Does labor supply modeling affect findings of transport policy analyses?

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Abstract

The transport and urban economics literature applies different labor supply approaches when studying economic or planning instruments. Some studies assume that working hours are endogenous while the number of workdays is given, whereas others model only decisions on workdays. Unfortunately, empirical evidence does hardly exist on account of missing data. Against this background, we provide an assessment of whether general effects of transport policies are robust against the modeling of leisure demand and labor supply. We introduce different labor supply approaches into a spatial general equilibrium model and discuss how they affect the welfare implication of congestion policies. We, then, perform simulations and find that in many cases the choice of labor supply modeling not only affects the magnitude of the policy impact but also its direction. While planning instruments are suggested to be quite robust to different labor supply approaches, the way of modeling labor supply may crucially affect the overall welfare implications of economic instruments such as congestion tolls. Based on these findings it becomes clear which labor supply approach is the most appropriate given specific conditions. Our study also emphasizes the need for better micro labor market data that also feature days of sickness, overtime work used to reduce workdays, the actual number of leave days, part-time work, days with telecommuting etc.

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1 Introduction

Since several decades transportation and urban economists have been discussing the efficiency and the impact of different transportation policies. In this regard the corresponding literature applies different labor supply approaches when studying economic (price based) or planning instruments. In many studies labor supply/leisure demand is treated as fixed (e.g. McDonald, 2009; Wrede, 2009) or the residual of a time endowment net of travel time (e.g. Brueckner, 2005; Lucas and Rossi-Hansberg, 2002; Rhee et al., 2014). However, there is also a number of studies where a labor/leisure choice is explicitly taken into account, either by assuming that working hours (per day) are endogenous while workdays are fixed (e.g. Anas and Kim, 1996; De Palma and Lindsay, 2004) or by assuming that the number of workdays is endogenous while working hours (per day) are given (Arnott, 2007; Tscharaktschiew and Hirte, 2010a).[1] In the overwhelming majority the decisions for the approach chosen seem to be based on convenience and tractability. Even within a certain field of interest, labor supply approaches are not consistently applied. For example, studies examining price based measures for tackling congestion make use of the endogenous working hours assumption (e.g. Anas and Xu, 1999), the endogenous workdays approach (Verhoef, 2005), or the assumption that labor supply is a residual (Brueckner, 2005). The same is true with respect to studies dealing with regulatory measures (land-use or traffic regulations). For example, Olwert and Guldmann (2012) assume endogenous working hours, Nitzsche and Tscharaktschiew (2013) apply the endogenous workdays approach, and Rhee et al. (2014) treat labor supply as residual.

From an empirical point of view, distinguishing labor supply decisions along the intensive margin, i.e. changes in hours worked or workdays for those who are working, and along the extensive margin, i.e. changes in labor-force participation respectively, is crucial since both margins are suggested to be imperfect substitutes (Blank, 1988; Blundell and MaCurdy, 1999; Dechter, 2013; Hammermesh, 1996; Heckman, 1993; Hanoch 1980a,b). For example, Blundell and MaCurdy (1999) and Heckman (1993) show that almost all of the observed variation in labor supply is generated by changes in labor force participation whereas working hours (intensive) responses – estimated conditional on working – tend to be very close to zero across different demographic subgroups and earnings levels (Kleven and Kreiner, 2006). Decisions on workdays belong to both categories, because changes in the number of workdays can be varied almost marginal by being ill, telecommuting etc. and, on the other hand, the number of workdays in a year depend on the share of the year

[1] Tables 7–9 in Appendix A provide a more extensive overview on studies relying on one of these approaches. Hereafter the former is referred to as 'workhours' approach and the latter 'workdays' approach.

someone is participating in the labor-force.

Differences concerning intensive and extensive responses are usually traced back to the presence of costs associated with labor force participation (Cogan, 1981). These costs may comprise indirect costs of labor force participation such as expenses to child care but also, in particular, monetary and time costs of commuting. These costs then may result in economies of scale in the extensive labor supply decision thereby making very low hours of work unattractive. If workers are able only to choose their number of working hours per day, these costs can be seen as fixed costs of labor supply. In contrast, if working hours are given while the number of workdays can be chosen, these costs are no longer fixed but become a variable cost. Theoretically, the effect of commuting costs on the number of workdays is ambiguous because an increase in monetary costs induces both an income and a substitution effect whereas in an working hours approach changes in labor supply are only induced by income effects.

These findings carefully suggest the application of the workdays approach (see also Fosgerau and Pilegaard, 2007). Unfortunately, due to data restrictions there is almost no empirical evidence on how workers explicitly respond to changes in commuting costs thereby making the application of either the workhours or workdays approach to some extent arbitrary. An exemption is Gutiérrez-i-Puigarnau and van Ommeren (2010) examining the effect of commuting distance on workers' labour supply patterns, distinguishing between weekly labour supply, number of workdays per week and daily labour supply, and accounting for endogeneity of distance by using employer-induced changes in distance. By using German data from the German Socio-Economic Panel for the years 1997-2007, their analyses suggest that commuting distance slightly increases daily and weekly labour supply while the number of workdays is hardly affected. Hence, workers with long commutes appear to increase their weekly hours mainly by increasing their daily labour supply, but the effects are relatively small.

