562
0700-0730	43.2	668	45.6	663	43.4	672
0730-0800	40.3	813	44.3	766	43.0	793
0800-0830	40.5	823	43.9	829	42.8	833
0830-0900	40.1	955	42.9	941	41.8	935
0900-1000	41.8	1681	43.3	1664	42.4	1726
1000-1100	41.4	1609	42.2	1633	41.4	1699
1100-1200	40.1	1725	40.1	1766	41.0	1664
1200-1300	36.7	1780	36.4	1947	40.1	1945
1300-1400	37.8	1677	36.3	1818	39.3	1907
1400-1500	36.9	1750	34.7	1829	38.9	1840
1500-1600	35.6	1868	32.5	1940	35.8	1910
1600-1630	32.3	862	28.2	891	34.0	948
1630-1700	28.8	772	25.5	833	30.2	861
1700-1730	30.6	761	25.8	840	29.1	889
1730-1800	38.8	912	34.4	975	35.7	1000
1800-1830	43.9	880	42.1	958	40.7	902
1830-1900	46.7	800	44.7	893	43.0	787
1900-2000	47.9	1250	46.6	1371	44.3	1373
2000-2100	48.8	923	47.3	1040	45.6	1057
2100-2200	84.1	15912	47.4	920	46.0	925

Plotting the data

From Table 2.1 we plotted the speed vs time of day as shown in Figure 2. 1 This shows that the speed reduces gradually during the day and is lowest during the evening peak period after which speeds return to close to the speed limit.

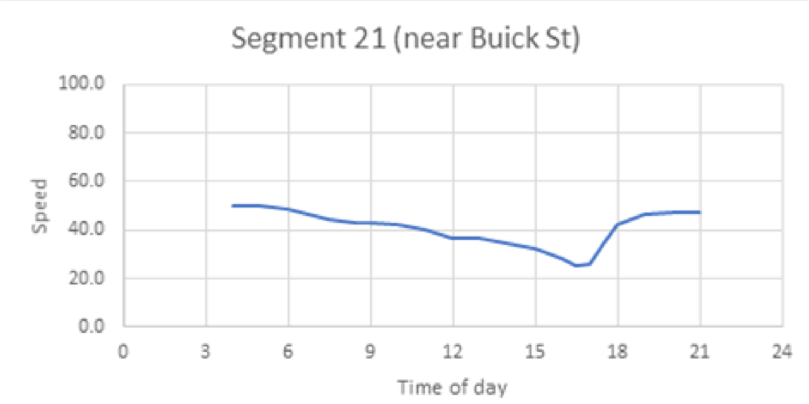

Figure 2. 1 Speed by time of day

The speed graph can be understood in the context of the demand and flow on the road during the day. In Figure 2.2 the y axis is the number of probes recorded by Tom Tom. The demand has been estimated assuming that the density of probes at any time is a close proxy for the demand. This will be the case except in extreme hyper-congestion. The demand per hour is thus estimated as demand = flow /speed * speed at capacity. It is less than the flow when traffic flow is intermittent, with gaps between groups of vehicles and equal to flow at capacity.

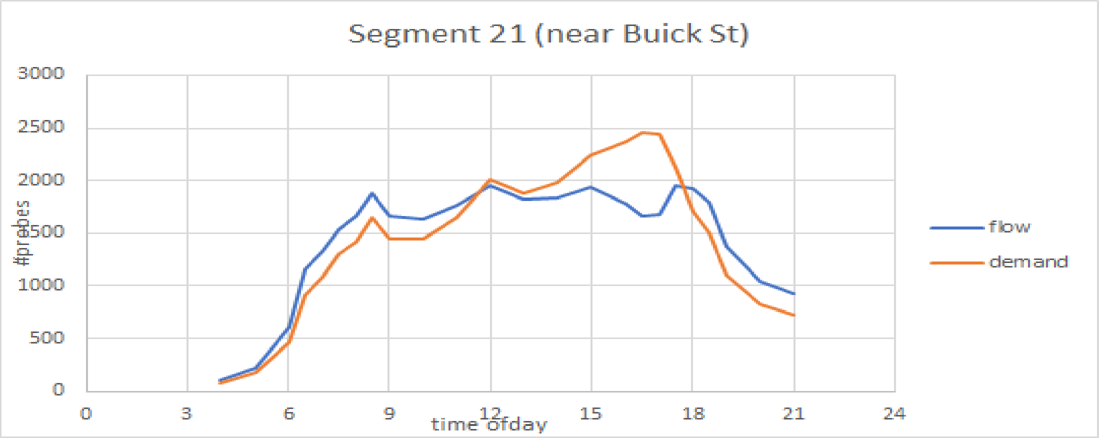

Figure 2. 2 Demand and flow by time of day

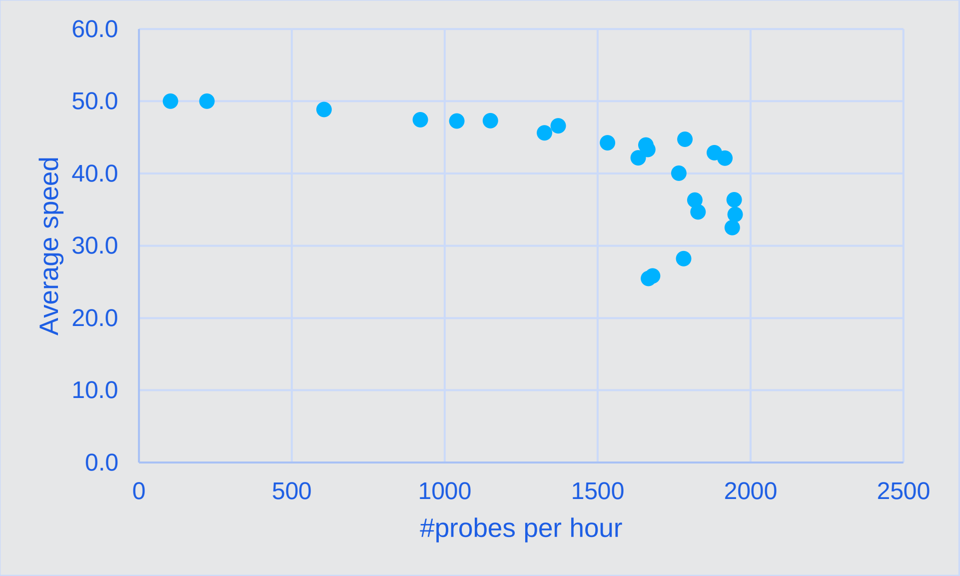

Figure 2. 3 Speed vs #probes per hour

The number of probes will represent the actual traffic level on the road provided the proportion of vehicles with GPS navigation is constant across the day. In Appendix 4 we compare the probe data with Waka Kotahi counts and show that there is a strong linear relationship between the two measures although the slope of the line (i.e. the sample factor) varies between sites.

Figure 2. 3 combines these data in a graph of speed vs #probes. This displays a classical “backward bending” curve with an implied maximum flow of 2000 probes per hour. The figure also displays the commonly observed phenomenon of a flow breakdown zone in the vicinity of the peak flow. The maximum flow achieved on any one day varies, the flow sometimes breaking early, and sometimes becoming “supersaturated” before dropping into the hyper-congested section of the curve.

We fitted a BPR function to this curve. The BPR function is of the form:

$t = t_0 + t_0 \alpha (Q/K)^\wedge\beta$

where t_0 is the travel time in free-flow conditions
Q is demand
K is capacity, and
α, β are coefficients.

In the BPR function, time t is linearly increasing with demand Q and thus a speed vs Q curve based on the BPR formula would be linearly decreasing and would not exhibit the backward bending phenomenon.

The backward bending phenomenon occurs because we observe the flow, not the demand. When demand exceeds capacity, increasing demand results in decreasing flow. Noting that except under severe hyper-congestion, the demand for travel will be closely represented by the traffic density, we can use the relationship between density and flow to write $Q \propto Ft$. Substituting this in the BPR function and setting α=0.33, β=4 and K = 1900 gives the curve shown in Figure 2. 4.

Comparing the observed speeds with the predicted speeds for Petone Esplanade, the standard error is 0.006 and the R^2 is 0.999.

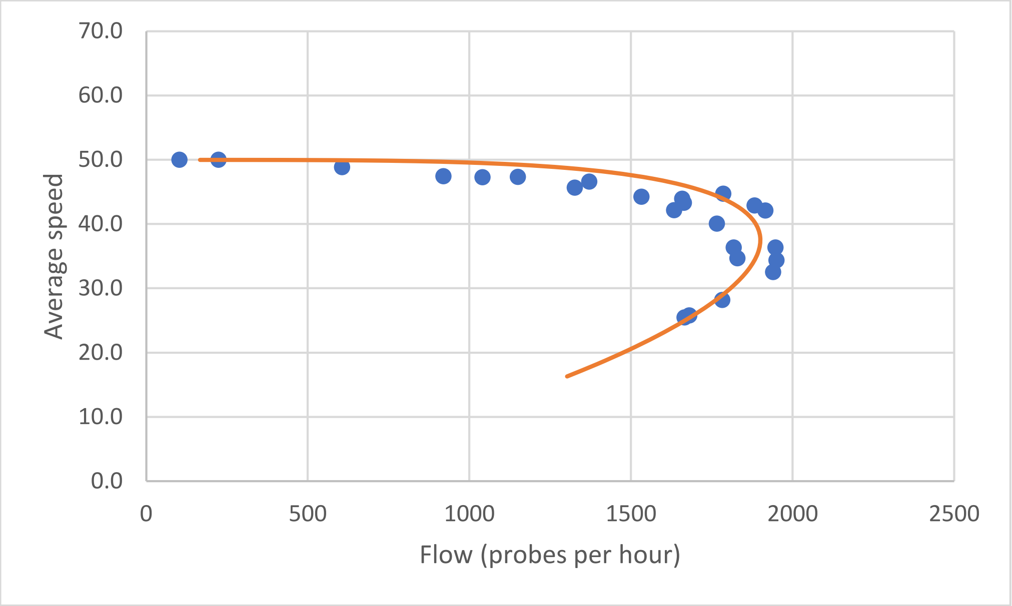

Figure 2. 4 speed vs flow showing BPR function

Estimating the congestion externality

As shown in Appendix 4, one of the properties of the BPR function is the simple formula for the congestion externality:

$E\mu = E * \mu = \mu\ \beta(t - t_0)$,

where μ = value of time; Eμ = congestion externality expressed in dollars.

Using this formula and quoting the externality in minutes, the externality by time of day measured in minutes per kilometre is shown in Figure 2.5. It can be seen that the externality is equal to around 0.7 minutes per kilometre in the am peak, rises to around two minutes in the middle of the day and reaches 4.5 minutes in the evening peak. The standard error is small at 0.0002 minutes, but the value of time cannot be known to anything like this degree of accuracy. We discuss the value of time in later sections.

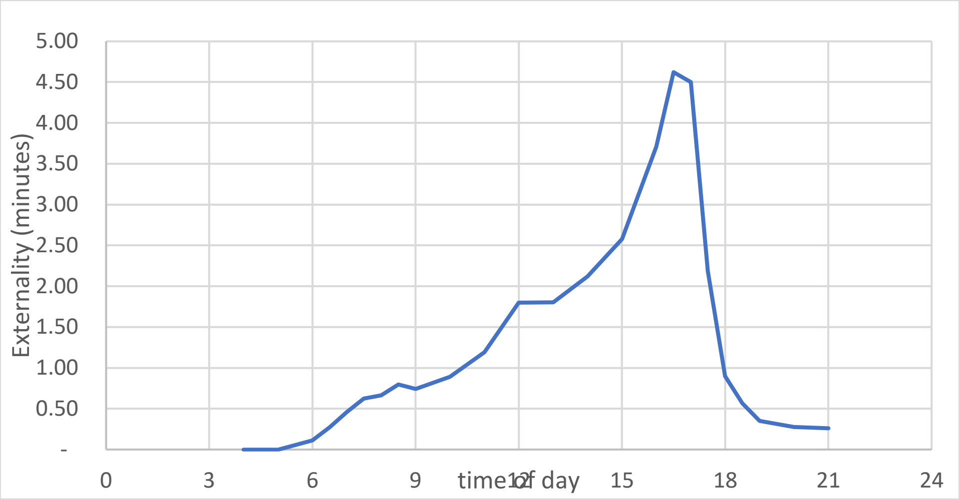

Figure 2. 5 Externality by time of day

Averaging and interpretation of data

All the graphs of observed data exhibit a degree of randomness, particularly in the region where the demand is near the road's capacity. Our analysis demonstrates that there are several effects at play.

Due to the limited coverage of the Waka Kotahi data, we have concentrated on using Tom Tom data for both the speeds and the counts (#probes). The #probes figure is the total number of records in each time period (hour or half hour during peak periods) during week days over ten weeks and the speeds are the average speeds in each time period. The graphs therefore compare average speeds with average number of observations in each period. Since the relationship between speeds and counts is non-linear, the average of the speeds is not the same as the speed associated with the average count. This will introduce errors in the observations.

To better understand the problem, we used Waka Kotahi counts and Tom Tom speeds for the same day for each day over a 10-day period for one location. The results are shown in Figure 2. 6. The sum of all observations is centre of the bottom row. It can be seen that the pattern is similar every day, but the point at which flow breakdown occurs and the observations switch to the hyper-congested (lower) section of the curve varies from day to day. Nevertheless, the envelope within which all observations fall is well defined.

The bottom right-hand graph tracks the sequence of the observations on one particular day. The observation that falls well inside the envelope occurs between the morning peak and midday and could well be simply the result of averaging.

We conclude that, while the theoretical framework seems to be well supported, application of a theoretical model to externally set values of time would be prone to errors that could be significant with heavily congested states as there is inherent variability. There is a strong body of evidence to suggest that capacity itself is a stochastic variable and is best described by a distribution with variability from day-to-day rather than a point on a graph. The resolution of this problem comes from the estimation of the value of time, which, following the Singapore approach, needs to be based on observation at the site rather than being externally set. The inherent variability is then subsumed within the calculation of the value of time. This is discussed further in Chapter 2.6.

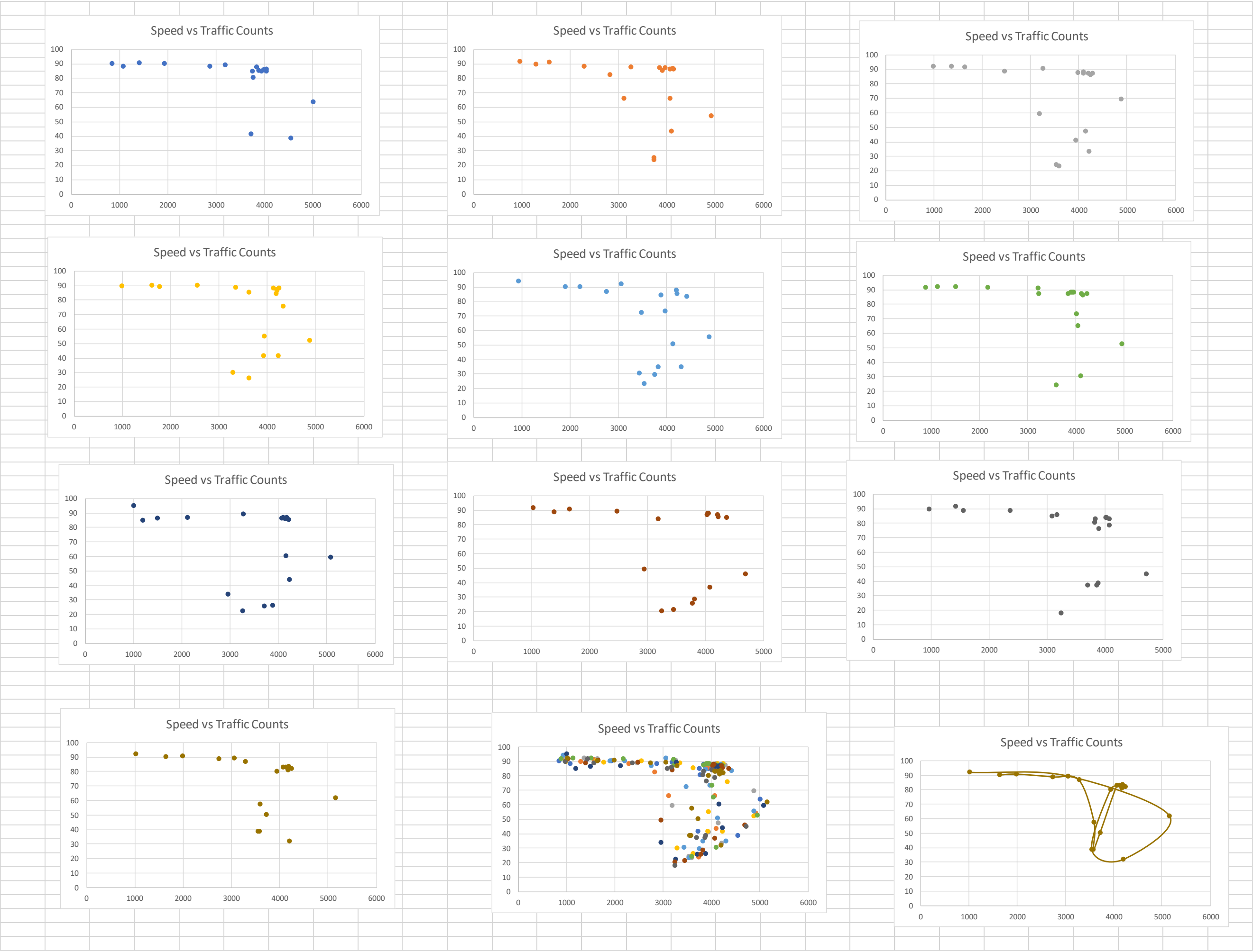

Figure 2. 6 Speed and Flow -daily observations over 10 days

Analysis of exceptions

While the approach described in the last chapter worked for the majority of the sites studied there were a number of important exceptions. These are described in this section.

