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Mode Choice and the Effects of Rapid Transit Improvements on Private Vehicle Use and Urban Development

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Abstract

Why do improvements in public transit sometimes result in an increase in private vehicle use, and sometimes result in a decrease? To better understand the underlying mechanisms, we study the impact of improvements in rapid transit (RT) within a monocentric model of the city that features congestion in commuting modes. Commuters choose between two different modes: public RT or private vehicles. While RT improvements increase city size, population, and aggregate land values, their effect on private vehicle use is ambiguous and depends on the extent of road congestion. Vehicle kilometres travelled (VKT) can increase after an RT improvement when the private road network is sufficiently congested. Policies to reduce road use in congested cities by improving RT should therefore be paired with additional disincentives to the use of private transportation.

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

JEL Classification: R12, R15, R41.

1.0 Introduction

Enhanced public transit (PT) provision is often advocated to reduce reliance on private vehicles, decrease energy consumption, and alleviate congestion on road networks. However, the empirical impact of PT on private road travel varies substantially across different contexts, often having no effect on private vehicle use, and sometimes increasing it. For example, while PT improvements have been shown to reduce road use in European cities (Garcia-López *et al.*, 2020), in U.S. cities, PT improvements either have no significant effect (Duranton and Turner, 2011) or else increase private vehicle use in the long-run (Beaudoin and Lin Lawell, 2018). Understanding the factors that moderate the impact of PT on private vehicle use is integral to the design and implementation of transport policy, particularly when reductions in private vehicle use are a policy goal.

Motivated by the need to better understand these moderating factors, we study the impact of Rapid Transit (RT) improvements on commuting mode uptake using a canonical model of urban development. Rapid Transit (RT) is a common form of PT that operates on dedicated corridors connecting residential suburbs to a centralised location of employment, including heavy rail and fully segregated light rail and bus services. RT presents a plausible set of transportation technologies to reduce reliance on private vehicles because it can offer fast commutes over long distances, and does not compete with private vehicles for space on potentially congested road networks. We employ a monocentric model of the city in the tradition of Alonso (1964), Muth (1969) and Mills (1967) that features congestion costs of the form used by Venables (2007) and different commuting mode options of the form used by Baum-Snow (2007) and Anas and Moses (1979). Households are located in housing on a flat disk around a central business district (CBD) and commute towards the CBD to work. They must choose one of two commuting modes: private road networks and a public RT option. RT offers a faster commute speed, but households must first commute to an RT corridor (or "line") in order to access it. The private road network offers a direct commute to the CBD, but at a lower speed. The monocentric framework provides a natural structure for modelling radial RT networks that are commonplace in many cities, and it is frequently used by urban and transport economists to understand how transit technologies and modes affect urban development more generally.[1]

Congestion is a key feature of the model that causes commuting costs within a given mode to increase with the number of commuters using the mode. Households face commuting costs that are comprised of a pecuniary cost, which is independent of mode use, and an opportunity cost of commuting time, which is increasing in the number of commuters using the mode, and reflects congestion.[2] Travel times (time per unit of distance travelled) are bounded from below by the inverse of a free flow speed that corresponds to a regulated speed limit that is attainable when the mode is uncongested. For the road commuting option, travel times are convex in the number of road commuters, following convention in the transport engineering literature

We use the model to examine the impact of improvements to the public RT commuting mode, allowing households to migrate in to (or out from) the city in response to policy changes. These improvements are modelled as exogenous reductions in RT commuting costs, and can include decreases in pecuniary costs, a reduction in travel times through increased RT capacity, or the construction of a new RT line.[3] We show that the effect of an RT improvement on distance-based measures of private vehicle use is ambiguous and depends on the initial amount of road network congestion, as measured by road use relative to road capacity. Specifically, the change in vehicle kilometres travelled (VKT) is increasing in road congestion, and becomes positive above a threshold level of initial road congestion. RT improvements can therefore increase VKT in cities where congestion on the road network is

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[1] See Anas and Moses (1979),Brueckner (2005), Baum-Snow and Kahn (2005), Brueckner and Selod (2006), Baum-Snow (2007), Arnott, 2007 and Brinkman, 2016, among others.

[2] Congestion in the RT mode can also be thought of as crowding effects. Commuting time costs increase with ridership, which is analogous to crowding being treated as a travel time multiplier, as is standard in transportation literature (Hörcher and Tirachini, 2021).

[3] The construction of a new RT corridor reduces travel times for households in the immediate vicinity of the new corridor.

sufficiently high, and decrease it in cities where congestion is sufficiently low.

The intuition behind the result is as follows. The RT improvement induces mode-switching from private vehicles to RT among incumbent residents, initially reducing VKT.[4] This mode-switching also reduces travel costs for road commuters because their commute time decreases as road congestion falls. These incipient reductions in commuting costs induce new households to move to the city, causing it to expand in both population and area. Total private vehicle usage – as measured by VKT – can *increase* when the rise in private VKT from new entrants exceeds the reduction in VKT from incumbent mode-switchers. Moreover, VKT can increase despite a net reduction in the number of road commuters because many of these new entrants take up residence beyond the original boundary of the city (i.e. the edge of the city prior to the improvement), and their commutes consequently cover a greater distance than those of the incumbent mode-switchers.

Convexity in how road travel times respond to road use is fundamental to generating the ambiguous effect of RT improvements on VKT. Convexity implies that the incipient reduction in travel cost from mode-switching is larger in more congested cities. A highly congested city, with a road speed far below the uncongested speed, experiences larger reductions in commuting costs than a city that has little congestion and road speeds that are already close to the free-flow speed. The larger the incipient reduction in commuting costs, the the greater the expansion of city population and area, and thus the more likely it becomes that the increase in VKT from new entrants exceeds the decrease in VKT from incumbent mode-switchers.

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

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[4] 'Incumbents' refers to households in the city prior to the policy change. 'New entrants' refers to households that move to the city as a result of the policy change.

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 caused by improved network capacity.[5] Demand is likely to 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 RT that induce car commuters to switch modes initially reduce congestion on road networks by reducing the number of road users. When demand for road use is elastic, the incipient reduction in congestion will induce large numbers of people that previously deferred journeys to start commuting, ultimately generating insubstantial reductions in traffic congestion and travel times.

We also extend the model to examine how agglomeration effects moderate the impact of RT improvements on vehicle use. Agglomeration externalities are another mechanism in addition to congestion that are fundamental to understanding the development of cities (Glaeser, 2008). They are also likely to moderate the impact of policies that encourage an in-migration of workers (such as RT improvements), since they can generate increasing returns to city population. We follow Venables (2007) and incorporate agglomeration effects by permitting wages to be increasing in the total workforce of the city. Agglomeration effects amplify population increases from RT improvements because wages rise as households in-migrate. Travel times are higher relative to when there are no agglomeration effects, as the increase in wages is partially offset by an increase in commuting costs. In cities with sufficiently high levels of agglomeration this can cause the change in VKT to invert from increasing in road network congestion to decreasing in road network congestion. This is because households can be compensated for reductions in living space with higher wages, which can generate a more compact city in response to rapidly increasing travel times in congested cities as population increases.

Our paper therefore provides two plausible explanations for the differential impacts of RT

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[5] 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.

improvements on road use emphasized in the extant urban development literature: congestion and agglomeration externalities. Our findings also underscore the need for policy coordination to meet VKT reduction targets. Improvements in public transit options may be insufficient, and additional disincentives required, to reduce private vehicle usage. These could include disincentives such as congestion charges, carbon taxes, or parking charges. To demonstrate the need for policy coordination, we revisit the modelled improvements in RT, examining the magnitude of an offsetting road use charge necessary to keep VKT constant. We show that under many plausible parametrizations that correspond to congested road networks, a positive road use charge is necessary to keep VKT constant after an RT improvement.

Our work is motivated by the large empirical literature on the impact of transportation network improvements on road utilization. While most of this work focuses on the effects of improvements in road network capacity on road usage in different contexts (seeHymel, 2019, for a recent review), comparatively less of of the literature has examined changes in private vehicle use following improvements in PT. Beaudoin and Lin Lawell (2018), Duranton and Turner (2011) and Garcia-López *et al.* (2020) investigate the response of private vehicle VKT to a plausibly exogenous increase in PT provision, but find different results. Beaudoin and Lin Lawell, 2018 study US cities and find that a 10 percent increase in PT capacity leads to a 0.7 per cent reduction in VKT in the short run, but a 0.4 percent net increase in VKT over the long run, while Duranton and Turner (2011) find statistically negligible effects of public bus service on private VKT in the US. In contrast, Garcia-López *et al.* (2020) find that a one percent increase in railway capacity reduces VKT by 0.5 percent on average in Europe.[6,7] This empirical work also suggests that the existing extent of private and public transport infrastructure is a primary mediating factor affecting these results. For example, Beaudoin and Lin Lawell, 2018 find that the initial decrease – and subsequent net

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[6] For further evidence on the mixed effects of PT provision, see Beaudoin and Lin Lawell, 2018 and Anderson, 2014 and the references therein.

[7] Studies that focus on close correlates of private vehicle use provide further evidence of the ambiguous impact of PT provision. For example, Gendron-Carrier *et al.* (2022) show that the opening of a new subway system in 58 cities around the world has an ambiguous effect on air pollution, with approximately a third of the sample experiencing an increase, and half experiencing a decrease.

increase – is larger in cities with higher levels of road congestion, while Garcia-López *et al.* (2020) also find that the impacts of rail capacity improvements are larger in cities with a high proportion of existing subway networks. Our theoretical framework provides a plausible mechanism for understanding these results. First, road congestion moderates the impact of RT improvements because there is less in-migration in comparatively uncongested cities that is ultimately driven by the convexity in how travel times respond to road use. Second, convexity also means that the marginal effect of RT improvements on VKT is diminishing, meaning that a unit RT improvement in a city starting from a low level of RT infrastructure generates a larger change in VKT than in a city starting from a high level of RT infrastructure, which accord with patterns in Europe.

Our paper builds on a large theoretical literature that uses the AMM framework to examine the impacts of transportation modes and technologies on urban development, including Anas and Moses (1979), Baum-Snow and Kahn (2005) and Baum-Snow (2007), and it also incorporates the congestion and agglomeration effects that feature prominently in the Venables (2007) model. Increasingly the AMM framework is also used to understand the effects of transportation policies on urban development, such as taxes and subsidies on mode use and transportation. Brueckner (2005) and Brueckner and Selod (2006) show that subsidisation of transport that is funded through taxation generates urban sprawl in the monocentric model. We find a similar result, in that a reduction in travel costs is associated with an increase in the city radius, albeit in a set-up that permits an increase in population via in-migration of households. Arnott (2007), Brinkman (2016) and Zhang and Kockelman (2016) use the monocentric framework to examine the impact of road use taxes on urban development and productivity in the presence of agglomeration externalities, finding that road congestion taxes reduce productivity. Our work suggests that congestion taxes paired with RT improvements can alleviate congestion while enhancing productivity when an RT mode is incorporated into the framework.

The remainder of the paper is organized as follows. Section 2.0 describes our model and equilibrium conditions. In section 3.0 we show how RT improvements in the model affect urban development and measures of private vehicle use. It concludes with the policy simulation that demonstrates the need for car use disincentives to keep VKT constant after an RT improvement in a congested city. Section 4.0 concludes.

2.0 Model

We explain the differential impacts of PT by developing a model that combines features of various monocentric models of urban development into a single framework. Our model is based on the conventional absentee landlord monocentric AMM model (see Duranton and Puga, 2015, for a detailed discussion of the model). We extend the model to incorporate multiple commuting modes (Anas and Moses, 1979;Baum-Snow, 2007), congestion costs,[8] and, eventually, agglomeration economies (Venables, 2007). We describe the basics of the AMM model before introducing the details on the salient features of the set-up.

The city lies on a flat plane and is comprised of a central business district (CBD) surrounded by suburbs that house workers. The land around the CBD suitable for housing development spans θ radians. Workers reside in the suburbs and commute towards the CBD to earn wages W. Their preferences over land L and a consumption numeraire C are described by a utility function $U(L, C)$ that is increasing in both arguments and strictly quasi-concave. Specifically, we assume Cobb-Douglas utility $U(L, C) = C^{1-\alpha}L^{\alpha}$. Households living at distance $x \in [0, \infty)$ from the CBD incur a commuting cost to earn the wage. For instructive purposes we measure x in kilometres (km). Land area per household and population density are endogenous outcomes of the model.

2.1 Mode Choice and Mode Catchments

Households choose between commuting to the CBD by private vehicle on road networks or by a public RT mode. The RT commuting option is intended to model a variety of fully

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[8] Baum-Snow (2007) also considers congestion as a supplementary extension of his model.

segregated PT modes, which are 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, and light rail, when it does not share space with private vehicles on road networks. Fully segregated contrasts against PT 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.

The city features r infinitely long and identical RT corridors radiating out from the CBD. Let ε denote the angular displacement from an arbitrary point on the city disk to the nearest RT line measured in radians. A household located at polar coordinates (x, ε) has two mode choices. First, they can travel directly to the CBD by road, which entails a per km cost of t over distance x. Second, they can commute by RT. 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 with radius x from the CBD to a rapid transit line. The length of this part of the commute is εx, and incurs a per km cost of t_W. Once they reach the line, they commute distance x to the CBD on the RT line, incurring a per km cost of t_R. The total distance of the RT commute is therefore $(1+\varepsilon)\,x \geq x$.

Households select the lower cost commuting option. Because both road and RT commuting costs are linear in x,they use RT if $t_R + t_W\varepsilon < t$. This results in the disk of the city being partitioned into catchments of road-commuting households and catchments of RT-commuting households (also see Anas and Moses, 1979, and Baum-Snow, 2007). Households located within $\frac{t-t_R}{t_w}$ radians of the line commute by RT. A necessary condition for RT use is $t > t_R$.

