UNIVERSITY OF AUCKLAND
Waipapa Taumata Rau
NEW ZEALAND

BUSINESS SCHOOL

Economic Policy Centre

The University of Auckland Business School

Agglomeration, Congestion, and the Effects of Rapid Transit Improvements on Cities

Ryan Greenaway-McGrevy and James Allan Jones

February 2022

Economic Policy Centre

WORKING PAPER NO. 007

Agglomeration, Congestion, and the Effects of Rapid Transit Improvements on Cities

Ryan Greenaway-McGrevy James Allan Jones*

The University of Auckland

Abstract

We study the impact of rapid transit (RT) within a monocentric city model that features agglomeration efficiencies and congestion frictions. While RT increases wages and city size, its effect on road vehicle use is ambiguous. Vehicle kilometres travelled (VKT) can increase when either agglomeration or congestion effects are sufficiently large. Policies to reduce VKT by developing RT should therefore provide additional (dis)incentives to public (private) transportation. Calibrating the model to Auckland, New Zealand, substantial improvements in RT capacity generate negligible changes in VKT. However, combining improvements with a congestion charge generates meaningful reductions in VKT while maintaining increases in wages.

Keywords: Agglomeration, Congestion, Mode Choice, Rapid Transit, Public Transport, Commuting Costs.

JEL Classification: R12, R15, R41.

*Jones is a Research Fellow at the Economic Policy Centre funded by the Kelliher Charitable Trust. We thank the Kelliher Charitable Trust for their financial support.

1.0 Introduction

Balancing living standards against environmental sustainability is arguably the most important policy priority of the twenty-first century. Because cities are increasingly the locus of economic activity (Glaeser, 2011), reducing the environmental footprint of the economy necessitates a transformation of urban form and transportation infrastructure in many countries. Rapid transit (RT), such as rail or subways, presents a plausible set of technologies to achieve this balance because RT is typically more energy efficient than private vehicle use, allowing more commuters to get to work with less energy use.

Motivated by the need to achieve this balance, this paper studies the impact of RT commuting corridors on commuting mode uptake, productivity, wages and city size. We employ a monocentric model of the city in the tradition of Venables (2007) that features both agglomeration and congestion effects, which are key factors affecting city development. Households are located on a flat disk around a central business district (CBD) and choose whether to commute to the CBD to earn city wages or remain at home and earn outside option wages. Agglomeration effects cause wages to rise with the total number of commuters. Households must also choose between two commuting modes: private road networks and a public rapid transit option. RT offers a faster commute speed, but households must first commute to a RT corridor (or "line") in order to use it. The private road network offers a direct commute to the CBD, but at a lower speed. Congestion effects cause commuting costs within a given mode to increase with the number of commuters using the mode.

We use the model to examine the impact of the construction of public rapid transit lines. While a new line increases wages, worker productivity and city size, its effect on private vehicle use is ambiguous and depends on the magnitude of the agglomeration and congestion effects. A new line induces mode-switching from private vehicles to rapid transit among incumbent residents,[1] however it also indirectly induces new entrants to commute to the city through both congestion

[1] 'Incumbents' refers to households in the city prior to the policy change.

and agglomeration mechanisms. Many of these new entrants use private vehicles. Total private vehicle usage – as measured by vehicle kilometres travelled (VKT) – can *increase* when the rise in private VKT from entrants exceeds the reduction in VKT from incumbent car users switching to rapid transit. Holding pecuniary commuting costs constant, this occurs when either agglomeration effects or congestion costs are sufficiently high.

The congestion mechanism operates by reducing the cost of commuting. Road network congestion initially falls as incumbents switch modes from private vehicles to rapid transit. This reduces commute times on the road network and induces many non-incumbent households beyond the city fringes to start commuting to the CBD. Because these trips cover a greater distance than those replaced by the rapid transit option, VKT can increase even when the total number of road commuters falls.

The agglomeration mechanism operates by increasing the gains from commuting. The new RT corridor induces non-incumbent households sufficiently close to the end of the new corridor to start commuting to the city.[2] These entrants increase wages via agglomeration economies, inducing additional non-incumbent households to commute to the CBD by either rapid transit or road networks. Equilibrium is restored as congestion costs eventually grow faster than agglomeration effects as city size increases.

The ambiguous impact of RT improvements on private vehicle use can be understood as a corollary of the well-known induced demand effects that result from increases in road network capacity. In transportation, induced demand refers to situations where increases in road network capacity are absorbed by additional commuters, such that travel times remain largely unimproved (Lee *et al.*, 1999). This phenomenon is often referred to as the "fundamental law of highways congestion" (Downs, 1962; 1992) or the "fundamental law of road network congestion" (Duranton and Turner, 2011). In economic terms, induced demand reflects elastic demand for road use in response to reductions in congestion causes by improved network capacity.[3] Demand is likely to

[2]We assume that the rapid transit line extends at least to the edge of the city.

[3]We use 'congestion' to refer to a measure of road use compared to road capacity. This differs to some uses in the transportation literature, however it is the same definition as used in telecommunications networks.

be elastic in a city where road speeds are suppressed due to congestion and trips are consequently deferred due to the high time-costs of commuting in traffic. Improvements in rapid transit that induce car commuters to switch to modes initially reduce congestion on road networks by reducing the number of road users. When demand for road use is high, the incipient reduction in congestion will induce large numbers of workers that previously deferred journeys to start commuting, ultimately generating insubstantial reductions in traffic congestion and traffic speeds.

This result provides a potential explanation for extant empirical work which finds an ambiguous effect of public transport improvements (PT) on the use of private road vehicles. For example, Duranton and Turner (2011) and Beaudoin and Lin Lawell (2018) find that PT improvements *increase* road use in the long run in US cities, while Garcia-López *et al.* (2020) find that PT improvements in European cities *reduce* road use. Our paper provides plausible explanations for the differential impacts of RT improvements on road network congestion in these different environs.

Our findings also underscore the need for policy coordination to meet emissions and energy reduction targets. The construction of additional public transit options may be insufficient and additional (dis)incentives required to reduce private vehicle usage. These could include disincentives such as congestion charges, carbon taxes, or parking charges, or incentives such as public transport subsidies.

To illustrate the need for policy coordination, we calibrate the model to Auckland, New Zealand, and examine the impact of RT capacity improvements. Transport is the third largest component of New Zealand's Greenhouse Gas Emissions, contributing 18 per cent to total emissions (MBIE, 2020). A proposed target of the New Zealand government's Emissions Reduction Plan (ERP) is to reduce total VKT by providing better public transport options in large cities.[4] However, we demonstrate that, although increasing RT capacity increase wages and productivity, it has a marginal effect on VKT, even when RT capacity is tripled. For example, increasing RT capacity by one-third causes VKT to increase by 0.01 per cent, while a tripling of capacity only

[4]See table 6 on page 56 of the ERP discussion document. Note this document will be formalised in May 2022. https://www.mpi.govt.nz/consultations/emissions-reduction-plan/

causes VKT to fall by 0.63 per cent. This indicates that reductions in VKT from incumbents switching to RT are nearly exactly offset by new entrant road users in response to RT improvements. We therefore consider pairing RT improvements with a road congestion charge sufficient to reduce VKT by 20 per cent. We show that wages increase provided that RT capacity is increased by at least 133 per cent. Further improvements in excess of 133 per cent result in larger wage increases. Extant work on the effect of a congestion tax in spatial equilibrium models finds that gains from less congestion are offset by reductions in agglomeration benefits (Brinkman, 2016). Our work suggests that RT capacity improvements, paired with a congestion tax, can reduce congestion while increasing wages.

Our rapid transit commuting option is intended to model a variety of fully segregated public transit modes. Fully segregated refers to vehicular systems that do not compete for space with cars on roads or highways and can reach speeds that exceed those attained by private vehicles on road networks. Heavy rail is a prototypical example. But it also encompasses separated busways, where buses effectively have their own road. Fully segregated contrasts against public transit that competes with private vehicles on roads. For example, many buses and light rail routes share road space, and travel at or below the posted speed limit on the road.

Our work builds on extant work in the urban development and transport economic literature. It extends the Venables (2007) model used by Hazledine *et al.* (2017) by allowing households to choose between road network and rapid transit commuting, thereby making the number of rapid transit users an endogenous outcome of the model. Mode choice is modelled through households selecting the lower cost commuting option, resulting in mode catchments comprised by households that exclusively use the commuting mode. This feature of the model incorporates the transport technology rays used in Anas and Moses (1979) and Baum-Snow (2007) in the case of highways. Our work differs to Baum-Snow (2007) in that we conceptualise the ray as a rapid transit line, rather than a highway.

The remainder of the paper is organized as follows. The following section provides a literature review. Section 3.0 describes the model and equilibrium conditions. In section 4.0 we show how the addition of a rapid transit line increases wages, productivity and city size, while having an ambiguous impact on private VKT. In section 5.0 we describe the data and model parameter sources used to calibrate the model to Auckland. This section goes on to illustrates the impact of construction of additional rapid transits lines to the outcome variables of interest: wages, city size and VKT for the specific case of Auckland. Section 6.0 concludes.

2.0 Literature Review

Our model directly builds on the Venables (2007) model used by Hazledine *et al.* (2017) by incorporating mode choice and transport technologies introduced in Anas and Moses (1979). Our model is also related to that of Brinkman (2016), who develops a spatial equilibrium city model incorporating both congestion costs and agglomeration efficiencies in order to model congestion pricing. Brinkman (2016) finds that a Pigouvian congestion charge reduces congestion, but that the welfare gains from less congestion are completely offset by reductions in productivity. However, his model does not feature mode choice between fully segregated rapid transit and road networks.

Our work is also motivated, in part, by the large empirical literature on the impact of transportation network improvements on road utilization. Much of this work focuses on the effects of improvements in road network capacity on road usage, generating the so-called "fundamental law of road network congestion". The fundamental law states that, on urban commuter highways, peak-hour traffic congestion will rise to the maximum capacity of the road network (Downs, 1962; 1992 and Duranton and Turner, 2011).

The fundamental law has been empirically investigated in a number of studies that also control for the endogeneity of road capacity investment and congestion.[5] Duranton and Turner (2011) and Hymel (2019) use an instrumental variable (IV) approach and estimate unit elasticities between road capacity (measured in lane kilometres), and VKT in panel data of major urban roads and interstate highways in the US. Elasticities of greater than one are found using a similar IV analysis

[5]While this topic has been extensively researched, many earlier studies do not account for endogeneity, and/or focus on single road case studies which are hard to generalize. For a review see Hymel (2019).

with data for Japan in Hsu and Zhang (2014) and for 545 European cities in Garcia-López *et al.* (2020). These results suggest that building additional highway capacity does not alleviate congestion, in fact, it may exacerbate it.

However, our focus is on changes in VKT following improvements in public transport, which has received less attention in the literature. Nonetheless, Duranton and Turner (2011) and Garcia-López *et al.* (2020) also investigate the response of VKT to an increase in public transit provision.[6] Duranton and Turner (2011) find no impact of increasing kilometres of public bus provision on VKT. This suggests that any VKT saved by road users who switch to public transit is being entirely replaced. However, Garcia-López *et al.* (2020) find that an increase in railway capacity of 1 per cent does lead to a reduction in VKT of 0.5 per cent. The model developed in our paper also shows that a PT improvement can have an ambiguous effect on VKT – and provides a potential explanation for the different results in the US and Europe. For example, we estimate that that VKT will increase (decrease) for a unit PT improvement in a city starting from a low (high) level of PT infrastructure, which accords with patterns in the US and Europe. In support of this idea, Garcia-López *et al.* (2020) find that the impacts of rail capacity improvements are magnified in cities with a high proportion of existing subway networks.

Other empirical evidence of the effect of PT on congestion is similarly mixed (see Beaudoin and Lin Lawell, 2018 and Anderson, 2014 and references therein). Beaudoin and Lin Lawell, 2018 tackle one potential issue relating to a focus on different time horizons.[7] They look at the impact of PT capacity investment on VKT over the short, medium and long term. Using an IV approach on US data, they find that a 10 per cent increase in PT capacity leads to a 0.7 per cent reduction in VKT in the short run as users shift to the new mode. However, in the long run, induced demand effects offset this to result in a 0.4 per cent net increase in VKT. Beaudoin and Lin Lawell, 2018 find that the initial decrease, and subsequent net increase, is larger for more congested cities. This accords with our model.

[6]Both papers use additional instrumental variables to account for the fact that public transit provision may also be endogenous to congestion and VKT.

[7]It is notable that there are five years between rounds in Garcia-López *et al.* (2020), who find a mitigating effect of PT on VKT, and ten years in Duranton and Turner (2011), who find no relationship.

Studies that use natural experiments to investigate the impact of PT capacity changes on road use sometimes find that PT substitutes for road use. For example, Anderson (2014) finds large increases in road congestion during a strike of Los Angeles PT workers. However, a key limitation of PT outage studies is the inability to generalise to the long-term. Other studies find an ambiguous effect. Gendron-Carrier *et al.* (2022) find that the opening of a new subway system in 58 cities around the world has an ambiguous effect on air pollution. Of the 58 cities in their sample, 26 cites experienced a decrease in pollution, 12 saw no change, and 20 experienced an increase in pollution. Gendron-Carrier *et al.* (2022) also look at a longer time horizon than Anderson (2014).[8]

3.0 The Model

The model describes a monocentric city in which employment is sufficiently dense in the CBD to generate agglomeration economies which do not occur in the more sparsely-populated suburbs. Workers are uniformly distributed in housing across a two-dimensional space around the CBD that spans $\theta \leq 2\pi$ radians. The higher productivity in the CBD generates a wage premium $y(N)$ which encourages workers to commute from the suburbs into the CBD each day. This wage premium is increasing in the number of workers N in the CBD to reflect agglomeration effects. Workers that do not commute earn a lesser outside option wage.

Workers that commute to the CBD face transportation costs that incorporate congestion costs. Commuting times are increasing in both the number of commuters and the distance of the housing from the CBD. Households commute iff the benefit of commuting (wage premium) exceeds the cost of commuting (travel cost). Because transport costs are increasing in distance from the CBD, only households located sufficiently close to the CBD will commute. Locations where commuting costs equal commuting benefits delineate the boundary of the city and define

[8] Gendron-Carrier *et al.* (2022) observe data for the 18 months pre and post a subway opening. This is much longer than Anderson (2014), who looks at a 35 day strike, but much shorter than Duranton and Turner (2011) and Garcia-López *et al.* (2020), who use 10 and 5 year intervals respectively.

the spatial equilibrium. Workers within the boundary commute to the city centre. Workers outside do not. A worker located at the boundary is indifferent as the wage premium is exactly offset by commuting costs.[9]

Workers can choose between two different commuting modes: private vehicles on road networks that take the worker directly to the CBD from their home, and rapid transit along designated corridors that emanate from the CBD at fixed locations. For ease of exposition, we refer to the rapid transit commuting mode as *rail* in the text that follows, while commuting by private vehicles is referred to as *road*. Households select the lower cost commuting option, resulting in mode catchments comprised by households that exclusively use the commuting mode. This results in the disc of the Venables model being partitioned into road-commuting catchments and rail-commuting catchments. Within rail catchments, the boundary of the city depends on the angular displacement from the nearest rail line. Within road catchments, the boundary is a constant distance from the CBD.