Legal speed limit

In a number of cases, the speed at capacity calculated from the BPR function is lower than the speed required to align the demand curve with the observed flows. We postulate that the reason is likely to be that the “free flow” speed used in the BPR function is artificially depressed by the legal speed limit. This suggests that the speed flow relationship should actually be of the form:

Speed = min (f(Q), L),

where f(Q) is the relationship between speed and demand, while L is the speed limit.

In practice speeds do fall with additional traffic even where clearly the unconstrained speed would be higher than the speed limit. Since we are interested in behaviour, we have used the observed free flow speed and calibrated the BPR function based on this.

Side friction and intersections

We included several urban arterials in the analysis. Some of these, such as Dominion Road in Auckland, exhibit significant speed reductions even when the volume of traffic is well below the theoretical capacity of the road. In these cases, the observed speed vs flow relationship is concave whereas the form of the BPR function is convex in the normal part of the curve. We hypothesise that the speed reduction will be due to side friction and/or the presence of multiple intersections rather than interaction between vehicles, with the speed trending towards a limit that probably reflects the setting of the traffic lights along the route. A logarithmic function fits the observed points with R^2 values greater than 0.9. The logarithmic speed vs flow function could be used to determine the underlying speed vs demand function and this could, in turn, be differentiated to give a value for Qdt/dQ. However, while Dominion Road northbound is best described by a logarithmic function which applies throughout the day, southbound shows evidence of both side friction and interaction between vehicles. Speeds at Dexter Avenue drop from 50 km/h to 40 km/h between 4am and 8am but subsequently are best described by a BPR pattern with “free speed” equal to 40 km/h (Figure 2. 7).

Since the initial slowing of traffic is, in both directions, due to increasing pedestrian activity, cars parking, etc, the relationship between vehicle speeds and flow is not causal. We are only interested in the effect on speed due to increasing traffic demand. Figure 2. 7 suggests that this may best be determined by a BPR function with the “free speed” set to equal the speed during the inter-peak period. Those roads such as Fitzherbert Avenue in Palmerston North where the speed flow curve is entirely concave are so because the density of traffic is too low for the backward bending phenomenon to be apparent.

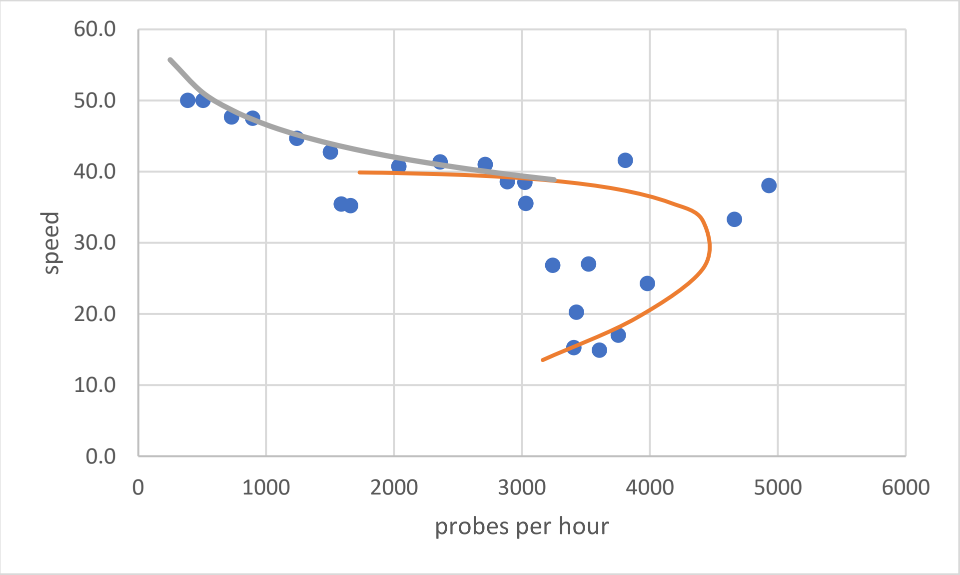

Figure 2. 7 Speed vs #Probes. Dexter Ave - Dominion Road Southbound

2.4 Total and average costs of congestion in three main cities

The previous chapter calculated the congestion externality over sections of specific roads. In each case calculations were undertaken for three locations within 1 – 2 kilometres of each other. It is apparent from the results that the congestion externality is very site-specific as well as time dependent. In order to get some measure of the overall average cost of congestion we need to look at entire journeys at a network level. In this chapter we look at the total cost of congestion in the three main cities and relate it to distance travelled to give an average congestion cost and an average congestion externality. We still (mostly for data availability reasons) distinguish broadly by time of day.

Measures estimated

Estimates of the free-flow and congested travel times were obtained for Auckland, Wellington and Christchurch from the regional transport models maintained in each centre. These data were used to calculate three related but distinct measures:

- By taking the difference between the am peak travel times and the free-flow travel times (obtained by assigning a uniform 5% of the total matrix) we were able to calculate the total delays and the average delay per kilometre due to interaction between vehicles.
- The congestion externality due to each vehicle is equal to four times the travel time difference calculated above multiplied by the value of time[12].
- The Hansen accessibility of each destination zone and the change in ranking of zones due to congestion.

To calculate the total delay, the time differences were calculated for each zone pair and multiplied by the number of trips between them. The total delay figure compares travel times with free-flow times to give a measure of the average cost imposed by vehicles traveling in the peak.

Welfare economics suggests that making individuals aware of and meeting the cost they impose on others would result in an efficient level of demand. In this case, the external cost of congestion is associated with the time cost of delays. While it is highly unlikely that travel patterns would remain unchanged, estimates of the external cost of congestion could be the starting point for further analysis based on elasticities.

To illustrate, we calculated the average congestion externality for all trips with destinations within the CBD cordon proposed in “The Congestion Question” report (Figure 2.8 – Auckland Policy Group, 2020). This is the SRMC for vehicles currently crossing the cordon in the morning peak and represents the social cost saving per vehicle dissuaded from crossing or persuaded to travel at a different time or by a different mode. For a fixed cordon charge, we estimated the equilibrium value if a flexible charge were introduced.by using the engineering result that the

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[12] That is $E\mu = = E^* \mu = \mu \beta (t-t_0)$ as derived in Appendix 4. The best fit is obtained when $\beta = 4$.

delay to all other vehicles (i.e. the congestion externality) is equal to the travel time at capacity.[13]

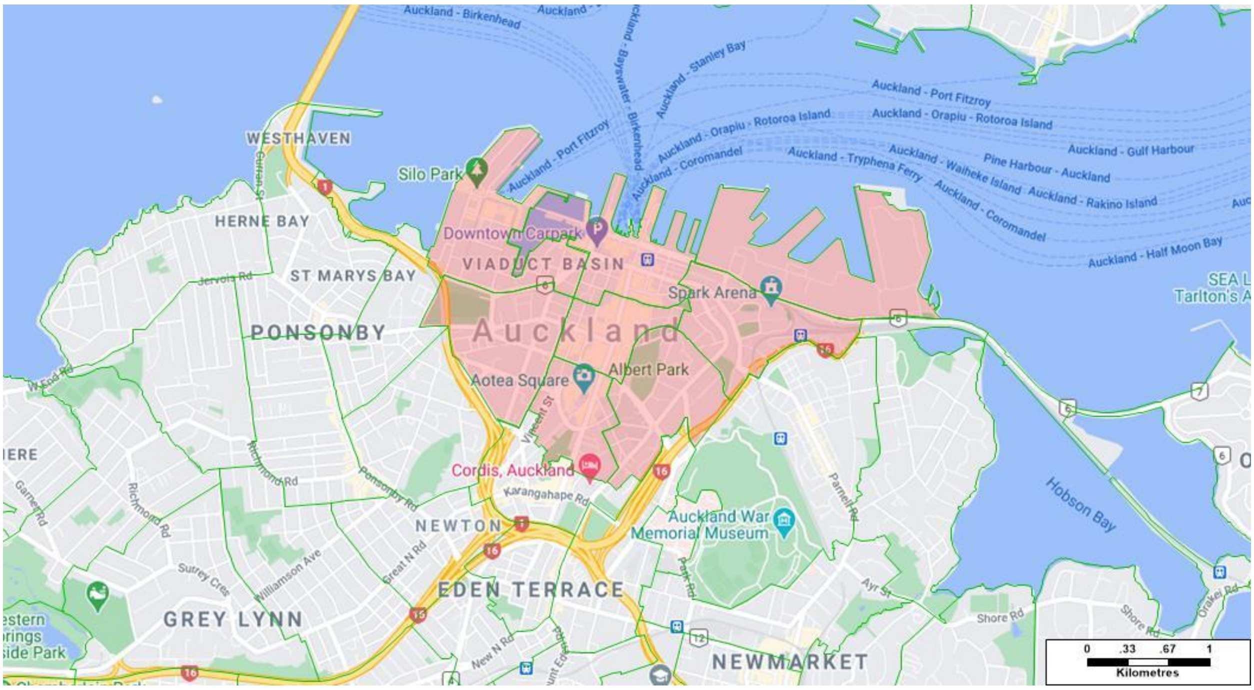

Figure 2. 8 CBD zone proposed for Auckland

Cities thrive because they are efficient labour markets (Bertaud 2014). They maximise the availability of labour for firms and the choice of employment, shopping and entertainment for people. Most cities form around a centre. This maximises the inherent benefits. Firms that occupy the centre benefit the most and land values there are consequentially highest. Congestion disrupts the relationship between location and benefit. We use a simplified form of Hansen measure to calculate the accessibility of each zone as:

$$Aj = \Sigma Si/cij,$$

where A_j is a measure of accessibility, S_i is the trip generation from zone i, and c_{ij} is the travel impedance between i and j. The larger A_j the lower the total cost of getting to zone j and thus for a business situated in j, the more people it has to choose from for workers and/or the more customers for its wares. Note that the value of A_j is totally independent of the characteristics of the zone.

The effect of congestion is to increase c_{ij} and this warps the time vs distance plane, increasing the relative attractiveness of non-central locations. We ranked the zones in each city both under free-flow and congested speeds and plotted the difference to show the impact of congestion on location attractiveness. The effect is most noticeable for Auckland but is also present for Wellington and Christchurch.

We considered using the result derived in Chapter 2.3 to calculate the travel time at capacity in order to calculate the total cost of congestion as defined by Wallis and Lupton (2013). The cost

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[13] At capacity, flow = $(Q + dQ)/(t + dt) = Q/t$. Hence $t = Q\, dt/dQ$.

of congestion figure compares travel times with a situation where all links are operating at capacity – i.e. only recognising congestion in the lower segment of the speed-flow curve. This is a more useful measure for policy analysis as it compares the current situation with what could physically be achieved considering the designed capacity through travel demand management measures such as dynamic road pricing, cordon charges, parking restrictions, ramp metering etc.

However, in calculating the measure used in that study, the fact that some roads are not congested was taken into account by setting the ‘speed at capacity’ on uncongested links at the observed speed (i.e. higher than the speed that would apply if the road was at capacity). This would have required special runs of the transport model, which was not considered necessary for the current study.

Comparison with previous total cost of congestion estimates

An estimate of the total cost of congestion was undertaken in 2013 by Wallis and Lupton. That study also used the Auckland regional model to provide estimates of travel volumes and times. However, a different technique was used to estimate the travel time at capacity involving undertaking additional model runs. Furthermore, the model network has been updated since that time. We were therefore unable to fully replicate the 2013 study. However, we were able to recalculate the cost based on the current value of travel time savings to provide a comparison between the figure obtained in 2013 (but based on a 2006 network) and the current estimate based on a 2018 network. We also provide an estimate of the annual cost of congestion for Wellington and Christchurch.

The Wallis and Lupton paper also included schedule delay costs, vehicle operating costs, environmental costs and road accident costs. The effect of including these was to double the direct cost estimated from actual travel. A more recent study for Auckland by NZIER (NZIER 2017) also considered the impacts beyond the direct time savings to freight operators and commuters. Their calculation considers the benefits to the wider community, giving an estimate between $0.9 and $1.3 billion in 2016 prices. There is a real danger in analysis of this nature that benefits will be double-counted. In this paper we estimate the direct delay costs and note that the effect of schedule delay costs and other consequential costs may increase the eventual cost to society from congestion.

Use of telco data

While transport modelling data will no doubt give a reasonable estimate of the free-flow and congested flow travel times, in some senses it begs the question. The congested travel times are calculated in the model using speed-flow formula that relate travel time to the volume/capacity ratio. The Auckland model uses an Akçelik function that can be shown to give very similar results to a BPR function. Our results could be criticised as being a reflection of the situation the modellers believed to be the case rather than what is really happening.

As an alternative to using model data, we did consider using mobile phone network data to track the movement of vehicles through the day. This could be used to record the average travel times between pairs of zones in the network by time of day in a similar way to the use of Tom Tom data and would enable the free-flow, peak-flow and congested flow times to be determined accurately. This approach could usefully be investigated further in the future.

2.5 Long run marginal costs

The long run marginal cost (LRMC) is the cost of expanding road capacity such that the existing traffic is not slowed by the marginal vehicle. Whether this cost is in fact incurred depends on the will of government to do something about it, but this depends on a number of policy and analysis considerations including whether capacity expansion is a realistic option.

We made an approximate estimate of the LRMC from the costs of recent contracts for road widening and construction in the main cities. If we assume that the new construction is primarily to provide additional peak capacity, that the peak lasts 2.5 hours on average, and a lane carries 1800pcu per hour, we can calculate the construction cost per additional passenger car unit (pcu) capacity.

Details of a sample of in the order of 15 -20 NZ state highway schemes which were either completed within the last 10 years or so, or are currently under construction or in an advanced state of planning, were requested from Waka Kotahi. Candidates schemes were requested that:

(1) are in urban or semi-urban (rather than rural) areas; and generally, in or in the vicinity of the main urban areas (principally Auckland, Hamilton, Tauranga, Wellington and Christchurch;

(2) focus primarily on providing significant increases in traffic capacity, and involving either new roads or substantial capacity improvements to existing roads;

(3) involve capital expenditures of at least $100 million (in current prices);

(4) generally exclude ‘abnormal’ schemes having either particularly high costs (e.g. involving substantial tunnelling or elevated sections) or particularly low costs. [14]

Waka Kotahi supplied data on 21 schemes with a combined cost of $7.55 billion. These would provide some 395 additional lane km, resulting in an average unit cost of $19.1 million/lane km. Excluding schemes that were categorised as ‘abnormal’ in cost terms (as they have particularly high costs as a result of substantial tunnelling or elevated sections), left 12 ‘normal’ schemes for further analysis. These 12 ‘normal’ schemes have a total cost of some $4.71 billion for 334 lane kms or $14.1 million per lane-kilometre. Regressing costs against lane kilometres gives an estimated cost per kilometre of $9.8 million/lane km with a regression coefficient (r^2) of 0.57 and a standard error of $2.5 million. However, as the cost of the Canterbury schemes is significantly lower than the others, this average may better be disaggregated as $6m/lane-km for Canterbury and $23m/lane-km for Auckland, Wellington and the Waikato.

The average cost over the twelve projects is $20 per pcu-km year[15], or annualising the capital cost at 10%, is equal to $2 per pcu-km. The figures by main centre are $0.80 per pcu-km for Canterbury, $3.10 for Auckland and $3.20 for Wellington and Waikato.