Furthermore, many instruments available and discussed to tackle transport related issues focus explicitly on workdays and others have a workday related component. In contrast, working hours are usually only indirectly affected. Here one can think of a cordon toll, a congestion toll, a fuel tax, an emission tax, a miles tax or parking fees. Their tax base depends in particular on the number of trips, i.e. the number of workdays but not on daily working hours (though of course less working hours allows more leisure and shopping travel during workdays). If workdays can be varied, there is a substitution in favor of daily working hours and, since working becomes more expensive on average, in favor of aggregate leisure time. In contrast, as mentioned before when workdays are fixed such measures provide a pure income effect but no substitution effects. As a consequence, welfare effects and other impacts of these and further related policies might differ depending on the labor supply approach employed.[2]

To sum up, neither are the labor supply responses along their margins fully clear which makes the right choice of the labor supply approach difficult nor are the implications of the different labor supply approaches on the findings of transport policy analyses known at all.

Against this background, we provide an assessment of whether general effects of transport policies are robust regarding magnitude and direction against the modeling of leisure demand and labor supply. To the best of our knowledge, this is the first study doing that. In order to account also for indirect effects we choose a general equilibrium approach that includes transport and spatial location decisions, i.e. the Anas-type model (see Anas and Xu, 1999). We apply this model to congestion as one of the most prominent issues in transportation economics and examine five policies aimed at tackling congestion: Pigouvian congestion tolls, a cordon toll, a miles tax, the investment in road infrastructure capacities to alleviate congestion, and a land-use type regulation (zoning).

We proceed as follows: We first analytically derive the value of times (VOTs) of the different approaches with constrained utility maximization. In addition to the existing traditional labor supply approaches (workhours or workdays) we propose a hybrid model where households decide simultaneously on working hours and workdays. Then we derive welfare changes induced by transport policies and show how labor supply modeling affects the welfare components in the second-best urban model. Since theory does not allow to derive the direction of the overall welfare effect unambiguously, we then perform simulations for the policies mentioned above and for a wide range of assumptions concerning landownership and revenue recycling. We also consider homogeneous and inhomogeneous leisure across days, because Hanoch (1975) and Oi (1976) emphasize that leisure on a workday and leisure on a non-workday are inhomogeneous and thus should be treated as different arguments in the utility function (evidence see Dechter, 2013). In contrast, all prior policy papers, among them the selection listed in Appendix A, implicitly assume that leisure is homogeneous, i.e. they do not care about whether leisure is enjoyed on workdays or non-workdays.

Most importantly we find that in many cases the choice of labor supply modeling not only

[2] For example, Kleven and Kreiner (2006) show that it is crucial to account for the presence of non-convexities created by fixed work costs. In the non-convex framework, tax and transfer reforms may generate first-order effects on government revenue. These revenue effects make e.g. the marginal cost of public funds substantially higher.

affects the magnitude of a policy impact but also its direction. While planning instruments are suggested to be quite robust to different labor supply approaches, the way of modeling labor supply crucially affects the overall welfare implications of economic instruments such as congestion tolls. The overall welfare effects of an economic instrument also depends on whether leisure is assumed to be homogeneous or inhomogeneous. Interestingly, we also find that in regard to the level of congestion the choice of the labor supply approach is of secondary importance. The reason is that the missing opportunity for commuters to adjust the frequency of commuting trips in a workhours approach is suggested to be offset by stronger relocation. The hybrid approach we suggest is less sensitive to changing modeling features and provides more conservative results. Eventually, we provide clear recommendations on which approach is adequate under which conditions. Our study is also important because it emphasizes the need to get better micro labor market data that also feature days of sickness, overtime work used to reduce workdays, the actual number of leave days, part-time work, days with telecommuting etc.

The remainder of the paper is organized as follows. In Section 2 we introduce the different labor supply approaches employing a spatial urban representative household model, derive individual first-order conditions and discuss differences in resulting VOTs and consumer prices. In Section 3 we extend the approach to a spatial general equilibrium model and discuss how different labor approaches may affect the welfare implication of anti-congestion policies. Here we choose Pigouvian congestion tolls for exposition. In Section 4 we then perform numerical simulations to verify size and sign of the effects involving all other policies under consideration. The findings of the simulation then result in recommendations under which conditions a certain labor supply approach might be most appropriate. Finally, Section 5 concludes.

2 General labor supply approaches

Before considering the welfare implication of different policies under different labor supply modeling procedures, we first describe the basic model setup and derive optimality conditions of the different labor supply approaches. This allows us to provide basics insight into how the approaches differ in particular with respect to the values of time (VOT)[3] and further prices.

[3]The theoretical and empirical literature on time valuation involves the studies of e.g. Becker, 1965; De Serpa, 1971; Jara-Díaz, 2007; Jara-Díaz et al., 2008; Johnson, 1966; Oort, 1969; Small, 2012; Small and Verhoef, 2007.