3.1 Mode Choice

The city features r infinitely long rail lines radiating out from the CBD.[10] Let $z \in \mathbb{R}^+$ denote a measure of (straight line) distance to the city centre (radius). For instructive purposes we measure z in kilometres (km). Let ε denote the angular displacement from the nearest rail line measured in radians. A household located at polar coordinates (z, ε) has two mode choices. First, they can travel directly to the CBD by road. The distance of this commute is z. Second, they can commute by rail. To model this commute we adopt the commuting path used by Anas and Moses (1979). Households must first travel along the arc of a circle at distance z from the CBD to a rapid transit line. The length of this part of the commute is εz. For instructive purposes, we refer to this connector travel mode as *walking*[11]. Once they reach the line, they commute distance z

[9] Workers within the boundary earn a wage premium that exceeds their travel costs. This surplus is captured by higher rental costs closer to the CBD. Workers are therefore indifferent between locations.

[10] For instructive purposes we often refer to $r$as an integer. However in the model we permit $r \in \mathbb{R}^+$ to allow differences in the capacity of lines.

[11] Connector travels modes could include actives modes such as walking and cycling, public transportation such as buses, or private vehicles.

to the CBD on the rail line. The total distance of the rail commute is therefore $(1+\varepsilon)\, z \geq z$.

3.2 Travel Costs

We assume that travel costs are increasing and linear in distance and that they can vary by each commuting mode (road, rail, and walking). Travel costs are also (weakly) increasing in the number of commuters using the mode, which reflects congestion effects. At this stage we proceed under the assumption that these costs are increasing in the number of mode users. In Section 4.2 we explore a complicated version of the model that decomposes travel costs into pecuniary costs, the opportunity cost of commuting time, and subjective costs of potential crowding within a vehicle (which is more salient for public transport options).

Let $TC_j\,(N_j)$ denote two-way (or round trip) travel costs per kilometre to and from the CBD, where $j \in \{RL, M, W\}$ denotes the Rail, Road and Walking modes, respectively, and N_j denotes the numbers of commuters using mode j. Note that N_{RL} is the total number of rail users using one line (or rapid transit ray). The total number of rail users is denoted $N_R = rN_{RL}$. The total number of people waling to each line is equal to N_{RL}. Households choose the cheapest commuting option given their location (z, ε). Total travel costs for the road commute are $TC_M\,(N_M) \times z$. Travel costs for the rail commute are $(TC_{RL}\,(N_{RL}) + \varepsilon TC_W\,(N_{RL})) \times z$.[12]

3.3 Mode Catchments

Households choose a commuting mode to minimize travel costs resulting in a city comprised of mode catchment areas. In each area all households use the same mode of transport. Consider a household that is indifferent between the road and rail commuting options, and let $\left(z, \frac{\theta_{RL}(z)}{2}\right)$ denote the polar coordinates for this household. For these households

$$TC_M\,(N_M) \times z = \left(TC_R\,(N_{RL}) + \tfrac{\theta_{RL}(z)}{2} TC_W\,(N_{RL})\right) \times z.$$

z can be cancelled out form both sides and we have an expression that is independent of distance to the CBD:

[12]Because the rail commuting distance is no less than that of the road commuting distance, rail travel costs cannot exceed road costs in order for there to be any rail commuters.

$$TC_M(N_M) = TC_R(N_{RL}) + \frac{\theta_{RL}}{2} TC_W(N_{RL}), \tag{1}$$

or

$$\theta_{RL} = 2 \times \frac{TC_M(N_M) - TC_R(N_{RL})}{TC_W(N_{RL})}. \tag{2}$$

Households within $\frac{\theta_{RL}}{2}$ radians of the rail line choose to commute by rail. θ_{RL} defines the radians of the rail catchment. We assume each rail line is identical and that the lines are located at sufficient distance to one-another that each catchment does not overlap. This implies that the total number of rail radians in the city is $\theta_R := r\theta_{RL}$.

We let $\theta_M = \theta - \theta_R$, define the radians of the road catchment of the city. Because road travel costs $TC_M(N_M)$ from location (z, ε) are constant for a given z, the road catchment is a circular segment. We define $\bar{z}$ as the distance at which a household located further than $\frac{\theta_{RL}}{2}$ radians from a rail line is indifferent between commuting and not commuting. This implies that total commute costs equal the wage premium $y(N)$. This can be re-arranged to give:

$$\bar{z} = \frac{y(N)}{TC_M(N_M)}.$$

By standard circular geometry the catchment of the road commuting mode spans a circular segment with area $\frac{1}{2}\bar{z}^2\theta_M$.

Households located within $\frac{\theta_{RL}}{2}$ radians from a rail line also choose to commute into the CBD provided that the wage premium exceeds total travel costs. However, because travel costs for rail commuters from location (z, ε) are not constant for a given z, the area of the rail catchment is not a circular segment. Figure 1 depicts this in an example city with two rail lines. The rail catchment area for each line is defined by the set of (z, ε) satisfying

$$(TC_R(N_{RL}) + \varepsilon TC_W(N_{RL})) \times z = TC_M(N_M)\bar{z},$$

and $0 \leq \varepsilon \leq \frac{\theta_{RL}}{2}$. This condition sets commuting costs of the marginal rail commuter to that of the marginal road commuter. As demonstrated in Figure 1, there are rail commuters who travel distances in excess of $\bar{z}$. To see why this is the case, consider the rail commuter who is indifferent between road, rail and the outside option wage. This individual will be located at polar coordinate $\left(\bar{z}, \frac{\theta_{RL}}{2}\right)$. An example of this individual is given by point A on the figure. Next consider the individual at coordinate $(\bar{z}, 0)$, denoted by point B. Since they are on the rail line, their walking costs are zero and the wage premium exceeds their costs of commuting. The indifferent commuter who lives on the rail line and whose total rail cost equals the wage premium is located at $(\bar{z}_{RL}, 0)$, shown by point C. Note that travel costs at $(\bar{z}_{RL}, 0)$ are equal to those at $\left(\bar{z}, \frac{\theta_{RL}}{2}\right)$. This means that we can solve for

$$\bar{z}_{RL} = \frac{TC_M(N_M)}{TC_{RL}(N_{RL})}\bar{z} \tag{3}$$

In the Appendix we show that the area of the rail catchment for each line satisfies

$$A_{RL} = \frac{\theta_{RL}}{2}\frac{TC_M(N_M)}{TC_R(N_{RL})}\bar{z}^2 = \frac{\theta_{RL}}{2}\frac{y(N)}{TC_R(N_{RL})}\bar{z} \tag{4}$$

[Insert Figure 1 here]

3.4 Distribution of Workers

Population is uniformly distributed at k people per square kilometre. The density function of uniformly distributed workers living at distance z from the CBD is

$$n\left(z\right) := zk.$$

Let $n_M\left(z\right)$ denote the total number of road users at distance z. $n_M\left(z\right)$ is the length of the arc of the circular segment of the road catchment at distance z multiplied by the density of workers, that is $n_M\left(z\right) = zk\theta_M$. Integrating this over $z = [0, \bar{z}]$ yields the total number of car commuters:

$$N_M := \frac{1}{2}\bar{z}^2 k\theta_M. \tag{5}$$

The distance travelled by an individual road users is $n_M\left(z\right) \cdot z$. Total distance travelled by road commuters within distance z is given by the integral of this expression over z:

$$D_M := k\bar{z}^3 \tfrac{\theta_M}{3} \tag{6}$$

This is our measure of VKT in the model. The average distance travelled by road commuters is

$$d = \frac{D_M}{N_M} = \frac{\frac{1}{3}k\bar{z}^3\theta_M}{\frac{1}{2}k\bar{z}^2\theta_M} = \frac{2}{3}\bar{z}$$

which we then invert to get the distance travelled by the marginal commuter:

$$\bar{z} = \frac{3}{2}d. \tag{7}$$

The total number of rail commuters is given by the area of the rail catchment from equation (4) multiplied by density k and the total number of rail lines:

$$N_R := r\frac{\theta_{RL}}{2}\tfrac{TC_M(N_M)}{TC_R(N_{RL})}\bar{z}^2 k = r\frac{\theta_{RL}}{2}\tfrac{y(N)}{TC_R(N_{RL})}\bar{z}k. \tag{8}$$

Total population of commuters is then given by

$$N := N_M + N_R \tag{9}$$

3.5 Wages

Wages feature agglomeration efficiencies. Agglomeration efficiencies enhance productivity: The greater the number of workers and firms in close proximity to one-another, the greater their collective productivity (Glaeser, 2008, pp 116–118). The wage premium for downtown workers is

$$y(N) = (1-\tau)\, cN^{\delta} \tag{10}$$

where $\delta \geq 0$ permits wages to be increasing in N to reflect agglomeration effects. τ is the tax rate on income.

3.6 Equilibrium

The model is closed by setting the benefit of commuting $y(N)$ to the cost of commuting $TC_M(N_M)$ and solving for $\bar{z}$. Road and rail commuting costs must satisfy the equivalence condition (1). In many cases the solution must be obtained numerically, particularly when the travel cost functions are complex. In the following section we provide both closed form and analytic solutions to the model based on different assumptions imposed on the travel costs functions.

4.0 Impact of Rapid Transit Improvements

In this subsection we analyse the effects of rapid transit improvements on wages, city size and VKT. We show how increases in rapid transit capacity have an ambiguous effect on VKT and depend on the magnitude of parameters that govern agglomeration and congestion effects.

We do this in two ways. First, we demonstrate these effects theoretically using a simplified version of the model that yields closed-form solutions. Second, we provide analytic solutions based on a numerical simulation of the model that uses a more complicated formulation of travel cost functions.

4.1 Theoretical Results

In this section we present a simple version of the model to illustrate how RT improvements have an ambiguous effect on VKT. Road congestion is given by:

$$t_M(N_M) = \alpha N_M^{\beta},$$

where $\alpha > 0$ and $\beta > 0$. $t_M(N_M)$ is the travel time per kilometre and is the inverse of speed. Hazledine *et al.* (2017) use a similar functional form for commuting speed. We assume that there are no pecuniary costs to commuting and subjective costs per minute spent commuting are constant, such that $TC_M(N_M) = t_M(N_M)$.[13]

Following Baum-Snow (2007), rapid transit line travel time per kilometre is $t_R = \kappa t_M(N_M)$, where $\kappa \in (0,1]$. We also assume that commuters travel to the rapid transit line along an arc and at a travel cost of $t_M(N_M)$. This is analogous to using private vehicles to get to the rapid transit line. Under (3) we have $\bar{z}_{RL} = \frac{\bar{z}}{\kappa}$. Then from (5) and (8) we have:

$$N = N_M + N_R = N_M\left(1 + \frac{r}{\kappa}\frac{\theta_R}{\theta_M}\right) = \frac{1}{2}\bar{z}^2 k\left(\theta_M + \frac{r\theta_R}{\kappa}\right) = \frac{1}{2}\bar{z}^2 k\theta^*,$$

for $\theta^* := \theta_M + \frac{r\theta_R}{\kappa}$. Next we solve for θ_R. Under (1) it follows that

$$t_M(N_M) = \kappa t_R + \frac{\theta_R}{2}t_R = \left(\kappa + \frac{\theta_R}{2}\right)t_M(N_M),$$

or[14]

$$\theta_R = 2(1-\kappa).$$

Thus we have

$$\theta_M = \theta - 2(1-\kappa)r,$$

and

$$\theta^* = \theta_M + \frac{r}{\kappa}\theta_R = \theta - 2(1-\kappa)r + 2(1-\kappa)\frac{r}{\kappa} = \theta + 2r(1-\kappa)\left(\frac{1-\kappa}{\kappa}\right),$$

[13] Note that $TC_M(N_M)$ is round trip (2 way) per kilometre costs and $t_M(N_M)$ is per kilometre travel time. Hence this expression implies that subjective commuting cost per minute are $\frac{1}{2}$ and omitted for simplicity.

[14] Note this implies that as $\kappa \to 0$ (or the RT line becomes infinitely fast) it follows that $\theta_R \to 2$, so that the commuter only faces costs of t_R per km to get to get to the RT line. These are the same costs they face if they commute directly to the CBD.

Equilibrium is attained by setting the wage premium equal to travel costs at $\bar{z}$,

$$cN^{\delta} = 2\bar{z}\alpha N_M^{\beta},$$

where we assume $\tau = 0$. Substituting in the above expressions for N and N_M and rearranging yields the solution for $\bar{z}$:

$$\bar{z} = \left[\frac{c}{2\alpha} \frac{2^{\beta-\delta}}{k^{\beta-\delta}} \frac{\theta^{*\delta}}{\theta_M^{\beta}} \right]^{\frac{1}{1+2(\beta-\delta)}}.$$

To analyse the effect of RT improvements on VKT, we take the partial derivative of D_M from (6) with respect to r. By the chain and product rules we have

$$\frac{\partial D_M}{\partial r} = \frac{k}{3}\bar{z}^3 \frac{\partial \theta_M}{\partial r} + 3k \left(\frac{\partial \bar{z}}{\partial r} \right)^2 \theta_M. \tag{11}$$

The first term captures displacement of incumbents moving to using rail. It is negative since

$$\frac{\partial \theta_M}{\partial r} = -2\left(1 - \kappa\right).$$

The second term captures the new entrants since it describes how $\bar{z}$ changes as r increases. Solving for $\frac{\partial \bar{z}}{\partial r}$ via the product rule yields

$$\frac{\partial \bar{z}}{\partial r} = \frac{\delta}{1+2(\beta-\delta)} \left[\frac{c}{2\alpha} \frac{2^{\beta-\delta}}{k^{\beta-\delta}} \frac{1}{\theta_M^{\beta}} \right]^{\frac{1}{1+2(\beta-\delta)}} \left(\frac{\partial \theta^*}{\partial r} \right)^{\frac{\delta}{1+2(\beta-\delta)}-1} - \frac{\beta}{1+2(\beta-\delta)} \left[\frac{c}{2\alpha} \frac{2^{\beta-\delta}}{k^{\beta-\delta}} \theta^{*\delta} \right]^{\frac{1}{1+2(\beta-\delta)}} \left(\frac{\partial \theta_M}{\partial r} \right)^{\frac{-\beta}{1+2(\beta-\delta)}-1},$$

where $\partial \theta^* / \partial r = \frac{2(1-\kappa)^2}{\kappa} > 0$ is the agglomeration effect and $\partial \theta_M / \partial r = -2\left(1 - \kappa\right) < 0$ is the congestion effect. Since $\partial \theta_M / \partial r$ is negative, both terms in the equation above are positive, meaning $\frac{\partial \bar{z}}{\partial r}$ is positive.

The ambiguous effect of RT improvements on VKT is now evident. The magnitude of the first term in (11) (which is strictly negative) may be greater or less than that of the second term (which is strictly positive) depending on other model parameters.

4.2 Numerical Simulation

We now consider a more complicated version of the model that incorporates the full suite of travel costs permitted under our framework. We select values for the relevant parameters and solve for endogenous variables $\bar{z}$, $y(N)$, θ_R, N_M, N_R, and D_M. We examine how $y(N)$, N and D_M change as we vary parameters that moderate agglomeration and congestions effects.

First we describe the components of the travel cost function. We then present simulated results.