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[14] Waka Kotahi found that this last requirement excluded a substantial proportion of (otherwise) candidate schemes. Therefore, in practice, a number of schemes were included in the sample that did not meet this criterion (mainly through having particularly high costs relative to the additional lane kilometres provided).

[15] Based on 3500 pcu per peak period

There is a conceptual problem in applying this rule to roads on which traffic flows are peaked in nature. Since capacity is primarily required for the peak, we have calculated the marginal costs for increases in the peak flows only – and calculated the capacity cost per unit of peak flow rather than for the all-day flow. The LRMC thus relates to peak travel only.

The standard rule to determine whether infrastructure investment is optimal (see for example Turvey 1968) is that the short-run marginal cost (SRMC), which is the cost imposed by the marginal user without adjusting capacity, must equal the long-run marginal cost (LRMC), which is the cost of adjusting capacity for the marginal user. It is optimal because, if the SRMC was higher than the cost of adding capacity, adding more capacity would reduce the net cost (and vice versa). Our analysis suggests that while overall SRMC is less than LRMC, there are situations in Auckland where the SRMC does exceed the LRMC and thus capacity expansion could be justified in economic terms.

Note that the analysis is at an abstract level. A real network contains many links each with different demands. Practical considerations limit the design opportunities – investments are lumpy and often indivisible. Actual investment decisions must be based on cost–benefit analysis, which can take these and other factors into account.

Table 2.2 Cost of NZ major road improvement schemes

Waka Kotahi region	Project name	Opening year	Scheme length (km)	# lanes - before	# lanes -after	Incr lane km (IWA)	Grade-sep junctions	Tot Cost $mill	Cost/lane km $mill	Existing (E) or New (N) route
Auckland	Southern Corridor Improvements	2021	9	2	3	**9**	**1**	**327.7**	**36.4**	**E**
Auckland	Manukau Hbour. Xing	2010	5	4	8	**20**	**4**	**274.6**	**13.7**	**E**
Auckland	Mt Roskill Extension	2009	4.5	0	4	**18**	**2**	**246.4**	**13.7**	**N**
Auckland	Northern Corridor Improvements (NCI)	2024	7	6	10	**28**	**5**	**793.7**	**28.3**	**N**
Canterbury	CHCH Northern Arterial Rural with QE2	2021	15	0	4	**60**	**6**	**297.3**	**5.0**	**N**
Canterbury	CHCH Southern Motorway HJR to Rolleston (Stage 2 & 3)	2021	20	0	4	**80**	**8**	**379.2**	**4.7**	**N**
Canterbury	Harewood Rd to Yaldhurst Rd 4 Laning	2019	4.9	2	4	**9.8**	**2**	**137.4**	**14.0**	**E**
Canterbury	Western Belfast By-Pass	2017	5	0	4	**20**	**3**	**174.6**	**8.7**	**N**
Waikato	SH1 Wex Hamilton Section	2021	22	3	4	**22**	**5**	**721.0**	**32.8**	**N**
Waikato	Te Rapa Section	2012	6	2	3	**6**	**3**	**160.3**	**26.7**	**N**
Wellington	Wellington RoNS (6) - SH1 Mackays to Peka Peka Expressway	2021	18	2	4	**36**	**4**	**744.7**	**20.7**	**N**
Wellington	Wellington RoNS (7) - SH1 Peka Peka to Otaki Expressway	2022	12.5	2	4	**25**	**2**	**449.4**	**18.0**	**N**
Total			**128.9**			**333.8**	**45**	**4706.4**	**14.1**	

Source Waka Kotahi/ consultant estimates

2.6 Value of time

A key variable in the estimation of congestion costs is the value of time: as the congestion externality is defined as $\mu\, Qdt/dQ$, (t=time, Q=demand) the answer is entirely dependent on the choice of the value of time µ. The problem is estimating its value. There are many different ways to establish the value of time, for example, based on average wage rates and average vehicle occupancy.

Evidence from the use of ‘value lanes’ in the USA imply that lane-users have very high values of time when calculated based on actual average travel time savings. This may be for a number of reasons including a high valuation of reliability rather than time or confirmation bias in the estimation of savings.

The approach now being adopted in Singapore (Li 2002) and for many of the value lanes in the USA is to circumvent the estimation problem by using the revealed estimate for the value of time. Thus, in Singapore, a target speed range is set: if speeds fall below the lower limit, the value of time must have been set too low, so the toll rate is raised. Conversely, if speeds exceed the upper limit, the toll rate is lowered. The toll reveals the value of time, it does not need to be known in advance. The revealed value is the aggregate value to all the occupants of the marginal vehicle, not just the driver.

We know from our analysis that the travel time vs demand curve can be approximated by a BPR function. Thus, the economic optimum condition is where the cost to users equals the congestion externality or $\mu Qdt/dQ = \mu\beta (t - t_0)$, *where t and Q are as before,* t_0 *is the free-flow time and* β *is the power coefficient of the BPR function.* The corresponding value of time is thus the value μ such that an additional cost of $\mu\beta (t - t_0)$ just results in all roads operating at or less than their capacity – where we identify roads operating at capacity by noting that (assuming a BPR function) the speed at capacity is $(\beta-1)/\beta$ times the free flow speed. In all our observations, the best fit for the BPR function is with $\beta = 4$, so that speed would be 75% of the free-flow speed.

Chapter 3 Results, commentary and conclusions

3.1 Results and commentary

Cost by location

We were able to estimate the average delay by time of day for a range of locations and from this calculate the short run marginal cost (i.e. the congestion externality) and the total cost of the congestion (i.e. that part of the cost that could be saved by operating the road at capacity) occurring at that site. Since all the costs are based on observed speeds but expressed in minutes or dollars (after applying a value of time), they are quoted as time or cost per vehicle kilometre since the occupancy may vary depending on whether and what intervention is considered. The congested conditions may extend more or less than one kilometre.

The results are shown graphically in Appendix 3 and summarised in Table 3.1, which summarises the speeds and costs at three locations on each road as follows:

- Free-flow speed is based on calibration of the BPR curve
- AM speed is the average speed between 8 and 8:30am
- IP speed is the average speed between 1pm and 2pm
- PM speed is the average speed between 5pm and 5:30pm
- Delay is the average delay (in minutes per kilometre) compared to free-flow
- Externality is the congestion externality cost in dollars per kilometre – i.e. the SRMC
- COC is the cost of congestion per year per kilometre at that location – i.e. the excess time cost due to the demand for the road exceeding its capacity.

The results are very site-specific, with the congestion externality ranging from zero (Waimakariri Bridge northbound) to $1.85/km (Dominion Road northbound) and the implied cost of congestion ranging up to $7 million per year per kilometre and averaging $1m per kilometre over the chosen sites. Some of the results may appear a little surprising - for example the low congestion externality attributed to State Highway 1 between Pukerua Bay and Paekakariki. This is likely due to bottlenecks that restrict the traffic flow at each end of this stretch and the 80km/h speed limit -- which mean that the free-flow speed and the speed at capacity are approximately the same.

Since the SRMC depends only on the traffic demand, the road capacity and free flow speed, there is no discernible distinction between urban and rural, vehicle type or road type other than that the free-flow speed on urban roads is usually lower and the presence of side friction or frequent intersections will affect the determination of the appropriate free speed to use.

The roads in Table 3.1 are listed separately by urban and state highway (with the Queenstown-Frankton road somewhere in between). The roads chosen are examples of urban and state highway roads that were chosen because they exhibited some form of congestion. They are not intended to be in any way representative of a class.

Table 3.1 Estimated congestion externality and cost of congestion at selected sites (3 locations per route section)

	Site 1 speeds				cost per kilometre			Site 2 speeds				cost per kilometre			Site 3 speeds				cost per kilometre		
	freeflow	AM	IP	PM	delay	externality	CoC	freeflow	AM	IP	PM	delay	externality	CoC	freeflow	AM	IP	PM	delay	externality	CoC
Urban roads (main cities)																					
Dominion Road, Auckland, heading N to CBD	25	12	20	14	0.89	1.85	2,766,688	25	12	20	14	0.70	1.45	2,173,176	35	24	26	29	0.36	0.75	1,474,931
Dominion Road, Auckland, heading S from CBD	25	25	22	19	0.22	0.45	675,482	40	25	22	19	0.47	0.97	1,313,109	25	10	17	11	1.46	3.03	2,929,269
Petone Esplanade from SH2 to Waione Street, heading E	50	40	38	31	0.32	0.66	455,888	50	40	38	31	0.37	0.77	556,824	45	42	39	29	0.19	0.39	287,138
Petone Esplanade from Waione Street to SH2, heading W	50	40	50	49	0.10	0.21	150,382	50	40	50	49	0.47	0.97	694,589	50	43	50	50	0.12	0.25	293,323
Memorial Ave from CBD to airport, Christchurch, heading W	50	41	49	30	0.15	0.31	434,928	40	41	49	30	0.29	0.61	866,054	30	27	23	21	0.39	0.81	1,034,567
Memorial Ave from airport to CBD, Christchurch, heading E	50	36	46	35	0.14	0.28	487,267	55	36	46	35	0.17	0.36	528,636	50	30	48	40	0.20	0.42	579,230
Road connecting Queenstown to Frankton, heading N	25	20	19	15	0.69	1.44	748,247	50	20	19	15	0.35	0.73	568,539	50	37	39	35	0.38	0.78	656,030
Road connecting Frankton to Queenstown, heading S	50	49	49	14	0.30	0.63	632,023	45	49	49	14	0.27	0.57	592,632	35	23	30	7	0.68	1.41	1,032,056
Urban roads (smaller cities)																					
Wanganui's Dublin St Bridge heading E from Dublin St to Jones St	45	39	39	35	0.21	0.43	69,438	45	39	39	35	0.17	0.36	58,920	35	29	31	24	0.30	0.63	101,890
Wanganui's Dublin St Bridge heading W from Jones St to Dublin St	40	9	35	35	0.47	0.98	146,208	45	9	35	35	0.54	1.12	167,162	40	7	26	31	0.91	1.89	277,316
Fitzherbert Avenue, Palmerston North, heading N from University to CBD	48	33	45	40	0.19	0.40	192,543	35	33	45	40	0.75	1.57	528,739	24	18	15	16	1.10	2.28	523,806
Fitzherbert Avenue, Palmerston North, heading N from University to CBD	25	19	23	22	0.28	0.59	167,239	30	19	23	22	0.51	1.06	329,597	30	26	30	25	0.09	0.19	80,582
State highway																					
SH1 Auckland Harbour Bridge to Takapuna, heading N	97	86	85	53	0.17	0.34	3,910,562	97	94	92	47	0.13	0.27	1,949,343	97	92	90	37	0.22	0.45	2,998,257
SH1 Takapuna to Auckland Harbour Bridge, heading S	98	31	94	90	0.36	0.75	4,925,456	100	31	94	90	0.46	0.95	7,040,561	92	71	83	34	0.29	0.60	5,571,821
SH1 @ Panama Road, heading N towards Auckland CBD	100	56	91	68	-	-	-	100	56	91	68	-	-	-	100	46	87	55	-	-	-
SH1 @ Panama Road, heading S away from Auckland CBD	95	85	85	66	0.11	0.23	1,666,406	95	85	85	66	0.07	0.16	1,129,800	100	89	89	69	0.11	0.23	1,716,293
SH1, Coastal Highway@Paekakariki, heading north from Wellington	75	70	70	56	0.12	0.24	203,003	80	70	70	56	0.08	0.17	144,362	80	74	73	57	0.12	0.26	216,106
SH1, Coastal Highway@Paekakariki, heading south to Wellington	75	75	75	73	0.01	0.02	20,224	80	75	75	73	0.08	0.17	144,362	75	73	72	70	0.04	0.09	82,579
SH2 from Ngauranga to Maungaraki, heading N	95	94	96	27	0.27	0.55	1,012,789	95	94	96	27	0.07	0.14	409,077	85	79	82	70	0.06	0.13	371,205
SH2 from Maungaraki to Ngauranga, heading S	95	81	97	95	0.28	0.59	714,168	75	81	97	95	0.34	0.70	1,233,423	95	60	93	72	0.12	0.26	766,521
SH1 @ Cobham Drive, Wellington, heading N from airport	40	15	42	35	0.28	0.57	1,535,042	40	15	42	35	0.16	0.33	1,151,014	40	6	36	25	1.19	2.47	5,954,541
SH1 @ Cobham Drive, Wellington, heading S towards airport	40	32	37	35	0.12	0.25	705,339	45	32	37	35	0.21	0.43	1,259,794	40	25	30	20	0.57	1.19	3,872,334
SH1, NE of Rolleston, heading north to Christchurch	73	67	67	68	0.08	0.16	83,178	80	67	67	68	0.04	0.09	59,008	-	73	72	69			
SH1, NE of Rolleston, heading north to Christchurch	90	68	69	68	0.20	0.42	239,890	100	68	69	68	0.23	0.48	277,380	85	63	63	63	0.24	0.50	303,285
SH1, Waimakariri Bridge, heading north from Christchurch	82	79	80	77	0.02	0.04	47,738	80	79	80	77	0.01	0.02	20,347	83	82	84	83	- 0.00	- 0.00	- 4,750
SH1, Waimakariri Bridge, heading south to Christchurch	96	95	95	97	0.08	0.18	228,903	89	95	95	97	0.10	0.20	334,645	88	84	86	87	0.04	0.08	135,717

Notes

Free-flow, AM, IP and PM are speeds at 4am, 8am, 1pm, and 5 pm

Delay is the delay in minutes per kilometre per vehicle relative to free flow

Externality is the average congestion externality cost (i.e. the SRMC) over one day.

The CoC is the annual avoidable congestion cost – i.e. based on the difference between the actual time and the time if the road were operating at capacity

The costs are averaged over 10 weeks. They thus measure recurrent congestion only.

Estimates of average and annual cost of congestion

Table 3.2 shows the estimates of the average congestion cost per kilometre and the total annual cost of congestion faced by motorists in the three largest urban areas: these were estimated as described earlier (Chapter 2.4) using the respective regional transport planning models: (note that these models reflect recurrent congestion only).

Table 3.2 Average congestion-related delays and costs

	AM peak trips	Free flow time (minutes)	Actual time (minutes)	Distance vehicle km (000)	Delay per AM peak $ (000)	AM Delay cost/km	Annual cost of delay	Annual Cost of Congestion
Auckland	543,500	6,164,000	9,366,500	5,776	$1,730	$0.31	$865 M	$400 M
Wellington	182,700	1,738,000	2,189,000	1,178	$243	$0.21	$122 M	$39 M
Christchurch	226,000	2,260,000	2,723,000	1,810	$250	$0.14	$125 M	$4 M

Note: Delay is calculated relative to free-flow while the cost of congestion is calculated relative to flow at capacity. While the total AM peak delay in Wellington and Christchurch is similar, a larger proportion of Wellington journeys are in hyper-congested conditions. Note that the Wellington Transport Model is different from the Christchurch Regional Model and that some of the difference may be due to the way each model treats heavily loaded roads.

Effect of congestion on accessibility

The effect of congestion can be seen in the case of Auckland by comparing the accessibility of the CBD (as measured by a Hansen index) between Figure 3. 1 and Figure 3. 2.