2.1 General setup

We assume an urban area that is composed of $J = 2$ zones ($j = 1$ is assumed to be the city (center) and $j = 2$ represents suburban areas) indexed i, j and k with fixed land supply A where i, j and k denote the residential, work, and shopping location, respectively. Firms may produce in each zone and households can live and work in each zone, too. Depending on location choice set ij, the utility function of a city household $u_{ij}(z_{ij}, q_{ij}, \mathcal{L}_{ij}) + \varepsilon_{ij}$ is composed of deterministic utility u_{ij} and a stochastic utility component, ε_{ij}, reflecting idiosyncratic preferences for location pattern ij (see Anas and Xu, 1999). In the first stage households decide on consumption, z, housing, q, and – depending on the labor supply approach considered – leisure demand $\mathcal{L}$,[4] given their location choice ij. In the second stage households choose their zone of residence i and their working zone j in a multinomial logit framework by comparing indirect utilities.

Assuming symmetry, this local decision determines the two-way commuting distance of household type ij, m_{ij},

$$m_{ij} \equiv m_i + \delta_{ij} m_j \,, \qquad \forall i, j, , \; \delta_{ij} = 0 \text{ if } i = j, \; \delta_{ij} = 1 \text{ if } i \neq j, \tag{1}$$

where m_i is distance traveled in zone i and $\delta_{ij} \in \{0, 1\}$ is an indicator that is unity if $i \neq j$ and zero otherwise. We assume that car is the only travel mode available and that for the time being road capacities are fixed and normalized to unity. In addition to commuting trips from zone i to zone j, there are shopping trips, where consuming one unit of z requires one shopping trip. Hence, the number of commuting trips (= workdays D_{ij} since we focus on on-site work ignoring telecommuting) plus the number of shopping trips (= the number of consumption bundles $\sum_k z_{ijk}$) determine the number of trips traveled by a household facing location pattern ij. We assume that congestion occurs only during peak hours where commuting takes place, while shopping trips are only made at off-peak hours. By assuming that every trip within a zone is of the same length, aggregating commuting traffic of all households residing in zone i and working in all zones j (including $i = j$) and of all households residing in zone j but commuting to zone i gives zone specific commuting traffic flow in zone i, F_i. Commuting travel time required for one unit of distance of two-way commuting in or through zone i, $t_i = t_i(f_i)$, then depends on peak traffic density $f_i = F_i/K_i$ where $t' > 0$ and K_i is road capacity. Accordingly, two-way commuting (shopping) travel time for a trip from zone i to zone

[4] The concrete shape of $\mathcal{L}$ will be specified below.

$j(k)$ is

$$t_{ij}(f_i, f_j) \equiv m_i t_i(f_i) + \delta_{ij} m_j t_j(f_j) \tag{2}$$

$$t_{ik}^z \equiv m_i t_i + \delta_{ik} m_k t_k. \tag{3}$$

In the following we denote leisure hours on a workday by ℓ, leisure days by L, leisure hours on a leisure day by l, daily working hours by h, workdays by D, daily time endowment by e, and endowment of days per year by E.

The utility function in the inhomogeneous leisure approach can be written

$$u_{ij}(z_{ij1,\ldots,}z_{ijJ}, q_{ij}, \mathcal{L}_{1ij}, \mathcal{L}_{2ij}), \tag{4}$$

while in the homogeneous leisure approach it is

$$u_{ij}(z_{ij1,\ldots,}z_{ijJ}, q_{ij}, \mathcal{L}_{1ij} + \mathcal{L}_{2ij}), \tag{5}$$

where $\mathcal{L}_1 \equiv \ell_{ij} D_{ij}$ and $\mathcal{L}_2 \equiv l_{ij} L_{ij}$ is aggregate leisure on workdays and leisure days. respectively. Households may shop in each district and spatially differentiated consumption is denoted by z_{ijk}, i.e. shopping of household type ij in zone k. Households are subject to monetary budget constraint (6a), a daily time constraint for a workday (6b), another for a leisure day (6c) and a yearly day restriction (6d). The set of constraints is

$$\sum_k (p_k + c_{ik}^z) z_{ijk} + r_i^q q_{ij} = \left(w_j^n h_{ij} - c_{ij}\right) D_{ij} + I \tag{6a}$$

$$eD_{ij} = (h_{ij} + t_{ij}) D_{ij} + \ell_{ij} D_{ij} + \sum_k t_{ik}^z z_{ijk} \tag{6b}$$

$$eL_{ij} = l_{ij} L_{ij} \tag{6c}$$

$$E = D_{ij} + L_{ij} \tag{6d}$$

where p_k is the price of the consumption goods basket in shopping location k, c_{ij} (c_{ik}^z) are monetary travel costs for commuting (shopping) trips from i to $j(k)$ including travel taxes τ where $\tau_{ij} \equiv \tau_i + \delta_{ij}\tau_j$, r_i^q is the housing land price per square foot in zone i, $w_j^n = (1 - \tau^w) w_j$ is the hourly net wage in working zone j, τ^w is the labor tax, I is non working income, and β is the exogenous share of shopping done on workdays. The time endowments per day are multiplied by the respective number of days just to tie Lagrangian multipliers to hours per day not hours per year.