[Figure 1 somewhere near here]

The left hand side of figure 1 exhibits the catchments for the case of a single RT line. For road commuters, travel costs are constant for a given distance to the CBD x. This means the road catchment is a circular sector. We use $\bar{x}$ to denote the radius of the sector. For RT commuters, travel costs depend on both x and the angular displacement ε from the RT line. The outer edge of the RT catchment is defined by the set of RT commuters that share the same commuting costs as the road commuters at the edge of the road catchment. They are located at polar coordinates (x, ε) satisfying

$$(t_R + \varepsilon t_W)\, x = t\bar{x},$$

$x > \bar{x}$ and $0 \leq \varepsilon < (t - t_R)/t_w$. The RT catchment spans $\theta_R = \frac{t-t_R}{t_w}$ radians. We let $\theta_M = \theta - \theta_R$ denote the radians of the road catchment of the city.

Commuting-mode cost minimisation allows us to define a uniform measure of distance for both road and RT commuting households that is useful for solving the AMM model with multiple commuting modes. Specifically, we define

$$z = \eta(\varepsilon)\, x, \eta(\varepsilon) = min\left(\frac{t}{t_R + t_W \varepsilon}, 1\right)$$

This enables us to re-express the per km travel cost of RT commuters $(t_R + t_W \varepsilon)\, x$ in terms of per km road commuting costs tz. The right hand side of figure 1 shows the RT catchment expressed in terms of distance z from the CBD. As illustrated in the Figure, adopting the uniform measure of distance z requires expanding the arc of the city disk from θ to θ^*, where

$$\theta^* = \theta + 2\theta_R \left(\frac{t}{t_R} - 1\right)$$

This ensures that the area of the circular sector of the RT catchment on the right is equal to the area of the RT catchment on the left. The dilated RT catchment spans

$$\theta_R^* = \theta_R \frac{t}{t_R} \tag{1}$$

radians. We refer readers to the Appendix to see why this is the case. Generalising to the case where there are r RT lines, the dilated city spans

$$\theta^{*}=\theta+2r\theta_{R}\left(\frac{t}{t_{R}}-1\right)=\theta+2r\frac{t-t_{R}}{t_{w}}\left(\frac{t}{t_{R}}-1\right) \tag{2}$$

radians, provided that relative travel costs are such that the catchments do not overlap.

Another useful implication of the dilated city disk geometry is that the population of road commuters N_M and RT commuters N_R is proportional to the dilated radians of the catchments:

$$\frac{N_M}{N_R}=\frac{\theta_M}{r\theta_R^{*}}$$

or since $N = N_M{+}N_R$,

$$N=N_M\left(1+\frac{r\theta_R^{*}}{\theta_M}\right)$$

2.2 Spatial Equilibrium

Given the uniform measure of distance z, the model is closed by standard assumptions: (i) setting land rents at the edge of the city $\bar{x}$ equal to exogenous agricultural rents, i.e., $R\left(\bar{x}\right)=\bar{R}$; (ii) the conventional population constraint, i.e.

$$\theta^{*}\int_{0}^{\bar{x}}\tfrac{1}{L(z)}z\,dz=N$$

where $\bar{x}$ denotes the radius of the dilated city; and (iii) the within city iso-utility condition (utility is equal at all locations), i.e. $U=\bar{U}$. These are the conventional assumptions used to solve the model.

Under these assumptions, we have

$$R\left(z\right)=\frac{\left(W-tz\right)^{\frac{1}{\alpha}}\left(1-\alpha\right)^{\frac{1-\alpha}{\alpha}}\alpha}{\bar{U}^{\frac{1}{\alpha}}} \tag{3}$$

and thus indirect demand for floorspace is

$$L\left(z\right)=\frac{\bar{U}^{\frac{1}{\alpha}}}{\left(W-tz\right)^{\frac{1-\alpha}{\alpha}}\left(1-\alpha\right)^{\frac{1-\alpha}{\alpha}}} \tag{4}$$

where $\bar{U}$ satisfies

$$\left(1-\alpha\right)^{\frac{1-\alpha}{\alpha}}\bar{U}^{\frac{1}{\alpha}}=\frac{\bar{R}}{\alpha\left(W-t\bar{x}\right)^{\frac{1}{\alpha}}}$$

We can then solve for population density $\frac{1}{L(z)}$ as

$$\frac{1}{L\left(z\right)}=\frac{\bar{R}}{\alpha}\frac{\left(W-tz\right)^{\frac{1-\alpha}{\alpha}}}{\left(W-t\bar{x}\right)^{\frac{1}{\alpha}}}$$

and thus solve for N

$$N=\theta^{*}\int_{0}^{\bar{x}}\tfrac{1}{L(z)}zdz=\frac{\theta^{*}\bar{R}}{1+\alpha}\frac{1}{t^{2}}\left[\left(W-tz\right)^{-\frac{1}{\alpha}}W^{\frac{1+\alpha}{\alpha}}\alpha-\left(\alpha W+t\bar{x}\right)\right]$$

Other outcomes of interest, such as commuter distance travelled, aggregate land value, and average population density can be obtained. Let $n_{j}\left(z\right)$ denote the total number of mode j users at distance x. $n_{j}\left(z\right)$ is the length of the arc of the circular segment of the road catchment at distance x multiplied by the density of workers, that is $n_{j}\left(z\right)=\frac{1}{L(z)}\theta_{j}^{*}z$. The distance travelled is $n_{M}\left(z\right)\cdot z$. Total distance travelled by users of mode j is then:

$$D_{j}=\int_{0}^{\bar{x}}\tfrac{1}{L(z)}\theta_{j}^{*}z^{2}dz \tag{5}$$

Another outcome of interest is aggregate land value. This is given by

$$V=\int_{0}^{\bar{x}}\theta^{*}R\left(z\right)zdz \tag{6}$$

Finally, population density is

$$S=\frac{N}{\theta^{*}\frac{1}{2}\bar{x}^{2}} \tag{7}$$

2.3 Travel Costs

Travel costs in the various modes incorporate both pecuniary and congestion costs. Congestion means that per km travel costs are weakly increasing in the number of commuters. To reflect this dependence, we let $t_j(N_j)$ denote two-way (or round trip) travel costs per kilometre to and from the CBD, where $j \in \{R, M, w\}$ denotes the RT, Road and to-RT modes, respectively, and N_j denotes the number of commuters using mode j, where $N_w = N_R$. Because travel costs are assumed to be the same on each RT line, the number of RT users on any specific line is $N_{RL} = N_R/r$. Total travel costs for the road commute are $t_M(N_M) \times x$. Travel costs for the RT commute are $(t_R(N_{RL}) + \varepsilon t_w(N_{RL}))\, x = t_M(N_M)\, z$.

2.31 Travel Cost Function

Travel costs are comprised of pecuniary costs and the opportunity cost of commuting time. Empirical studies find that the the opportunity cost of commuting time is valued at half of the gross wage rate (Small, 2012). We therefore set the opportunity cost of time to a proportion of the wage. 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 RT mode does not compete with private vehicles for space on the road network.

Pecuniary Cost The pecuniary cost per kilometre travelled per year in each mode is g_j for $j \in \{R, M, w\}$.

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 $\xi \in [0, 1)$ of the wage (Bertaud and Brueckner, 2005; Kulish *et al.*, 2012). Thus ξW denotes the opportunity cost of time spent commuting.

Congestion Function Commute times (or the inverse of commute time – commuting speed) are often held constant in the conventional AMM framework. We model travel times as increasing in the number of commuters in order to capture congestion.

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)[9]. The per kilometre time to travel one kilometre in mode j is:

$$s_j\left(N_j\right) = s_{f,j}\left(1 + \gamma_j\left(\frac{N_j}{N_{j,cap}}\right)^{\beta_j}\right) \tag{8}$$

where $s_{f,j}$ is the free flowing travel time per kilometre of the mode and $N_{j,cap}$ a measure of capacity of the transport mode.

Travel times approach free-flow travel times as the the ratio of commuters to capacity approaches zero. This is an important feature of the congestion function as it means that travel times are bounded from below (equivalently, commuting speeds are bounded from above). As the number of users approaches and exceeds the capacity of the route, $s_j\left(N_j\right)$ increases rapidly. The travel time function is convex provided that $\beta_j > 1$. We assume that $\beta_M = 4$ but consider various values of $\beta_R \geq 0$.

Although we characterise equation (8) as a congestion function that impacts travel times, in the case of RT it can serve as a 'crowding' function which specifies a per km cost on the representative household that is increasing in ridership relative to capacity (i.e.$\frac{N_j}{N_{j,cap}}$). The emerging consensus in transport economics is to model subjective costs of crowding in public transit as a travel time multiplier increasing in the density of commuters (Hörcher and Tirachini, 2021) (Also see Li and Hensher, 2011 and Wardman and Whelan, 2011). 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 – and therefore incurs a higher cost.[10] The marginal change in per km cost is increasing in ridership. The case of

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

[10] An alternative approach is to model crowding costs as reducing household utility. Hörcher and Tirachini (2021) suggest that the travel time multiplier has become the consensus approach to modelling crowding

$\beta_R = 1$ would correspond to constant crowding costs with ridership[11].

Following the extant literature, γ_M and β_M are assigned the values 0.15 and 4 for road commuting (Hazledine *et al.*, 2017). For RT commuting we also set γ_R to 0.15 but consider various values of $\beta_R = \{0, 0.5, 1, 2, 4\}$. We therefore examine how our results are sensitive to variation in the structural congestion parameter that governs how quickly commute speeds fall with additional commuters. High values of β_R can represent increasing journey times from non-linear crowding functions, physical congestion or bunching in the RT infrastructure, and congestion in platforms affecting boarding times and entry and exit of the stations. Lower values of β_R can also be used to model endogenous increases in RT capacity in response to changes in RT use. These endogenous responses make speeds observationally equivalent to a function with a smaller structural congestion exponent. For example, if $N_{R,cap} = N_R^{\rho}$ for some elasticity of supply parameter $\rho \geq 0$, and labelling the structural congestion exponent μ, we have $\left(\frac{N_R}{N_{R,cap}}\right)^{\mu} = {N_R}^{\mu(1-\rho)}$. The case of $\beta_R = 0$ corresponds to perfect elasticity of RT supply, such that travel time costs remain constant no matter the number of mode users.

Eq. (8) also describes the to-RT commuting mode thereby allowing it to also be subject to congestion or crowding costs. It could represent local bus, park and ride, or walking modes. Note that with appropriately chosen travel function parameters, our framework can also be used to model radial highway networks, where each RT corridor instead represents a highway offering faster travel to the CBD than road travel.

Travel Cost Function by Mode Given the travel costs components outlined above, annual per kilometre travel costs for road users are

$$t_M\left(N_M\right) = 2\left(s_M\left(N_M\right)\xi W + g_M\right)$$

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costs in the recent literature.

[11] Above a threshold of passenger density, linear crowding functions have been found to be a good to fit to the data (Whelan and Crockett, 2009, Wardman and Whelan, 2011, Haywood and Koning, 2015).

Their total commute cost is then

$$t_M(N_M) \times x = 2x\left(s_M(N_M)\xi W + g_M\right), \tag{9}$$

For RT users located at polar coordinate (x, ε), annual per kilometre travel costs are

$$t_R(N_{RL}) = 2\left(s_R(N_{RL})\xi W + g_R\right),$$

and

$$\varepsilon \times t_w(N_{RL}) = 2\varepsilon\left(s_w(N_{RL})\xi W + g_w\right)$$

for the RT and to-RT components of their journey respectively. Their total commute costs are

$$\left(t_R(N_{RL}) + \varepsilon t_w(N_{RL})\right) \times x = 2x\left(\xi W\left(s_R(N_{RL}) + \varepsilon s_w(N_{RL})\right) + g_R + \varepsilon g_w\right) \tag{10}$$

3.0 Impact of Rapid Transit Improvements

In this section we use the monocentric model to analyse the effects of RT improvements on private vehicle use and urban development. The model is too complicated to yield closed-form solutions of the outcome variables of interest. We therefore provide analytic solutions based on a numerical simulation of the model.

We examine three different forms of RT improvements: (i) construction of a new RT corridor; (ii) an increase in RT capacity; and (iii) a reduction in RT fare. These improvements are modelled across different parametrisations of road congestion.

We first solve the model holding wages, population and speed fixed. This ensures that the key outcome variables are the same in the baseline calibration across different parametrisations of congestion. In particular, city radius and utility are the same. We also fix RT speed and the number of corridors, which in turn implies that the number of RT users and car users is also the same across all parametrisations.

We then alter a parameter that corresponds to a specific RT improvement and solve the model allowing the endogenous outcomes to change. This enables us to study the impact of rapid transit improvements via comparative statics and under open city assumptions. In order to model in-migration in response to the improvement, we apply the conventional 'open city' assumption of holding utility fixed at $\bar{U}$. For (i), we increase r. For (ii), we increase $N_{R,cap}$. For (iii), we decrease g_R.

To model different amounts of road congestion we vary the road capacity parameter $N_{M,cap}$. Because congested speed and the number of road users is held fixed in the baseline calibration, a lower $N_{M,cap}$ corresponds to greater congestion, as the road network speed is further below the free-flow speed. We use the ratio of road network speed to free flow speed $(s_{f,M}/s_M(N_M))$ as a measure of congestion prior to the policy change.[12] The congestion ratio is bounded between zero and one, with higher levels corresponding to faster speeds, and thus lower levels of congestion. We depict changes in outcome variables as a function of the congestion ratio to show how road congestion prior to the RT improvement moderates the impact of a RT improvement on private vehicle use and other features of urban development.[13] Specifically, we are interested in changes in eleven outcome variables of interest: Road VKT, RT VKT, road speed, RT speed, road commuters, RT commuters, population, city radius, aggregate land value, land area and average population density. However, under open city assumptions, population density is constant, which implies that the percent increase in average land values and total land area is the same as the percent increase in population. Refer to the Appendix for a proof of these results. We therefore do not depict changes for aggregate land value, land area and average population density.

For the purposes of these exercises we assume the to-RT mode is free and thus $g_w = 0$. We also assume that the to-RT mode operates at free flowing speeds, even during peak hours. Hence $s_W(N_W) = s_{f,W}$. Both of these assumptions are favourable to RT uptake. In

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[12] Note that congested and free flow speeds are given by $\frac{1}{s_M}$ and $\frac{1}{s_{f,M}}$ respectively.

[13] Outcomes could instead be plotted against increases in the road capacity parameter without any change to our analysis or findings. However, this parameter arguably lacks a corresponding real-world measure, unlike the congestion ratio, which tells us how far road speed is from its free flow speed.

particular, the costs of the to-RT commute do not increase with mode-switching to RT.