4.21 Travel Cost Function

Travel costs are comprised of pecuniary costs, the opportunity cost of commuting time, and subjective costs of crowding. Following Kulish *et al.* (2012) the opportunity cost of time is a proportion of the wage. To model the subjective costs of crowding, we follow the transport literature surveyed by Wardman and Whelan (2011). Subjective costs are weakly increasing in mode users and amplify the opportunity cost of commuting time.

Commute times in each mode are subject to congestion so that commute times are weakly increasing in the number of mode users. The congestion function for a given mode depends only on commuter usage of the given mode, and is independent of usage in the other mode. This is a critical feature of the model and reflects that the rail mode does not compete with private vehicles for space on the road network.

Pecuniary Cost. The pecuniary cost per kilometre travelled in each mode is g_j for $j \in \{r, m, w\}$. We assume the walking mode is free and thus $g_w = 0$.

Congestion Function. We use an exponential travel time function typically used by transportation engineers and commonly referred to as the 'Bureau of Public Roads congestion function' (United States. Bureau of Public Roads., 1964)[15]. This defines the time to travel a kilometre in mode j as the following:

$$t_j(N_j) = t_{f,j}\left(1 + \alpha\left(\frac{N_j}{N_{j,cap}}\right)^{\beta}\right) \tag{12}$$

[15] A version of this travel function is used in Larson and Yezer (2015)

where, for road commuting, α and β are assigned the values 0.15 and 4 respectively.[16] $t_{f,j}$ is the free flowing travel time per kilometre of the mode. N_j is the number of users of mode j. $N_{j,cap}$ is the capacity of the transport mode. When N_j is small relative to $N_{j,cap}$, $t_j\left(N_j\right) \approx t_{f,j}$ and the network is uncongested. As the number of users approaches and exceeds the capacity of the route, $t_j\left(N_j\right)$ increases rapidly.

We assume that both rail and walking modes operate at free flowing speeds, even during peak hours. Hence we set $t_j\left(N_j\right) = t_{f,j}$ for $j = R, W$.

Opportunity Cost of Time. It is typical in the literature to use an opportunity cost for time spent commuting that is based on a proportion of the individuals wage. For example, Kulish *et al.* (2012) use a rate of 60 per cent of the wage. We define the opportunity cost of time as

$$G_T = \xi\left(\frac{y\left(N\right) + \bar{y}}{8 \times 60}\right), \qquad (13)$$

where $y\left(N\right)$ is the daily wage premium in the CBD and $\bar{y}$ is the daily wage for non-commuters. These are added together and divided by 480 to get a per minute total CBD wage, to match the per-minute per-kilometre of the travel time functions. Note that we assume an 8 hour workday. ξ is the proportion of the wage attributable to the opportunity cost of time.

Subjective Costs of Crowding. It is common in the transport policy and engineering literature to model subjective costs of public transit as increasing in number of commuters.[17] Motivated by this literature, we define a subjective cost function that is increasing with the number of users in a mode as follows:

$$\gamma_j\left(N_j\right) = G_T N_j^{s_j}, \quad s_j \geq 0 \qquad (14)$$

$\gamma_j\left(N_j\right)$ is the subjective cost per minute spent travelling. This is derived by augmenting the

[16] When parametrized with α and β as described above, Equation (12) implies that travel times on a road at full capacity are approximately 87 per cent of the free flow travel times. This is a common scenario for road transportation engineers whereby a moderately congested road at a slower speed carries a greater volume of vehicles per minute than an uncongested road at full speed.

[17] See Li and Hensher (2011), Wardman and Whelan (2011) and Li *et al.* (2020) and references therein.

opportunity cost of time with a 'crowding multiplier' given by $N_j^{s_j}$. The intuition is that each minute spent travelling in a crowded environment feels longer to the user than the equivalent time spent in an uncrowded environment. s_j is the elasticity of subjective costs with the number of mode users.

The multiplier effect has been observed in stated preference surveys. For example, Haywood and Koning (2015) find that PT users accept hypothetically slower journeys in exchange for less crowding. The multiplier is also evidenced in revealed preference studies, where users shift to slower, less crowded, journey modes when informed of crowding in their first route choice (Zhang *et al.*, 2017).

We assume that $s_j = 0$ for road and walking modes. This implies that there are no crowding costs to road or walking travel and that we can simplify the subjective cost function for each mode to the opportunity cost of time: G_T.

Travel Cost Function by Mode. Given the travel costs components outlined above, as well as the simplifications for each mode, round trip per kilometre travel costs now take the form of

$$TC_M\left(N_M\right) = 2\left(t_M\left(V_M\right)G_T + g_M\right),$$

for road users. For rail users located at polar coordinate (z, ε) we have round trip per kilometre costs of

$$TC_{RL}\left(N_{RL}\right) = 2\left(t_{f,R}\gamma_R\left(N_{RL}\right) + g_R\right),$$

and

$$\varepsilon \times TC_W\left(N_W\right) = \varepsilon 2 t_{f,w} G_T$$

for the rail and walking components of their journey respectively.

The total commute cost for a commuter at located at (z, ε) is:

$$TC_M(N_M) \times z = 2z\left(t_M(V_M)G_T + g_M\right), \tag{15}$$

to commute by road. To commute by rail their total commute costs will be:

$$\left(TC_{RL}(N_{RL}) + \varepsilon TC_W(N_W)\right) \times z = 2z\left(t_{f,R}\gamma_R(N_{RL}) + g_R + \varepsilon t_{f,w}G_T\right) \tag{16}$$

For the commuter on the edge of the city who is indifferent between road and rail travel we have:

$$y(N) = 2\bar{z}\left(t_M(V_M)G_T + g_M\right) = 2\bar{z}\left(t_{f,R}\gamma_R(N_{RL}) + g_R + \frac{\theta_{RL}}{2}t_{f,w}G_T\right). \tag{17}$$

4.22 Results

We solve the model by finding $\bar{z}$, N_M and N_R such that $y(N)$ in (10) is equal to road costs in (15) and that the equivalence of costs by mode for marginal users in equation (17) is satisfied. With appropriately chosen parameters, our equilibrium can be expressed as a system of simultaneous equations as follows:

$$\begin{aligned} N_R &= rA_{RL}k, \\ N_M &= \tfrac{1}{2}\bar{z}^2k\left(\theta - r\theta_{RL}\right), \\ TC_M(N_M) \times \bar{z} &= (1-\tau)\,c\,(N_R + N_M)^{\delta}. \end{aligned} \tag{18}$$

Noting that A_{RL} and θ_{RL} are given by equations (4) and (2) respectively. We have three equations with three unknowns and the system is solved numerically. Table 6 in the Appendix contains the values of the parameters selected for the simulation exercise. Parameters are informed by the extant literature or else selected to mimic typical outcomes in a mid-sized city.

To explore how the impacts of RT improvements depend on agglomeration and congestion, we solve the model for various values of the parameters that govern agglomeration effects (δ), vehicle capacity $(N_{M,cap})$ and RT capacity (r), and observe the resulting change in the outcome variables of interest. We employ a graphical analysis to examine how congestion and agglomeration mediate the impact of RT improvements on wages, city size and VKT. We begin by examining the level of these variables for various parametrizations of agglomeration efficiencies and congestion effects while holding rapid transit capacity constant. We then consider how the variables change in response to an increase in RT capacity.

[Insert Figure 2 here]

Static Equilibrium. First we analyse equilibrium outcomes under various parametrizations of agglomeration efficiencies and congestion effects. Figure 2 exhibits the city radius $(\bar{z})$ (or size), wages $(y(N))$, road VKT, and road network speed for a city with a single transit line. These are plotted for various values of the road capacity parameter $(N_{M,cap})$ and the agglomeration parameter (δ). Variation in these parameters tell us how congestion (decreasing in $N_{M,cap}$) and agglomeration (increasing in δ) affect the endogenous variables of interest.

City size is increasing in road network capacity and agglomeration efficiencies. Increasing road capacity reduces the costs of commuting by reducing travel costs, while agglomeration efficiencies increase the benefits of commuting by increasing wages. Either effect increases city radius.

Wages are increasing in agglomeration efficiencies, and in road capacity provided that $\delta > 0$. The latter effect is due to a larger city radius when the costs of commuting fall, which increases commuters and thus wages via agglomeration provided $\delta > 0$. Speed is increasing in road capacity and is decreasing in δ. The latter effect is due to agglomeration efficiencies increasing the benefits to commuting. Commuters are compensated for slower commutes with higher wages, and are therefore able to tolerate lower commuting times. Finally, VKT is increasing in both road capacity and agglomeration efficiencies, since city radius is increasing in both these variables.

The surfaces plotted in Figure 2 also tell us about the elasticity of demand for road network usage in response to reductions in congestion. The magnitude of this demand elasticity is useful for understanding how private vehicle use changes in response to the other variables in the model, including RT capacity. City size is concave in road network capacity, which reflects the fact that commuting speeds approach their free flow rate as road capacity increases. At high levels of network capacity, further increases in capacity do not reduce commuting costs by all that much because speeds are already at their upper bound.

This means that demand elasticity for road network usage is decreasing in road capacity. To understand why, it is instructive to decompose commuting costs into speed and distance. Distance accounts for a larger proportion of commuting times in cities with higher levels of vehicle capacity since commuting speeds approach free-flow rates. For the marginal worker located just beyond the city radius, the distance is marginally too great to induce them to commute to the CBD. Demand for road use is consequently unresponsive to capacity improvements, since any increase in capacity will not reduce travel costs for this commuter.[18] Conversely, a city with less road capacity has lower commuting speeds and is smaller because the network is congested. For a worker located just beyond the city boundary, it is speed, rather than distance, that prevents them from commuting to the CBD. Demand for road use is consequently highly responsive to capacity improvements, since an increase in road network capacity will increase speeds and induce road commuting uptake.

Agglomeration increases demand elasticity for road usage by increasing the benefits to commuting to the CBD. It therefore increases the level of network capacity at which the network reaches its free flow capacity, since commuters are more willing to bear increased commuting costs when the return to commuting is higher. This reasoning shows that road network speed is a useful indicator of demand elasticity for road network usage. Demand is responsive when speed is low. Demand becomes less responsive as speed increases and eventually becomes unresponsive as speed reaches it free-flow upper bound.

[Insert Figure 3 here]

[18] This commuter will be induced to commute if wages increase, so demand is more elastic when the agglomeration parameter is large.

Impact of an Additional Rapid Transit Line. Next we examine how the four variables of interest change when an additional public rapid transit line is built. Figure 3 plots the log difference in each variable against road capacity and agglomeration. City size, wages and speed all increase. VKT only decreases in regions of the parameter space where network capacity is high and agglomeration effects are low. Otherwise VKT increases. We discuss the impacts on city size, wages and speed before turning to VKT.

The magnitude of the increases in city size, wages and speed are decreasing in road network capacity. This reflects elastic demand for road network usage. As discussed above, demand is elastic when road network capacity is low. The additional rapid transit line removes some incumbent road commuters from the network. This additional capacity in the road network is absorbed by additional commuters at the fringe of the city who now find it optimal to commute to the CBD given the faster commuting speeds. Although uptake of that capacity by new entrants is high, in equilibrium an increase in commuting speed must be maintained in order to sustain these additional commuters. Conversely, in cities with inelastic demand, the additional capacity on road networks does not increase city size by as much because commuting speeds were already close to free flow rates.

The magnitude of the increases in city size, wages and speeds are increasing in the agglomeration effect. The additional rapid transit line brings more commuters into the CBD, which increases wages when there are agglomeration efficiencies. Increased wages attract additional commuters into the CBD, further increasing the city size until travel costs equal benefits for the marginal commuter.

Next, we discuss the changes in VKT. VKT decreases when both vehicle capacity is high and agglomeration effects are low. These are regions of the parameter space in which demand for road network usage is inelastic, since road network speed is high. When demand is inelastic, the reduction in private vehicle use among incumbents outweighs the increase from new entrants.

Conversely, demand is elastic when either agglomeration effects are strong, or vehicle capacity is low. When agglomeration effects are strong, the additional transit line brings additional workers into the CBD, which increase wages via agglomeration effects. Higher wages incentivize new entrants to commute to the CBD via the road network even when roads are uncongested, since the benefits to commuting have increased while commuting costs remain constant. When vehicle capacity is low, the additional rail line releases capacity on the private road network, increasing commuting speeds. This reduces the cost of commuting for workers at the fringes of the city, inducing them to start commuting to the CBD. The congestion and agglomeration effects work in the same direction and reinforce one-another: The largest increase in VKT in the plotted surface occurs when vehicle capacity is low and agglomeration effects are high.

This means that in certain regions of the parameter space where demand for road usage is elastic, increases in RT capacity will not reduce VKT, but increase them. In the section 5.2 we discuss policy coordination strategies that can reduce VKT in these regions of the parameter space.

Impact of Increases in Rapid Transit Capacity. Finally, we consider significant increases in the number of rapid transit lines, from one through to forty lines. Figure 4 plots the level of the wages, city size, speed and VKT against the agglomeration parameter and the number of RT lines. We set road capacity to 35, which is in the middle of the range considered in Figures 2 and 3.

City radius is increasing in the number of rail lines, since additional lines reduce commuting costs through lesser road congestion and increase commuting benefits through agglomeration effects. Wages are consequently increasing in rail lines when $\delta > 0$ since city size is increasing in rail lines. Road network speeds are increasing in rail lines since these remove car commuters from the road.

[Insert Figure 4 here]

VKT is increasing in agglomeration effects. However, in contrast to wages, city size and speed, it is not monotonic in RT capacity. VKT is decreasing in RT lines for sufficiently low levels of the agglomeration elasticity parameter and initially increasing for sufficiently high levels of the parameter. The marginal effect of RT capacity is decreasing and becomes negative at sufficiently high levels of RT capacity for all permissible values of the delta parameter. This means that cities that begin with a low level of RT capacity initially experience increases in VKT before they experience decreases. Cities with an already high level of RT capacity will experience reductions in VKT from further improvements. Figure 5 illustrates this point by plotting the change in VKT against unit increases in RT capacity for various levels of the agglomeration parameter.

The decreasing marginal effect of increases in RT capacity on VKT reflects reductions in demand elasticity for road usage as RT capacity increases. Road network speeds increase with RT capacity. Demand elasticity for road usage then falls as speed approaches its free flow rate. As discussed above, this is because the cost to commuting for the marginal commuter is determined by distance rather than speed.

Agglomeration effects mediate the rate at which road speed approaches the free flow rate in response to increase in RT capacity. The rate is decreasing in the agglomeration parameter, meaning that stronger agglomeration effects slow the rate at which speed approaches the free-flow rate. This is because marginal increases in RT capacity increase city size and wages via the agglomeration channel, increasing the incentive to commute for the marginal commuter. The tipping point at which increases in RT capacity induce decreases in VKT is increasing in the agglomeration parameter.

[Insert Figure 5 here]

Our model provides a plausible explanation for the differential impact of PT improvements on vehicle use established in the empirical literature. US studies typically find that improvements in PT capacity cause an increase in VKT in the long-run (Duranton and Turner, 2011; Beaudoin and Lin Lawell, 2018). Our model would predict that this occurs because such cities have high wages, strong agglomeration efficiencies, and/or are beginning from a low level of RT capacity. Conversely, Garcia-López *et al.* (2020) show that PT improvements in Europe precipitate large reductions in VKT on average. Our model would predict this to occur in cities with lower wages, low agglomeration effects and/or are starting from a relatively large amount of PT capacity.