2.2 VOTs and consumer prices with different approaches

We now give a short overview on the individual decisions and the resulting VOTs for different labor supply approaches. We immediately start with the most interesting case whose features are usually not taken into account. The endogeneity of workdays as well as working hours and the fact that the valuation of leisure depends on the day under consideration, i.e. leisure is inhomogeneous.

2.2.1 Inhomogeneous hybrid approach (Yi)

For the time being we drop indices i, j and k and write c as two-way travel costs for commuting and t as two-way commuting time. Further we write z instead of z_{ijk} $\forall k$ and use c^z for two-way monetary transport costs for shopping and t^z for two-way shopping travel time. Then the Lagrangian becomes

$$\begin{aligned}\mathcal{L} = u\left(z, q, \underset{\ell D}{\mathcal{L}_1}, \underset{lL}{\mathcal{L}_2}\right) + \lambda\left\{\left(w^n h - c\right) D + I - \left(p + c^z\right) z - r^q q\right\} + \gamma\left\{E - L - D\right\} \quad (7)\\ + \mu\left\{eD - \left(h + t\right) D - \ell D\right\} + \rho\left\{eL - lL\right\},\end{aligned}$$

where λ, γ, μ and ρ are the Lagrangian multiplies of the corresponding constraints. Differentiating yields the first-order conditions (FOCs) and eventually the VOT of an hour on a workday, VOTh^{Yi}, the VOT of a leisure day, VOTL^{Yi}, and the VOT of a leisure hour on a leisure day, VOTl^{Yi} (see Appendix B.1):[5]

$$\text{VOTh}^{Yi}: \quad \frac{\mu}{\lambda} = w^n = \frac{u_{\mathcal{L}_1}}{\lambda}, \quad (8)$$

$$\text{VOTL}^{Yi}: \quad \frac{\gamma}{\lambda} = w^n\left(e - t\right) - c \quad (9)$$

$$\text{VOTl}^{Yi}: \quad \frac{\rho}{\lambda} = \frac{\gamma}{\lambda}\frac{1}{e} = \frac{w^n\left(e - t\right) - c}{e} = w^n - \frac{w^n t + c}{e}. \quad (10)$$

The VOTh^{Yi} is equal to the net wage. The VOT of a leisure day is equal to the value of the time endowment of a day minus time and monetary travel costs that cannot be avoided when working. The VOTl^{Yi} equals the VOTL^{Y} divided by the daily time endowment because transferring one leisure hour on a leisure day into one working hour implies turning the whole leisure day into a workday thereby considering commuting costs that cannot be avoided. The full consumer price of consumption goods, P^{Yi}, is the sum of the

[5]Because of the fact that the hybrid approach is the most general case which basically includes the workdays and workhours approach as special cases, for convenience we provide the derivation of the FOCs only for the hybrid approaches.

gross price of the composite commodity plus monetary and time costs of the shopping trip

$$P^{Yi} = \frac{u_z}{\lambda} = p + c^z + w^n t^z. \tag{11}$$

Because shopping may occur on both types of days the time cost is the weighted average of the VOT of an hour on a workday and the VOT of an hour on a leisure day, where the weights are the shares of shopping trips on the respective type of day.

2.2.2 Inhomogeneous workhours approach (Hi)

In the inhomogeneous workhours approach daily working hours are endogenous but workdays are given. The Lagrangian is equivalent to (7) except for the fact that we now write $\bar{D}$ instead of D and that, due to the exogeneity of days, the yearly day restriction linked to the Lagrangian multiplier γ now drops. The VOT of an hour on a workday, VOTh^{Hi}, the VOT of an hour on a leisure day, VOTl^{Hi} and the full consumer price of consumption then are

$$\text{VOTh}^{Hi}: \quad \frac{\mu}{\lambda} = w^n \tag{12}$$

$$\text{VOTl}^{Hi}: \quad \frac{u_{\mathcal{L}_2}}{\lambda} = \frac{\rho}{\lambda}$$

$$P^{Hi} = \frac{u_z}{\lambda} = p + c^z + w^n t^z. \tag{13}$$

2.2.3 Inhomogeneous workdays approach (Di)

In the inhomogeneous workdays approach daily working hours are given whereas workdays can by chosen. The Lagrangian is (7) with $\bar{h}$ instead of h. Because $\bar{h}$ is fixed the opportunity cost of an hour of leisure on a workday cannot be equal to w^n. The VOTs are

$$\text{VOTh}^{Di}: \quad \frac{u_{\mathcal{L}_1}}{\lambda} = \frac{\mu}{\lambda} \tag{14}$$

$$\text{VOTL}^{Di}: \quad \frac{\gamma}{\lambda} = w^n\bar{h} - c + \frac{\mu}{\lambda}\left(e - \bar{h} - t\right) \tag{15}$$

$$\text{VOTl}^{Di}: \quad \frac{u_{\mathcal{L}_2}}{\lambda} = \frac{\rho}{\lambda} = \frac{\gamma}{\lambda}\frac{1}{e} = \frac{w^n\bar{h} - c}{e} + \frac{\mu}{\lambda}\left(\frac{e - \bar{h} - t}{e}\right). \tag{16}$$