Under the open city assumption, worker income net of travel costs is constant for a household at the edge of the city, i.e.

$$W - t\bar{x} = K \tag{11}$$

where K is a constant that is dependent on the equilibrium level of utility $\bar{U}$. This is a key result that is instructive to understanding results from the model. In particular, because wages are fixed, changes in commuting speeds or pecuniary costs are offset by proportional changes in city radius. Refer to the Appendix for the derivation of equation (11).

3.1 Results

In the baseline calibration of the model we set parameters and variables to values that approximate a mid-sized city. The housing share of income α is set to 0.2. Exogenous wages are $100,000, land rent is $100,000 per square km, and pecuniary costs for RT and road are $0.5 per km (which equates to $20 a day for round trip for a commute of 20km each way). We set endogenous variables as follows: population is 500,000 households, road speed is 35km/h, RT speed is 50km/h, to-RT commuting speed is 35km/h, we have a single RT corridor, and the city arc is set to 2π. For a summary see table 1 in the Appendix. This results in 465,629 road commuters, and the remaining commuters take RT. To vary the congestion ratio in the baseline calibration, we consider values of $N_{M,cap}$ between 250,000 and 450,000, resulting in congestion ratios between 0.356 and 0.853.[14]

We consider the following improvements:

1. Construction of a new RT corridor: We increase r from 1 to 2.
2. Increase in RT capacity: We increase $N_{R,cap}$ by 25%.

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[14] We also considered alternative parametrisations such as $W = \$200,000$, $\alpha = 0.3$,$\beta_M = 0.8, 0.9, 1, 1.1, 2$, and doubling N and $N_{M,cap}$ values. Our key conclusions remain unchanged. Results available on request.

3. Decrease in RT fare: We decrease g_R by 25%.

We address each policy in the subsections below.

3.11 Additional Rapid Transit Corridor

[Figure 2 somewhere near here]

[Figure 3 somewhere near here]

Figures 2 and 3 plot the log difference in each variable against the congestion ratios considered. City radius, population, land values, RT commuters, and road and RT speeds all increase.[15] VKT only decreases in regions of the parameter space where congestion is low. Otherwise VKT increases. The number of car commuters decreases. We discuss each result in turn.

Population and the number of RT commuters increase in response to RT improvements that reduce the intensive margin of travel costs (i.e. costs per kilometre). In the case of a new RT corridor, travel time costs are reduced directly reduced for households located sufficiently close to the new corridor. As these households switch from road to RT modes, commuting speeds for the remaining road commuters increase as the total number of road commuters decrease. The radius of the city increases in order to ensure travel costs are unchanged for the edge household (see (2) above). However, increases in road speed exceed the increase in radius: Because pecuniary costs are positive, there must be a proportionately larger decrease in travel time cost to ensure that the commuting cost for the edge household is unchanged.

The magnitude of the increases in road speed are increasing in road congestion – or, equivalently, decreasing in the congestion ratio. This is because road travel times are increasing and convex in road commuters under (8), and are bounded from below by the inverse of the free-flow road speed. Policies that reduce the number of road users therefore result in larger increases in road speed in cities with higher initial levels of congestion. The reduction in

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[15] Although the change in (log) aggregate land value is omitted from the figure, recall that the increase in aggregate land values is the same as the increase in population.

travel costs from faster speeds generate increases in population and city radius. The magnitude of these increases are larger in more congested cities because the reduction in travel costs is greater, given the convexity of the road travel time function.

Because population density is constant, the population increase is accommodated through an equivalent increase in the area of the city. For example, when the RT congestion exponent is four and the road congestion ratio is 0.4, the (log) population of the city increases by a little less than 0.06. Land area (not pictured) increases by the same amount.[16] However, increase in population exceeds the increase in city radius because the additional RT corridor also increases the effective radians θ^* of the city (see (2) above).

Next we examine changes in private vehicle use, beginning with the number of road commuters. The number of households commuting by car falls since road speed increases. Like population, the change in the road-commuting population is decreasing in road network capacity, since the increases in road commuting speed are greatest in congested cities. The decrease in car commuters also indicates there is a decrease in the land area of the car commuting catchment. This also means that the reduction in car commuting population is more than offset by the increase in RT commuting population in order to generate the overall increase in city population.

The change in VKT depends on the initial level of road congestion. For low levels of the congestion ratio – i.e., when roads are highly congested and speed is far below the free flow speed – the change in VKT is positive. Like population, land area, and radius, the change in VKT is increasing in road congestion. However, unlike these other outcomes, it becomes negative beyond a sufficiently low level of road congestion – or, equivalently, a sufficiently high level of road capacity.[17] VKT can increase despite a net reduction in the number of road commuters because many of the new entrants take up residence beyond the original boundary

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[16] The same reasoning applies to the land area of the RT and car commuting catchments of the city, i.e. the increase in land area of the RT catchment is equal to the increase in the number of RT commuters.

[17] Unreported simulation results verify that convexity in the travel function is necessary to generate increases in VKT. These show that $\beta_M > 1$ (i.e. convexity) is necessary for there to be an increase in VKT over a non-zero interval of the congestion ratio beginning at zero. $\beta_M > 1$ becomes necessary and sufficient when pecuniary travel costs are zero. Results are available upon request.

of the city (i.e. the edge of the city prior to the improvement). Their commutes consequently cover a greater distance than those of the incumbent mode-switchers. This means that, in regions of the parameter space where road congestion is sufficiently high, the construction of RT lines will not reduce VKT, but increase it due to the in-migration of households.[18] These predictions are similar to the empirical patterns documented by Beaudoin and Lin Lawell (2018), who show that, above a threshold level of road congestion, the long run response of auto travel to PT investment is positive and increasing in the initial level of road congestion.[19]

Finally we examine changes in RT use. The increase in RT commuters is less than proportional to the increase in the number of RT lines. This reflects the increase in road speeds: The angle of each individual RT effective radian θ_R^* shrinks as a result of faster commuting speeds on roads (see (11) above). The change in RT commuters is consequently increasing in road capacity, since increases in road network speed approach zero as road capacity rises. RT speeds also increase, since the increase in RT commuters is less than proportional to the increase in the number of RT lines.

3.12 Increases in Rapid Transit Capacity

Next we increase RT capacity by 25%. Changes in the outcomes variables follow similar patterns to those described above in response to an additional RT line.[20] In the interests of brevity, we will only comment on key differences.

The primary difference is that the magnitude of the changes are increasing in the RT congestion exponent parameter: Increases in population, city radius, commuting speeds and RT commuters are greater for a congestion exponent of four than a congestion exponent of

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[18] The net effect on global VKT depends on whether the new entrants are driving more or less compared to their previous residence. This is not modelled.

[19] Beaudoin and Lin Lawell (2018) do not provide an explanation of this finding. While their conceptual framework is similar to our model in that it relies on in-migration eroding differences in travel costs between cities (see their discussion on p. 452), it does not extend to modelling travel costs and urban development. Convexity in the travel time function provides a plausible explanation for their finding because it implies that PT investments will have a smaller incipient (or short-run) impact on road travel costs in cities that have less road congestion, and thereby generating less in migration over the long run.

[20] Note that RT speed and travel cost is independent of RT capacity when $\beta_R = 0$. This parametrisation has been excluded from the charts below since RT capacity is irrelevant.

two. The impacts are larger in magnitude because the increase in RT speed is greater for higher values of the parameter. This can easily be observed by taking the derivative of the congestion function (8) with respect to mode capacity.

[Figure 4 somewhere near here]

[Figure 5 somewhere near here]

3.13 Decrease in Rapid Transit Fare

Next we decrease pecuniary RT costs by 25%. Changes in the outcomes variables follow similar patterns to those described above. Like the additional RT line, the magnitude of the changes in outcome variables are decreasing in the RT congestion parameter.

The direct reduction in commuting costs is invariant to the congestion exponent because initial RT speed is fixed. This reduction in RT commuting cost increases RT use. RT travel times rise faster with additional commuters when the congestion exponent is larger – limiting the overall increase in population, city radius and the number of road commuters.

An interesting corollary of this result is that the increase in VKT is greater when the RT congestion exponent is lower in highly congested cities. Recall that one justification of a lower RT congestion exponent is an endogenous response in public transit capacity to increase demand for public transit use. As the RT exponent approaches zero, supply of PT capacity becomes infinitely elastic. This capacity response causes the increase in VKT to be larger. This seemingly paradoxical result is however consistent with highly elastic induced demand for road network use.

[Figure 6 somewhere near here]

[Figure 7 somewhere near here]

3.14 Diminishing marginal effects of RT improvements on VKT

These results illustrate that changes in VKT decrease with further RT improvements. This is because, with each incremental RT improvement, road speeds get closer to their free flow rate, resulting in smaller increases in city population. Thus improvements in cities that already have substantial RT infrastructure generate smaller changes in VKT (noting that the changes can be negative – and thus the reductions in VKT become larger in areas of the parameter space where the change in VKT is negative).

To illustrate this point, we return to the policy simulation of increasing the number of RT lines r, plotting the change in VKT and road speed for the $\beta_{RT} = 1$ case for $r = 3, 5, 7, 9$, so that the incremental increase in r is constant (and fixed at two). Figure 8 exhibits the change in road VKT and road speed in a highly congested city with $N_{M,cap} = 250,000$, which results in a congestion ratio of 0.356. We see that the marginal change in VKT is falling as r grows large, reflecting diminishing marginal effect of RT improvements on VKT. This also implies that the threshold level of road capacity at which changes in VKT become negative gets smaller as r grows larger.

The marginal increase in road speed from incremental increases in the number of lines is falling in r. For example, increasing the number of RT lines from 1 to 3 increases (log) road speed by 0.0678. Increasing the number of RT lines from 1 to 5 increases (log) road speed by 0.1299 – slightly less than double the increase from going from one to three lines.

Sufficiently large RT improvements can therefore result in VKT reductions in comparatively congested cities. This result also offers a plausible explanation for why PT improvements results in a reduction in car use in European cities but not American cities. European cities typically already have well-developed RT networks and capacity, whereas US cities typically do not. This is consistent with Garcia-López *et al.* (2020), who find that reductions in car use from RT capacity improvements are greater in cities with a high proportion of existing subway networks.

[Figure 8 somewhere near here]

3.15 Discussion

The results presented above indicate that qualitative predictions regarding the effect of RT improvements on distance-based measures of private vehicle use depend on the amount of road congestion. From a policy-making perspective, it is instructive to know when RT improvements are likely to generate increases in VKT, particularly if limiting or reducing VKT is a policy target. The difference between observed road network speeds and free-flow speeds (speed limits) is a useful indicator of the amount of congestion and thus the demand elasticity for road network usage. When observed speeds are far below free flow speeds, demand is more elastic, meaning that increases in VKT are more likely to result from an RT improvement.

We also briefly to discuss several stylized features of the model and how they may affect observed outcomes. Monocentrism accords with our goal of examining the effects of RT, which are frequently radial in nature, connecting outer suburbs to a location where jobs are concentrated. In addition, as discussed in Glaeser, 2008 (pp. 57–58), the monocentric model is observationally equivalent to a set-up in which households need only commute towards the CBD for employment. The model also abstracts from the funding of RT improvements. However, the benefits of the RT improvement are capitalized into land values, and thus a land value tax provides an efficient mechanism for funding the public investment Arnott and Stiglitz (1979).

Commuters choose the lowest cost mode, which implies perfect substitutability between road network and RT commuting. This assumption features in many monocentric stylised models of commuting mode (Anas and Moses, 1979; Baum-Snow and Kahn, 2005; Baum-Snow, 2007), but better accords with long-run responses to changes in the costs of commuting, since empirical estimates of the cross price elasticity of demand between PT and private vehicle commuting are larger over long-run horizons (Litman, 2004; 2021, Donna 2021). The cross price is often also larger for RT modes such as light and heavy rail compared to buses (Litman, 2021). Our adoption of open city assumptions – in which households in-migrate to the city to take advantage of reductions in transport costs – accords with a long-run time frame. Nonetheless, these empirical estimates of cross price elasticities rarely imply perfect substitution. Because mode-switching is a key mechanism driving in our model, we anticipate that imperfect substitution between RT and road commuting would lessen the magnitude of changes, but consequently not the qualitative implications: If fewer road commuters switch to RT after an improvement, the incipient reduction in VKT from incumbents switching is smaller, but the incentive to in-migrate is also commensurately smaller.

The model also abstracts from commute scheduling responses to increased congestion (e.g. commuters may choose to commute at off peak times by mutual agreement with employers). Nonetheless, the model straightforwardly generalizes to a set-up in which employers permit a flexible work schedule under which employees may arrive at and depart from work during windows of arbitrary duration (e.g. 7am to 11am and 3pm to 7pm). This can be accommodated by defining the capacity parameter N_{cap} to span the commuting window, such that a given congestion ratio is observationally equivalent to a set of potential commuting windows. Larger windows correspond to a larger number of commuters and thus greater city population. Proportional changes in the outcome variables of interest will therefore be the same in response to proportional changes in the parameters of the model that govern RT improvements.[21] More sophisticated theoretical treatments of scheduling decisions in the extant literature posit that commuters are willing to reduce travel times by deviating from an optimal arrival time thereby incurring a 'scheduling cost' that reduces utility (see section 2.4.1 of Small, 2012 for a review). Although our model precludes commuter heterogeneity and scheduling, we anticipate that incorporating commute scheduling would not impact the basic implications of the model. Deferred commutes would imply that travel times increase at a slower rate with additional commuters than otherwise as the incipient reduction in travel times from an RT improvement reduces trip deference. Relative to the no-scheduling case, the smaller reduction in travel times generates less mode-switching, less in-migration, and thus less city expansion in response to RT improvements. However, less trip deference also increases household utility, and thus city size and population must expand in order to keep utility constant under the open city assumption. We anticipate that the basic lessons of the model – that improvements in RT can increase VKT in sufficiently congested cities due to

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[21] This does not hold in the extension to agglomeration effects, where wages are increasing in N.

city expansion – continues to hold in a set-up where time-saving commute delays come at the cost of reduced utility.