5.0 Calibration and Policy Evaluation

In this section we calibrate the model to Auckland in order to simulate the impacts of rapid transit line construction. This policy evaluation exercise is motivated by New Zealand's Emission Reduction Plan (ERP), which proposes a strategy to reduce total VKT by providing better public transport options. We first describe the data that are used to calibrate the model and inform key parameter choices. The calibrated model provides us with a set of parameters that match observed outcomes of interest. We refer to this solution as the baseline calibration. We then simulate policy outcomes by changing key parameter values and solving for the outcome variables of interest.

5.1 Calibration and Data

We first calibrate the model to match observed values of the endogenous variables for the Auckland region. We solve for $\bar{z}$, V_M, $V_{M,cap}$, c, G_T, g_M, s_R, θ_{RL}, θ_M, and θ, using equations (4), (5), (7), (8), (10), (12), (13), (17), and (19). A step-by-step procedure for this is shown in Appendix section A.4. All remaining parameters are chosen based on data.

Much of the data used for the baseline calibration is obtained from the 2018 census. Geographic delineations are based on 2018 Statistical Area 2 (SA2) area units and the Auckland Territorial Authority.[19] We describe the methods and sources of data in detail below. Table 8 in Appendix A.4 displays a summary of model parameters, endogenous variables, and corresponding data sources.

5.11 CBD and Non-CBD Regions

We require a geographic delineation of the CBD. Commuters to CBD regions are used for estimation of travel time and speed, while the wage premium is estimated based on the difference in incomes paid by firms located inside and outside of the CBD.

[19]In urban areas SA2s generally have populations of 2000-4000 residents.

There are 563 SA2 regions that make up the Auckland Territorial Authority.[20] The CBD of Auckland is typically designated in relation to a ring of highways around the centre of the city.[21] The SA2 regions within the ring of highways have a large number of inbound commuters and a high density of jobs per square kilometre. They also have relatively few outbound commuters. These patterns are also true of several adjacent regions outside of the highway ring. The motorway definition is arbitrary, so the fringe regions have been included as part of our definition of the Auckland CBD. We designate 23 SA2 areas to be CBD regions, illustrated in figure 6.

[Insert Figure 6 here]

5.12 Density

We estimate the density of potential CBD commuters using the stats NZ 'Functional Urban Area' (FUA)[22] classification for SA1 regions. We match this to the larger SA2 level using the modal FUA of the composite SA1 blocks. The FUA classification allows us to identify small urban areas and rural areas that are integrated within the major Auckland urban area to form the core city and it's commuting zone[23].

The density parameter k is calculated as the total number of employed and self-employed workers in the Auckland FUA, divided by the total FUA land area. This results in a density of 0.169 thousand workers per square kilometre**.** Note that this is the density of workers, not the density of residents.

5.13 Commuter Numbers by Mode

Several parameters are chosen or calibrated in the baseline calibration to match the current number of commuters by mode type, (N_M and N_R). Commuter numbers are obtained from 2018 census data. The census identifies the usual means of travelling to work for employed individuals aged

[20]In our analysis several low population regions comprising of inlet water areas, forest blocks or island regions are excluded due to lack of commuter numbers.
[21]Hazledine *et al.* (2017) define the CBD as a group of census area units that fall entirely within this ring of highways. Maré (2008) include additional adjacent regions. Our definition of the CBD is similar to that used in Maré (2008).
[22]https://www.stats.govt.nz/methods/functional-urban-areas-methodology-and-classification
[23]Note that this comprises a smaller area within the wider Auckland region

15 years or older, and reports the number of commuters by mode between every pair of SA2 regions.[24] We focus on the commuters whose place of work is located in a SA2 within the CBD.

The total number of commuters by mode is summarized in table 1. We now introduce two additional complications to the modelling exercise. First, the total number of workers in the CBD also include 'other' and 'unknown' commuters. 'Other' commuter modes include bike, walking, ferry, and working from home. 'Unknown' commuters are workers whose specific mode choice is suppressed in the census data for confidentiality.[25]

The second complication is that we also include data on bus commuters. For the purposes of calibrating the model, road commuters are a combination of private vehicle (or car) users and shared-grade bus commuters. Commuting speeds, distances and travel costs for road commuters are derived from a commuter-weighted average of the relevant figures for the car and bus modes. Similarly, RT speeds and costs are a weighted average of rail and fully segregated bus figures.

We allocate bus users to either the road or RT mode depending on whether their bus route uses majority shared-grade or fully segregated infrastructure. Table 7 in the appendix shows that fully segregated bus travel is very similar in speeds to rail travel, so both can be combined as our RT mode. Bus travel on road networks is much slower than on fully segregated busways, and slightly slower than private road vehicles.

In order to make bus induced congestion comparable to private vehicle congestion, we convert shared-grade bus users to per-private-vehicle equivalents. We then use vehicle equivalents in place of N_M in the travel time equation (12). We define vehicle equivalents to be the total number of cars, plus the the number of shared-grade buses converted to car equivalents. The total number of each vehicle type is determined by dividing the total number of commuters in that mode by

[24]This includes both full and part time work, along with self-employed individuals.

[25]Subtotals for routes and modes with less than 6 users are suppressed for data confidentiality. These number are included the total resident population and total employment figures for each SA2 region. This results in 40K commuters to the CBD whose travel route cannot be determined. These numbers are included in the productivity and population density calculations, but not assigned to any travel mode.

the average number of people per vehicle. This results in the following equation:

$$V_M = \frac{N_C}{p_C} + \rho \frac{N_B}{p_B}, \tag{19}$$

where V_M is the number of vehicle equivalents, N_j is the total number of commuters of mode j and derived from the census commuter data.[26] p_j is the number of people per vehicle in each mode and ρ is the number of cars represented by each bus.

The number of commuters per car is based on the census commuter data. Individuals report if their commute is as a driver or as a passenger. Across the entirety of the Auckland region, 581,499 persons report that they are the driver in their commute, and 33,624 report that they are a passenger. This implies a car occupancy ratio amongst commuters of 1.06.[27] This also holds if we only focus on CBD commuters[28]. The number of commuters per bus and number of cars per bus are set as 24 and 3 respectively following in Hazledine *et al.* (2017).

[Insert Table 1 here]

5.14 Travel Speeds by Mode

Travel times and distances are not recorded as part of the census. We calculate weighted average travel times and distances for each transport mode by combining census data on commuter numbers and flows with Google Maps predicted travel times and distances.

Automated Google Directions API calls are made for route-finding between the GPS coordinates of the centroids of pairs of SA2 regions. The estimated travel times and distances for travel by private car, bus, and rail, are recorded for a commute to and from the CBD region. We collect data on the best estimate for congested travel times in peak traffic. We set the AM commute to

[26] Note that in equation (19), N_C is the total number of car commuters and includes individuals who report that they are drivers or passengers.

[27] Note that this figure is a little lower than the NZ travel survey based on older data, which estimates an average for 2011-2014 of 1.1 people per car for Auckland.The results also hold using the larger figure

[28] We cannot perform this calculation for our exact CBD region because to do so uses disaggregated SA2 level data where the small number of passengers in a route are frequently suppressed for confidentiality. Instead we can use the Waitemata Local Board Area, which includes the CBD and a few surrounding suburbs, where the implied occupancy rate is also 1.06.

arrive before 9am, and the PM commute to leave after 5pm.[29] We estimate free-flowing travel times using off-peak commutes travelling at midday. Additional information on this process is available in Appendix A.3.

Commuter weighted average travel times and distances by mode is calculated by combining the API results with the commuter numbers from the census data. The average travel speed is defined as the weighted average travel distance divided by the weighted average travel time. Table 2 shows the weighted average speeds for each travel mode.

Average commute distance is obtained from a commuter weighted combination of car and shared-grade bus commute distances. This produces an estimate for d of 12.54 kilometres.

[Insert Table 2 here]

Table 7 in Appendix section A.3 shows additional detail on travel speeds by mode in both peak and off peak travel. For road vehicles there is a significant reduction in speed for peak travel. This suggests that the road is over capacity and congested at this time. For rapid transit travel, we note that peak and off peak travel speeds are approximately equal. This suggests that rapid transit in Auckland is not at a bottleneck and speeds are unaffected by the high number of peak-hour patrons. This matches observations for many RT networks around the world. Despite high numbers of rush-hour commuters and significant levels of crowding, travel speeds are often unaffected.[30] Similarly, we find that walk times are also unaffected.

5.15 Pecuniary costs by mode

Pecuniary costs for bus and rail travel are sourced from public transport performance data from Waka Kotahi NZ Transport Agency (NZTA). We divide the total rail fare revenue for the Auckland region in 2018 by the total passenger kilometres travelled in the same period. This produces a per-passenger-kilometre cost of 19.4c/km. The same process is followed for bus travel, yielding 23.7c/km. We assume the same bus costs for shared-grade and fully segregated bus travel. Note

[29] Note that, while Google travel time estimates are not available for past dates, the contemporary travel estimates are based on historical travel times. Direction request are made for travel on 04/08/2021.

[30] See Haywood and Koning (2015) and Huang *et al.* (2005) for examples of this in Paris and Beijing respectively

that public transport is subsidised in Auckland by around 50 per cent. These figures represent the average cost to the user per kilometre travelled, they do not represent the cost of providing the service. We use a passenger weighted average of rail and bus costs to get a value for pecuniary rail costs (g_R) of 21.2c/km.

Pecuniary costs for cars and private vehicles are solved for in the baseline calibration because it is difficult to calculate pecuniary running costs without imposing assumptions on the age and composition of the fleet, along with assumptions about driving habits.

5.16 Opportunity costs of time

The opportunity cost of time spent commuting is typically set to be a proportion of the wage. We follow Kulish *et al.* (2012) and use 60 per cent of the per-minute wage to represent the per-minute opportunity costs of time. This is the parameter ξ in the model.

5.17 CBD Wage Premium and Agglomeration Elasticity

The baseline calibration requires an estimate of the wage premium for commuters to the CBD. Wage estimates are based on 2018 census data for the median income by SA2 workplace location and income source. We use the median values for income deriving from an employer and the same for income from self-employment. We first define the average income in a SA2 region to be the weighted average of the median income from employment and self-employment, weighted by the total number of people reporting a non-zero value for each income source. We then define the CBD wage to be the weighted average of the average wage in each CBD region, weighted by the total number of individuals working in said region as a proportion of all people working in the CBD. The non CBD wage is similarly defined for regions outside of the CBD. As seen in Table 3, the difference in average wages suggests a wage premium of 33 per cent for the Auckland CBD.

[Insert Table 3 here]

We choose the agglomeration parameter based on existing empirical work on agglomeration effects in Auckland. The NZTA Economic Evaluation Manual (EEM), (NZTA, 2018) outlines a method to accommodate agglomeration effects deriving from a change in commuter numbers.

In this framework, an increase in commuter numbers is an increase in the effective density of employment in a region, which increases firm level productivity. The elasticity of productivity with density for different industries is given in the EEM table A10.1. These figures are based on Maré and Graham (2009) who use longitudinal micro-data on firm level productivity for New Zealand. By employing local industry fixed effects to control for firm heterogeneity, they produce elasticity estimates while also accounting for the fact that higher productivity firms tend to self select into high density regions.

Maré and Graham (2009) estimate the average elasticity with employment density across all industries to be 0.065. Note that this includes industries such as agriculture and mining which have relatively low elasticity of productivity, and are also not present in the CBD. Industries that dominate the CBD, such as retail, finance and professional services all have much higher elasticities.

We produce an industry employment weighted average agglomeration elasticity of $\delta = 0.076$ for the CBD. We use 2018 census data for employment by industry type in the Waitematā local board area and combine this with the agglomeration estimates from the EEM to get the weighted average elasticity. The Waitematā Local Board Area includes the CBD and a few surrounding suburbs. We use this aggregated region total to avoid losing information if small employment numbers are suppressed at the SA2 level for confidentially. The estimate of δ for Auckland as whole is $\delta = 0.074$. We also conduct a sensitivity analysis using the larger agglomeration elasticity of $\delta = 0.1$, as used in Hazledine *et al.* (2017).

5.2 Policy Simulation

Following calibration of the model to Auckland, we simulate the impact of a policy change by adjusting the relevant parameter and solving for the new equilibrium. This is achieved by using numerical optimization to find values of $\bar{z}$, N_M and N_R that satisfy the simultaneous set of equations outlined in equation (18). For more detail, see section A.5 in the appendix.

We conduct several policy simulations. First, we progressively increase RT capacity by a third, from 33 per cent additional capacity to 200 per cent additional capacity. This corresponds to the addition of one through to nine extra RT lines, since the model is calibrated with three RT lines in the baseline. As we illustrate below, additional RT capacity initially results in a small increase in VKT. As the number of lines increases, we do see a corresponding decrease in VKT. However, even with 200 per cent extra capacity, VKT is only reduced by 0.63 per cent. This suggests that public transit investment will have minimal impact on greenhouse gas emissions.

Because VKT is not substantially reduced, even for a large increase in public transit infrastructure, we consider a coordinated policy designed to meet the aim of the ERP of a 20 per cent reduction in road transport emissions.[31] The policy combines the RT capacity increases with a per-km congestion tax for each road user.

[Insert Table 4 here]

[Insert Table 5 here]

Tables 4 and 5 exhibits the results. Both panels consider improvements to RT capacity through additional RT lines.[32] In column (2) of table 4, we see that the addition of a single RT line increases wages by 0.14 per cent and city size by 1.3 per cent. It also increases VKT by 0.01 per cent. The calibrated model suggests that Auckland has agglomeration and congestion effects that are sufficiently strong to generate a small increase in road use from a RT improvement. As more lines are added, total VKT decreases compared to the baseline. However, even with a 200 per cent increase in RT capacity, the reduction in VKT is only 0.63 per cent. Despite significant mode shift by incumbents to the new RT lines, enough new entrants commute by road to the CBD to negate much of the associated drop in VKT. An RT improvement alone will not cause a meaningful reduction in greenhouse gas emissions.

Next, we consider combining the RT improvements with a congestion charge sufficient to reach a 20 per cent reduction in VKT. This policy target is directly informed by the Emissions Reduction Plan (ERP). Results are shown in table 5.

[31] Note that we assume that the RT capacity increase is carbon neutral in both investment and operation.

[32] Auckland is simulated with three lines in the baseline, so each additional RT line is equivalent to increasing RT capacity by 1/3rd.

Column (1) shows the congestion charge in isolation, without any rapid transit improvements. To reduce VKT by 20 per cent we require a congestion tax of 26c/km. This represents a 44 per cent increase in the pecuniary costs of road vehicle use. The tax also causes a 15 per cent reduction in the number of road users – or 10,000 individuals. Of these, over 1300 are close enough to a RT line to switch commute mode. However, the remainder choose not to commute at all, shown by a 6 per cent reduction in city size, and a 0.5 per cent drop in wages through a lost workers that reduce agglomeration benefits. Road speeds are improved by 22 per cent, showing that the congestion charge has reduced congestion, however speeds are still far from the free flow level of 34km/h.