VOTL, i.e. the VOT of a leisure day, is the average daily net wage plus the time left for leisure and shopping on a workday evaluated with VOTh, the value of leisure time on a workday. The latter is present because leisure hours on a workday can be varied by varying the number of shopping trips. The full consumer price of consumption is

$$P^{Di} \equiv \frac{u_z}{\lambda} = p + c^z + \frac{\mu}{\lambda} t^z \tag{17}$$

2.2.4 Homogeneous hybrid approach (Yh)

If preferences for leisure do not differ across types of leisure, it follows that $u_{\mathcal{L}_1} = u_{\mathcal{L}_2}$. Then, in the presence of commuting costs, increasing hours on workdays is cheaper than transferring one hour of leisure on leisure days into worktime (the latter requires an additional commuting trip). Thus, households will prefer raising working hours on workdays as much as possible. We therefore need an additional restriction (lower bound) concerning the number of leisure hours on a workday, $\bar{\ell}$, and add the constraint $\ell \leq \bar{\ell}$ with a multiplier π. The Lagrangian is

$$\begin{aligned}\mathcal{L} = u\left(z, q, \underbrace{\mathcal{L}_1 + \mathcal{L}_2}_{\ell D + lL}\right) + \lambda\left\{\left(w^n h - c\right) D + I - \left(p + c^z\right) z - r^q q\right\} + \gamma\left\{E - L - D\right\} \quad (18)\\ + \mu\left\{eD - \left(h + t\right) D - \ell D - tz\right\} + \rho\left\{eL - lL\right\} + \pi\left(\bar{\ell} - \ell\right) D.\end{aligned}$$

In this case, we have to distinguish two cases. However, as we show in Appendix B.2 $\ell > \bar{\ell}$ is not feasible, thus leisure is chosen so that it meets the lower bound, i.e. $\ell = \bar{\ell}$. The VOTs with π as the shadow price of the leisure restriction are then (see Appendix B.2):

$$\text{VOTh}^{Yh}: \quad \frac{\mu}{\lambda} = w^n \tag{19}$$

$$\text{VOTL}^{Yh}: \quad \frac{\gamma}{\lambda} = \frac{\mu}{\lambda} + \frac{\pi}{\lambda} = w^n e - \left(w^n t + c\right) \frac{e}{e - \ell} \tag{20}$$

$$\text{VOTl}^{Yh}: \quad \frac{\rho}{\lambda} = \frac{\gamma}{\lambda}\frac{1}{e} = w^n - \frac{w^n t + c}{e - \ell}. \tag{21}$$

The VOT of an hour on a leisure day, VOTl^{Yh} is the VOT of an hour on a workday diminished by full travel costs. However, in contrast to Yi (10) travel costs are relatively more weighted due to the fact that less time is available for working, i.e. the leisure time restriction is binding. The full consumer price is

$$P^{Yh} \equiv \frac{u_z}{\lambda} = p + c^z + \left(\beta w^n + (1 - \beta)\left[w^n - \frac{\left(w^n t + c\right)}{e - \ell}\right]\right) t^z. \tag{22}$$

2.2.5 Homogeneous workhours approach (Hh)

This approach is widely used in all the studies modeling endogenous working hours per day and fixed workdays (see Table 7 in Appendix A). From the Lagrangian (18) with $\bar{D}$ instead of D and by dropping the yearly day restriction we obtain the uniform VOT of an hour on a workday and a leisure day, respectively

$$\text{VOTh}^{Hh} = \text{VOTl}^{Hh}: \qquad \frac{\mu}{\lambda} = w^n = \frac{\rho}{\lambda} \tag{23}$$

and the full consumer price of consumption

$$P^{Hh} = \frac{u_z}{\lambda} = p + c^z + w^n t^z. \tag{24}$$

The value of an hour is just the hourly net wage. Since commuting costs fixed costs in this approach, they do not enter into the VOT. The allocation of consumption across types of day doesn't matter since leisure is homogeneous, thus β does not appear in full consumer price of consumption.

2.2.6 Homogeneous workdays approach (Dh)

Assuming that leisure is homogeneous and that workdays are endogenous whereas working hours per day are fixed is the common assumption of those studies listed in Table 8 of Appendix A. From the Lagrangian (18) with $\bar{h}$ instead of h we get

$$\text{VOTh}^{Dh} = \text{VOTl}^{Dh}: \qquad \frac{\mu}{\lambda} = \frac{\rho}{\lambda} = \frac{w^n\bar{h} - c}{\bar{h} + t} \tag{25}$$

$$\text{VOTL}^{Dh}: \qquad \frac{\gamma}{\lambda} = \frac{w^n\bar{h} - c}{\bar{h} + t}e \tag{26}$$

$$P^{Dh} = \frac{u_z}{\lambda} = p + c^z + \frac{\mu}{\lambda}t^z = p + c^z + t^z\frac{w^n\bar{h} - c}{\bar{h} + t}. \tag{27}$$

Because workdays and, thus, the number of commuting trips are now flexible, the cost of commuting become a variable cost in this approach. Therefore, full commuting costs do enter inter the VOT and the value of an hour on a day is the disposable net wage after monetary commuting cost and commuting time are taken into account. The numerator in (25) is the disposable daily labor income and the denominator in (25) is the total time needed to supply one full working day.