We have also abstracted from fixed costs of mode-use that have featured elsewhere in the literature. Baum-Snow and Kahn (2005) show that fixed costs to mode use (time costs for PT use and pecuniary for vehicle use) can dominate mode choice decisions in the monocentric model when either is sufficiently high. But in intermediate cases, distance to the RT line is the deciding factor in mode choice selection, resulting is separate mode catchments across the city. Finally, wages are fixed and exogenous. Although a standard feature of monocentric models of urban development, models of inter-regional equilibrium in the tradition of Roback (1982) posit downward sloping demand curves: Wages would decrease with in-migration in the short run as the supply of workers increases. This also raises the returns to capital and other factors of production, incentivising investment that pushes wages and capital rents back towards their original levels. Wages are constant in the long-run under constant returns to scale (CRS) in production provided the rental rate on capital is fixed in the long run. Thus our fixed wage assumption accords with a long-run view of labour markets that feature CRS production functions and frictionless capital markets. However, urban economic models often posit increasing returns to scale via agglomeration effects. We examine these results next.

3.2 Extension to Agglomeration Effects

In this subsection we introduce agglomeration effects into the model. Agglomeration effects are a determinant in the development of cities (Glaeser, 2008) and are integral to models of urban development in the tradition of Venables (2007). The greater the number of workers and firms in close proximity to one-another, the greater their collective productivity (Glaeser, 2008, pp 116–118).

Agglomeration effects potentially amplify policies that generate city expansion because they generate increasing returns to scale. We therefore incorporate agglomeration effects into our AMM model to examine how they moderate the impact of RT improvements on VKT and urban development. Following Venables (2007) we allow wages $W(N)$ to be weakly increasing in the number of workers N as follows

$$W(N) = cN^{\delta} \tag{12}$$

where $\delta \geq 0$. (12) nests production functions with increasing returns and the non-labour inputs to production held fixed (see p.121 of Glaeser, 2008).

Allowing wages to be increasing in N complicates the solution to the model under open city assumptions, but these can be obtained numerically. Because wages are dependent on N,multiple equilibria that satisfy the open city condition (11) are possible at sufficiently large values of δ. We select the equilibrium corresponding to the smallest increase in population since this accords with the reasoning behind agglomeration – they amplify policies that attract workers to a city. For large values of delta, there is often a second equilibrium at a significantly smaller city. We disregard this outcome as massive reductions in city population from a RT improvement are unlikely.

For these exercises we expand the outcome variables of interest to include changes in average population density and wages, as these are no longer unchanged in response to a RT improvement. We also include the change in aggregate land values, as this is no longer the same as the change in population when agglomeration effects are present, and the change in land area, as this is no longer proportional to the change in population.

In the interests of parsimony we focus on one form of RT improvement: The construction of an additional RT corridor. The Figure below exhibits changes in outcomes across two dimensions of the parameter space: The agglomeration elasticity parameter δ and road capacity $N_{M,cap}$. The results with $\delta = 0$ are the same as those depicted in Figure 2 above. In order to analyse how agglomeration effects moderate changes in the outcomes of interest, we examine changes relative to $\delta = 0$. The exponent on the RT congestion function is set to one.[22]

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[22] Results are similar to when the RT congestion exponent is set to four, and are available upon request.

We observe that agglomeration effects amplify the increases in population, land value and the number of RT commuters: The increases in these variables grow larger as δ increases. This is because wages are increasing in city population and thus any policies that generate an increase in population (such as a reduction in travel costs) are amplified via higher wages. Population density is also increasing in δ.

The change in road commuters is also increasing in δ and becomes positive beyond a threshold level of the agglomeration parameter. The change in road speed is likewise decreasing in the agglomeration parameter and becomes negative beyond the same threshold. Because wages have increased when agglomeration effects are present, commuting costs for a household located at the edge of the city must also increase in order for their utility to remain unchanged.[23] The increase in their commuting costs requires an increase in the intensive (travel time per km) and/or extensive margin (city radius). Because road travel times increase rapidly (exponentially) with additional commuters in congested cities, the increase in city radius becomes smaller as δ grows large in cities with high levels of road network congestion (e.g. with a congestion ratio of 0.4),[24] and can even become negative. Conversely, in cities with high levels of road capacity that are less congested, travel costs rise comparatively slowly with additional commuters, necessitating comparatively larger increases in city radius to keep commuting costs unchanged for the edge household. Thus the change in city radius is initially larger as δ grows large in cities with comparatively low levels of congestion (e.g. with a congestion ratio of 0.8).

The effect of the RT improvement on VKT therefore varies according to both agglomeration and congestion parameters. The change in VKT is increasing in δ in the regions of the parameter space considered. For cities with comparatively low levels of road congestion (e.g. with a congestion ratio of 0.8), the change in VKT rises rapidly as δ increases and becomes

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[23] Because rural land rent is exogenous, and preferences are homothetic, the amount of land and the outside good purchased by edge household is unchanged, implying that household income after travel costs is unchanged.

[24] In the city with a congestion ratio of 0.4, city radius increases by 2% for $\delta = 0$ and 1.9% for $\delta = 0.2$. Changes in city radius can become negative for sufficiently high levels of δ or alternative parametrisations.

positive beyond a threshold level of the parameter. This pattern reflects the increase in city radius in these cities as δ grows large. For cities with comparatively high levels of road network congestion (e.g. with a congestion ratio of 0.4), the change in VKT is still increasing, but at a much slower rate, going from 0.7% to 1.3% between $\delta = 0$ and $\delta = 0.2$.[25] Again, this pattern reflects smaller increases in city radius in comparatively congested cities. For small values of the agglomeration parameter in the neighbourhood of zero, the predictions of the model with only congestion hold: VKT is increasing in congested cities and decreasing in uncongested cities after an RT improvement. For large levels of the parameter, this prediction is inverted: changes in VKT are greater in uncongested cities.

The increase in population density via a reduction in land area per household is integral to this result. However, it is important to note that, in practice, there may be substantial frictions that impede this margin of adjustment, such as land use regulations (minimum lot sizes or floor-to-land-area ratios) and legally-defined parcel boundaries. These frictions present significant impediments to the redevelopment of a city (see the discussion in Duranton and Puga, 2015). We can anticipate less compact forms of urban development in response to RT improvements when land use regulations restrain increases in population density, and increases in VKT become more likely under these scenarios. This also highlights the usefulness of pairing land use reforms (such as upzoning) with RT improvements when targeting reductions in VKT.

[Figure 9 somewhere near here]

[Figure 10 somewhere near here]

3.3 Policy Simulation

In this subsection we illustrate that RT improvements must be coupled with a dis-incentive to road use in order to keep VKT constant. We focus on a cities with a high level of road

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[25] The change in VKT can eventually become negative as δ increases in highly congested cities. Results available on request.

congestion (with congestion ratios between 0.35 and 0.55), and find the per km road use charge charge required to keep road VKT constant as the number of RT lines increases.

The top panels of Figure 11 below illustrate the change in VKT as the number of RT corridors increases in the absence of the per km tax on road use. The function is concave, reflecting the diminishing marginal impact of RT improvements on VKT discussed above. The bottom panel then illustrates the per km level of the road use charge that would be required to keep VKT constant. It is also concave in the number of RT corridors – reflecting the relationship between VKT and the number of RT lines.

In the Appendix, we present similar results for the other RT improvements considered in the paper: an increase in RT capacity and a decrease in pecuniary RT costs. These experiments reinforce a basic policy lesson: In highly congested cities, RT improvements must be paired with disincentives to road use to keep VKT constant. If a reduction in VKT is the policy goal, then even larger road use taxes should be considered. These policy prescriptions align with those recommended by Duranton and Turner (2011), who also advocate for disincentives to achieve reductions in car use, based on their empirical findings.

In the Appendix, we also present results for an increase in RT corridors with agglomeration effects when the agglomeration elasticity is 0.05 and 0.1. We include changes in wages and road congestion speeds as additional outputs in order to demonstrate that the VKT-neutral road charge paired with an additional RT corridor can both increase road speeds (alleviate congestion) and increase wages. Thus RT improvements pared with road use charges present a method to reduce congestion while increasing productivity. A related literature demonstrates that road congestion taxes reduce productivity when cities are subject to agglomeration externalities in production (Arnott, 2007; Brinkman, 2016; Zhang and Kockelman, 2016). Our findings suggest that road use taxes paired with RT improvements can alleviate road congestion while enhancing productivity when an RT mode is incorporated into the framework.

[Figure 11 somewhere near here]

4.0 Conclusion

This paper studies the effects of improvements in RT using a monocentric model of urban development that features congestion effects and choices in commuting mode. Households choose between private vehicle commuting to the CBD via road networks or public transport commuting via rapid transit corridors that emanate from the CBD at fixed locations. While RT improvements increase city size and population, their impact on private vehicle usage is ambiguous and depends on the amount of road congestion. In particular, VKT can increase after a rapid transit improvement when road congestion is sufficiently high.

In-migrants to the city generate this ambiguous effect. Improvements in RT decrease the costs of RT commuting and induces many incumbent households to switch from road to RT commuting. Mode-switching alleviates congestion on roads, reducing travel times for road commuters. This generates welfare improvements that are then arbitraged away as households move into the city. Many of these households use roads to commute, and thus it is possible for VKT to increase.

VKT increases in comparatively congested cities because the increase in population in response to an RT improvement is larger. Cities with high levels of road congestion experience greater reductions in road network travel times from mode-switching because commuting speeds are far below their free-flow rates. Conversely, cities with low levels of road congestion do not experience substantial reductions in road travel times from mode-switching because road network speeds are already close to their free-flow rate. Increases in population in comparatively uncongested cities are consequently smaller because the reductions in travel costs are smaller.

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.

We extend the model to include agglomeration effects by allowing wages to be increasing in the number of households. Agglomeration effects amplify the mechanisms generating in-migration, generating larger increases in population. For small levels of agglomeration, changes in VKT remain increasing in road network congestion. However, because population density is endogenous, cities with sufficiently high levels of agglomeration can experience an inversion of the relationship between congestion and VKT, with changes in VKT decreasing in the level of road congestion. Households in-migrate until the increase in wages is offset by an increase in travel costs for a household at the edge of the city. In congested cities, it is travel times that adjust to ensure this equivalence, as travel times rapidly increase with in-migrants. In uncongested cities, it is commuting distances that increase to generate the requisite increase in commuting costs.

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 private transit. An increase in RT network capacity could be accompanied by, for example, a congestion charge on private vehicle use. Our policy simulations suggest that modest road use taxes are sufficient to offset increases in VKT.

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A Appendices

A.1 Key Results

1.11 Area of RT Catchment

We approximate the area of the catchment of a RT line using integration by quadrature. For any ε, we can calculate the distance to the CBD $\bar{x}_{\varepsilon}$ of the RT commuting individual who shares the same travel costs as a road commuter at distance $\bar{x}$ as:

$$\bar{x}_{\varepsilon} = \frac{t}{t_R + \varepsilon t_w}\bar{x}.$$

Consider the area of the triangle originating at $(0, 0)$ and terminating at polar coordinates $(\bar{x}_{\varepsilon_1}, \varepsilon_1)$ and $(\bar{x}_{\varepsilon_2}, \varepsilon_2)$ respectively, where $\varepsilon_2 = \varepsilon_1 + \Delta$ for some $\Delta > 0$. The area of this triangle is given by $\frac{1}{2}\bar{x}_{\varepsilon_1}\bar{x}_{\varepsilon_2}\sin(\Delta)$. 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 RT catchment. Analytically we have

$$A_{RL} = 2 \times \frac{1}{2}\sin\left(\frac{\theta_{RL}}{2D}\right)\sum_{i=0}^{D-1}\frac{t}{\left(t_R + \frac{i}{D}\frac{\theta_{RL}}{2}t_w\right)}\frac{t}{\left(t_R + \frac{i+1}{D}\frac{\theta_{RL}}{2}t_w\right)}\bar{x}^2$$

$$= D\sin\left(\frac{\theta_{RL}}{2D}\right)\frac{t^2}{t_R\left(t_R + \frac{\theta_{RL}}{2}t_w\right)}\bar{x}^2$$

$$= D\sin\left(\frac{\theta_{RL}}{2D}\right)\frac{t}{t_R}\bar{x}^2$$

where A_{RL} denotes the area of the RT 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:

$$A_{RL} = \frac{\theta_{RL}}{2}\frac{t}{t_R}\bar{x}^2 = \frac{\theta^*_{RL}}{2}\bar{x}^2,$$

1.12 Constant Density

In this section we demonstrate that population density is unchanged when wages are constant and under constant utility after a change in travel costs from $t_1$to t_2. Because utility is constant, a reduction in t requires an expansion in $\bar{x}$ because

$$t\bar{x} = \alpha^{-\alpha}\left(1-\alpha\right)^{\alpha-1}\bar{U}\bar{R}^{\alpha} + W \tag{13}$$

holds for all t and $\bar{x}$, noting that the R.H.S of (13) is a collection of constant terms.[26] Thus it follow that $t_1\bar{x}_1 = t_2\bar{x}_2$. This implies that

$$N_1 = \frac{\theta^*\bar{R}}{\left(1+\alpha\right)t_1^2}\left[\left(W - t_1\bar{x}_1\right)^{-\frac{1}{\alpha}}W^{\frac{1+\alpha}{\alpha}}\alpha - \alpha W - t_1\bar{x}_1\right]$$

can be re-expressed as

$$N_1 = \frac{\theta^*\bar{R}}{\left(1+\alpha\right)t_1^2}\left[\left(W - t_2\bar{x}_2\right)^{-\frac{1}{\alpha}}W^{\frac{1+\alpha}{\alpha}}\alpha - \alpha W - t_2\bar{x}_2\right]$$

such that

$$\frac{N_2}{N_1} = \frac{t_1^2}{t_2^2} = \frac{\bar{x}_2^2}{\bar{x}_1^2}$$

Thus $\frac{N_2}{N_1}$ is equal to $\frac{A_2}{A_1}$, noting that $A = \frac{1}{2}\theta^*\bar{x}_2^2$ is the land area of the city.