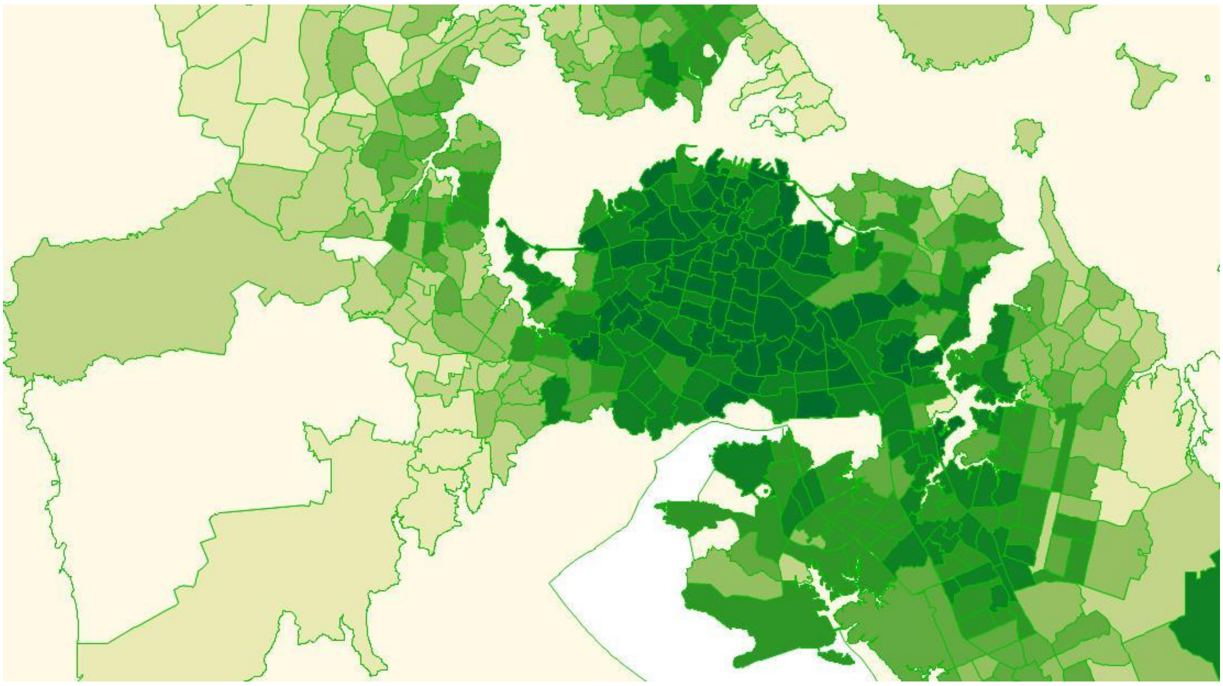

Figure 3. 1 Accessibility of destination zones

The Hansen measure (Hansen 1959) is simply the sum of the AM peak trip productions for each origin zone divided by the free-flow travel time. The higher the value the more accessible the zone, represented by a deeper shade of green. Note that the measure is independent of the characteristics of the zone itself. The index simply measures the attractiveness of the location.

In Figure 3. 1, the measure of separation is the free-flow travel time. It can be seen from the figure that the Auckland CBD is the prime position.

In Figure 3. 2 the measure of separation is the congested travel time in the AM peak. It can be seen that although the centre of the city is still attractive, the focus of maximum accessibility has moved South. This would tend to cause the centre of employment to move south, a response that can be observed in practice, with extensive light industrial employment in particular now concentrated in the southern suburbs.

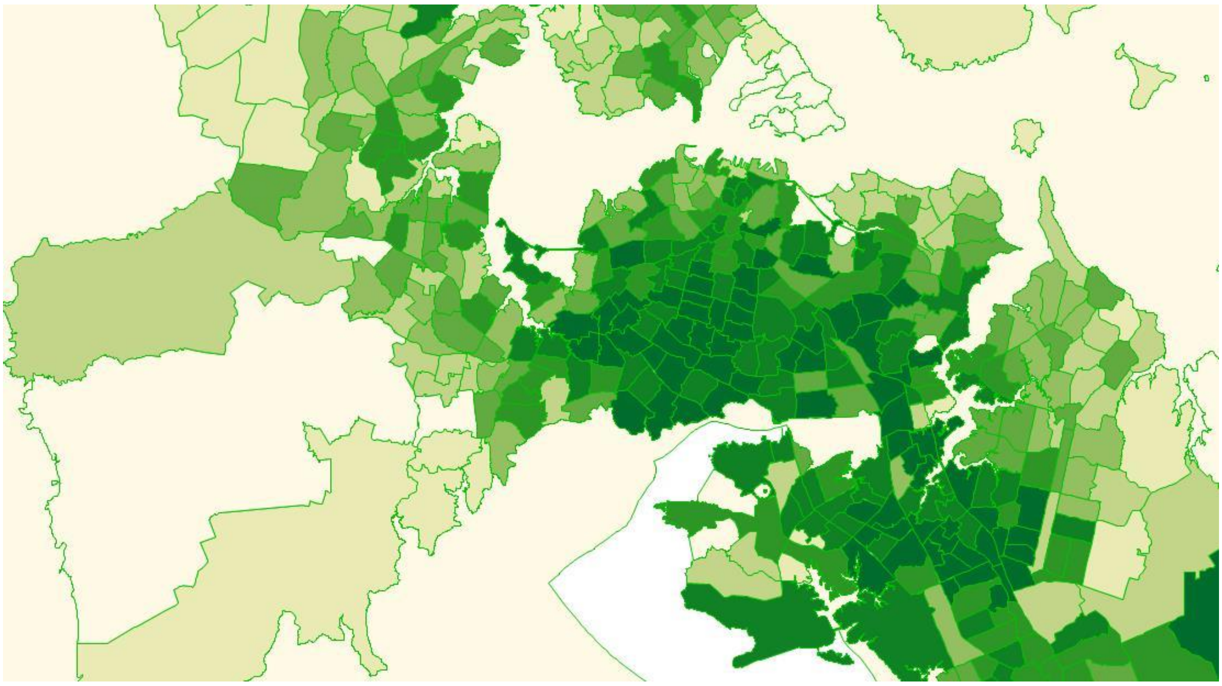

Figure 3. 2 Accessibility under morning peak congested conditions

Long run marginal costs

Road construction involves lumpy investments, so this concept has practical issues, but the theoretical result is simple – that the optimum network is where the short run and the long run costs are the same. This leads to the rule in an un-tolled network to expand capacity if the benefit:cost ratio is greater than 1.0. This is where the social marginal cost (SMC) exceeds the cost of expanding the capacity (LRMC) and in a tolled network to expand capacity if the toll revenue exceeds the cost of expansion - i.e. where the toll (set equal to the SMC) exceeds the cost of expansion (which is by definition the LRMC).

Implications for congestion pricing

The analysis shows that the congestion externality varies significantly by both location and time of day. Hence attempting to use pricing to influence demand is fraught with difficulty.

Until recently little other relevant data on values of travel time was available. In theory the value should be the value of time of the marginal driver at that specific place and time, which will be higher where the demand is high relative to the capacity of the road.

There are now a number of examples of variable toll systems internationally from which appropriate relationships could potentially be derived. However, a more promising approach would be to use the revealed preference approach to extract the value of time. This approach is used in Singapore for setting an optimal toll, that is to heuristically change the toll to achieve a target speed under the gantry. Whereas Singapore changes the toll rate on a periodic basis, the same approach is used by value lane operators to set tolls dynamically.

A cordon charge, will, like a stopped clock, only be right (briefly) twice a day. To truly reflect the SRMC, a charge per kilometre would have to be continuously varied by route and by time of day, such as that being implemented in Singapore. However, a charge based on the actual excess travel time would closely track the optimum charge. This requires setting a charge for each journey equal to a pre-set rate times the excess travel time (i.e. the difference between the actual time and the free-flow time). The rate would be set to ensure that all roads operate at or below capacity – i.e. at speeds no less than 75% of their free-flow speed – and would only need adjusting infrequently. Such a toll would be self-adjusting – if the charge is too high, motorists will avoid that route or time of day, resulting in speeds increasing and the toll reducing.

3.2 Conclusions

The social marginal cost on a road section may be derived from the travel time and the free-flow information, assuming that the relationship between travel time and demand is represented by a BPR function. In most cases, a BPR function (interpreted as described in Appendix 4) provides a satisfactory fit to the observed data and related traffic speeds to vehicle density on the road. We therefore have been able to use data on traffic volumes and speeds collected on a number of urban roads across both islands to fit a BPR function to the data. This enabled us to estimate the congestion externality by time of day. The resulting estimates of the short run marginal cost (SRMC) are very location-specific.

The average congestion cost per kilometre faced by motorists in the three largest urban areas was estimated using the respective regional transport planning models. Auckland motorists face disproportionately high congestion costs compared with the other urban areas. Nevertheless, the average delay costs per vehicle kilometre in Auckland (and also the other centres) are much lower than the cost of expanding capacity (the long run costs). If only trips to the CBD are considered, the SRMC is much higher than the average delay cost and exceeds the LRMC.

The average delay cost per kilometre is not very helpful as the cost does vary so significantly across the network. However, it is useful to inform travel demand policies such as congestion pricing. For example, “The Congestion Question” (TCQ) report considered a cordon charge for entering the Auckland CBD. When designing a congestion charging scheme, the ability to initially achieve an optimum charge will be influenced by the need to make trade-offs, including managing equity concerns and the costs associated with more sophisticated charging mechanisms. Recognising these trade-offs, TCQ proposes an initial flat rate access charge, but does not rule out variable pricing in the future. Using the results from this paper, we calculate that about 5% of all AM peak trips responsible for 14% of the congestion delays currently cross this cordon. The average delay for these trips is 15 minutes and the short run marginal cost is $33 per trip. This means that the marginal vehicle dissuaded from travelling at the peak would initially reduce total delay costs by $33. The equilibrium SRMC that would result in the peak demand for travel just equalling the road capacity across the cordon would be $7.70 per trip. Note however that the COVID situation and post-COVID adjustments may reduce the demand – and hence the SRMC - for CBD-oriented trips, at least in the shorter term.

This working paper provides important insights to inform the level and design of congestion or related pricing, as illustrated using one of the options considered in “The Congestion Question” report. Analyses from this paper suggest the desirability of further research in two main areas: (i) on the value of time (the mean and its distribution) using the revealed preference approach; and (ii) on the use of mobile data to obtain information on real-time traffic demand, as discussed in Chapter 4.3.

Chapter 4 Limitations and future updates

4.1 Guidance for updating

There should be little problem in updating the analyses in this paper from time to time, following the same approach. The Tom Tom data used for the road-specific analysis is maintained as a time series. This would allow comparison between the then current situation and the situation in 2019 when the data for this analysis was collected. There is thus no need to limit the analysis to the same sites for comparability. Conversely, it should be possible to obtain data for the same sites and replicate the results. Use of the regional transport models for comparisons is more problematical. We found it difficult to replicate earlier work due the change in zoning systems and other model enhancements.

4.2 Any limitations and exclusions

The primary emphasis of the work was to provide a method to calculate the marginal cost at a specific location and to give examples of the calculation and the results. The average congestion cost analysis using the regional transport models is interesting and gives an idea of the scale of the problem, but, as discussed in this report, the figures obtained have limitations. In particular, they reflect the assumptions about congestion built into the models themselves.

4.3 Potential areas for further work

There are two areas for further work.

- **Use real time mobile data instead of model data of traffic demand**. The site-specific nature of congestion means that any estimates need to be used with care. In particular identifying whether the congestion is due to interaction between vehicles or whether it can mainly be ascribed to side friction. The observed behaviour may reflect bottlenecks before or after the observed location rather than the characteristics of the chapter itself: Whether this is important or not depends on the use to which the data is to be put.

  Transport models provide an easy-to-use source of network data, but again this needs to be interpreted with care – these data already incorporate assumptions about the behaviour of traffic. As an alternative to using model data, we did consider using mobile phone network data to track the movement of vehicles through the day. This could be used to record the average travel times between pairs of zones in the network by time of day in a similar way to the use of Tom Tom data and would enable the free-flow, peak flow and congested flow times to be determined accurately. This approach should be investigated further in the future.

- **Use revealed preference evidence for estimating values of time**. The cost of congestion requires knowing the value road users place on travel time delays and reliability. All the delay times calculated have been monetised using a standard value of time based on the Waka Kotahi evaluation manual (MBCM). This assumes that the affected trips are those of the general population. In situations where tolls are introduced, the characteristics of the motorists paying the toll will differ from the general population. Evidence from the use of value lanes in the USA imply very high values of time savings by users of these lanes. This may be for a number of reasons including a high valuation on reliability rather than time or confirmation bias in the estimation of savings. This is an area for further study should policies including the use of tolls be considered.

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Appendix 2 : Listing of DTCC Working Papers

The table below lists the Working Papers prepared as part of the DTCC Study, together with the consultants responsible for their preparation.

Ref	Topic/Working Paper title	Principal Consultants	Affiliation
MODAL TOPICS			
C1.1	Road Infrastructure – Marginal Costs	David Lupton	David Lupton & Associates
C1.2	Road Infrastructure – Total & Average Costs		
C2	Valuation of the Road Network	Richard Paling	Richard Paling Consulting
C3	Road Expenditure & Funding Overview		
C4	Road Vehicle Ownership & Use Charges		
C5	Motor Vehicle Operating Costs		
C6	Long-distance Coaches	David Lupton	David Lupton & Associates
C7	Car Parking	Stuart Donovan	Veitch Lister Consulting
C8	Walking & Cycling		
C9	Taxis & Ride-hailing		
C10	Micro-mobility		
C11.2	Rail Regulation	Murray King	Murray King & Francis Small Consultancy
C11.3	Rail Investment		
C11.4	Rail Funding		
C11.5	Rail Operating Costs		
C11.6	Rail Safety		
C12	Urban Public Transport	Ian Wallis & Adam Lawrence	Ian Wallis Associates
C14	Coastal Shipping	Chris Stone	Rockpoint Corporate Finance
C15	Cook Strait Ferries		
SOCIAL AND ENVIRONMENTAL IMPACT TOPICS			
D1	Costs of Road Transport Accidents	Glen Koorey	ViaStrada
D2	Road Congestion Costs	David Lupton	David Lupton & Associates
D3	Health Impacts of Active Transport	Anja Misdrak & Ed Randal	University of Otago (Wellington)
D4	Air Quality & Greenhouse Gas Emissions	Gerda Kuschel	Emission Impossible
D5	Noise	Michael Smith	Altissimo Consulting
D6	Biodiversity & Biosecurity	Stephen Fuller	Boffa Miskell

Note:
The above listing incorporates a number of variations from the initial listing and scope of the DTCC Working Papers as set out in the DTCC Scoping Report (May 2020).

Appendix 3 : Graphs of speed vs time and volume

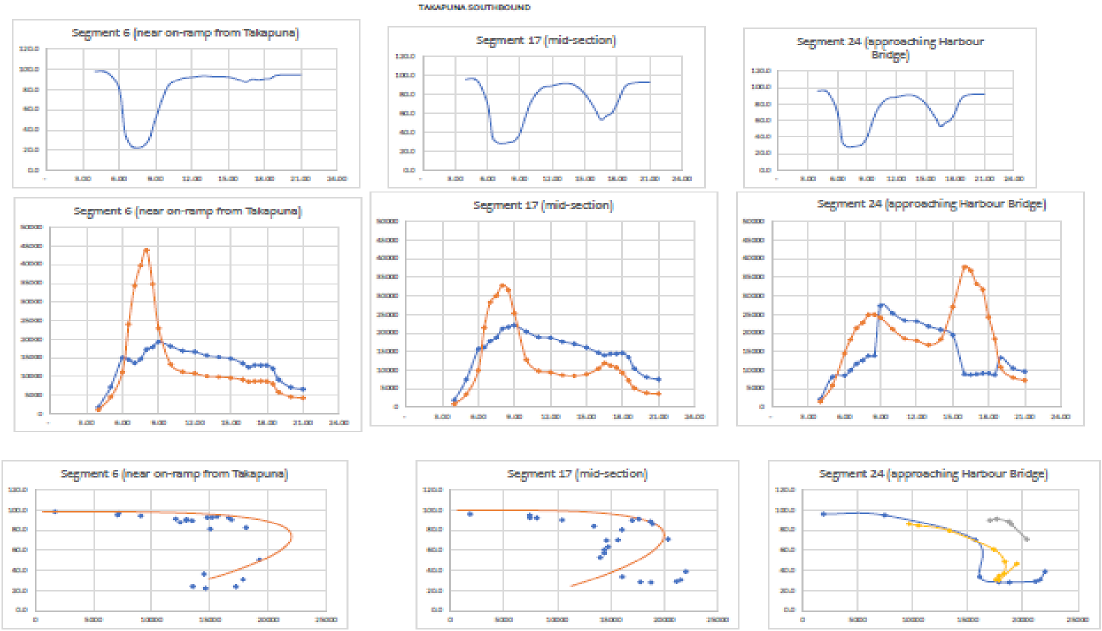


Figure A3.1 SH1 Auckland Harbour Bridge to Takapuna, heading South

Note that the capacity of the bridge changes after the AM peak and again before the PM peak using a movable median barrier

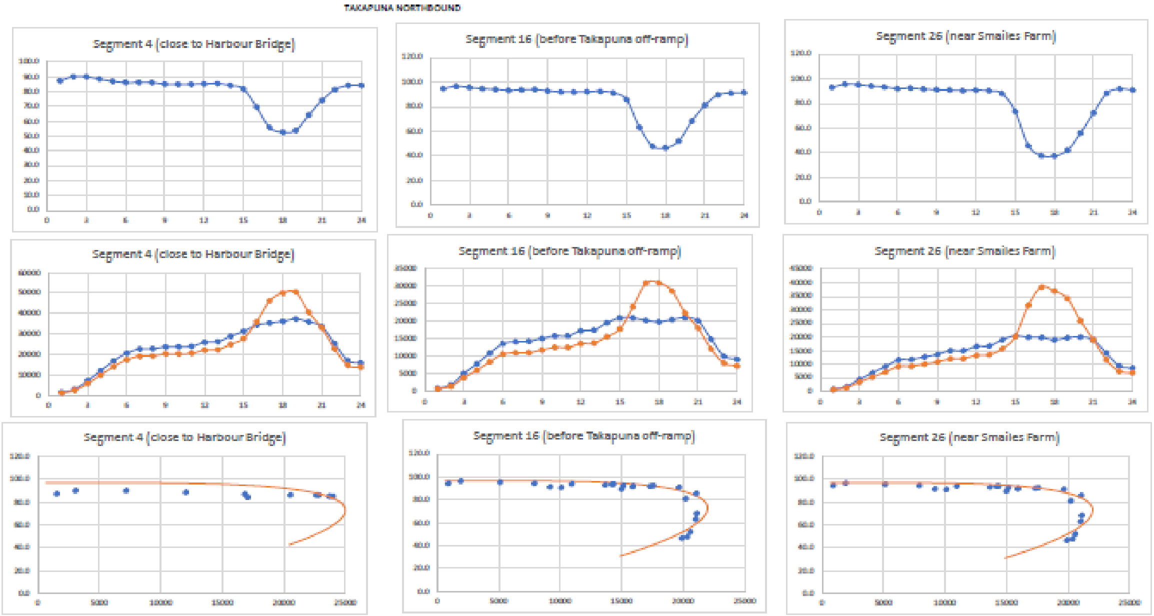


Figure A3.2 SH1 Auckland Harbour Bridge to Takapuna, heading North

Key to graphics

- Top row – Speed vs time of day
- Second row - Demand (red) and Flow (blue) vs time of day;
- Third row – Speed vs observed flow (blue) and BPR estimate (red).