2.2.7 Summary of VOTs

Table 1: VOTs in different labor supply approaches

Approach	u	VOTh: $\frac{\mu}{\lambda}$	VOTL: $\frac{\gamma}{\lambda}$	VOTl: $\frac{\rho}{\lambda}$
Yi	$u(z, q, \mathcal{L}_1, \mathcal{L}_2)$	w^n	$w^n e - (w^n t + c)$	$w^n - \frac{(w^n t + c)}{e}$
Yh	$u(z, q, \mathcal{L})$	w^n	$w^n e - (w^n t + c)\frac{e}{e - \ell}$	$w^n - \frac{(w^n t + c)}{e - \ell}$
Hi	$u(z, q, \mathcal{L}_1, \mathcal{L}_2)$	w^n	–	$\frac{\rho}{\lambda}$
Hh	$u(z, q, \mathcal{L})$	w^n	–	w^n
Di	$u(z, q, \mathcal{L}_1, \mathcal{L}_2)$	$\frac{u_{\mathcal{L}_1}}{\lambda} = \frac{\mu}{\lambda}$	$w^n \bar{h} - c + \frac{\mu}{\lambda}\left(e - \bar{h} - t\right)$	$\frac{\rho}{\lambda} = \frac{\gamma}{\lambda}\frac{1}{e}$
Dh	$u(z, q, \mathcal{L})$	$\frac{w^n \bar{h} - c}{\bar{h} + t}$	$\frac{w^n \bar{h} - c}{\bar{h} + t} e$	$\frac{w^n \bar{h} - c}{\bar{h} + t}$

Table 2: Full consumer prices for shopping in different labor supply approaches

Approach	u	$p + c^z + \frac{\mu}{\lambda} t^z$
Yi	$u(z, q, \mathcal{L}_1, \mathcal{L}_2)$	$p + c^z + \beta w^n$
Yh	$u(z, q, \mathcal{L})$	$p + c^z + w^n t^z$
Hi	$u(z, q, \mathcal{L}_1, \mathcal{L}_2)$	$p + c^z + w^n t^z$
Hh	$u(z, q, \mathcal{L})$	$p + c^z + w^n t^z$
Di	$u(z, q, \mathcal{L}_1, \mathcal{L}_2)$	$p + c^z + \frac{\mu}{\lambda} t^z$
Dh	$u(z, q, \mathcal{L})$	$p + c^z + \frac{w^n \bar{h} - c}{\bar{h} + t} t^z$

Table 1 and Table 2 summarize the VOTs and the full consumer prices of the different labor supply approaches. As can be seen, the VOT of an hour on a workday is the same in the hybrid and the workhours approach. However, there are differences among the approaches in all other VOTs and the full consumer prices.

In Yh the change in travel costs (e.g. due to a congestion toll) has a stronger impact on the VOT of a leisure day and, thus, might provoke stronger effects on the number of days compared with the Yi approach. Further changes will occur due to differences in the full consumer price.

A comparison of the homogeneous and the inhomogeneous workdays approach shows that in Dh the daily net wage (the numerator of the VOT of leisure days) is evaluated with $e/(h + t) > 1$ and, thus the direct price effects of higher travel cost is stronger than in

Di. This also affects consumer prices. Hence, differences in responses of workdays and location choices between Di and Dh can be expected.

The consequences of these and further differences for policy analyses is examined in the following. We first derive the welfare effects of several policies aiming at reducing congestion and, subsequently, we turn to the simulations.

3 The Welfare Effects of Congestion Policies

In the following we discuss the welfare effects of five different policies to alleviate congestion: Pigouvian congestion tolls, a cordon toll, a miles tax, the investment in road infrastructure capacities, and a land-use type regulation (zoning). The aim is to see whether or not the labor supply approach affects the outcome of these policies in a similar way. We, first, complete the model and derive marginal welfare effects of these policies. Further, we derive optimal policies and discuss the effect of labor supply modeling. For lack of space here we focus on the congestion toll for exposition. We use the inhomogeneous hybrid approach (Yi) as starting point for our exposition because it is the most general model without any restrictions on the choice of leisure and labor.

3.1 Closing the Model

Each household decides on its spatial choice set ij that maximizes its expected utility. Since ε_{ij} is stochastically distributed among households for each ij, a household's probability for choosing ij is $\Psi_{ij} = \Pr\left[V_{ij} + \varepsilon_{ij} > V_{\tilde{i}\tilde{j}} + \varepsilon_{\tilde{i}\tilde{j}}, \forall\, \tilde{ij} \neq ij\right]$. We assume that ε_{ij} is i.i.d. Gumbel distributed with mean zero, variance σ^2 and dispersion parameter $\Lambda = \pi/\left(\sigma\sqrt{6}\right)$. This implies that the choice probabilities are given by the multinomial logit model (e.g. Small and Rosen, 1981; Anas and Rhee, 2006)

$$\Psi_{ij} = \frac{\exp\left(\Lambda V_{ij}\right)}{\sum_{a=1}^{J}\sum_{b=1}^{J}\exp\left(\Lambda V_{ab}\right)}. \tag{28}$$

Output of local consumption goods is $X_i = f\left(Q_i, M_i\right)$. It is produced by a representative firm applying a constant returns to scale production function with aggregate land demand Q_i and labor demand M_i.