---

[26] Equation (13) can be rearranged to get equation (11) in the main text as follows: $W - t\bar{x} = -\alpha^{-\alpha}\left(1-\alpha\right)^{\alpha-1}\bar{U}\bar{R}^{\alpha}$

1.13 Land value and Population

Aggregate land value can be solved for as

$$V = \int_0^{\bar{x}} \theta^* R\left(z\right) z dz = \frac{\alpha J_R \theta^*}{\left(\alpha+1\right)\left(2\alpha+1\right)} \left[\left(W-\bar{x}\right)^{\frac{\alpha+1}{\alpha}} \left(\alpha W + t\bar{x}\left(\alpha+1\right)\right) - \alpha W^{\frac{2\alpha+1}{\alpha}}\right]$$

Then using the same arguments as in the previous subsection we have

$$\frac{V_2}{V_1} = \frac{t_1^2}{t_2^2} = \frac{N_2}{N_1}$$

1.14 Multiple Equilibria under Agglomeration Effects

To demonstrate multiple equilibria we consider a city with no RT. Under open city assumptions we must find t, $\bar{x}$ and W that satisfy

$$W - t\bar{x} = \alpha^{-\alpha}\left(1-\alpha\right)^{\alpha-1} \bar{U}\bar{R}^{\alpha}$$

Where wages now also depend on N when agglomeration effects are present. We assume that pecuniary costs are zero for instructive purposes. Thus

$$1 - \xi s(N)\bar{x}(N) = \frac{\alpha^{-\alpha}\left(1-\alpha\right)^{\alpha-1} \bar{U}\bar{R}^{\alpha}}{W(N)}$$

Equilibria are given by N such that the left hand side of the equation is equal to the right hand side. The right hand side is a function that is monotonically decreasing and convex in N. The function of the left hand side is more complicated. $s(N)$ is convex an monotonically increasing in N. $\bar{x}(N)$ is also increasing in N.

A.2 Additional Policy Simulation Results

[Figure 12 somewhere near here]

[Figure 13 somewhere near here]

[Figure 14 somewhere near here]

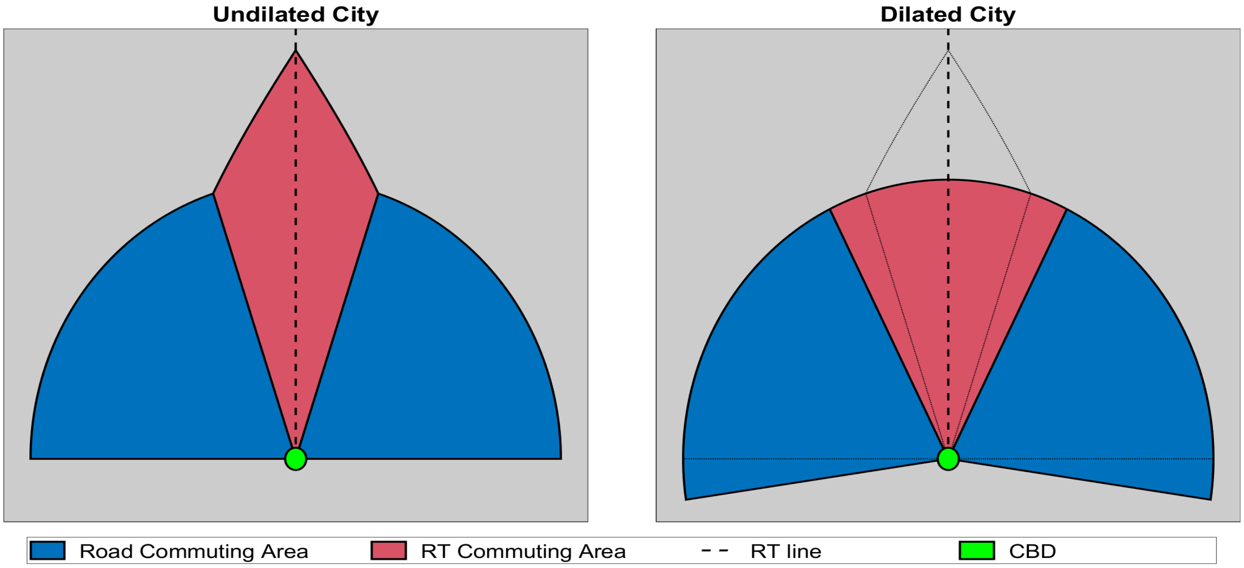
[Figure 15 somewhere near here]

A.3 Additional Tables

[Table 1 somewhere near here]

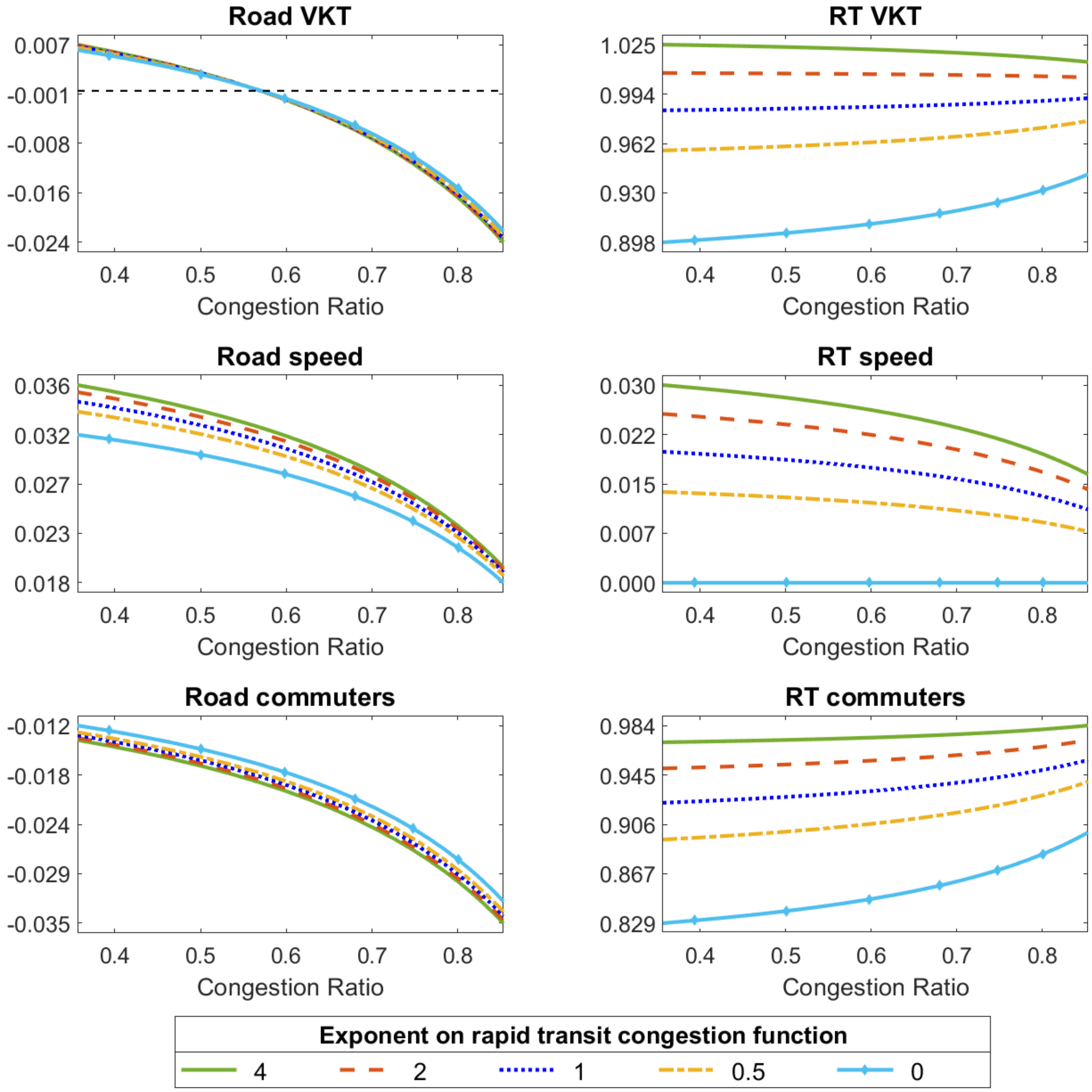
Figures

Figure 1: City Diagram



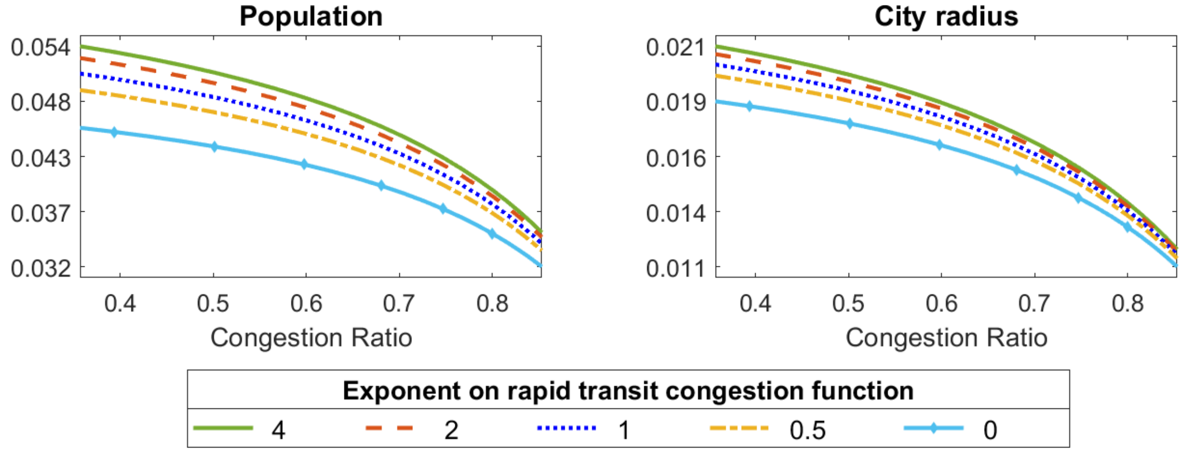
Example of the city disk spanning half a circle and with one RT line.

Figure 2: Impact of an additional RT line



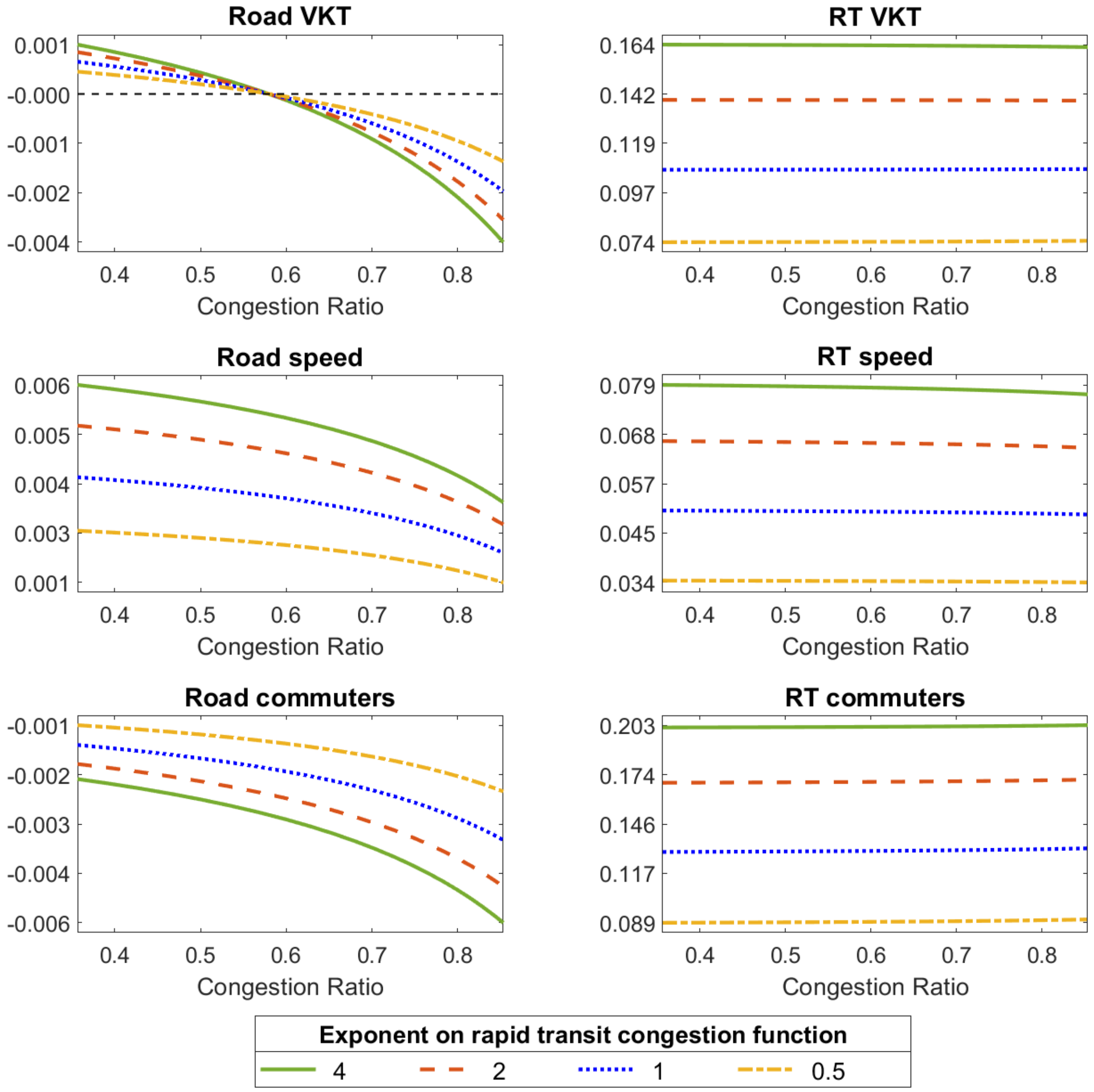
Notes: Log differences in outcome variables when the number of RT lines r is increased from one to two. Changes are plotted against road congestion ratios prior to the policy change. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. Changes are plotted for various values of the RT congestion exponent β_R in (8).