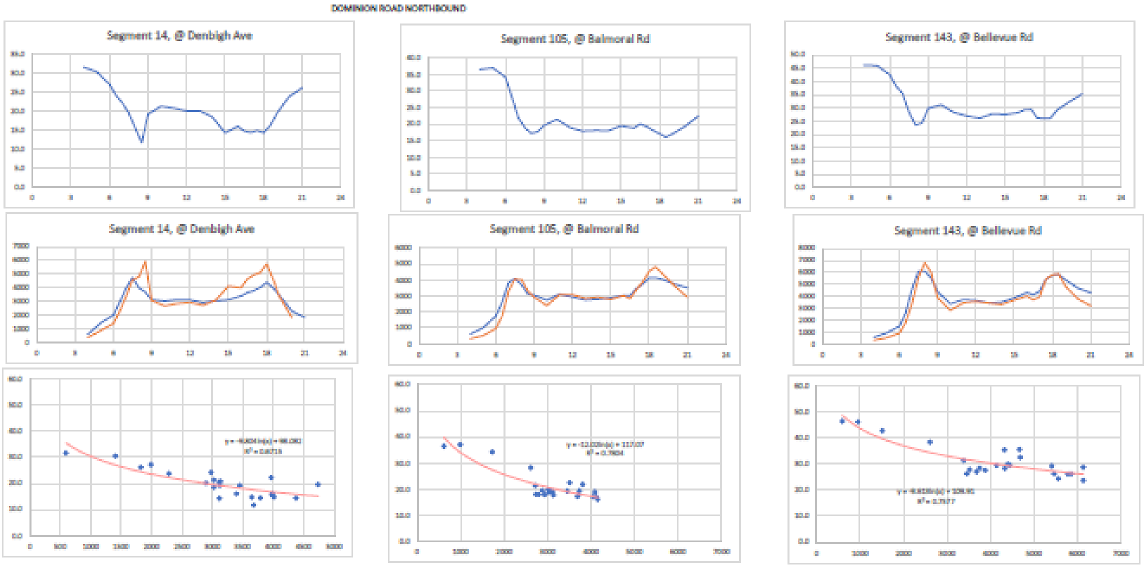


Figure A3.3 Dominion Road, Auckland, heading N to CBD

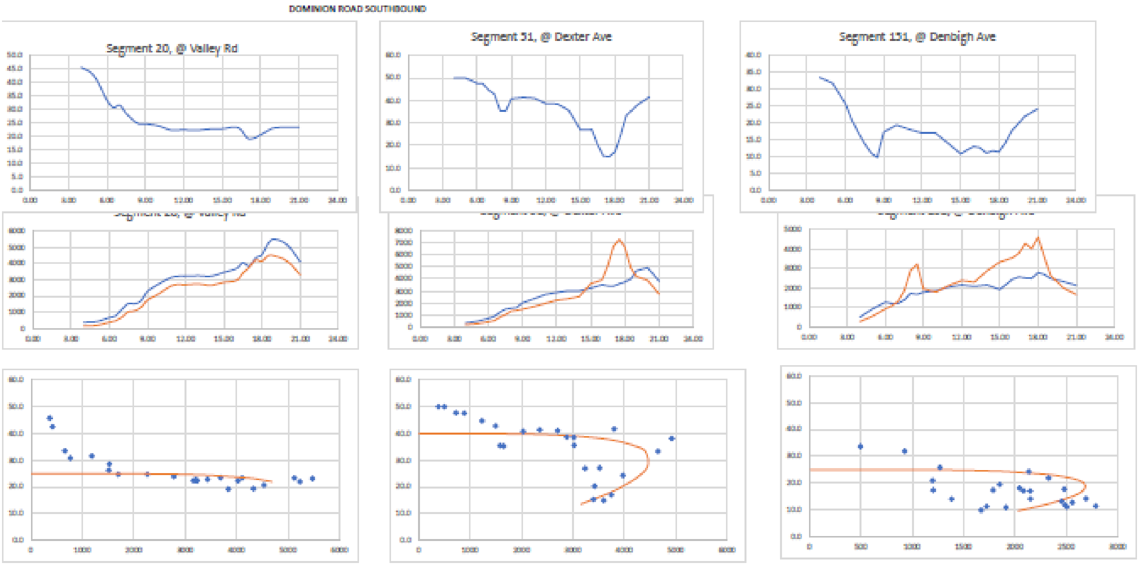


Figure A3.4 Dominion Road, Auckland, heading S from CBD

Key to graphics

- Top row – Speed vs time of day
- Second row - Demand (red) and Flow (blue) vs time of day
- Third row – Speed vs observed flow (blue) and BPR estimate (red).

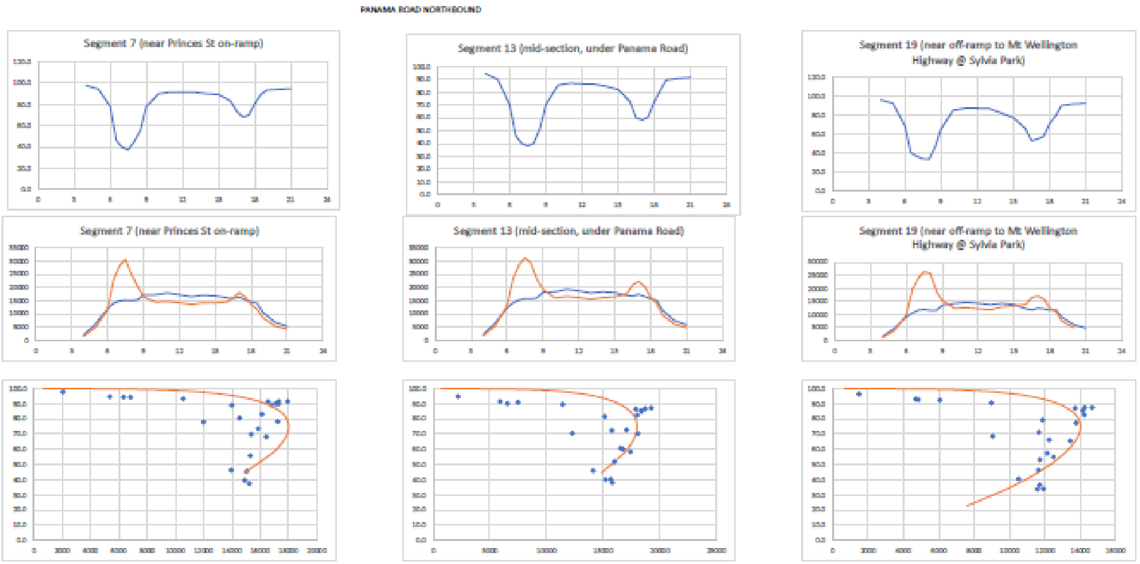


Figure A3.5 SH1 @ Panama Road, heading N towards Auckland CBD

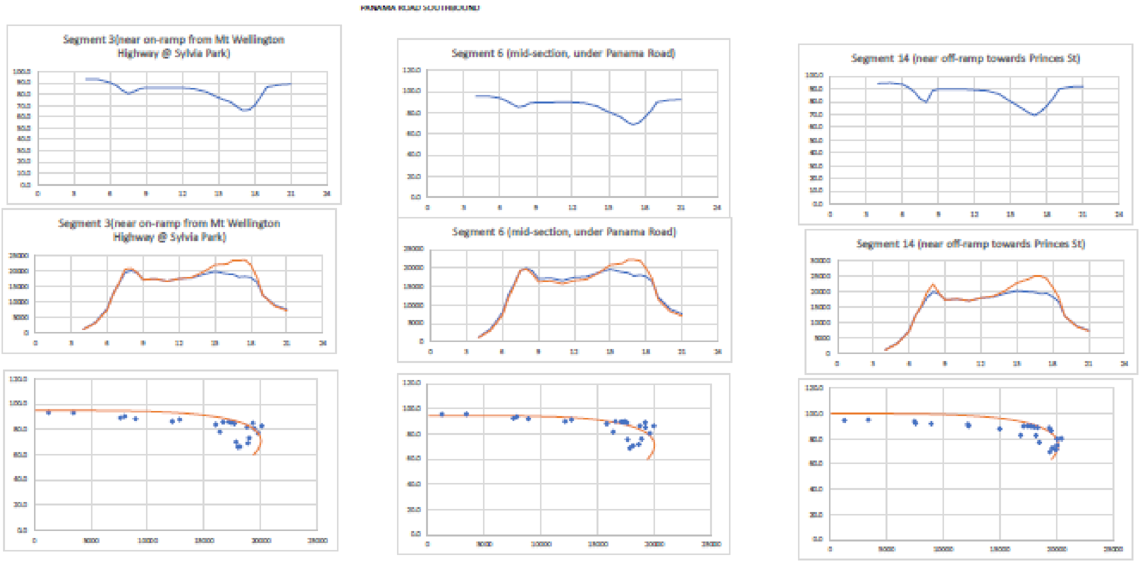


Figure A3.6 SH1 @ Panama Road, heading S away from Auckland CBD

Key to graphics

Top row – Speed vs time of day

Second row - Demand (red) and Flow (blue) vs time of day

Third row – Speed vs observed flow (blue) and BPR estimate (red).

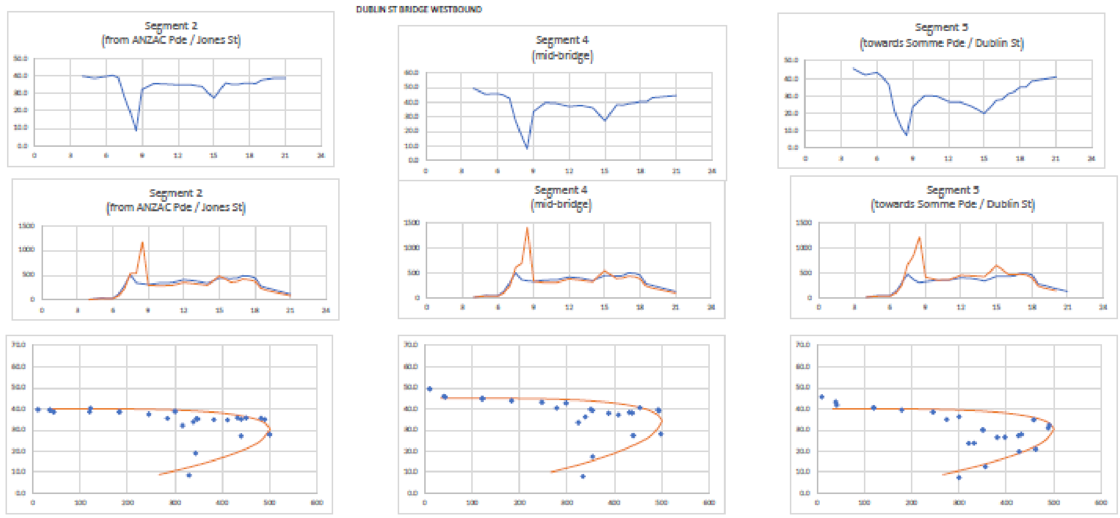


Figure A3.7 Wanganui's Dublin St Bridge heading W from Jones St to Dublin St

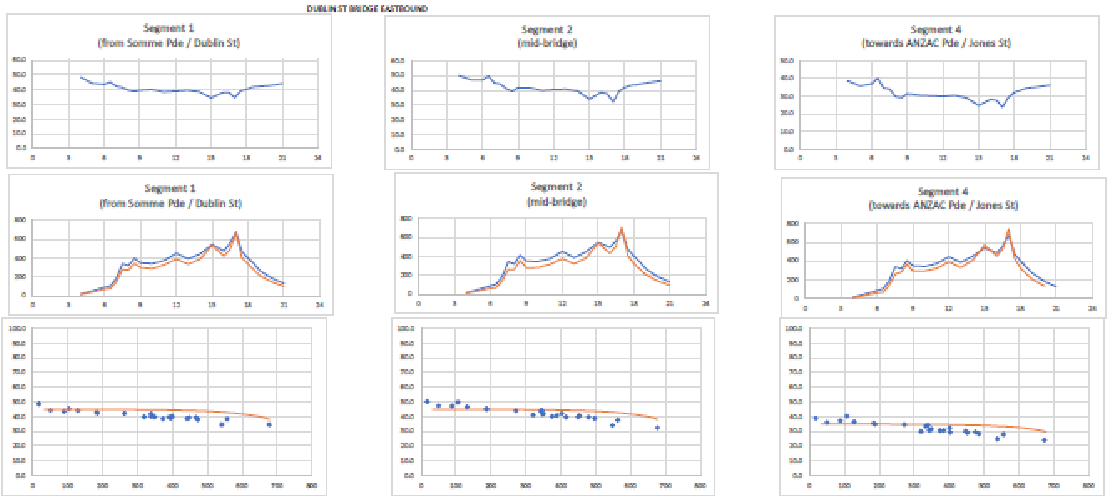


Figure A3.8 Wanganui's Dublin St Bridge heading E from Dublin St to Jones St

Key to graphics

- Top row – Speed vs time of day
- Second row - Demand (red) and Flow (blue) vs time of day
- Third row – Speed vs observed flow (blue) and BPR estimate (red).