The government levies a wage tax τ^w, a miles (distance) tax τ^m per unit of distance, Pigouvian congestion tolls τ_i^t per trip on a congested route and a cordon toll for entering zone 1, the City, τ^c. Public expenditures comprise opportunity cost of road infrastructure $r_i s_i A_i$ where A_i is the total available land area in zone i and s_i is the share of land in zone i allocated to road infrastructure. The government balances its budget either by adjusting τ^w (hereafter referred to as labor tax recycling) or by granting/levying a per capita lump-sum transfers/tax τ^{ls} (total transfer/tax payment then is $T^{ls} = N\tau^{ls}$).[6] The budget constraint of the government is

$$\tau^w T^w + \sum_i \tau_i^t T_i^t + \tau^m T^m + \tau^c T^c + \tau^{ls} N = \sum_i r_i s_i A_i \tag{29}$$

where the tax bases are (assuming shopping occurs during off-peak time and does not add to congestion)

$$T^w \equiv N \sum_i \sum_j \Psi_{ij} w_j h_{ij} D_{ij} \tag{30}$$

$$T_i^t \equiv F_i = N \sum_j \Psi_{ij} D_{ij} + N \sum_{j \neq i} \Psi_{ji} D_{ji} \tag{31}$$

$$T^m \equiv N \sum_i \sum_j \Psi_{ij} m_{ij} D_{ij} + N \sum_i \sum_j \Psi_{ij} \sum_k m_{ik} z_{ijk} \tag{32}$$

$$T^c \equiv N \sum_i \sum_{j \neq i} \Psi_{ij} D_{ij} + N \sum_i \sum_j \Psi_{ij} \sum_{k \neq i} m_{ik} z_{ijk}. \tag{33}$$

and

$$F_i \equiv N \sum_j \Psi_{ij} D_{ij} + N \sum_{j \neq i} \Psi_{ji} D_{ji} \tag{34}$$

is commuting traffic flow during the peak hours in zone i. It is used to calculate equilibrium (congested) travel times $f_i = F_i/K_i$, where road capacity

$$K_i = \kappa s_i A_i. \tag{35}$$

is proportional to the land area allocated to roads with κ as road capacity scale parameter used to calibrate reasonable levels of congestion.

Local land, labor and consumption goods markets clearing requires

$$A_i = Q_i + N \sum_j \Psi_{ij} q_{ij} + s_i A_i, \qquad \forall i \tag{36}$$

[6]If $\tau^w T^w + \sum_i \tau_i^t T_i^t + \tau^m T^m + \tau^c T^c > \sum_i r_i s_i A_i$, i.e. aggregate tax revenue exceeds expenditure, then $\tau^{ls} < 0$ is a transfer, otherwise it is tax.

$$N\sum_i \Psi_{ij}h_{ij}D_{ij} = M_j, \qquad \forall j \tag{37}$$

$$X_k = N\sum_i\sum_j \Psi_{ij}z_{ijk}, \qquad \forall k, \tag{38}$$

where the left-hand side represents supply and the right-hand side corresponding demand.

In the case of zoning there are two local land markets in each zone: one for residential use such that $\zeta_i (1-s_i) A_i = N\sum_j \Psi_{ij}q_{ij}$ and the other for business use implying $(1-\zeta_i)(1-s_i) A_i = Q_i$, where ζ is the share of land available for residences. Eventually, we define aggregate land rents (ARL)

$$ALR \equiv N\sum_i\sum_j \Psi_{ij}r_iq_i + \sum_i r_i^q Q_i + \sum_i r_i s_i A_i. \tag{39}$$

3.2 Marginal welfare effect

Welfare is calculated as the expected value of the maximized utilities (see Small and Rosen, 1981, Anas and Rhee, 2006). Under the assumption that idiosyncratic tastes ε_{ij} for a specific location choice set ij are i.i.d. Gumbel distributed, welfare is

$$W = E\left[\max_{(ij)}\left(V_{ij}+\varepsilon_{ij}\right)\right] = \frac{1}{\Lambda}\ln\sum_i\sum_j \exp\left(\Lambda V_{ij}\right). \tag{40}$$

The marginal welfare effect of a Pigouvian congestion toll levied in zone k then is

$$\frac{dW}{d\tau_k^t} = N\sum_i\sum_j \Psi_{ij}\frac{dV_{ij}}{d\tau_k^t}. \tag{41}$$

After using public budget constraint (29), the zero profit conditions and the market clearing conditions (38)–(36) and manipulating, we obtain the marginal welfare effect of levying a Pigouvian toll levies in zone k assuming for the time being that the government uses lump-sum tax recycling (see Appendix C):[7]

$$\frac{1}{\lambda}\frac{dW}{d\tau_k^t} = \left(MEC^t - \tau_k^t\frac{Adj^t}{-dF/d\tau_k^t}\right)\left(-\frac{dF}{d\tau_k^t}\right) + TI^t + RE^t \tag{42}$$

[7]Derivations for the other policies are available upon request from the authors.

where marginal external congestion costs are (with$\frac{dt_{ij}}{d\tau_i^t} = t_i' \frac{dF_i}{d\tau_i^t} + \delta_{ij} t_j' \frac{dF_j}{d\tau_i^t}$)

$$MEC^t = \frac{N}{\lambda} \sum_i \sum_j \Psi_{ij} \lambda_{ij} D_{ij} \frac{dt_{ij}/d\tau_k^t}{dF/d\tau_k^t}, \tag{43}$$

and

$$\lambda \equiv \sum_i \sum_j \Psi_{ij} \lambda_{ij}. \tag{44}$$

the average (expected) marginal utility of income.