Combining the congestion charge with RT improvements offsets the productivity loss by replacing lost car commuters with RT commuters. A significant investment of 100-133 per cent of additional RT capacity is required before wages approach and exceed pre-policy levels. The city radius is smaller than in the baseline until RT capacity increases by 167 per cent or more. The congestion charge required to reduce VKT by 20 per cent decreases as RT capacity increases.

Note that we make no assumptions on the uses of the congestion charge revenue. A charge that is used to subsidise RT will increase the number of RT users per line. This may cause wages to exceed pre-policy levels with a smaller level of RT capacity improvements. This modelling is left for future research.

In the Appendix we consider policy simulation results with a slightly larger agglomeration elasticity of $\delta = 0.1$, which is the value used by Hazledine *et al.* (2017). Our results remain qualitatively similar, however the increases and decreases to almost all variables are slightly larger in magnitude. With this larger elasticity, increasing RT lines capacity by only 1 line cause a larger increase in total VKT of 0.05 per cent.

6.0 Conclusion

This paper studies the effects of improvements in rapid transit using a monocentric model in the tradition of Venables (2007) that features both agglomeration efficiencies and congestion effects. Households choose between private vehicle commuting to the CBD via road networks or public transport commuting via rapid transit rays that emanate from the CBD at fixed locations. While rapid transit improvements increase wages, city size, and population, their impact on private vehicle usage is ambiguous and depends on the magnitude of road congestion and agglomeration effects. In particular, vehicle kilometres travelled can increase after a rapid transit improvement when either agglomeration effects are large or congestion costs are high.

This finding is a corollary of the well-known induced demand effects from enhancements of road network capacity. Increases in road network capacity often result in significant increases in private vehicle commuters rather than reductions in commuting times. This is consistent with a high elasticity of demand for road use in response to changes in network congestion. Improvements in rapid transit capacity induce car users to switch modes, thereby freeing up space on road networks and reducing congestion. In situations where demand is elastic, this will induce commuters who had previously opted to not commute to use the roads, increasing congestion close to pre-improvement levels. Demand is likely to be elastic when road speeds are suppressed due to congestion and trips are deferred due to high time-costs of commuting in traffic.

This finding has stark implications for policymakers that use rapid transit improvements for reducing private vehicle use and to alleviating congestion. It suggests that, in the face of elastic demand for road capacity, policymakers must accompany public transit improvements with additional (dis)incentives to public (private) transit. We calibrate the model to Auckland, showing that a 33 per cent increase in RT capacity results in a 0.01 per cent increase in VKT. In order to reduce VKT by 20 per cent, a congestion tax of $0.26 per km is required. This causes a reduction in CBD workers, reducing wages and productivity via the agglomeration channel. To achieve the required reduction in VKT, while also increasing CBD workers and productivity, the policymaker can combine a tax of \$0.22 per km with an increase in RT capacity of 133 per cent.

References

Anas, A. and Moses, L. N. (1979): 'Mode choice, transport structure and urban land use', *Journal of Urban Economics*, 6(2), 228–246, http://dx.doi.org/10.1016/0094-1190(79)90007-X. 5, 6, 9

Anderson, M. L. (2014): 'Subways, strikes, and slowdowns: The impacts of public transit on traffic congestion', *American Economic Review*, 104(9), 2763–2796, http://dx.doi.org/10.1257/aer.104.9.2763. 7, 8

Baum-Snow, N. (2007): 'Suburbanization and transportation in the monocentric model', *Journal of Urban Economics*, 62(3), 405–423, http://dx.doi.org/10.1016/j.jue.2006.11.006. 5, 15

Beaudoin, J. and Lin Lawell, C. Y. (2018): 'The effects of public transit supply on the demand for automobile travel', *Journal of Environmental Economics and Management*, 88, 447–467, http://dx.doi.org/10.1016/j.jeem.2018.01.007. 4, 7, 25

Brinkman, J. C. (2016): 'Congestion, agglomeration, and the structure of cities', *Journal of Urban Economics*, 94, 13–31, http://dx.doi.org/10.1016/j.jue.2016.05.002. 5, 6

Downs, A. (1962): 'The Law of Peak-Hour Expressway Congestion', *Traffic Quarterly*, 16(3). 3, 6

Downs, A. (1992): *Stuck in traffic: Coping with peak-hour traffic congestion*, Brookings Institution Press. 3, 6

Duranton, G. and Turner, M. A. (2011): 'The fundamental law of road congestion: Evidence from US cities', *American Economic Review*, 101(6), 2616–2652, http://dx.doi.org/10.1257/aer.101.6.2616. 3, 4, 6, 7, 8, 25

Garcia-López, M.-À., Pasidis, I., and Viladecans-Marsal, E. (2020): 'Congestion in highways when tolls an Railroads Matter: Evidence from European Cities', IEB Working Paper, Institut d'Economia de Barcelona. 4, 7, 8, 25

Gendron-Carrier, N., Gonzalez-Navarro, M., Polloni, S., and Turner, M. A. (2022): 'Subways and Urban Air Pollution', *American Economic Journal: Applied Economics*, 14(1), 164–196, http://dx.doi.org/10.1257/app.20180168. 8

Glaeser, E. (2011): *Triumph of the city: How urban spaces make us human*, Pan Macmillan. 2

Glaeser, E. L. (2008): *Cities, Agglomeration and Spatial Equilibrium*, Oxford University Press, Oxford. 13

Haywood, L. and Koning, M. (2015): 'The distribution of crowding costs in public transport: New evidence from Paris', *Transportation Research Part A: Policy and Practice*, 77, 182–201, http://dx.doi.org/10.1016/j.tra.2015.04.005. 19, 30, 42, 52

Hazledine, T., Donovan, S., and Mak, C. (2017): 'Urban agglomeration benefits from public transit improvements: Extending and implementing the Venables model', *Research in Transportation Economics*, 66, 36–45, http://dx.doi.org/10.1016/j.retrec.2017.09.002. 5, 6, 14, 27, 29, 32, 34, 41, 51

Hsu, W. T. and Zhang, H. (2014): 'The fundamental law of highway congestion revisited: Evidence from national expressways in Japan', *Journal of Urban Economics*, 81, 65–76, http://dx.doi.org/10.1016/j.jue.2014.02.002. 7

Huang, H. J., Tian, Q., and Gao, Z. Y. (2005): 'An equilibrium model in Urban transit riding and fare polices', in Megiddo, N., Xu, Y., and Zhu, B. (eds.) 'International Conference on Algorithmic Applications in Management', Springer Berlin Heidelberg, 112–121, http://dx.doi.org/10.1007/11496199_14. 30

Hymel, K. (2019): 'If you build it, they will drive: Measuring induced demand for vehicle travel in urban areas', *Transport Policy*, 76(December 2018), 57–66, http://dx.doi.org/10.1016/j.tranpol.2018.12.006. 6

Kulish, M., Richards, A., and Gillitzer, C. (2012): 'Urban Structure and Housing Prices: Some Evidence from Australian Cities', *Economic Record*, 88(282), 303–322, http://dx.doi.org/10.1111/j.1475-4932.2012.00829.x. 17, 18, 31, 51

Larson, W. and Yezer, A. (2015): 'The energy implications of city size and density', *Journal of Urban Economics*, 90, 35–49, http://dx.doi.org/10.1016/j.jue.2015.08.001. 17

Lee, D. B., Klein, L. A., and Camus, G. (1999): 'Induced traffic and induced demand', *Transportation Research Record*, 1(1659), 68–75. 3

Li, Z. and Hensher, D. A. (2011): 'Crowding and public transport: A review of willingness to pay evidence and its relevance in project appraisal', *Transport Policy*, 18, 880–887, http://dx.doi.org/10.1016/j.tranpol.2011.06.003. 18

Li, Z. C., Huang, H. J., and Yang, H. (2020): 'Fifty years of the bottleneck model: A bibliometric review and future research directions', *Transportation Research Part B: Methodological*, 139, 311–342, http://dx.doi.org/10.1016/j.trb.2020.06.009. 18

Maré, D. C. (2008): 'Labour Productivity in Auckland Firms', Motu Economic and Public Policy Research, http://dx.doi.org/10.2139/ssrn.1272196. 27

Maré, D. C. and Graham, D. J. (2009): 'Agglomeration Elasticities in New Zealand', Motu Economic and Public Policy Research, http://dx.doi.org/10.2139/ssrn.1433644. 32, 51

Ministry of Business Innovation and Employment (2020): 'Energy in New Zealand', , Ministry of Business Innovation and Employment, https://www.mbie.govt.nz/dmsdocument/11679-energy-in-new-zealand-2020. 4

New Zealand Transport Agency (2018): *Economic Evaluation Manual*. 31

United States. Bureau of Public Roads. (1964): *Traffic assignment manual for application with a large, high speed computer*, US Department of Commerce, Bureau of Public Roads, Office of Planning, Urban Planning Division, 37 edn. 17

Venables, A. J. (2007): 'Evaluating urban transport improvements: Cost-benefit analysis in the presence of agglomeration and income taxation', *Journal of Transport Economics and Policy*, 41(2), 173–188. 2, 5, 6, 35

Wardman, M. and Whelan, G. (2011): 'Twenty years of rail crowding valuation studies: Evidence and lessons from British experience', *Transport Reviews*, 31(3), 379–398, http://dx.doi.org/10.1080/01441647.2010.519127. 17, 18

Zhang, Y., Jenelius, E., and Kottenhoff, K. (2017): 'Impact of real-time crowding information: a Stockholm metro pilot study', *Public Transport*, 9, 483–499, http://dx.doi.org/10.1007/s12469-016-0150-y. 19

A Appendices

A.1 Area of Rail Catchment

We approximate the area of the catchment of a rail line using integration by quadrature. For any ε angle from the rail line, we can calculate the distance to the CBD $\bar{z}_\varepsilon$ of the rail commuting individual who is indifferent between commuting and earning the outside option wages as the following:

$$\bar{z}_\varepsilon = \frac{TC_M\left(N_M\right)}{\left(TC_R\left(N_{RL}\right) + \varepsilon TC_W\left(N_W\right)\right)}\bar{z}.$$

Consider the area of the triangle originating at $(0,0)$ and terminating at $(\bar{z}_{\varepsilon_1}, \varepsilon_1)$ and $(\bar{z}_{\varepsilon_2}, \varepsilon_2)$ respectively, where $\varepsilon_2 = \varepsilon_1 + \Delta$ for some $\Delta > 0$. The area of this triangle is given by $\frac{1}{2}\bar{z}_{\varepsilon_1}\bar{z}_{\varepsilon_2}\sin\left(\Delta\right)$. We calculate this area for each $\varepsilon_1 = 0, \Delta, 2\Delta, \ldots, (D-1)\Delta$ where $\Delta = \frac{\theta_{RL}}{2D}$ for some integer $D \geq 1$. We then sum the area of the individual triangles and multiply by 2 to approximate the area of the rail catchment. Analytically we have

$$A_{RL} = 2 * \frac{1}{2}\sin\left(\frac{\theta_{RL}}{2D}\right)\sum_{i=0}^{D-1}\frac{TC_M\left(N_M\right)}{\left(TC_R\left(N_{RL}\right) + \frac{i}{D}\frac{\theta_{RL}}{2}TC_W\left(N_W\right)\right)}\frac{TC_M\left(N_M\right)}{\left(TC_R\left(N_{RL}\right) + \frac{i+1}{D}\frac{\theta_{RL}}{2}TC_W\left(N_W\right)\right)}\bar{z}^2$$

$$= D\sin\left(\frac{\theta_{RL}}{2D}\right)\frac{TC_M^2\left(N_M\right)}{TC_R\left(N_{RL}\right)\left(TC_R\left(N_{RL}\right) + \frac{\theta_{RL}}{2}TC_W\left(N_W\right)\right)}\bar{z}^2$$

$$= D\sin\left(\frac{\theta_{RL}}{2D}\right)\frac{TC_M\left(N_M\right)}{TC_R\left(N_{RL}\right)}\bar{z}^2$$

where A_{RL} denotes the area of the rail catchment. Note that as $D \to \infty$ we have arbitrarily small Δ as thus a better approximation of the area. Now

$$\lim_{D\to\infty}\sin\left(\frac{\theta_{RL}}{2D}\right) \times D = \frac{\theta_{RL}}{2},$$

so for D sufficiently large our expression for the area approaches:

$$A_{RL} = \frac{\theta_{RL}}{2} \frac{TC_M(N_M)}{TC_R(N_{RL})} \bar{z}^2,$$

or

$$A_{RL} = \frac{\theta_{RL}}{2} \frac{y(N)}{TC_R(N_{RL})} \bar{z}$$

which give us an analytical expression for the area of the rail section. Note that after substituting in the appropriate cost function for road and rail we have:

$$A_{RL} = \frac{\theta_{RL}}{2} \frac{(t_M(V_M) G_T + g_M)}{(t_{f,R}\gamma_R(N_{RL}) + g_R)} \bar{z}^2,$$

or

$$A_{RL} = \frac{\theta_{RL}}{4} \frac{y(N)}{(t_{f,R}\gamma_R(N_{RL}) + g_R)} \bar{z}.$$

A.2 Parameters for Results Section

[Insert Table 6 here]

A.3 Travel time and distance estimation

Travel times and distances are calculated using automated Google Directions API calls for route-finding between the GPS coordinates of the centroids of pairs of SA2 regions. The estimated travel times and distances for travel by private car, bus, and rail, are recorded for a commute to and from the CBD region. We collect data on the best estimate for congested travel times in peak traffic. We set the AM commute to arrive before 9am, and the PM commute to leave after 5pm.[33] We estimate free-flowing travel times using off-peak commutes travelling at midday.

API requests are only made for public transit (PT) travel modes where there are some commuters using that mode. Occasionally, the Google Directions will be unable to find a route for PT, for example, when the centroid of a region is located far from any PT connection. This occurs in

[33]Note that, while Google travel time estimates are not available for past dates, the contemporary travel estimates are based on historical travel times. Direction request are made for travel on 04/08/2021.

61 out of 2254 public transit routes and is limited to more rural regions with very low commuter numbers. These commuters are excluded from the speed and distance averaging. They are still included in the employment calculations.

The Google Direction requests return the best estimate of average time in traffic for the fastest route at that time of day. For private car, the route originates and terminates at the roadside closest to each GPS centroid. For the public transport modes, the best route includes some walking to and from each centroid to a PT stop. This walking distance and time is subtracted from the journey totals so that PT totals represent the distance and times on the public transport mode only.[34] We use the walking times and distances to inform the average walking speed for commuters. In addition, for all modes we also retrieve the travel time in average traffic. This represents (relatively) uncongested travel for a journey made at midday. Travel data requests are made for all pairs of SA2s in the commuting data where the 'work' SA2 is located in the CBD. In total we have 93,426 commuters using 4,920 separate routes. Bus travel that utilises the North Western Busway, is combined with rail travel to give our RT mode. This is due to the fact the northern busway is almost entirely fully segregated, in contrast to all other bus routes.

Commuter weighted average travel times and distances by mode is calculated by combining the API results with the commuter numbers from the census data. The average travel speed is defined as the weighted average travel distance divided by the weighted average travel time. Table 7 shows the weighted average speeds, for both peak and off-peak travel for each mode.