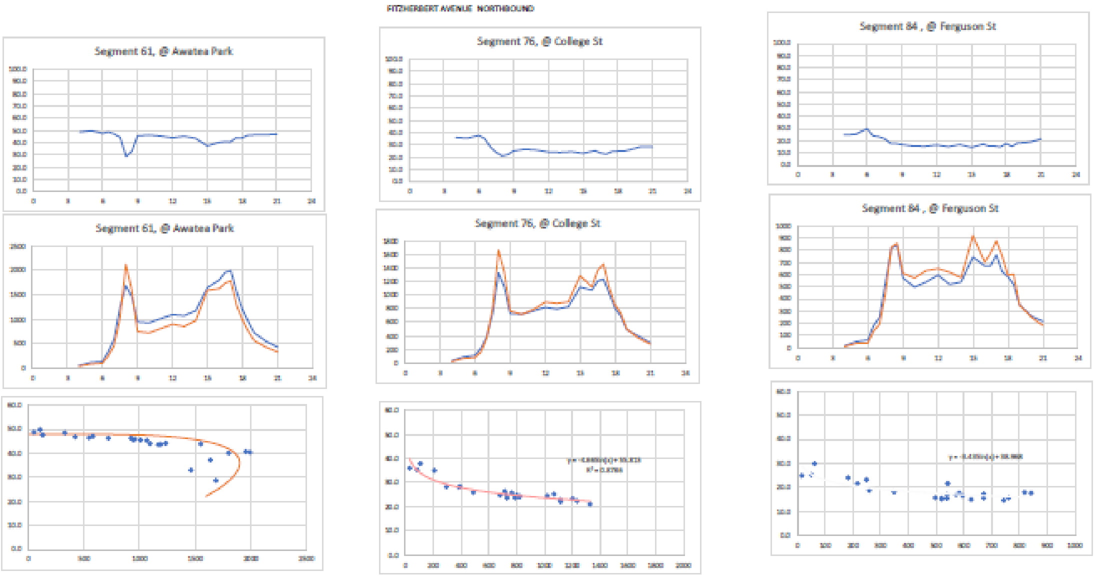


Figure A3.9 Fitzherbert Avenue, Palmerston North, heading N from University to CBD

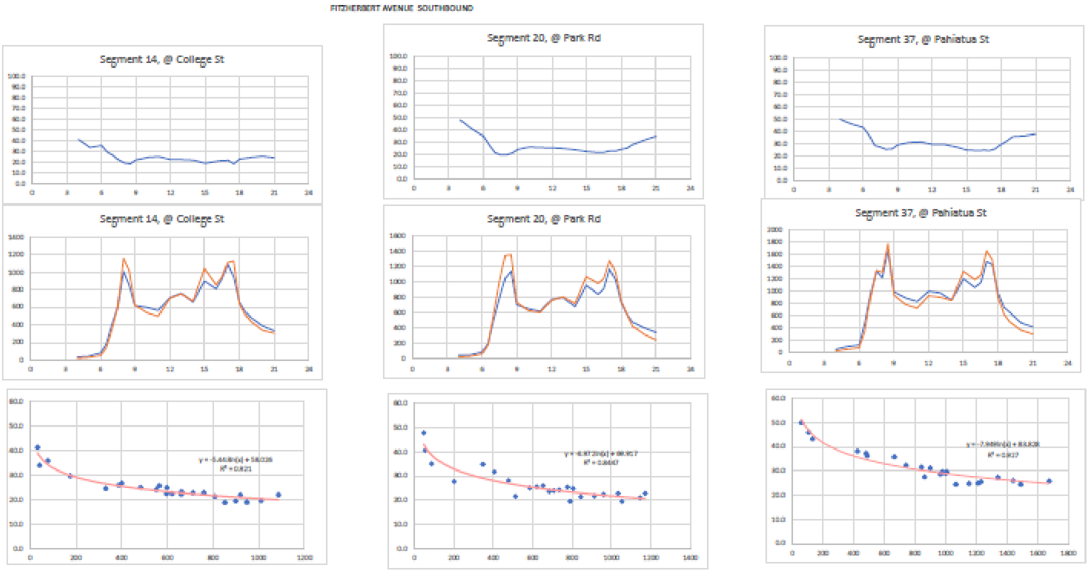


Figure A3.10 Fitzherbert Avenue, Palmerston North, heading S from CBD to the University

Key to graphics

Top row – Speed vs time of day

Second row - Demand (red) and Flow (blue) vs time of day

Third row – Speed vs observed flow (blue) and BPR estimate (red).

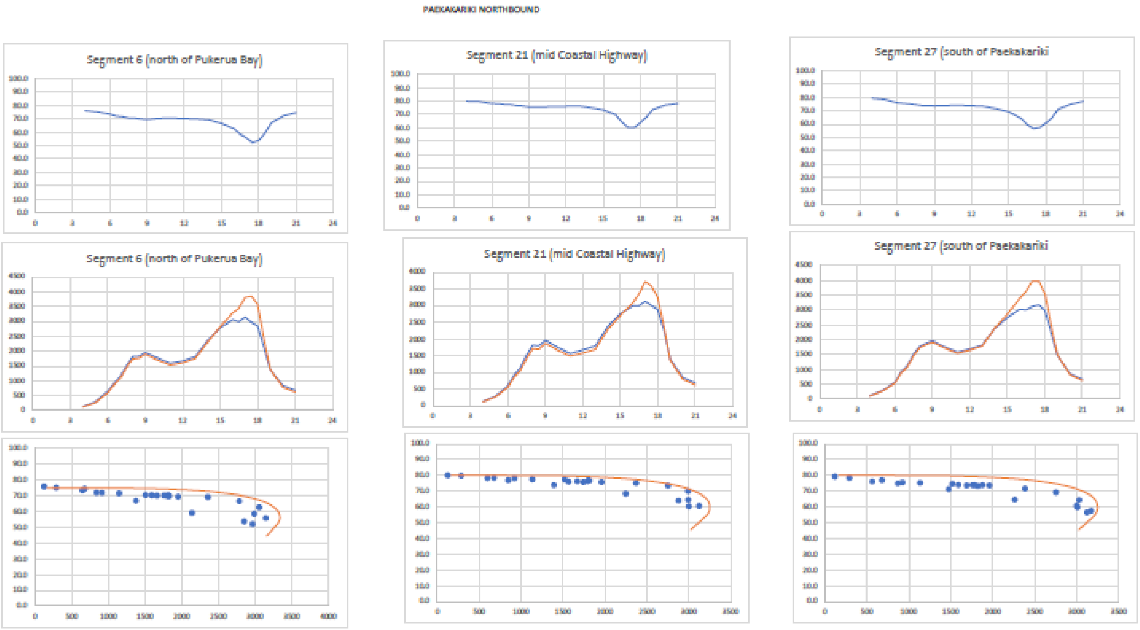


Figure A3.11 SH59, Coastal Highway at Paekakariki, heading north from Wellington

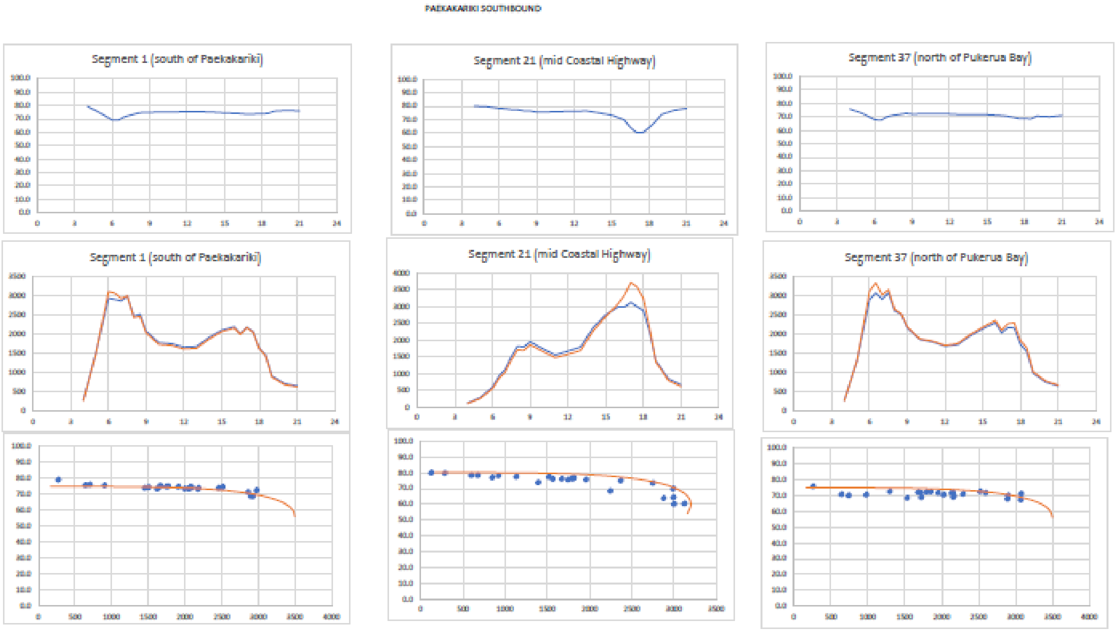


Figure A3.12 SH59, Coastal Highway at Paekakariki, heading south to Wellington

Key to graphics

- Top row – Speed vs time of day
- Second row - Demand (red) and Flow (blue) vs time of day
- Third row – Speed vs observed flow (blue) and BPR estimate (red).

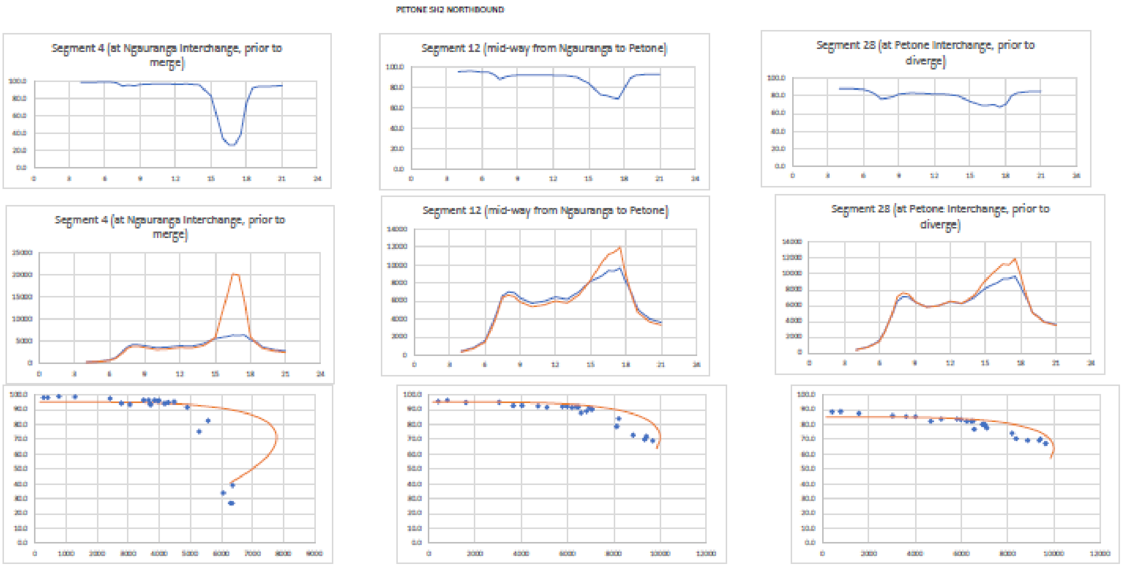


Figure A3.13 SH2 from Ngauranga to Maungaraki, heading N

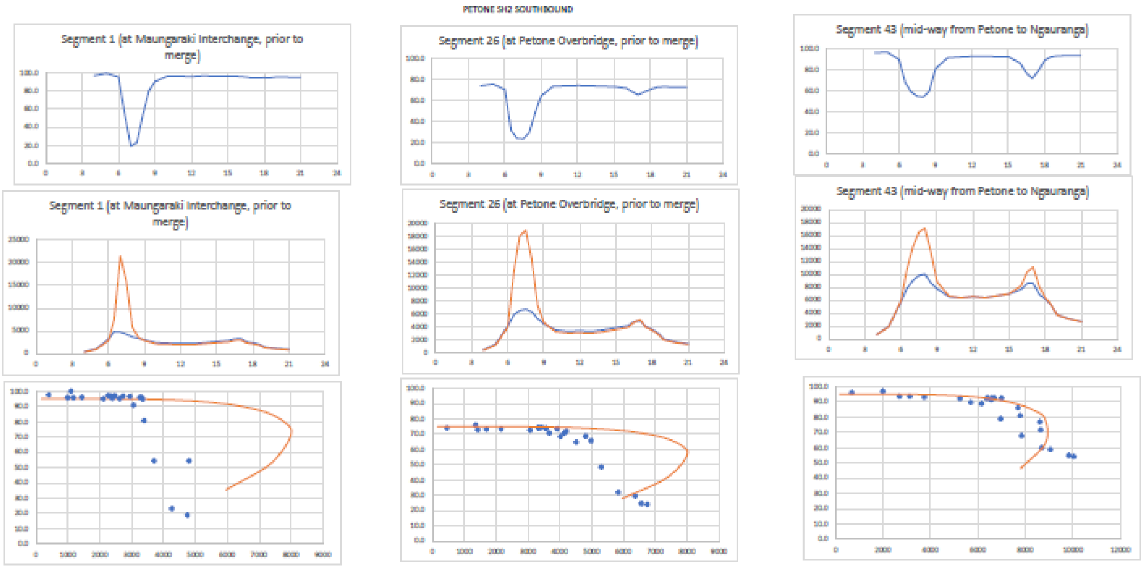


Figure A3.14 SH2 from Maungaraki to Ngauranga, heading S

Key to graphics

Top row – Speed vs time of day

Second row - Demand (red) and Flow (blue) vs time of day

Third row – Speed vs observed flow (blue) and BPR estimate (red).

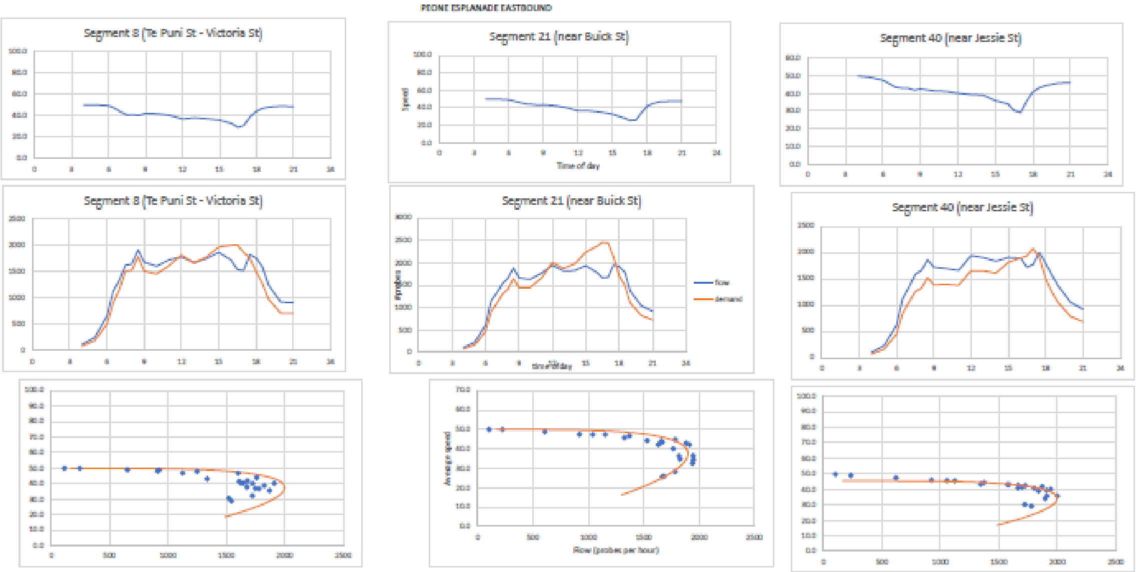


Figure A3.15 Petone Esplanade from SH2 to Waione Street, heading E

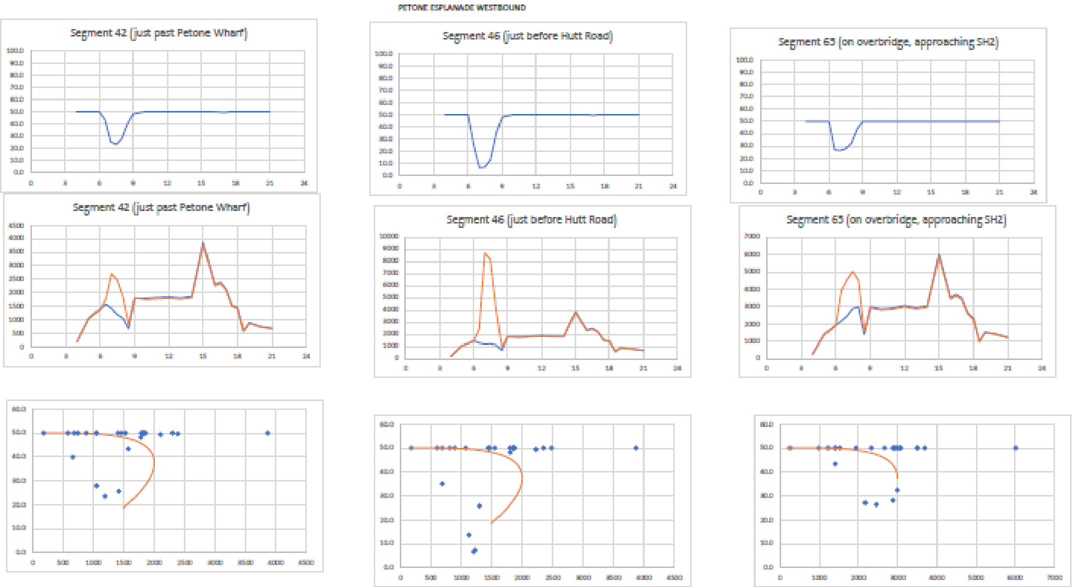


Figure A3.16 Petone Esplanade from Waione Street to SH2, heading W

Key to graphics

- Top row – Speed vs time of day
- Second row - Demand (red) and Flow (blue) vs time of day
- Third row – Speed vs observed flow (blue) and BPR estimate (red).