Figure 3: Impact of an additional RT line (continued)



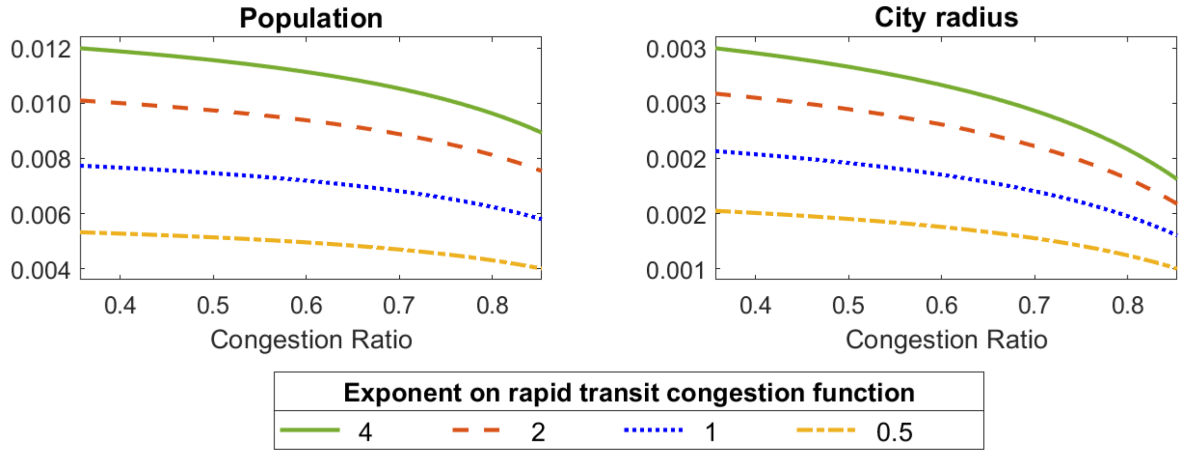
Notes: Log differences in outcome variables when the number of RT lines r is increased from one to two. Changes are plotted against road congestion ratios prior to the policy change. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. Changes are plotted for various values of the RT congestion exponent β_R in (8).

Figure 4: Impact of increasing RT capacity



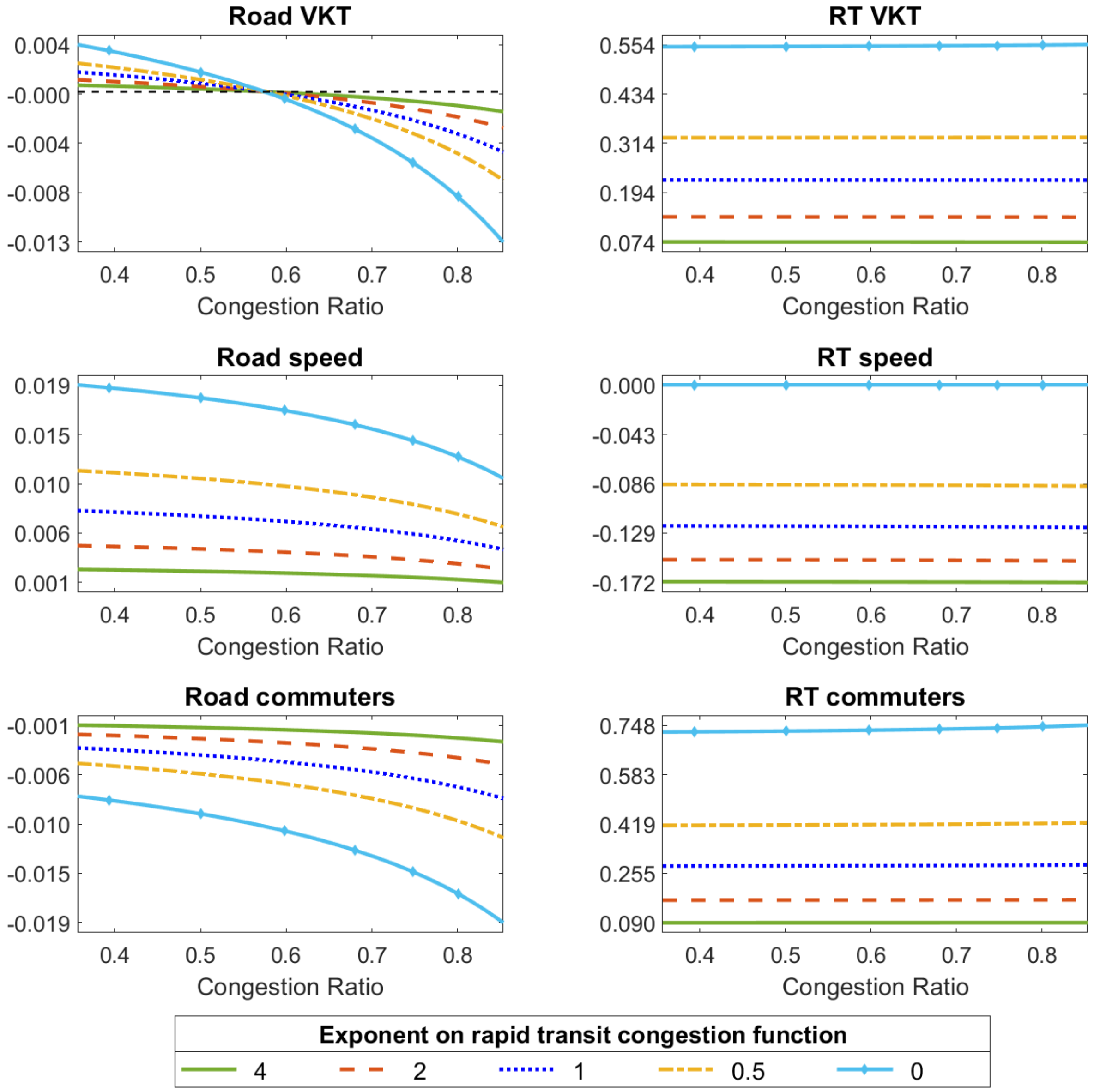
Notes: Log differences in outcome variables when RT capacity $N_{R,cap}$ is increased by 25%. Changes are plotted against road congestion ratios prior to the policy change. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. Changes are plotted for various values of the RT congestion exponent β_R in (8). RT travel costs are independent of RT capacity when $\beta_R = 0$ and consequently this parametrisation is excluded from the charts.

Figure 5: Impact of increasing RT capacity (continued)



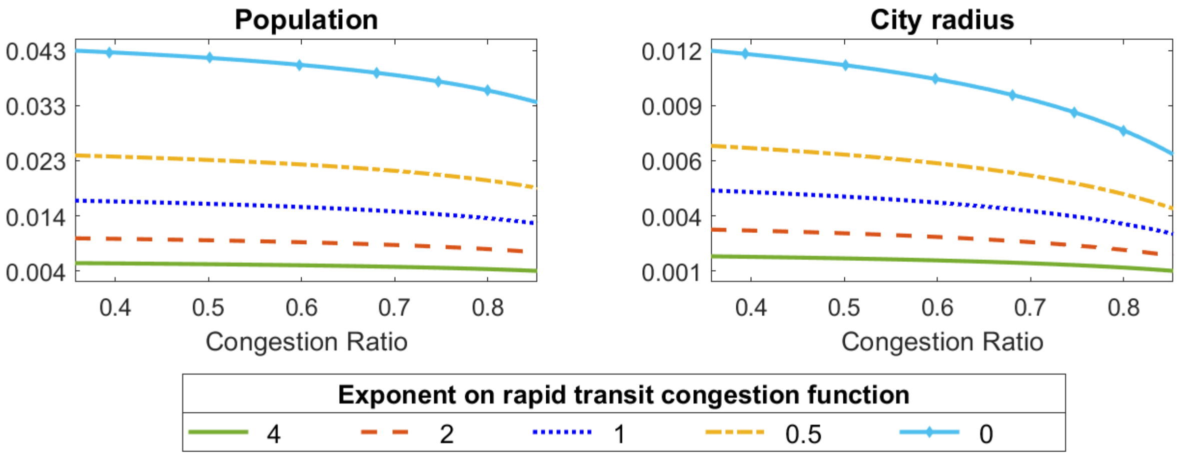
Notes: Log differences in outcome variables when RT capacity $N_{R,cap}$ is increased by 25%. Changes are plotted against road congestion ratios prior to the policy change. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. Changes are plotted for various values of the RT congestion exponent β_R in (8). RT travel costs are independent of RT capacity when $\beta_R = 0$ and consequently this parametrisation is excluded from the charts.

Figure 6: Impact of a reduction in RT pecuniary cost



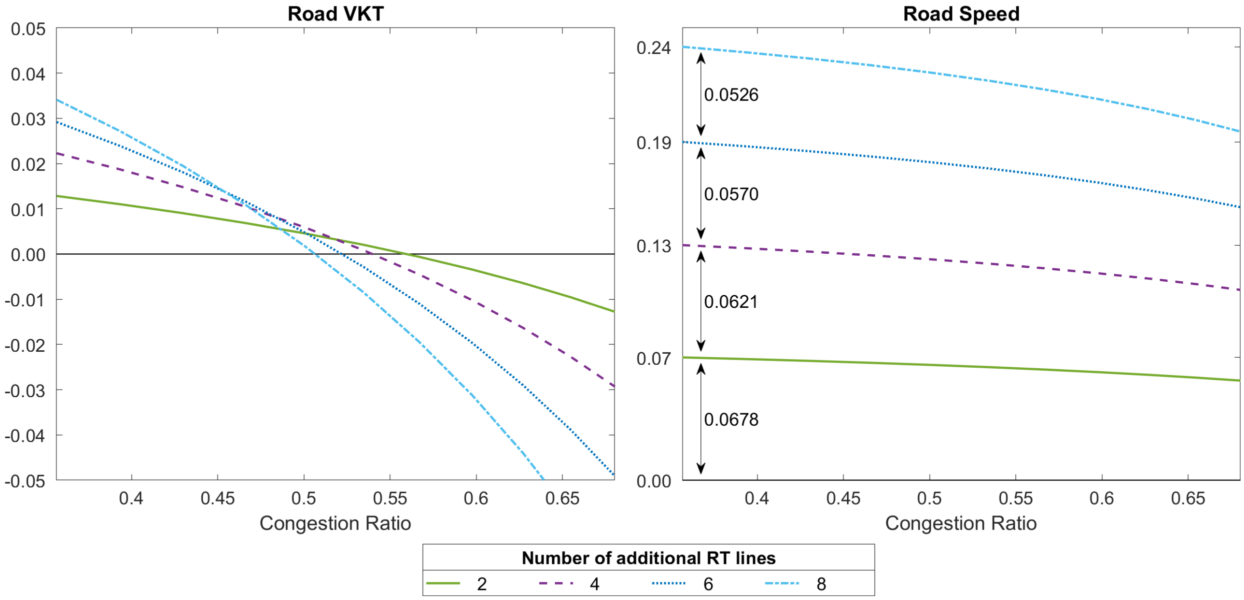
Notes: Log differences in outcome variables when the RT pecuniary cost g_R is decreased by 25%. Changes are plotted against road congestion ratios prior to the policy change. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. Changes are plotted for various values of the RT congestion exponent β_R in (8).

Figure 7: Impact of a reduction in RT pecuniary cost (continued)



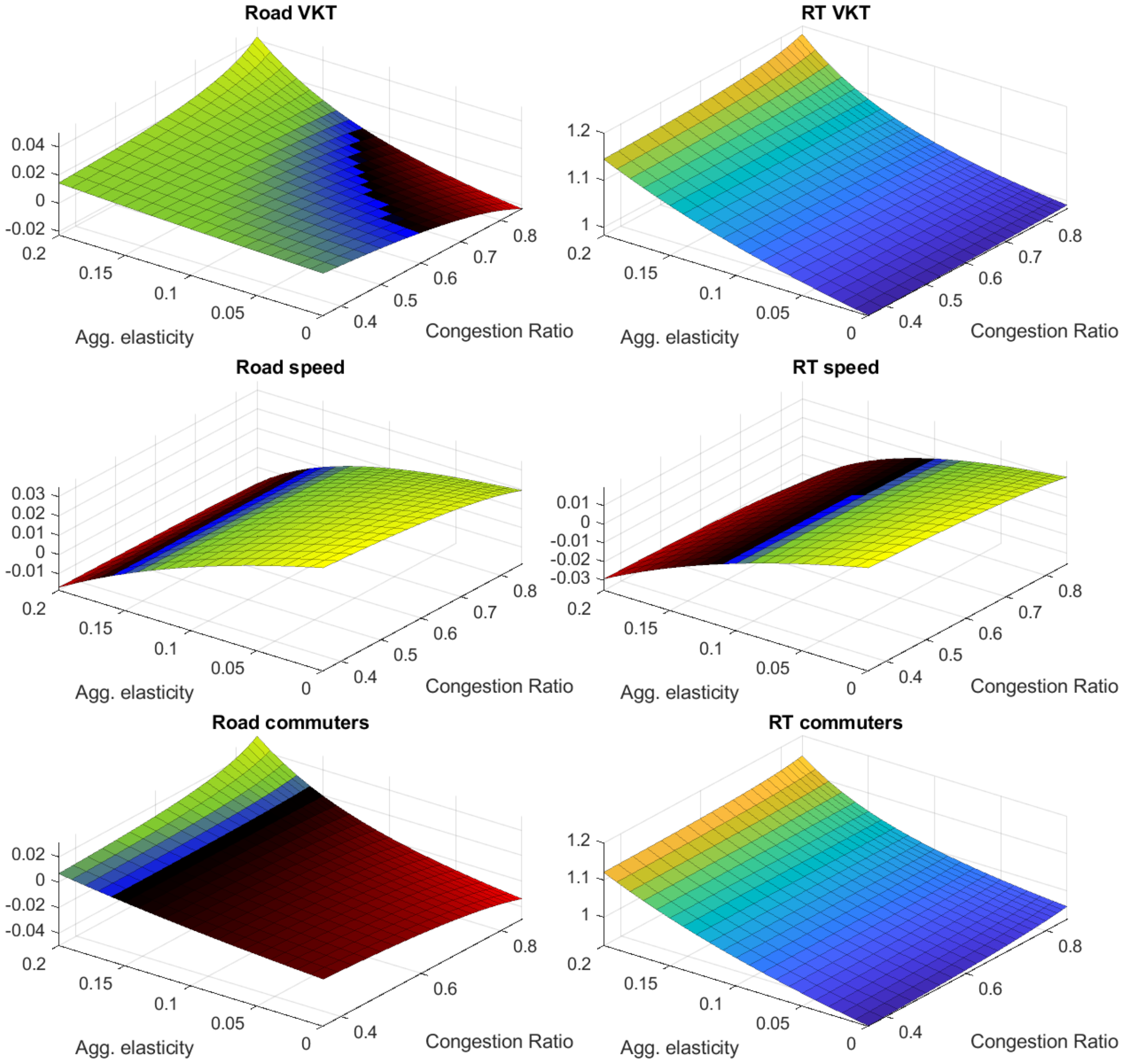
Notes: Log differences in outcome variables when the RT pecuniary cost g_R is decreased by 25%. Changes are plotted against road congestion ratios prior to the policy change. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. Changes are plotted for various values of the RT congestion exponent β_R in (8).