[Insert Table 7 here]

A.4 Step by Step Model Calibration

This section outlines the process to calibrate the model to Auckland as discussed in section 5.0. To identify all the key components we need to solve for $\bar{z}$, V_M,$V_{M,cap}$, c, G_T, g_M, s_R, θ_{RL}, θ_M, and θ. All other parameters have direct estimates from the data. All parameters along with their sources are summarized in table 8.

[34] Any walking steps made as part of transfers during a public transit route are similarly excluded.

1. The radius of the city, $\bar{z}$, is obtained from equation (7) using the estimate for the average car commute distance from the commuter data.

2. The total number of road vehicle equivalents, $V_M(N_M)$, is determined using equation (19) by inputting the total number of car and bus users from the commuter data, along with parameters for p_C, p_B and ρ sourced from the census data and Hazledine *et al.* (2017).

3. The capacity of the road network, $V_{M,cap}$ is solved for by rearranging equation (12) to give:

$$V_{M,cap} = V_M(N_M)\left(\frac{t_M(V_M) - t_{f,M}}{\alpha t_{f,M}}\right)^{-\frac{1}{\beta}},$$

and inputting estimates for the travel time parameters $t_{f,M}$ and $t_M(V_M)$ from the commuter data. Values for α and β are informed by the common values used in transportation literature.

4. The intercept of the production function, c, is obtained by rearranging equation (10) to give:

$$c = \frac{y(N)}{(1-\tau)N^{\delta}}$$

and inputting estimates for the total number of CBD workers, N, from the commuting data, along with a choice for the tax rate τ.

5. We solve for a pre-policy value for the opportunity cost of time, G_T, using equation (13).

6. We solve for g_M by looking at the marginal road commuter at the city limit and re-arranging equation (17) to get:

$$g_M = \frac{y(N)}{2\bar{z}} - t_M(V_M)G_T.$$

7. The angle of each rail arc, θ_{RL}, must be solved for using numerical optimisation. We obtain an expression for the elasticity of subjective commuting by rapid transit, s_R, by looking at the rail user at the edge of the city who is indifferent between road and rail commuting.

Rearranging equation (17) we get:

$$s_R = \frac{\ln\left(\frac{\frac{y(N)}{2\bar{z}} - g_R - \frac{\theta_{RL}}{2} t_{f,w} G_T}{t_{f,R} G_T}\right)}{\ln\left(N_{RL}\right)}.$$

In the above the travel speed for walking and rail, $t_{f,w}$ and $t_{f,R}$ come from the commuting data, and pecuniary rail costs g_R is given by the weighted average costs per kilometre for rail and bus users from the NZTA public transport data. This expression is substituted into the following optimisation:

$$\arg\min_{\theta_{RL}} f\left(\theta_{RL}\right) = N_{RL} - \frac{y\left(N\right) \bar{z} \theta_{RL}}{4\left(t_{f,R} G_T N_{RL}^{s_R} + g_R\right)} k,$$

which is derived from equations (4), (8) and (17). The value of θ_{RL} that minimises the above expression is found through numerical optimisation. Note that N_{RL} is given by $\frac{N_R}{r}$ where N_R is derived from the commuting data, and the number of rail lines, r, is chosen to approximately match the Auckland network. The density of workers per kilometre, k, is obtained from the census data. Note that after calibrating the elasticity of subjective congestion, s_R, we find a similar relationship between an increase in passenger density, and an increase in subjective crowding costs as found empirically by Haywood and Koning, 2015.

8. The radius of the road segment, θ_M is solved by rearranging equation (5) to get:

$$\theta_M = \tfrac{2N_M}{\bar{z}^2 k},$$

where N_M is given by the addition of estimates for the total number of car and bus users in the city.

9. Finally the total city arc is now given by $\theta = \theta_M + r\theta_{RL}$.

[Insert Table 8 here]

[Insert Table 9 here]

A.5 Simulating a policy change after calibration

To estimate the impact of a change in r, or another policy change, we need to use numerical optimisation to find the values of $\bar{z}$, N_R and N_M of the new equilibrium. These can then be used to find the key outcomes for interest, such as VKT and wages.

First we need to find an expression for V_M in terms of N_M. Reminder:

$$V_M = \frac{N_C}{p_C} + \rho \frac{N_B}{p_B},$$

and

$$N_M = N_C + N_B.$$

We need a way to convert N_M to vehicle equivalents V_M. For simplicity we assume the ratio of bus to cars remains constant[35]: $qN_C = N_B$. In which case:

$$V_M = \frac{N_C}{p_C} + \rho \frac{qN_C}{p_B} = N_C \frac{(p_B + \rho q p_C)}{p_C p_B}$$

$$N_M = N_C + qN_C = N_C (1 + q)$$

$$N_C = \frac{N_M}{(1 + q)}$$

$$V_M = N_M \frac{(p_B + \rho q p_C)}{(1 + q) p_C p_B} = \lambda N_M.$$

Now we can get a value of $t_M (V_M)$ where required using equation (12).

We can express our system of equations as:

$$N_R = Ak,$$

$$N_M = \tfrac{1}{2} \bar{z}^2 k (\theta - r\theta_{RL}),$$

[35] We could also assume only car uses get added, which requires a different expression, but doesn't change the key result

$$y\left(N\right)=2z\left(t_{M}\left(V_{M}\right)G_{T}+g_{M}\right).$$

Using the marginal rail users at the radius of the city we get an expression for θ_{RL}:

$$\theta_{RL}=2\frac{\frac{y(N)}{2\bar{z}}-t_{f,R}\gamma_{R}\left(N_{RL}\right)-g_{R}}{t_{f,w}G_{T}},$$

and $y\left(N\right)$ can be obtained from:

$$y\left(N\right)=\left(1-\tau\right)c\left(N_{R}+N_{M}+N_{O}+N_{U}\right)^{\delta}.$$

When these two equations are substituted into the system of equations above we have three equations, with three unknowns. These can be solved for numerically. The key outcomes of interest are the radius of the city: $\bar{z}$, the total number of commuters in each mode, N_R and N_M, the wage premium $y\left(N\right)$, the road speed $t_M\left(V_M\right)$ and the total VKT for road vehicles. The number of road vehicles per user is given by dividing both sides of $V_M=\lambda N_M$ by $N_{M,}$, therefore the number of vehicles per user is λ. The total distance travelled by all road users is

$$D_{M}=k\bar{z}^{3\frac{\theta_{M}}{3}},$$

and total VKT is simply $D_M\lambda$.

A.6 Sensitivity Analysis

[Insert Table 10 here]

[Insert Table 11 here]

Tables

Table 1: Total number of CBD commuters by mode for Auckland

Mode	Model parameter	Number of commuters to CBD	
Car	N_C	55,935	
Bus	N_B	15,678	
Road total	$N_M = N_C + N_B$		71,613
Rail	-	6,768	
Northern busway	-	4,686	
Rapid Transit total	N_R		11,454
Other	N_O		16,989
Unknown	N_U		40,602
Total	$N = N_M + N_R + N_O + N_U$		140,658

This displays the pre-policy totals for commuters to the CBD for each transport mode type. These are derived from 2018 census data. Note that bus users are split. 'Car' commuters include individuals who report that they commute to the CBD as a driver or a passenger in a private vehicle. 'Bus' represents shared-grade bus travel, and is combined with car users to get the total number of road users in the city. The only major piece of fully segregated bus infrastructure in Auckland is the Northern busway. Users of this mode are combined with the total number of rail users to get the total number of rapid transit users in the city. 'Other' commuter modes include bike, walking, ferry and work from home. 'Unknown' commuters are workers whose specific mode choice is suppressed in the census data for confidentiality.

Table 2: Average Commute Distance, time and Commute speed for Auckland

	Model parameter	min/km	km/h
Road Speed			
Congested	$t_M\ (V_M)$	2.80	21.43
Free Flowing	$t_{M,f}$	1.74	34.48
Rapid Transit	$t_{R,f}$	2.12	28.24
Walking	$t_{W,f}$	12.75	4.64

This shows the travel speeds by mode for commuters to CBD regions. All speeds are the commuter weighted average commute distance divided by the commuter weighted average of commute time across all routes between SA2 regions and the CBD. In addition, road speed is a commuter weighted average of shared-grade bus speeds and private vehicle speeds. Rapid transit is a commuter weighted average of fully segregated bus speeds and rail speeds. The model parameters are inverse of speed and represent travel time in minutes per kilometre. For clarity we also display the speed in kilometres per hour. Walking speeds are derived from the walking steps to and from public transit. Peak and off-peak speeds for all modes are shown in table 7 in Appendix section A.3.

Table 3: Average Wages for CBD and non-CBD regions

	Total number of workers	Weighted average yearly wage	CBD Wage premium
All of Auckland	549,969	$64,959	
Non-CBD	409,311	$59,931	
CBD only	140,658	$79,592	33 per cent

This shows the total number of workers across Auckland and in CBD and non-CBD regions. It also shows the worker weighted average wage paid to individuals who's workplace is located in each region. The difference between CBD and non-CBD wages suggests a 33 per cent CBD wage premium.

Table 4: Policy Simulation for Auckland: Increasing RT Capacity

Variable	Pre-Policy	Increase in Rapid Transit Capacity 33%	67%	100%	133%	167%	200%
CBD wage premium ($/day)	57.40	57.47	57.55	57.62	57.68	57.75	57.81
% change	-	*0.14*	*0.27*	*0.39*	*0.50*	*0.61*	*0.71*
City radius (km)	18.81	19.05	19.28	19.51	19.72	19.92	20.12
% change	-	*1.29*	*2.52*	*3.70*	*4.83*	*5.91*	*6.94*
Road commuters (1000s)	71.60	70.69	69.81	68.96	68.13	67.32	66.53
% change	-	*-1.27*	*-2.50*	*-3.69*	*-4.85*	*-5.98*	*-7.08*
RT Commuters (1000s)	11.50	14.98	18.31	21.51	24.58	27.54	30.39
% change	-	*30.27*	*59.23*	*87.02*	*113.73*	*139.44*	*164.26*
Road Speed (km/h)	21.40	21.81	22.21	22.59	22.97	23.33	23.68
% change	-	*1.93*	*3.79*	*5.59*	*7.34*	*9.04*	*10.68*
Total VKT (1000s km)	685.92	685.96	685.66	685.05	684.16	683.01	681.62
% change	-	*0.01*	*-0.04*	*-0.13*	*-0.26*	*-0.42*	*-0.63*

Policy Simulation: Increases in RT capacity. Note that the wage premium is after tax. % change is compared to the pre-policy baseline displayed in column (1). Auckland is simulated with three RT lines in the baseline, so each additional RT line is equivalent to increasing RT capacity by 1/3rd.

Table 5: Policy Simulation for Auckland: Increasing RT Capacity paired with a congestion change to reduce VKT to 20% of pre-policy levels

Variable	Pre-Policy	33%	67%	100%	133%	167%	200%
	Increase in Rapid Transit Capacity						
CBD wage premium ($/day)	57.10	57.20	57.28	57.37	57.45	57.52	57.59
% change	*-0.51*	*-0.35*	*-0.19*	*-0.05*	*0.09*	*0.22*	*0.34*
City radius (km)	17.65	17.93	18.21	18.47	18.72	18.96	19.19
% change	*-6.16*	*-4.66*	*-3.21*	*-1.83*	*-0.49*	*0.79*	*2.03*
Road commuters (1000s)	61.04	60.08	59.18	58.35	57.56	56.83	56.14
% change	*-14.75*	*-16.09*	*-17.34*	*-18.51*	*-19.60*	*-20.63*	*-21.59*
RT Commuters (1000s)	12.87	16.71	20.37	23.84	27.16	30.32	33.35
% change	11.91	45.34	77.10	107.32	136.15	163.68	190.03
Road Speed (km/h)	26.06	26.46	26.82	27.16	27.46	27.74	28.00
% change	21.79	23.65	25.35	26.91	28.34	29.66	30.87
Total VKT (1000s km)	548.73	548.73	548.73	548.73	548.73	548.73	548.73
% change	-20.00	-20.00	-20.00	-20.00	-20.00	-20.00	-20.00
Congestion Charge ($/km)	0.26	0.25	0.24	0.23	0.22	0.20	0.19

Policy Simulation: Increases in RT capacity while reducing total VKT to 20% of the baseline level, as displayed in column (1) in table 4. The 20% reduction in VKT is achieved through the addition of a per kilometre congestion charge for each road user. Note that the wage premium is after tax. % change is compared to the pre-policy baseline displayed in column (1) of table 4. Auckland is simulated with three RT lines in the baseline, so each additional RT line is equivalent to increasing RT capacity by 1/3rd.

Table 6: Summary of model parameters for the numerical simulation section

Name		Value
Free flowing road speed (min/km)	$t_{M,f}$	1.3
Rapid transit speed (min/km)	$t_{R,f}$	2.2
Walking speed (min/km)	$t_{W,f}$	12.75
Pecuniary rapid transit costs ($/km)	g_R	0.19
Pecuniary road costs ($/km)	g_M	0.60
Elasticity of subjective congestion	s_R	0.26
Opportunity cost of time percentage	ξ	60%
Travel time equation intercept	α	0.15
Elasticity of travel time with congestion	β	4
Number of workdays per year	-	230
After tax average daily wage for non-CBD workplaces ($)	$\bar{y}$	182.61
Intercept of production function	c	32
Marginal tax rate	τ	30%
Density of workers (1000s/km^2)	k	0.11
Total arc of the city (radians)	θ	4

A summary of the model parameters used in the simulations in section 4.2

Table 7: Average Commute speeds by mode for Auckland

Mode	Average commute speed (km/h)
Car	
Peak	23.26
Off-Peak	45.37
Bus (shared-grade)	
Peak	16.65
Off-Peak	18.58
Rail	
Peak	28.03
Off-Peak	27.96
Bus (fully segregated)	
Peak	27.41
Off-Peak	28.61
Walking	
Peak	4.62
Off-Peak	4.64

Weighted average commute speeds for both peak and off-peak travel for each travel mode. Figures based on commuter weighted average travel distances and average travel times derived by combining census commuting data with google travel estimates for each commute route.

Table 8: Summary of model parameters and data sources for calibration to Auckland

Name		Value	Data Source
Number of road commuters	N_M	71,613	2018 Census
Number of car commuters	N_C	55,935	
Number of bus commuters	N_B	15,678	
Number of RT commuters	N_R	11,454	
Number of other commuters	N_O	16,989	
Number of unknown commuters	N_U	40,602	
Total commuters	N	140,658	
Number of people per car	p_C	1.06	
Number of people per bus	p_B	24	Hazledine *et al.* (2017)
Number of buses per car	ρ	3	
Congested road speed (min/km)	$t_M\left(V_M\right)$	2.80	2018 Census and google directions travel time estimates
Free flowing road speed (min/km)	$t_{M,f}$	1.74	
Rapid transit speed (min/km)	$t_{R,f}$	2.12	
Walking speed (min/km)	$t_{W,f}$	12.75	
Travel time equation intercept	α	0.15	Bureau of Public roads, Hazledine *et al.* (2017)
Elasticity of travel time with congestion	β	4	
Elasticity of productivity with employment density	δ	0.076	Maré and Graham (2009)
Number of workdays per year	-	230	Hazledine *et al.* (2017)
After tax average daily wage for non-CBD workplaces	$\bar{y}$	\$209.13	2018 Census
After tax average wage for CBD workplaces	$\bar{y}_{CBD}$	\$266.52	
After tax daily wage premium	$y\left(N\right)$	\$57.40	$\left(\bar{y}_{CBD} - \bar{y}\right)$
Marginal tax rate for an individual earning \$79,592	τ	34.4%	IRD
Pecuniary RT costs (\$/km)	g_R	0.212	NZTA
Density of workers (1000s/km^2)	k	0.169	2018 Census
Opportunity cost of time percentage	ξ	60%	Kulish *et al.* (2012)
Initial number of rail lines	r	3	

Summary of the data informed parameters for the model as calibrated to Auckland.