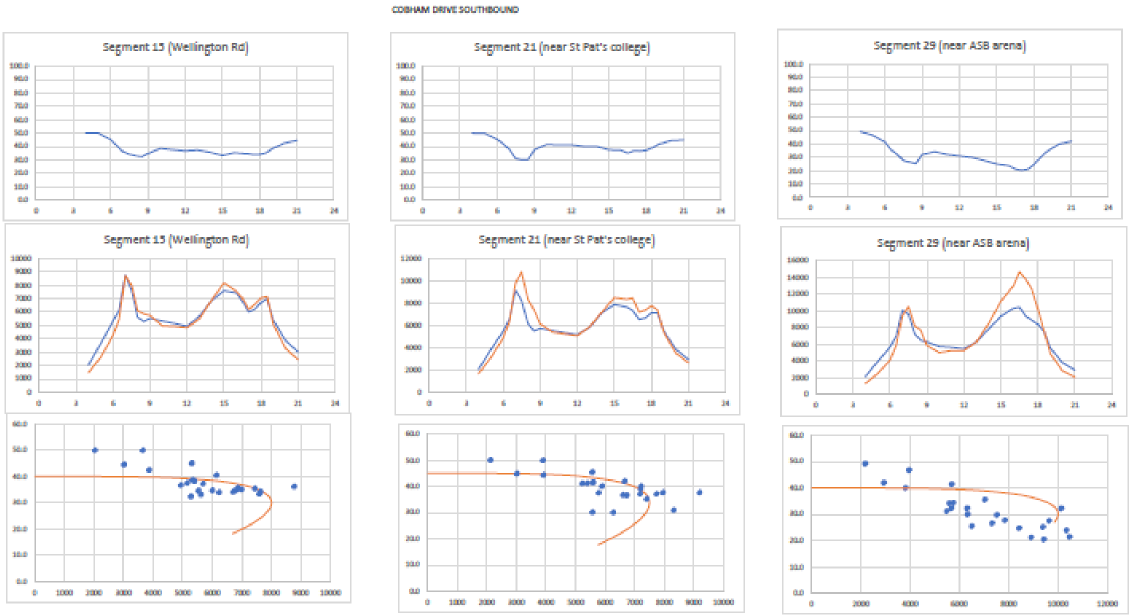


Figure A3.17 SH1 @ Cobham Drive, Wellington, heading N from airport

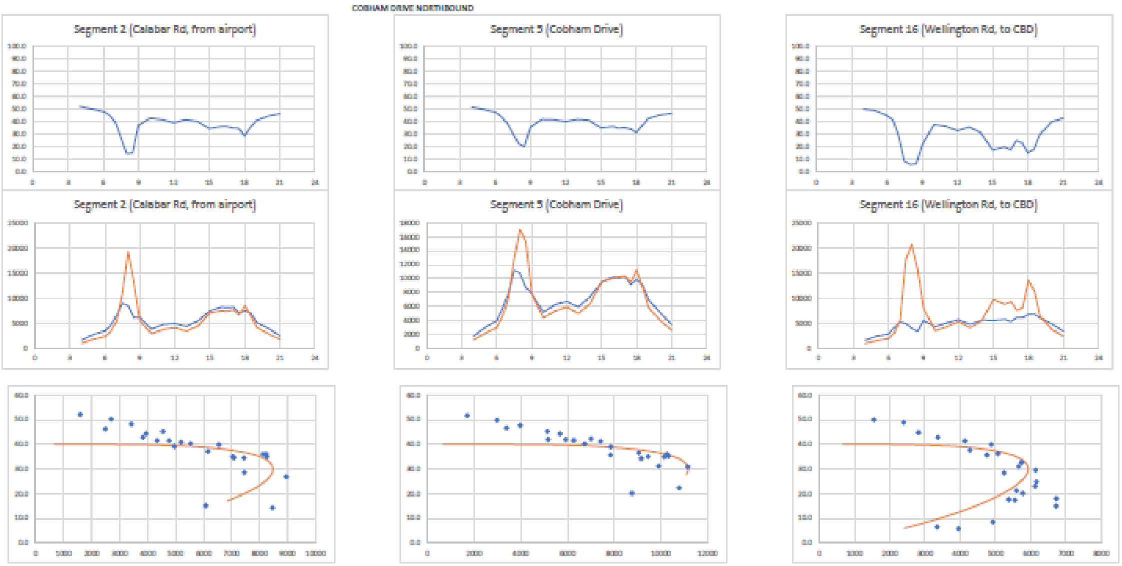


Figure A3.18 SH1 @ Cobham Drive, Wellington, heading S towards airport

Key to graphics

Top row – Speed vs time of day

Second row - Demand (red) and Flow (blue) vs time of day

Third row – Speed vs observed flow (blue) and BPR estimate (red).

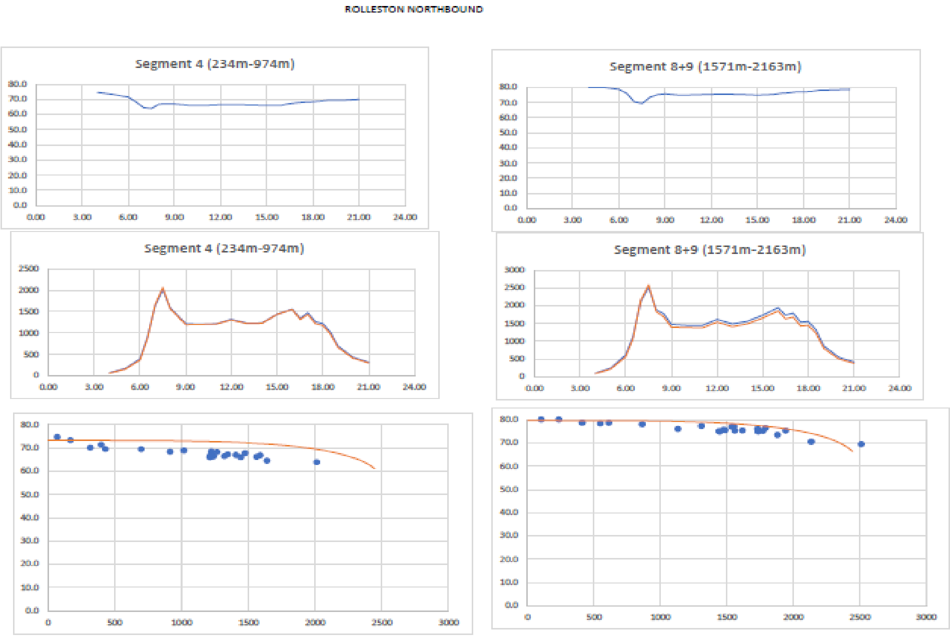


Figure A3.19 SH1, NE of Rolleston, heading north to Christchurch

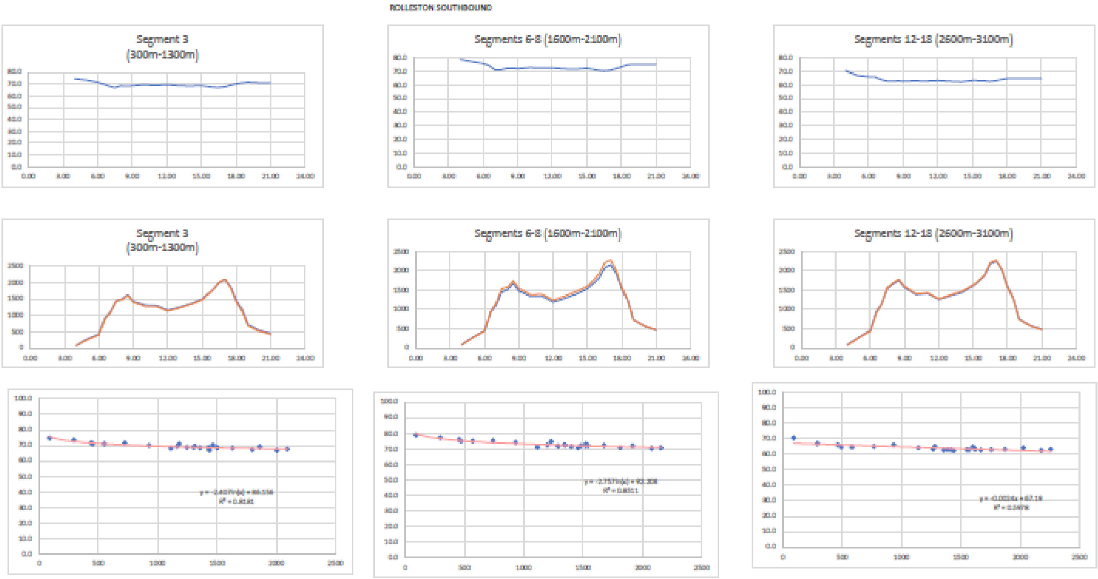


Figure A3.20 SH1, NE of Rolleston, heading South from Christchurch

Key to graphics

Top row – Speed vs time of day

Second row - Demand (red) and Flow (blue) vs time of day

Third row – Speed vs observed flow (blue) and BPR estimate (red).

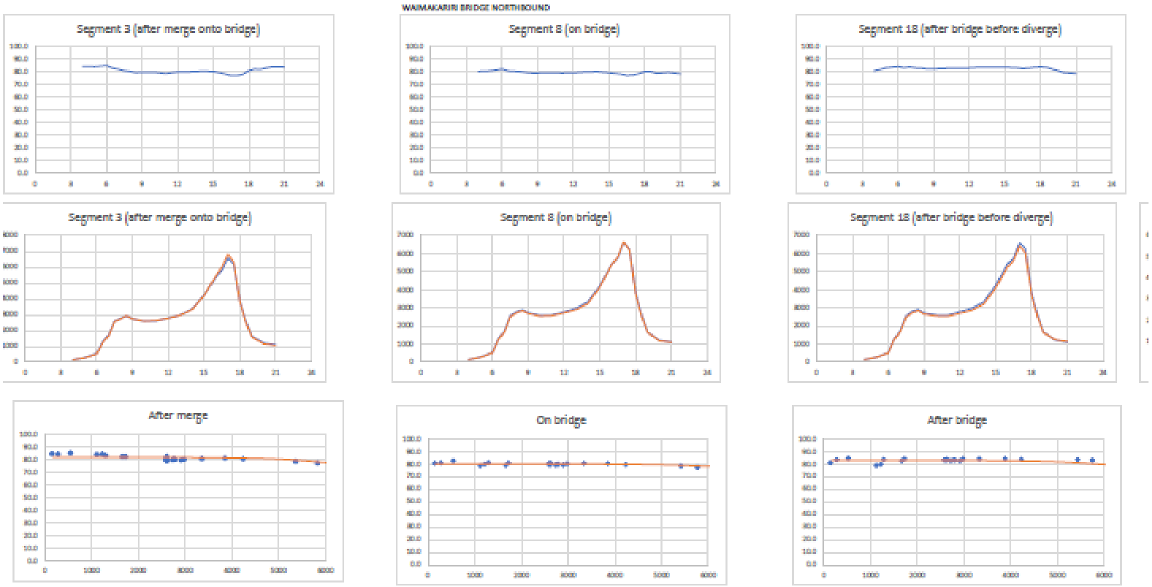


Figure A3.21 SH1, Waimakariri Bridge, heading north from Christchurch

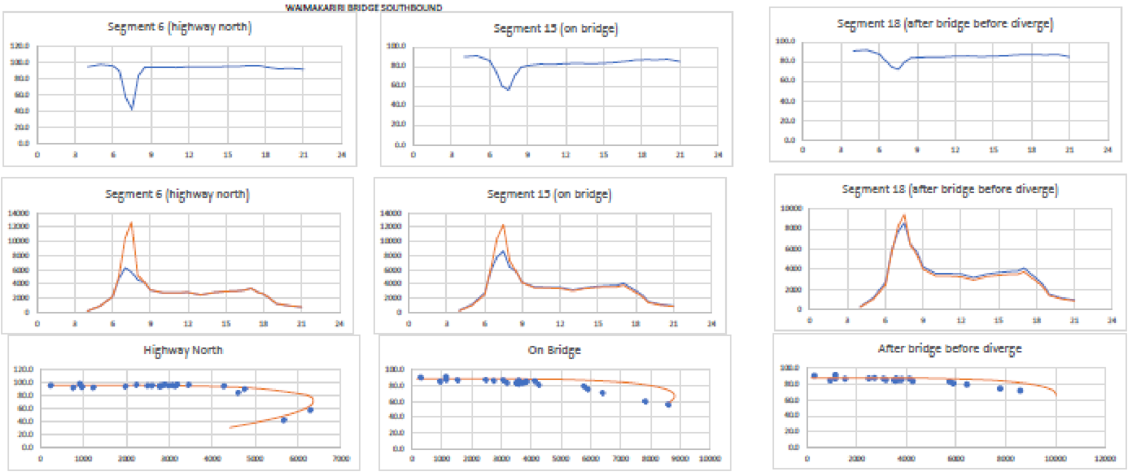
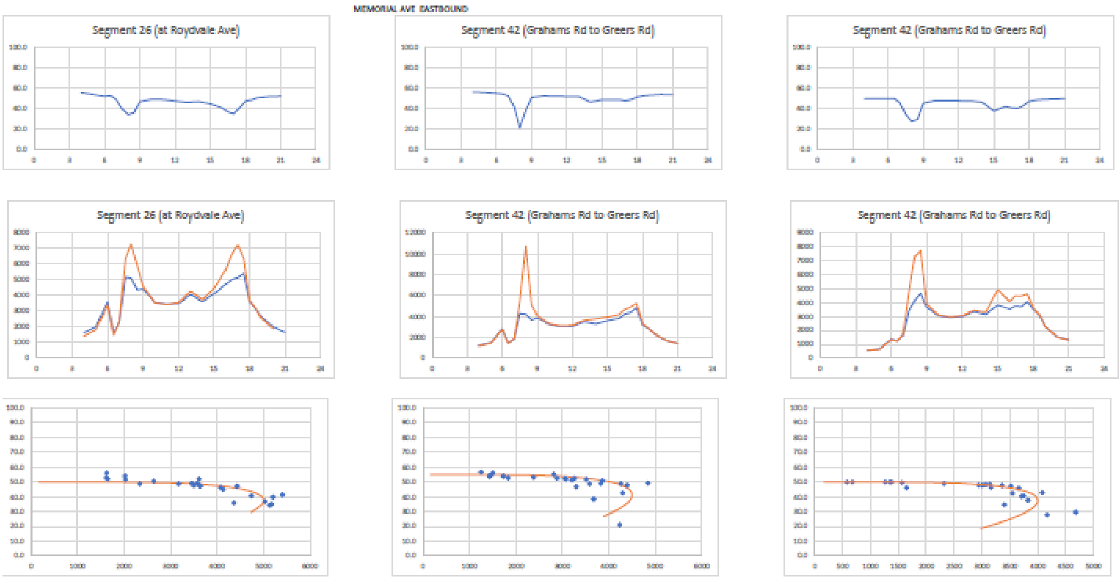


Figure A3.22 SH1, Waimakariri Bridge, heading south to Christchurch

Key to graphics

Top row – Speed vs time of day
Second row - Demand (red) and Flow (blue) vs time of day
Third row – Speed vs observed flow (blue) and BPR estimate (red).



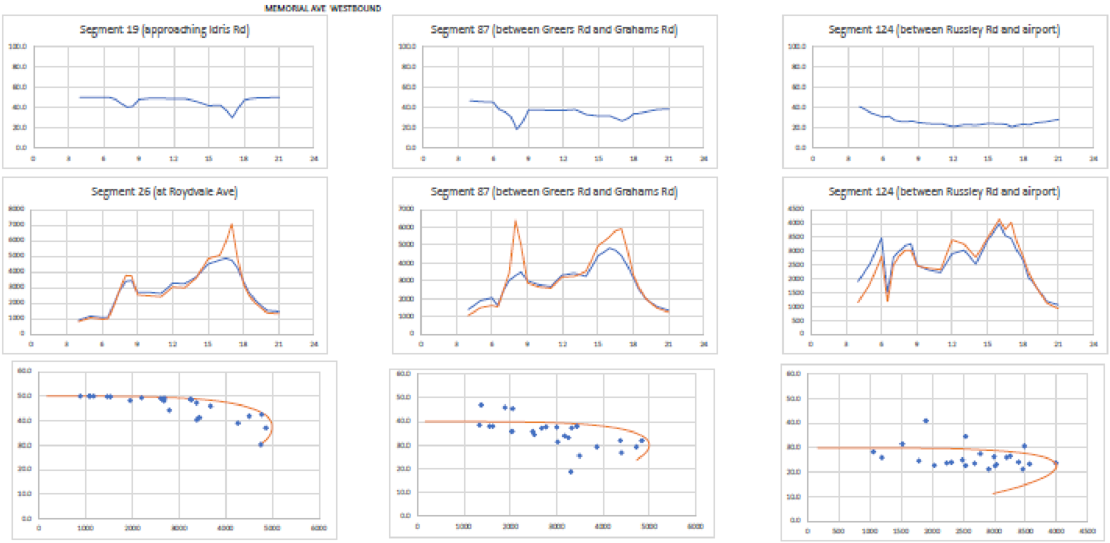


Figure A3.23 Memorial Ave from CBD to airport, Christchurch, heading E

Figure A3.24 Memorial Ave from airport to CBD, Christchurch, heading W

Key to graphics

Top row – Speed vs time of day
Second row - Demand (red) and Flow (blue) vs time of day
Third row – Speed vs observed flow (blue) and BPR estimate (red).