Figure 8: Diminishing marginal effects of RT improvements on Road VKT



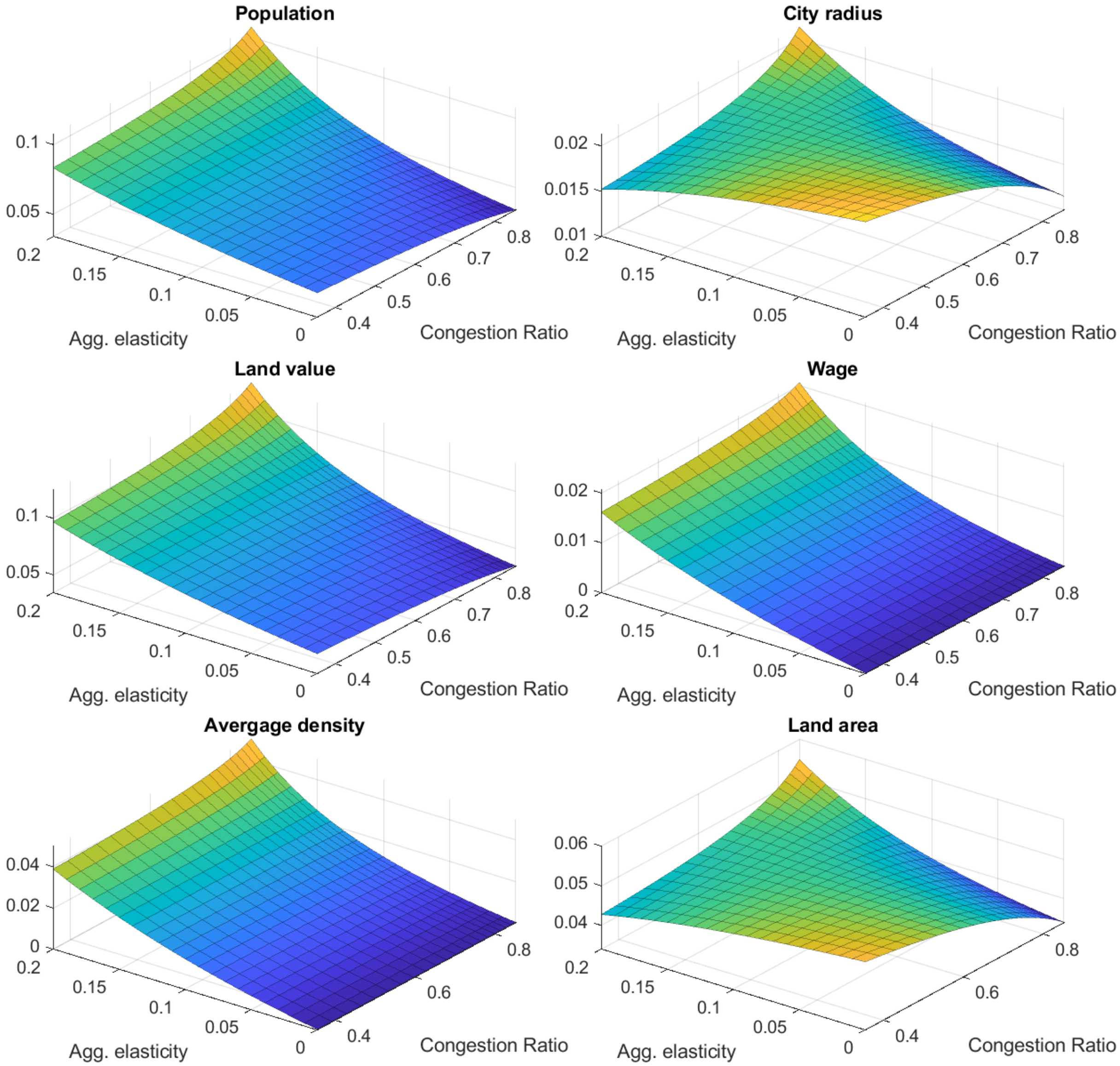
Notes: Log differences in VKT and road speed from additional RT lines plotted against road congestion ratios prior to the policy change. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. The RT congestion function exponent β_R is set to one. Number of RT lines r prior to policy changes is one.

Figure 9: Impact of an additional RT line conditional on different levels with agglomeration efficiencies



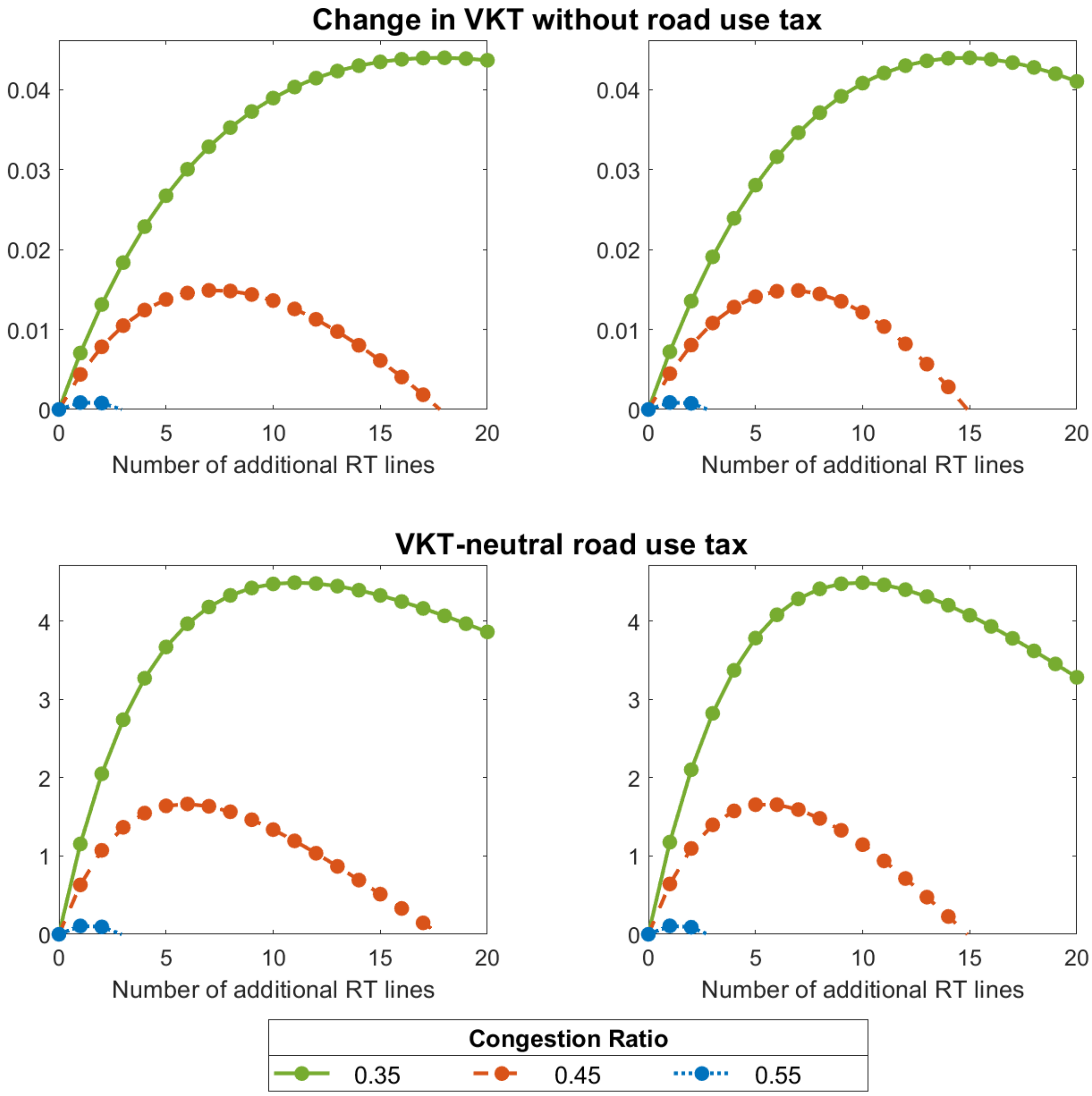
Notes: Log differences in outcome variables when the number of RT lines r is increased from one to two. Changes are plotted against road congestion ratios prior to the policy change and agglomeration elasticity parameters δ. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. The RT congestion function exponent β_R is set to one in all calibrations. To clarify the boundary between positive and negative values, the plots with negative numbers are colour-graded using a diverging scale. Positive values are displayed as blue close to zero, then graded to yellow for larger values. Negative numbers are shown as black close to zero, grading through to red for more negative values.

Figure 10: Impact of an additional RT line with agglomeration efficiencies (continued)



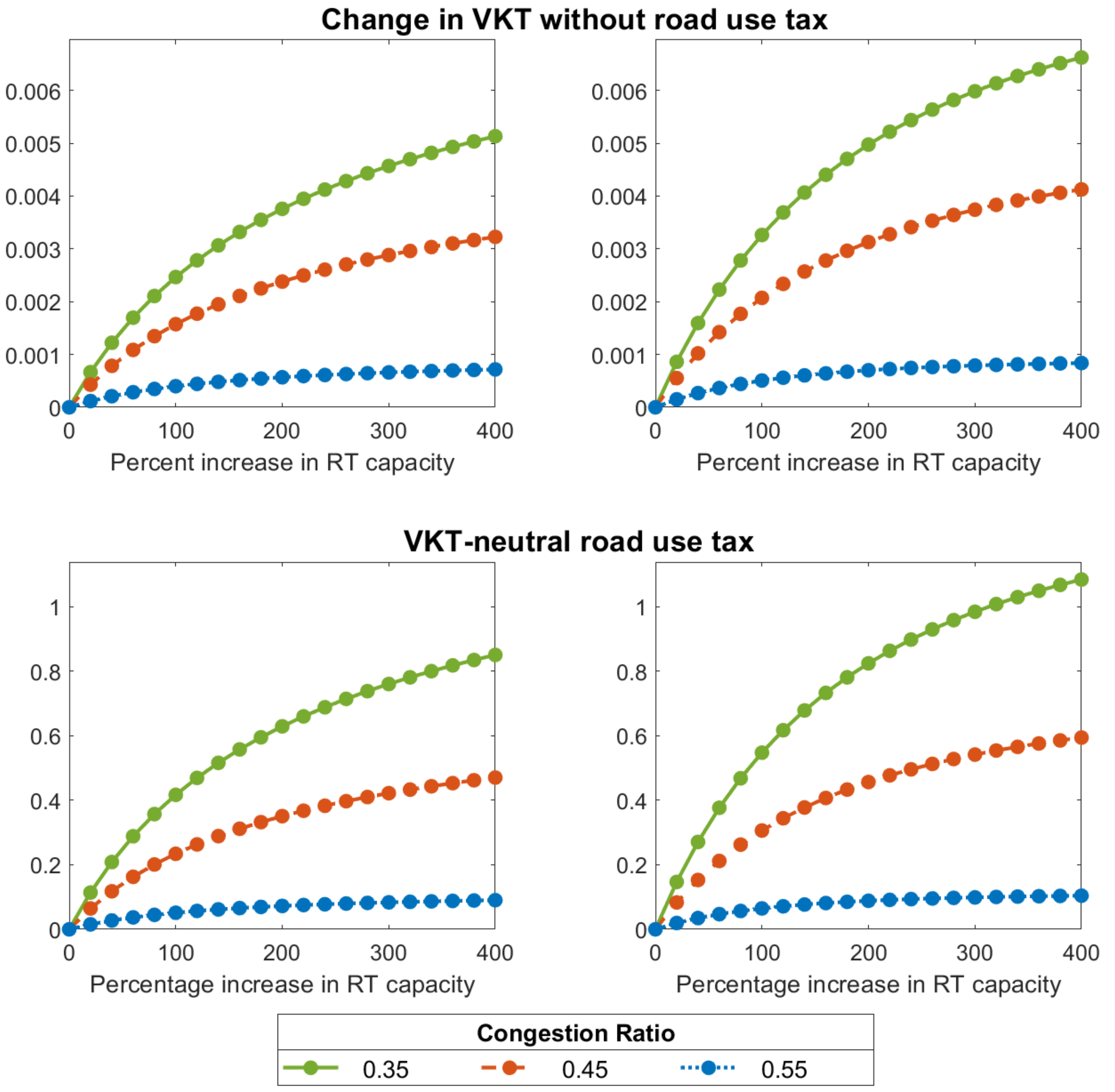
Notes: Log differences in outcome variables when the number of RT lines r is increased from one to two. Changes are plotted against road congestion ratios prior to the policy change and agglomeration elasticity parameters δ. The congestion ratio is road network speed divided by free-flow speed, meaning that road congestion is decreasing in the ratio. The RT congestion function exponent β_R is set to one in all calibrations.