Table 9: Summary of solved for parameters in the baseline calibration to Auckland

Name		Value	Notes
Radius of the city (km)	$\bar{z}$	18.81	
Road vehicle Equivalents	V_M	54,690	
Road Network capacity	$V_{M,cap}$	38.50	Auckland is significantly over road capacity (congested)
Intercept of production function	c	60.08	
Opportunity cost of time ($/min)	G_T	0.333	
Pecuniary road costs ($/km)	g_M	0.592	
Pecuniary car costs ($/km)	g_C	0.691	
Elasticity of subjective congestion	s_R	0.252	Similar to Haywood and Koning (2015) who find ∼0.3
Angle of each rail segment (radians)	θ_{RL}	0.15	
Total angle of the rail area (radians)	$r\theta_{RL}$	0.46	
Radius of the road segment (radians)	θ_M	3.58	
Total arc of the city (radians)	θ	4.04	

Summary of the parameters solved for in the baseline calibration following the step-by-step procedure, when calibrating the model to Auckland.

Table 10: Sensitivity analysis for Policy Simulation for Auckland: Increasing RT Capacity

Variable	Pre-Policy	Increase in Rapid Transit Capacity					
		33%	67%	100%	133%	167%	200%
CBD wage premium ($/day)	57.40	57.50	57.60	57.69	57.78	57.86	57.94
% change	-	0.18	0.36	0.52	0.67	0.82	0.95
City radius (km)	18.81	19.06	19.29	19.52	19.73	19.94	20.14
% change	-	1.31	2.56	3.75	4.90	6.00	7.05
Road commuters (1000s)	71.60	70.71	69.85	69.01	68.19	67.40	66.63
% change	-	-1.24	-2.45	-3.62	-4.76	-5.86	-6.94
RT Commuters (1000s)	11.50	14.99	18.34	21.55	24.64	27.62	30.49
% change	-	30.36	59.44	87.38	114.25	140.14	165.15
Road Speed (km/h)	21.40	21.80	22.19	22.57	22.94	23.29	23.64
% change	-	1.89	3.71	5.48	7.20	8.86	10.48
Total VKT (1000s km)	685.92	686.25	686.23	685.91	685.30	684.42	683.30
% change	-	0.05	0.05	0.00	-0.09	-0.22	-0.38

Agglomeration elasticity $\delta = 0.1$. In the main text $\delta = 0.076$. Note that the wage premium is after tax. % change is compared to the pre-policy baseline displayed in column (1). Auckland is simulated with three RT lines in the baseline, so each additional RT line is equivalent to increasing RT capacity by 1/3rd.

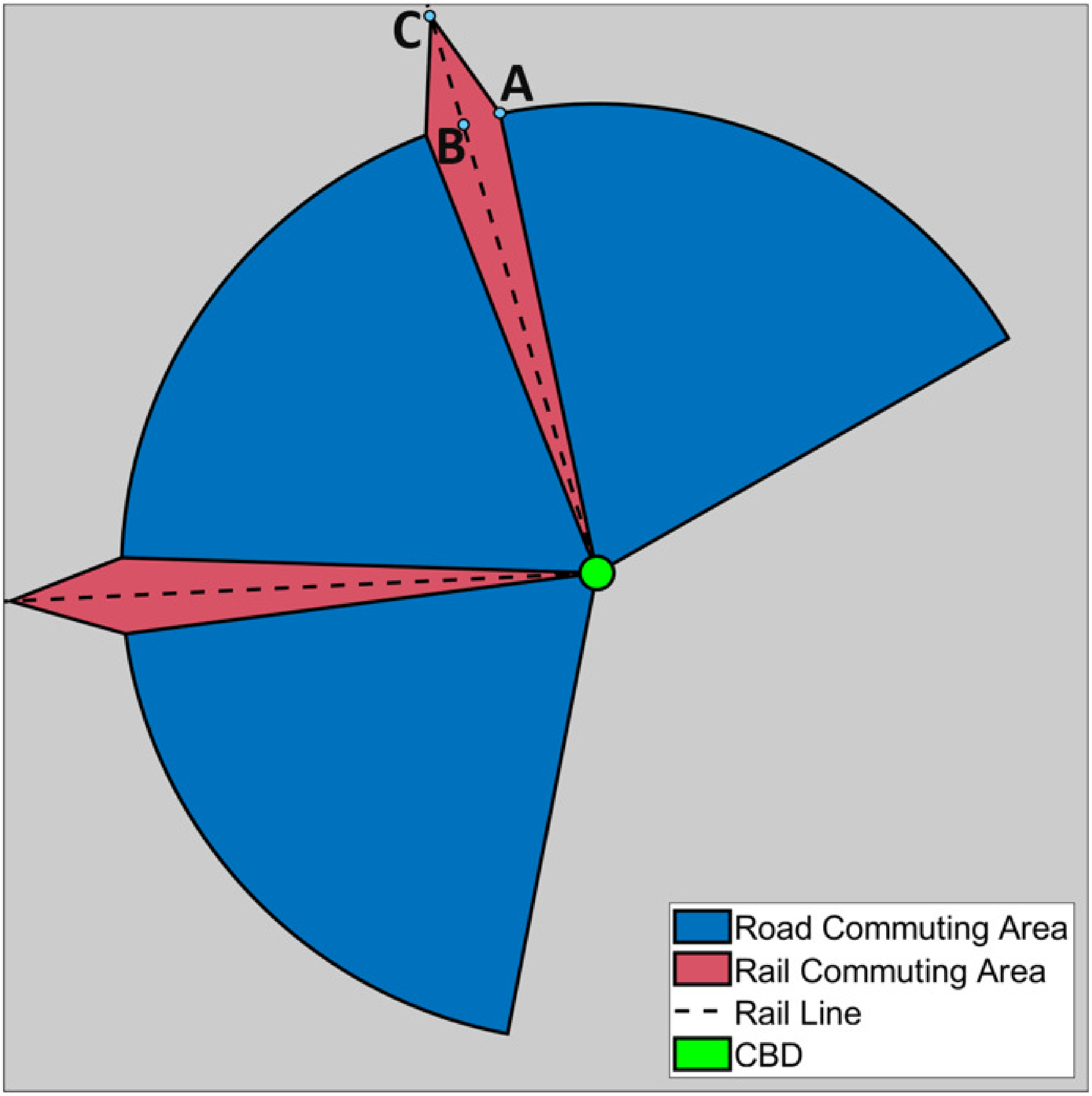
Table 11: Sensitivity analysis for Policy Simulation for Auckland: Increasing RT Capacity with a congestion change to reduce VKT to 20% of pre-policy levels

		Increase in Rapid Transit Capacity					
Variable	Pre-Policy	33%	67%	100%	133%	167%	200%
CBD wage premium ($/day)	57.01	57.13	57.25	57.36	57.46	57.56	57.65
% change	-0.68	-0.46	-0.26	-0.07	0.12	0.29	0.45
City radius (km)	17.65	17.93	18.20	18.47	18.72	18.96	19.20
% change	-6.17	-4.67	-3.22	-1.83	-0.49	0.81	2.05
Road commuters (1000s)	61.05	60.09	59.19	58.35	57.56	56.82	56.13
% change	-14.74	-16.08	-17.34	-18.51	-19.61	-20.64	-21.61
RT Commuters (1000s)	12.83	16.68	20.34	23.83	27.17	30.36	33.42
% change	11.55	45.02	76.88	107.26	136.27	164.02	190.62
Road Speed (km/h)	26.06	26.45	26.82	27.15	27.46	27.75	28.01
% change	21.78	23.64	25.34	26.91	28.35	29.67	30.90
Total VKT (1000s km)	548.73	548.73	548.73	548.73	548.73	548.73	548.73
% change	-20.00	-20.00	-20.00	-20.00	-20.00	-20.00	-20.00
Congestion Charge ($/km)	0.26	0.25	0.24	0.23	0.22	0.21	0.20

Agglomeration elasticity $\delta = 0.1$. In the main text $\delta = 0.076$. The 20% reduction in VKT is achieved through the addition of a per kilometre congestion charge for each road user. Note that the wage premium is after tax. % change is compared to the pre-policy baseline displayed in column (1) of table 10. Auckland is simulated with three RT lines in the baseline, so each additional RT line is equivalent to increasing RT capacity by 1/3rd.

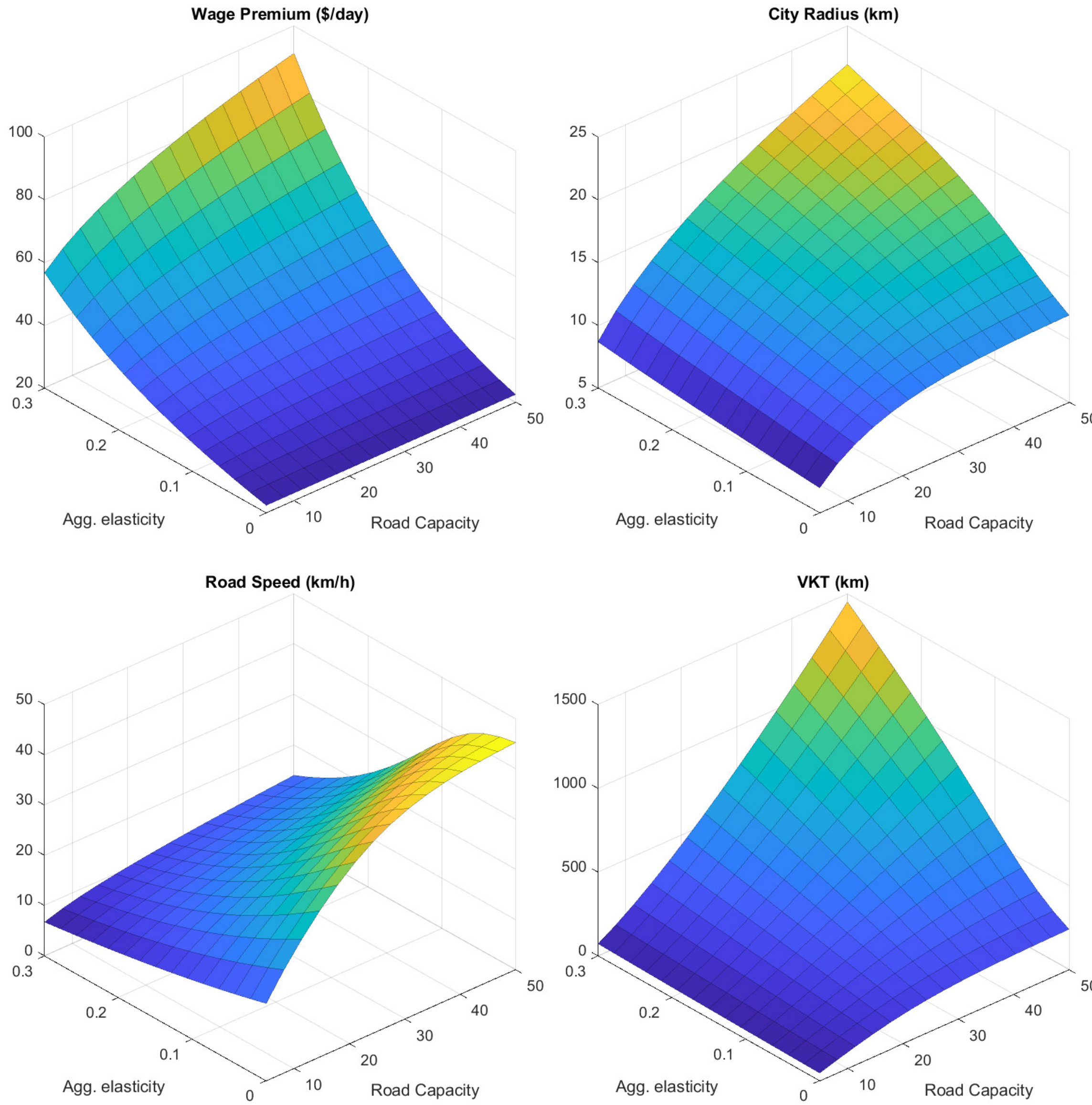
Figures

Figure 1: City Diagram



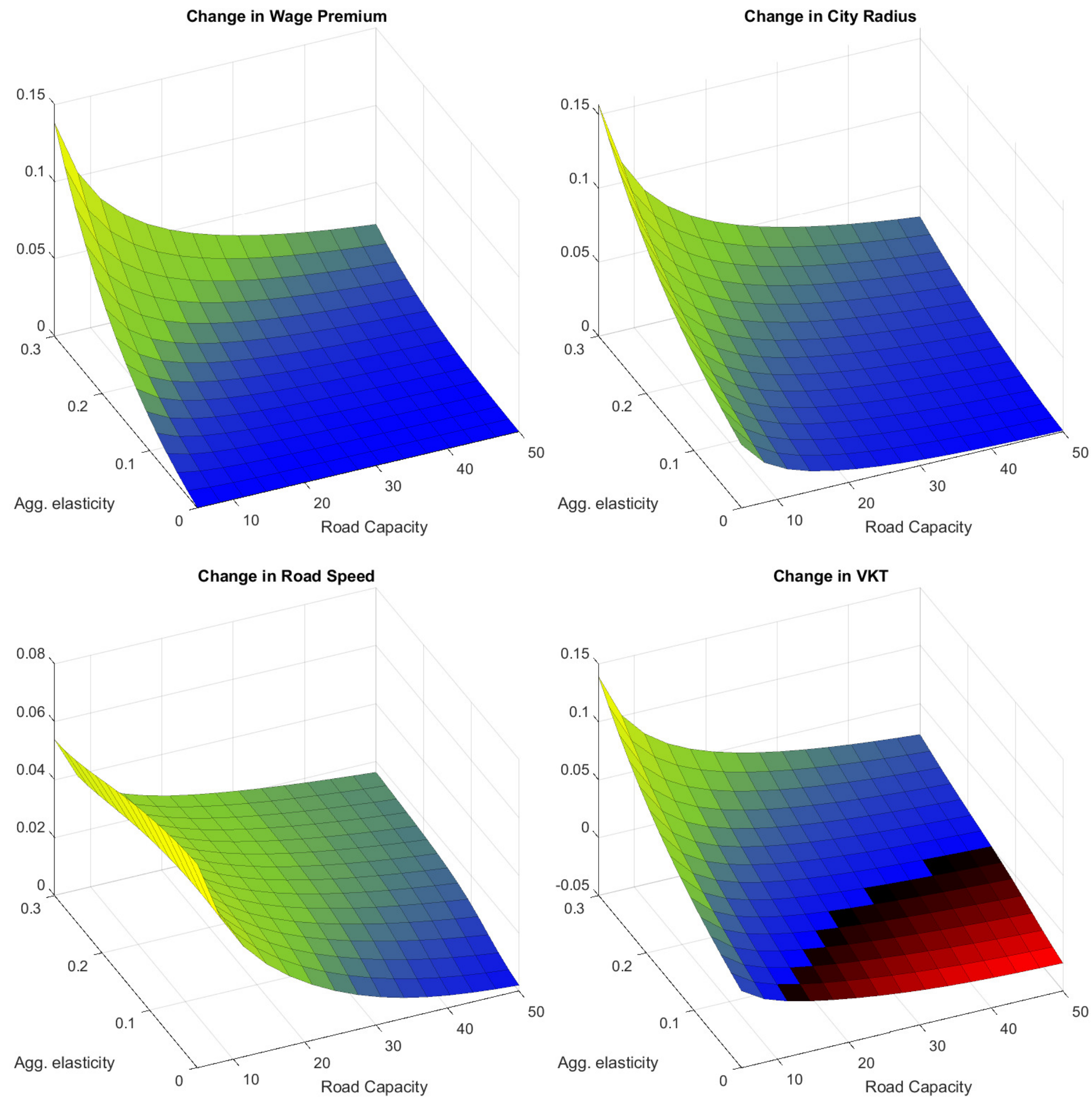
An example of a city with two rail lines.