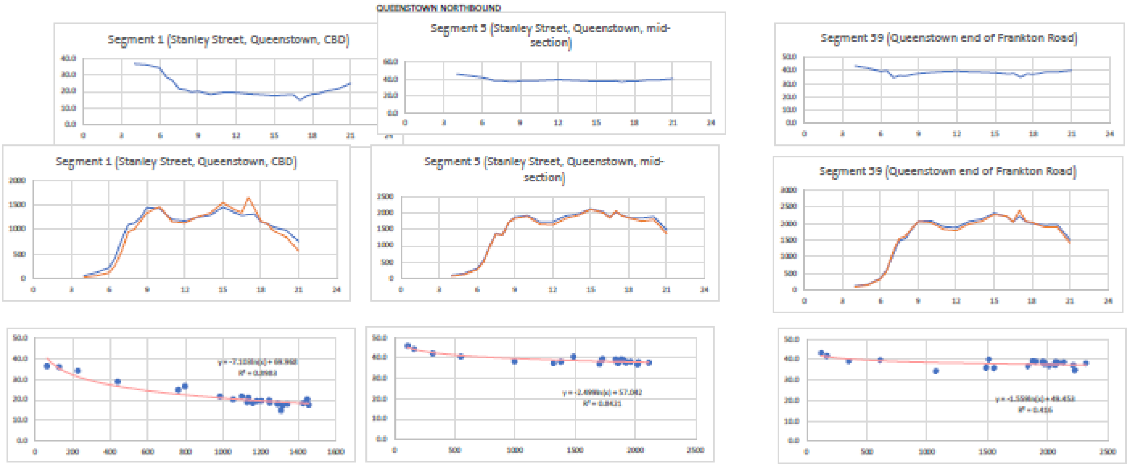


Figure A3.25 Road connecting Queenstown to Frankton, heading N

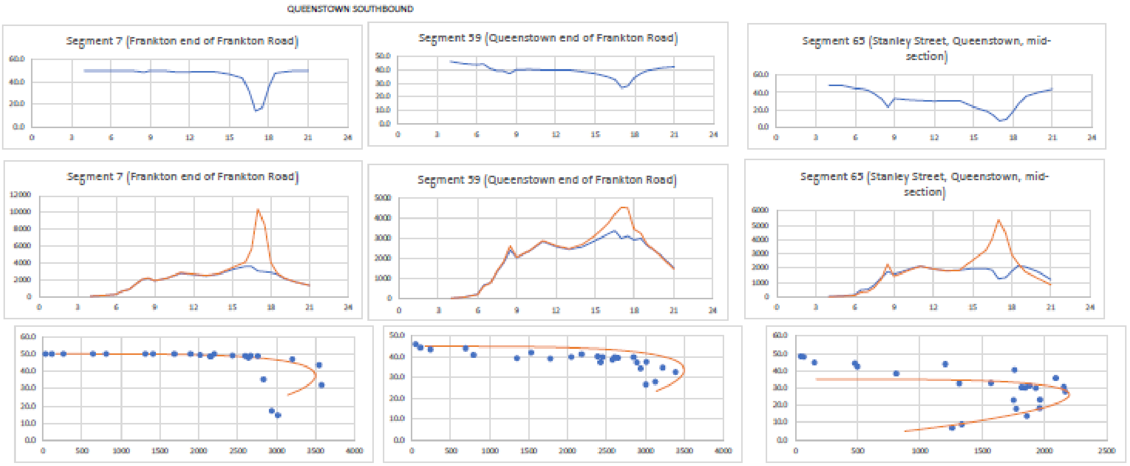


Figure A3.26 Road connecting Frankton to Queenstown, heading S

Key to graphics

- Top row – Speed vs time of day
- Second row - Demand (red) and Flow (blue) vs time of day
- Third row – Speed vs observed flow (blue) and BPR estimate (red).

Appendix 4 : Characteristics of the BPR function

The Bureau of Public Roads (BPR) function is of the form

$$t = t_0 + t_0\, \alpha (Q/K)^{\beta}$$

Where t = travel time

t_0 = travel time under free flow

Q = demand

K = capacity

α and β are constants.

Typically, β = 4. This accords with our findings. We show below that a value of 4 for β implies a value of 0.33 for α, although other values are sometimes used.

The BPR function has some nice mathematical properties. Since

$$t = t_0 + t_0\, \alpha (Q/K)^{\beta}$$

therefore

$$dt/dQ = t_0\, \alpha\, \beta\, Q^{(\beta-1)} / K^{\beta}$$

So the congestion externality E is given by:

$$E = Q.dt/dQ = t_0\, \alpha\, \beta\, (Q/K)^{\beta}$$ (NB “E “ measured in minutes)

Or $E = \beta\,(t - t_0)$

In terms of the travel time elasticity, the elasticity ε is given by:

$$\varepsilon = dt/t \;/\; dQ/Q$$

$$= Q/t\; dt/dQ$$

$$= \beta\,(t - t_0)/t$$

The BPR function does not have a classic “backward bending” shape because Q is the demand, not the flow. In fact as noted by Gwilliam[16], the way demand affects travel time is through the density of the traffic. The BPR function is actually measuring time vs traffic density.

Flow is equal to density x speed. To get an expression for the flow, we divide the density by the travel time giving $F \propto Q/t$.

We will choose to use t_c the travel time at capacity, as the constant of proportionality. That way Q= F at capacity. When Q > capacity, we have hyper-congestion. When Q< capacity, we have F > Q which may seem impossible, but is in fact the situation where there are gaps in the traffic – traffic moves in bunches and within any bunch F > Q but because there are gaps between bunches, the total vehicles in any one hour is equal to Q.

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[16] Ken Gwilliam, personal correspondence

From the point of view of the economics, we are interested in the relationship between demand and travel time. However, in real life, it is the flow that we measure, not the demand.

Flow is maximum when dF/dQ =0 or $(t\ dQ/dQ – Q\ dt/dQ\ )/t^2 = 0$

ie $t = Q\ dt/dQ$

ie when t = E (measured in minutes)

Thus we can write

$$t_c = t_0\ \alpha\ \beta\ (Q/K)^\beta = t_0\ \alpha\ \beta$$

But we know $t_c = t_0 + t_0\ \alpha$

Hence $\alpha = 1/(\beta-1)$

and $t_c = t_0\ \beta/(\beta -1)$

The shape of the speed vs flow curve depends on the value of β. The following figure shows the curve generated when β = 1.5, 2 and 4.

Initially we tried fitting the BPR curve to Tom Tom data allowing the value of β to be determined from the data. This resulted in some curves with β of 2 or less. This is because in a number of cases, the speed appears to drop at a much higher rate than that implied by a BPR with β =4. Further inspection of these cases suggested that the reason for the rapid reduction in speeds at comparatively low volumes was the concomitant increase in side friction during the period 6am to 8am. Re-defining the 'free speed' to be the speed of traffic in the presence of day-time side friction resulted in a better fitting curve and a β of 4.

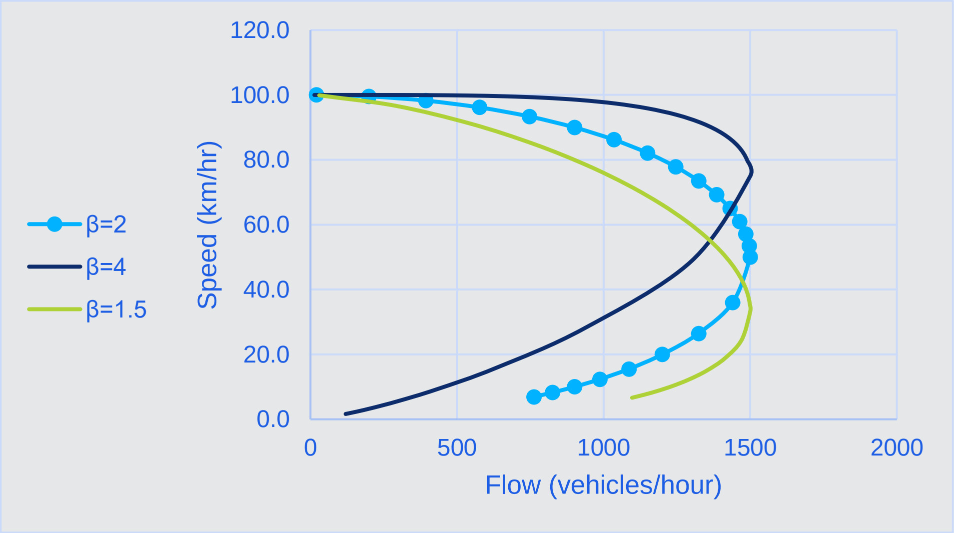

Figure A5.1 Speed vs flow (different values of beta)

Appendix 5 : Capital costs for road network capacity increases

A5.1. Introduction

This Appendix provides information on the capital costs of major new road schemes in NZ, based on state highway projects that have been either completed (opened to traffic) in the last 10 years (from 2009 onwards) or are now at an advanced state of planning and construction (to be opened by 2024). This information has been analysed to derive typical capital costs per lane kilometre for major new road projects and for major projects involving widening of existing routes. These typical costs are then applied elsewhere in this working paper (Chapter 2.5) to provide estimates of the typical long run marginal costs (LRMC) of expanding road capacity, expressed on a per vehicle (or PCU) kilometre basis.

A5.2. Data collection and analysis

IWA issued a questionnaire to Waka Kotahi requesting details of a sample of in the order of 15 -20 NZ state highway schemes which were either completed within the last 10 years or so, or are currently under construction or in an advanced state of planning (refer above). The questionnaire specified that candidates schemes should:

(1) be in urban or semi-urban (rather than rural) areas; and generally in or in the vicinity of the main urban areas (principally AKL, HAM, TAU, WLG, CHC);
(2) focus primarily on schemes providing significant increases in traffic capacity, and involving either new roads or substantial capacity improvements to existing roads;
(3) involve capital expenditures of at least $100 million (in current prices); and
(4) generally exclude ‘abnormal’ schemes having either particularly high costs (eg involving substantial tunnelling or elevated sections) or particularly low costs. [17]

Based on IWA’s questionnaire, Waka Kotahi provided data on 21 schemes covering the aspects set out in table F1.

The analysis of the data provided was a relatively trivial task. It focused on deriving for each scheme:

(i) the effective increase in lane km resulting from the scheme, as the product of the increase in the number of lanes provided by the scheme (ie new # lanes – previous # lanes) * scheme length;
(ii) the total scheme costs (the breakdown of costs into the six categories shown in table F.1 was used only in subsidiary analyses); and
(iii) the total scheme cost/lane km.

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[17] NZTA found that this last requirement excluded a substantial proportion of (otherwise) candidate schemes. Therefore, in practice, a number of schemes were included in the sample that did not meet this criterion (mainly through having particularly high costs relative to the additional lane kilometres provided).

A5.3. Findings and commentary

Table F.2 summarises the key results for each scheme and in aggregate. In reviewing the schemes and their cost results, we comment as follows:

- There are 21 schemes in the list: six of these relate to the AKL WRR scheme but include no cost information for the individual sections. Therefore, we have treated this as only a single scheme (with an overall cost of some $2.2 billion). This reduces the number of schemes for which the key cost information is available to 16 (including the WRR as a single scheme).
- One of these schemes, the Tauranga Eastern Link, appears to effectively involve no road space expansion (both the existing road and the new road involve four lanes total). Therefore, no cost per incremental lane kilometre can be calculated -- so this scheme has not been included in the analyses, reducing the number of schemes with useful information to 15.
- The 15 schemes have a combined cost of $7.55 billion. They provide some 395 additional lane km, resulting in an average unit cost of $19.1 million/lane km..
- Three of these 15 schemes have been categorised as ‘abnormal’ in cost terms, as they have particularly high costs as a result of substantial tunnelling sections (Vic Park Tunnel, WRR - Waterview Tunnel section) or elevated sections (Newmarket Viaduct). The exclusion of these schemes leaves 12 ‘normal’ schemes for further analysis. These 12 ‘normal’ schemes have a total cost of some $4.71 billion, with a weighted average unit cost (i.e. total cost/total lane km) of $14.1 million/lane km.
- These 12 ‘normal’ schemes are divided equally (4 each) between Auckland, Canterbury and Wellington/Waikato (taken together). The weighted average costs for each of these 4 regional groups are $21.9 million/lane km for AKL, $5.8 million/lane km for CAN and $23.3 million/lane km for WLG/WAI.
- The much lower costs for the CAN schemes are striking. It appears that these lower costs reflect: (i) relatively flat terrain; (iI) the schemes generally being in the outer parts of the metropolitan area where there is little development and land is relatively cheap.

A5.4. Conclusions

Based on the information currently available, as in Table F.2, and having regard to the purpose of this work, we conclude that a ‘representative’ cost for providing additional road capacity (primarily at-grade) in the urban/semi-urban parts of the NZ major centres would be around ***$15 million per lane km.***

Table F.1: Scheme data requested from Waka Kotahi

Data specification	Notes
Waka Kotahi region	All schemes relate to state highways
Scheme location – city/region	
Scheme name	
Area type – Urban/semi-urban	No ‘fully rural’ schemes are included
Year of scheme completion/opening	Actual or planned
New route vs upgrade of existing route	In some cases, schemes are a combination of new route and route upgrade
Scheme length (km)	
# lanes - previous route (if any)	
# lanes – improved or new route	
# grade-separated intersections	
Scheme capital costs ($2018/19), divided into:	Scheme costs were provided on an annual basis up to 2013, on a monthly basis for subsequent years. Costs provided **excluded** any third party contributions (such contributions were very minor for the schemes covered)
** *Planning and business case costs*	
** *Investigation costs*	
** *Design costs*	
** *Land and property costs*	
** *Other pre-implementation costs*	
** *Construction costs*	
Additional comments - scheme features etc	
Source references etc	Web references etc providing further scheme information

Table F.2 Data provided by Waka Kotahi

Region	Project name	Opening year	Scheme length (km)	# lanes - before	# lanes -after	Incr lane km (IWA)	Grade-sep intersections	Tot Cost $mill	Cost/lane km $mill	Existing (E) or New (N) route
Auckland	Southern Corridor Improvements	2021	9	2	3	**9**	**1**	**327.7**	**36.4**	**E**
Auckland	Manukau Hbour. Xing	2010	5	4	8	**20**	**4**	**274.6**	**13.7**	**E**
Auckland	Mt Roskill Extension	2009	4.5	0	4	**18**	**2**	**246.4**	**13.7**	**N**
Auckland	Northern Corridor Improvements (NCI)	2024	7	6	10	**28**	**5**	**793.7**	**28.3**	**N**
Canterbury	CHCH Northern Arterial Rural with QE2	2021	15	0	4	**60**	**6**	**297.3**	**5.0**	**N**
Canterbury	CHCH Southern Motorway HJR to Rolleston (Stage 2 & 3)	2021	20	0	4	**80**	**8**	**379.2**	**4.7**	**N**
Canterbury	Harewood Rd to Yaldhurst Rd 4 Laning	2019	4.9	2	4	**9.8**	**2**	**137.4**	**14.0**	**E**
Canterbury	Western Belfast By-Pass	2017	5	0	4	**20**	**3**	**174.6**	**8.7**	**N**
Waikato	SH1 Wex Hamilton Section	2021	22	3	4	**22**	**5**	**721.0**	**32.8**	**N**
Waikato	Te Rapa Section	2012	6	2	3	**6**	**3**	**160.3**	**26.7**	**N**
Wellington	Wellington RoNS (6) - SH1 Mackays to Peka Peka Expressway	2021	18	2	4	**36**	**4**	**744.7**	**20.7**	**N**
Wellington	Wellington RoNS (7) - SH1 Peka Peka to Otaki Expressway	2022	12.5	2	4	**25**	**2**	**449.4**	**18.0**	**N**
Total			**128.9**			**333.8**	**45**	**4706.4**	**14.1**	

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