Figure 11: Road use charge required to keep VKT constant with additional RT lines



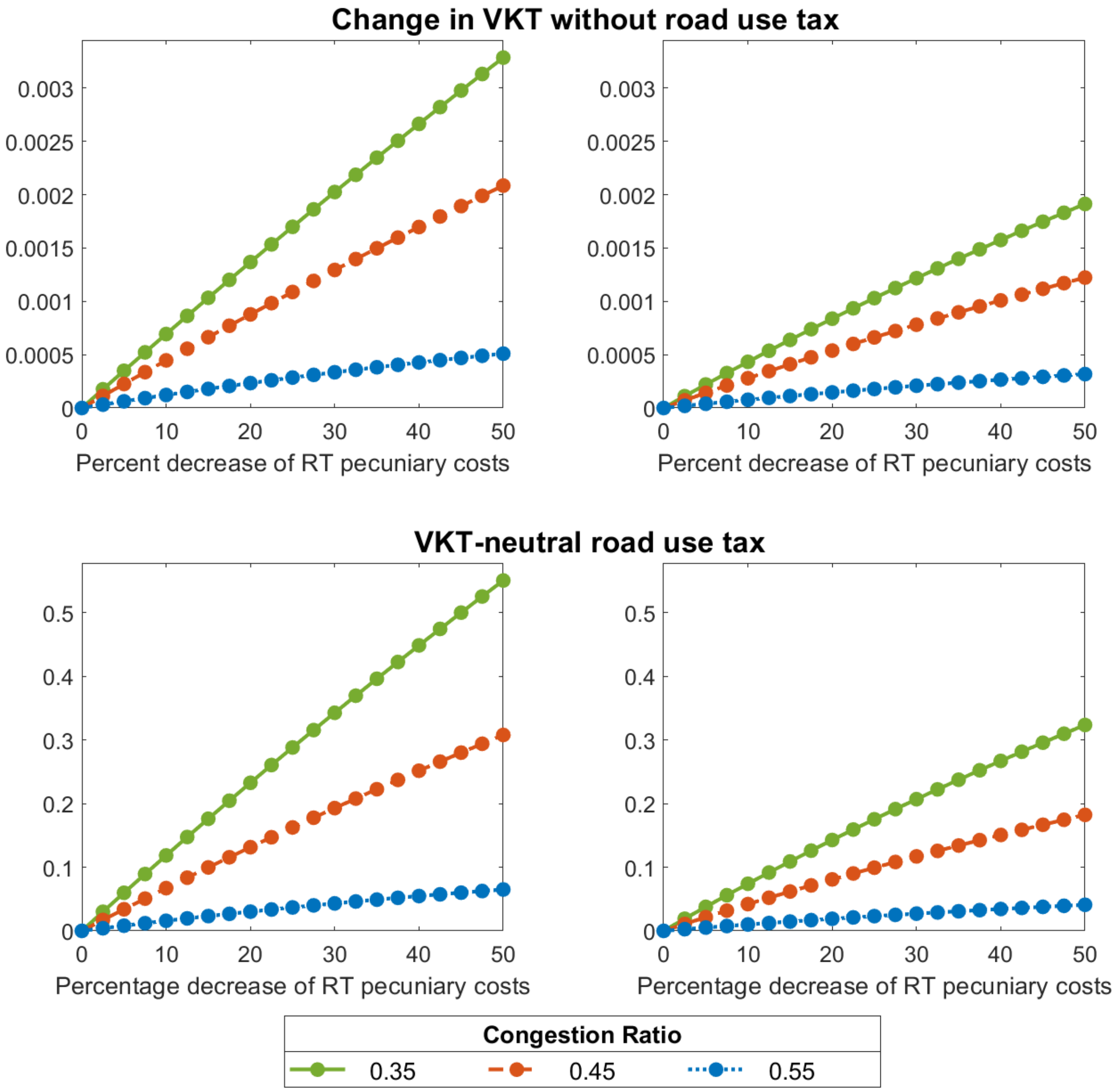
Notes: The top figures show the log differences in VKT as the number of RT corridors increases for different levels of the road congestion ratio. A larger congestion ratio corresponds to less road congestion. The bottom figure shows the road use charge (cents/km) required to ensure VKT does not increase. The figures on the left depict results with an RT exponent of one. The figures on the right depict results with an RT exponent of two. The city begins with a single RT line.

Figure 12: Required road use charge to keep VKT constant with increase in RT capacity



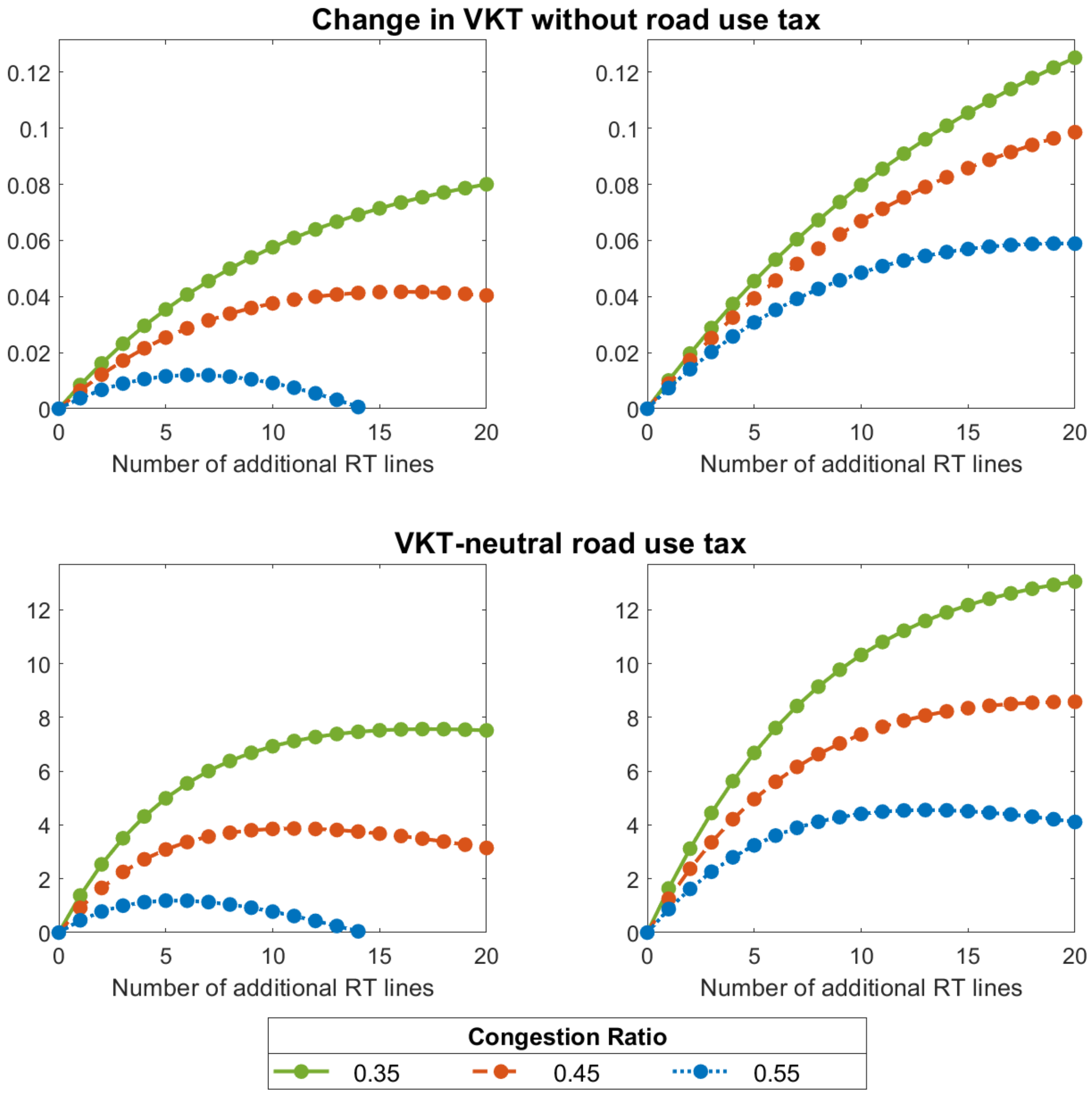
Notes: The top figures show the log differences in VKT as the capacity of the RT network increases for different levels of the road congestion ratio. A larger congestion ratio corresponds to less congestion. The bottom figures show the road use charge (cents/km) required to ensure VKT does not increase. The figures on the left depict results with an RT exponent β_R of 1. The figures on the right depict results with an RT exponent β_R of 2. The city has a single RT line.

Figure 13: Required road use charge to keep VKT constant with decrease in RT pecuniary cost



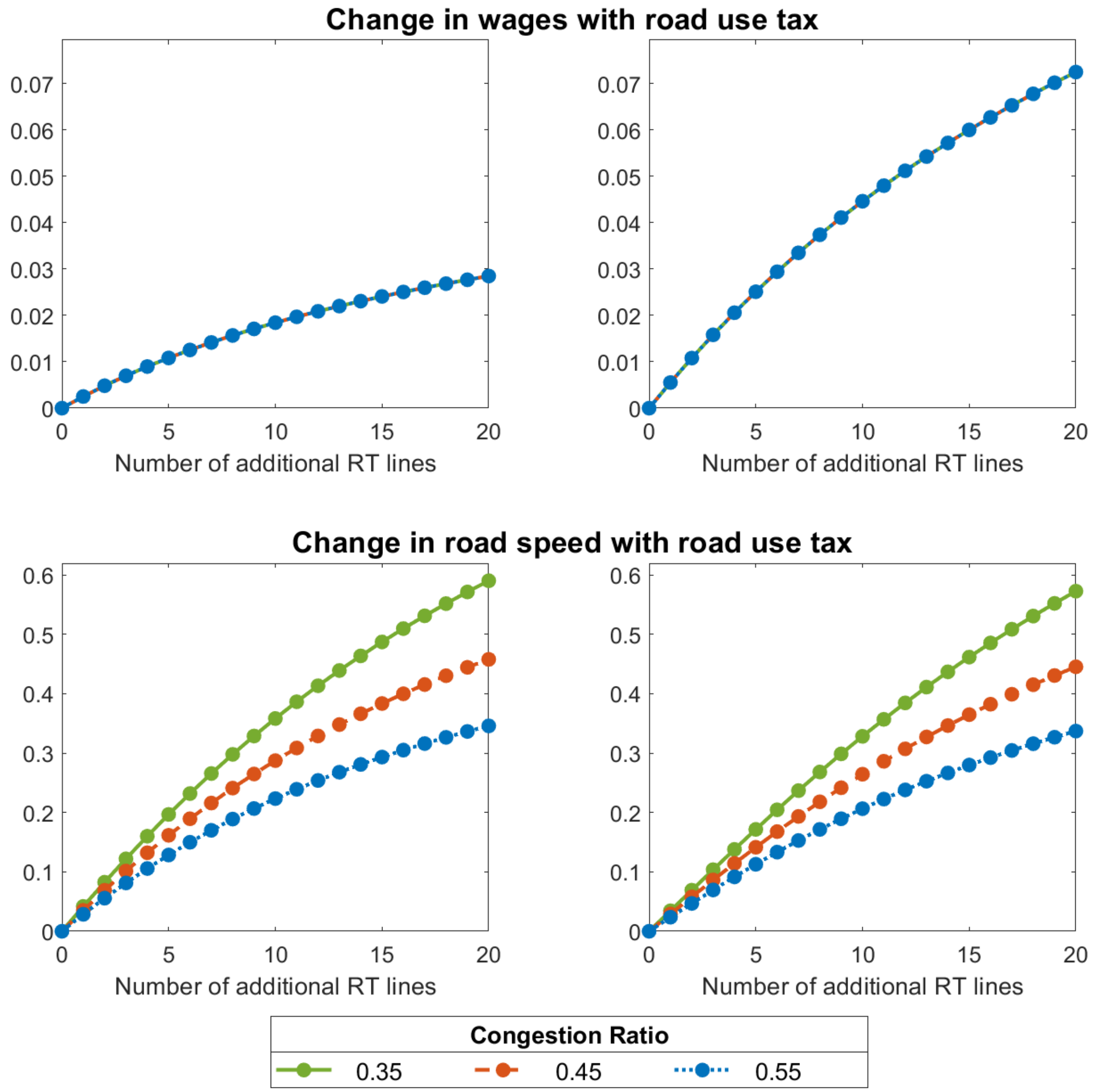
Notes: Notes: The top figures show the log differences in VKT as the pecuniary cost of RT commuting decreases for different levels of the road congestion ratio. A larger congestion ratio corresponds to less congestion. The bottom figures show the road use charge (cents/km) required to ensure VKT does not increase. The figures on the left depict results with an RT exponent β_R of 1. The figures on the right depict results with an RT exponent β_R of 2. The city has a single RT line.

Figure 14: Required road use charge to keep VKT constant with agglomeration effects



Notes: The top figures show the log differences in VKT as the number of RT corridors increases for different levels of the road congestion ratio. A larger congestion ratio corresponds to less congestion. The bottom figures show the road use charge (cents/km) required to ensure VKT does not increase. RT exponent β_R is 1 in all figures. The figures on the left depict results with an agglomeration elasticity of 0.05, the right show results for an agglomeration elasticity of 0.1. The city begins with a single RT line.

Figure 15: Required road use charge to keep VKT constant with agglomeration effects (continued).



Notes: The top figures show the log differences wages as the number of RT corridors increases and an offsetting VKT-neutral road use charge is imposed. The bottom figures show changes in road speed. RT exponentβ_R is 1 in all figures. The figures on the left depict results with an agglomeration elasticity of 0.05, the right show results for an agglomeration elasticity of 0.1. The city begins with a single RT line.

Tables

Table 1: Summary of model parameters for the baseline specification

Name	Variable	Value
Initial city population	N	500,000
Initial wages (\$)	W	100,000
Exogenous agricultural rents (\$)	$\bar{R}$	100,000
Initial congested road speed (km/hour)	$\frac{1}{s_M}$	35
Initial congested RT speed (km/hour)	$\frac{1}{s_R}$	50
Free flowing RT speed (km/hour)	$\frac{1}{s_{R,f}}$	100
to-RT speed (no congestion) (km/hour)	$\frac{1}{s_W}$	35
Pecuniary rapid transit costs (\$/km)	g_R	0.50
Pecuniary road costs (\$/km)	g_M	0.50
Opportunity cost of time percentage	ξ	50%
Travel time equation intercept for road	γ	0.15
Elasticity of travel time with congestion for road	β_M	4
Number of workdays per year	-	240
Exponent on land in utility function	α	0.3
Total arc of the city (radians)	θ	2π
Initial number of RT lines	r	1

A summary of the model parameters used in the baseline specification.