Figure 2: Simulated equilibrium outcomes under different parametrizations of agglomeration and congestion effects.



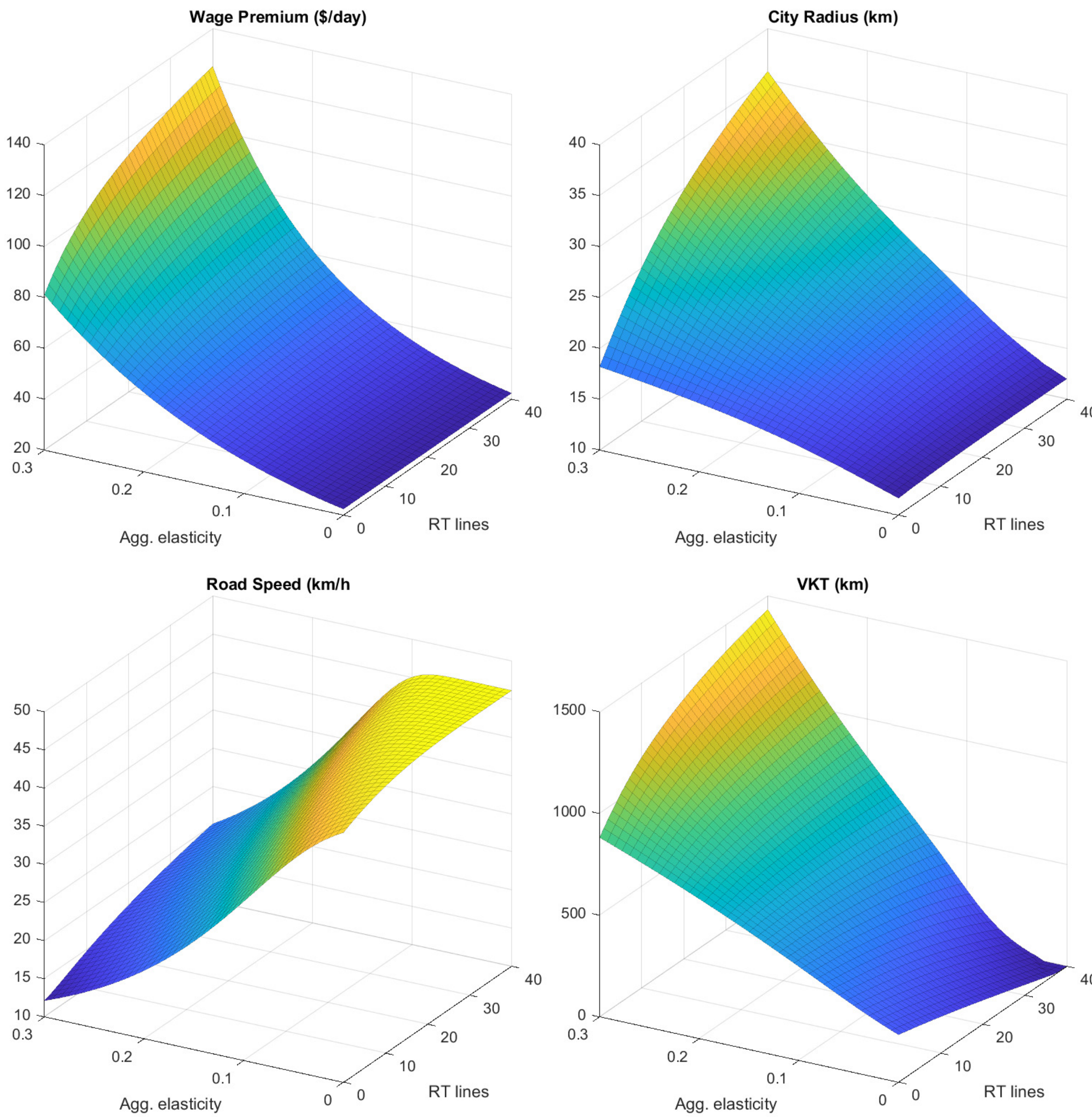
The agglomeration elasticity parameter is δ from equation 10 and the road capacity parameter is $N_{M,cap}$ from equation 12. The city contains a single rapid transit line. Refer to table 6 for values of other model parameters selected.

Figure 3: Changes in simulated outcomes from an additional rapid transit line.



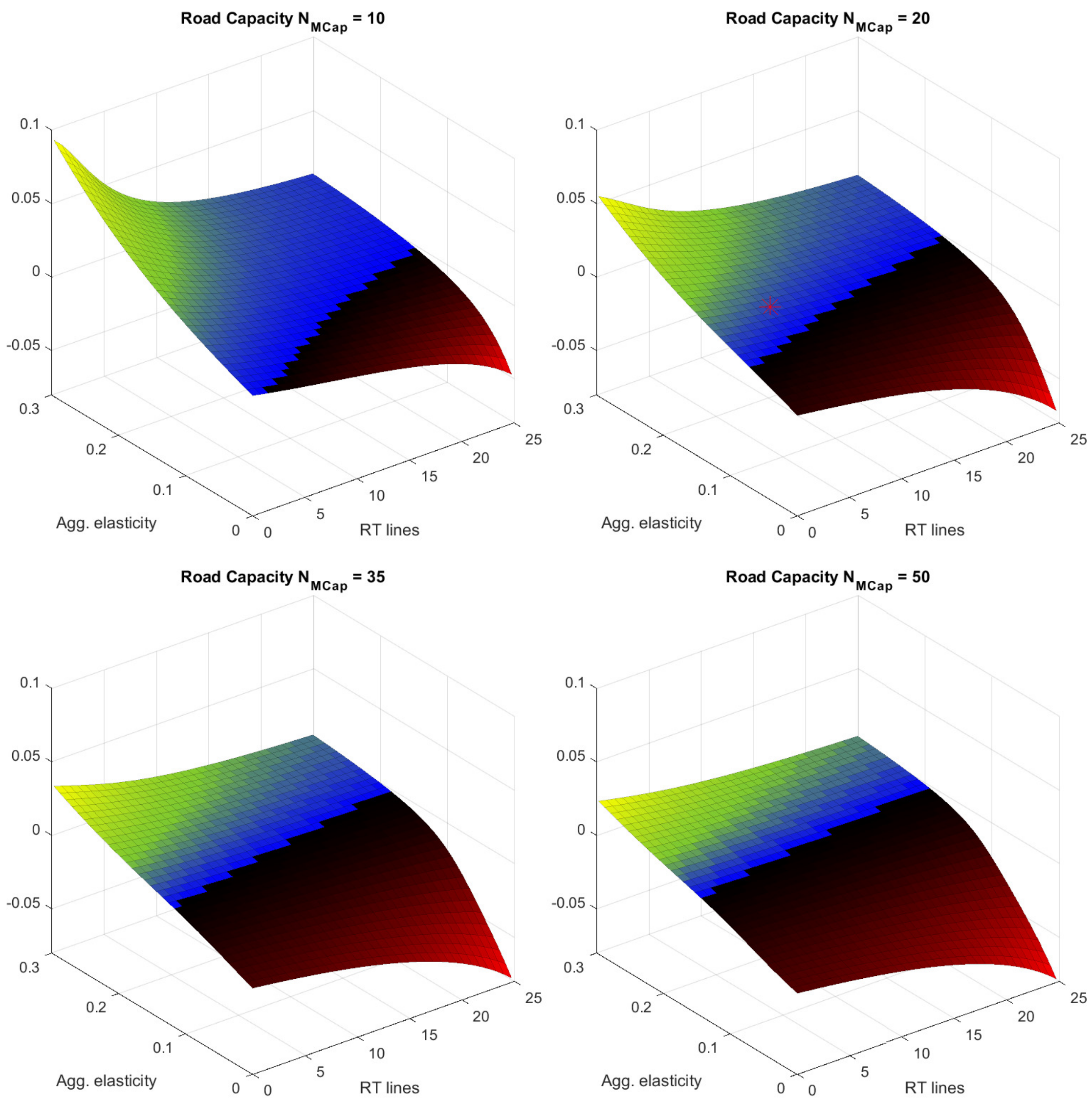
The z-axis depicts the log difference in the outcome variable when the number of rapid transit lines increases from one to two. The agglomeration elasticity parameter is δ from equation 10 and the road capacity parameter is N_{MCap} from equation 12. Refer to table 6 for values of other model parameters selected. For clarity regarding positive and negative z-axis values, the graphs are shown with a bifurcating colour scale around zero. The colour-map shows dark blue for the smallest positive z-value in each chart, and grades to yellow for the largest value. For z-axis values less than zero, the colour-map grades from bright red for the most negative, to black for values approaching zero. Only change in VKT has any negative regions. Note that the simulated data is generated and plotted over a grid.

Figure 4: Simulated equilibrium outcomes under different parametrizations of agglomeration effects and rapid transit capacity.



The agglomeration elasticity parameter is δ from equation 10. Rapid transit capacity is measured in the number of rapid transit lines. Road capacity parameter N_{MCap} is set to 35. Refer to table 6 for values of other model parameters selected.

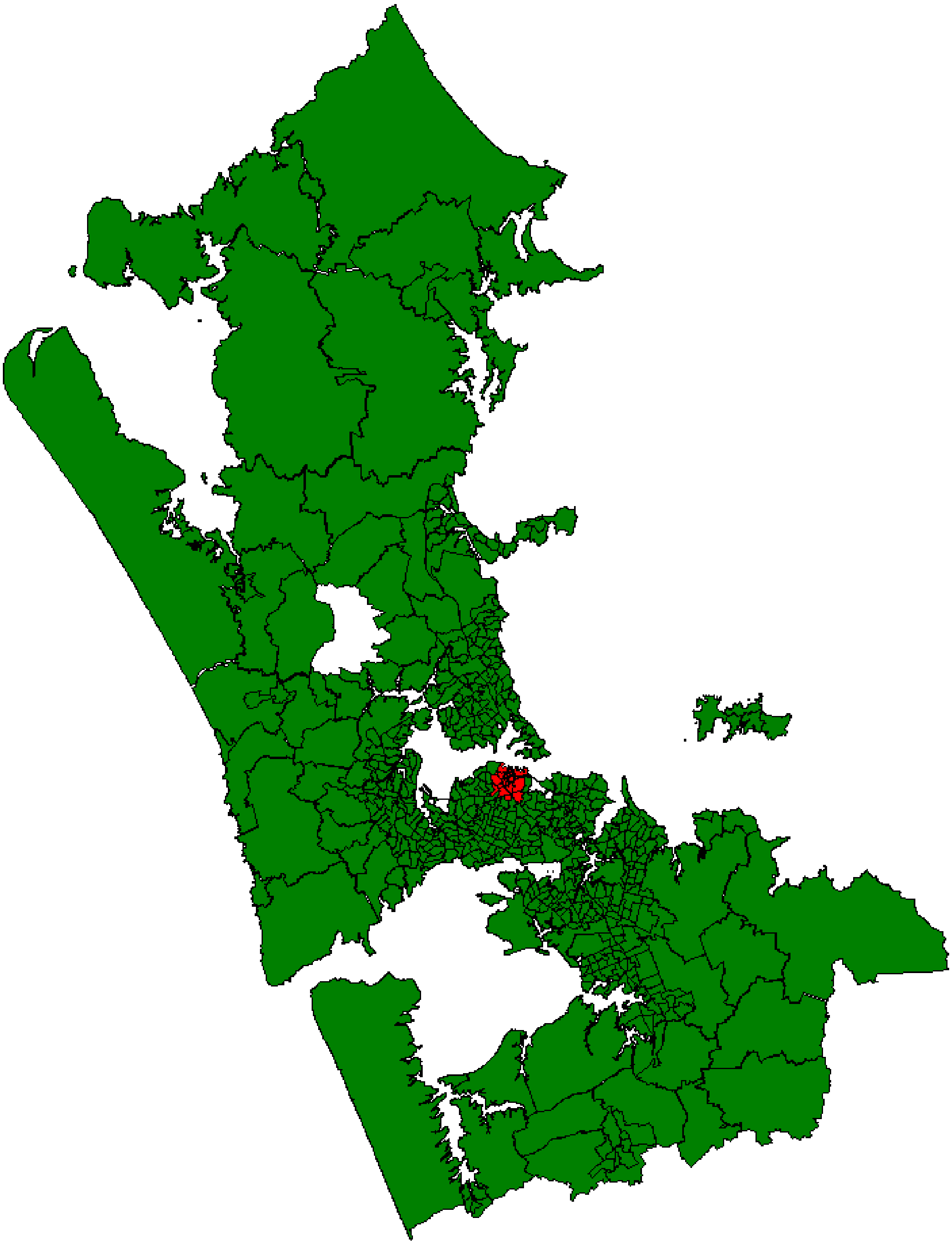
Figure 5: Change in VKT from unit increases in RT capacity.



Log differences in VKT from unit increases in RT capacity, plotted against various parametrizations of the agglomeration elasticity parameter (δ) and RT capacity. The agglomeration elasticity parameter is δ from equation 10. Rapid transit capacity is measured in the number of rapid transit lines. The RT lines-axis displays the baseline number of rail lines. The z-axis shows the percentage change in VKT when one additional rail line is added to this baseline. The four charts show the results for increasing level of road capacity (N_{MCap}) from 5 to 50. This parameter is N_{MCap} from equation 12. Refer to table 6 for values of other model parameters selected.

For clarity regarding positive and negative z-axis values, the graphs are shown with a bifurcating colour scale around zero. The colour-map shows dark blue for the smallest positive z-value in each chart, and grades to yellow for the largest value. For z-axis values less than zero, the colour-map grades from bright red for the most negative, to black for values approaching zero. Note that we show RT improvements of up to 25 lines on this chart. To interpret the surface, consider the example point in the chart where road capacity is 20, denoted with a '*'. Note that the value at $\delta = 0.135$ and $r = 6$ is 0.01. This means that increasing the number of RT lines from 6 to 6+1 increases VKT by 1 per cent.

Figure 6: CBD and non-CBD regions of Auckland



The SA2 regions of Auckland included in our analysis. CBD regions are marked in red. With the exception of the Waiheke island regions, the other non-mainland regions are excluded.