The marginal welfare effect of an anti-congestion policy depends on the net social marginal costs plus tax interaction plus redistribution effects. The latter arise due to differences in the marginal utility of income. If we consider labor tax recycling instead of lump-sum tax recycling, an additional tax recycling effect would be present.

To interpret welfare changes with respect to congestion tolls we have to specify the terms in (42). First, welfare depends on the net social marginal costs ,i.e. the difference between marginal external congestion costs and the weighted congestion toll $\left(MEC^t - \tau_k^t \frac{Adj^t}{-dF/d\tau_i^t} \right)$. With a Pigouvian toll this term vanishes.

Tax interaction, redistribution and adjustment terms are, respectively,

$$\begin{aligned} TI^t \equiv \tau^w N \sum_i \sum_j \left(\Psi_{ij} w_j h_{ij} \frac{dD_{ij}}{d\tau_k^t} + \Psi_{ij} w_j D_{ij} \frac{dh_{ij}}{d\tau_k^t} + w_j h_{ij} D_{ij} \frac{d\Psi_{ij}}{d\tau_k^t} \right) \\ + N \sum_{i \neq k} \tau_i^t \left[\sum_j \left(\Psi_{ij} \frac{dD_{ij}}{d\tau_k^t} + D_{ij} \frac{d\Psi_{ij}}{d\tau_k^t} \right) + N \sum_{j \neq i} \left(\Psi_{ji} \frac{dD_{ji}}{d\tau^k} + D_{ji} \frac{d\Psi_{ji}}{d\tau^k} \right) \right] \end{aligned} \tag{45}$$

$$RE^t \equiv MEC^t \left(\frac{dF}{d\tau_k^t} \right) \left(\phi^E - 1 \right) + Y^t \left(\phi^Y - 1 \right) - N \sum_i \sum_j \Psi_{ij} \delta^k D_{ij} \left(\phi^T - 1 \right) \tag{46}$$

$$Adj^t \equiv - \sum_i \sum_j \delta^k \left(\Psi_{ij} \frac{dD_{ij}}{d\tau_k^t} + D_{ij} \frac{d\Psi_{ij}}{d\tau_k^t} \right) \tag{47}$$

$$\frac{dF_i}{d\tau_k^t} = N \sum_j \left(\Psi_{ij} \frac{dD_{ij}}{d\tau_k^t} + D_{ij} \frac{d\Psi_{ij}}{d\tau_k^t} \right) + N \sum_j \left(\Psi_{ji} \frac{dD_{ji}}{d\tau_k^t} + D_{ji} \frac{d\Psi_{ji}}{d\tau_k^t} \right) \tag{48}$$

$$\frac{dF}{d\tau_k^t} = N \sum_i \sum_j \left(\Psi_{ij} \frac{dD_{ij}}{d\tau_k^t} + D_{ij} \frac{d\Psi_{ij}}{d\tau_k^t} \right) + N \sum_i \sum_{j \neq i} \left(\Psi_{ij} \frac{dD_{ij}}{d\tau_k^t} + D_{ij} \frac{d\Psi_{ij}}{d\tau_k^t} \right), \tag{49}$$

indicator δ^k is unity if i or j equals k and zero otherwise. The distribution characteristics ϕ (see Feldstein, 1972) are defined in (114). All terms, except for RE and TI include changes in workdays and location only. Even changes in travel times depend on changes in traffic flows that are determined by changes in workdays and location. In contrast, the tax interaction effect (TI) depends also on working hours.

From (50) in connection with (45) - (48) we can deduce the following:

Remark 1 *In a workhours approach the welfare effects of Pigouvian congestion tolls are only determined by relocation and changes in daily working hours.*

Proof. Set $dD_{ij}/d\tau = 0$ in (49) and (48). Then, all terms (except for TI) exclusively include relocation effects. ■

Further, in Yh, Di and Dh all components of the welfare change, except for redistribution, depend only on changes in workdays and relocation. The impact on working hours appears only in Yi, Hi and Hh. Hence, we expect that Yi implies results closer to the workhours approaches (Hi, Hh) while the Yh delivers numbers more similar to the results of the workdays approach (Di, Dh).

Remark 2 *(No relocation). Assume there are prohibiting spatial relocation costs and tax interaction. Then in workhours approaches (Hi, Hh) MEC is zero implying no direct effect of tolls on social welfare. In contrast MEC deviates from zero in the hybrid approaches (Yi, Yh) and workdays approaches (Di, Dh) if there is a small change in the number of workdays. This is even true if there are is no relocation. Then, social welfare is affected by congestion tolls.*

Proof. If $d\Psi/d\tau_k^t = 0$ and since $D = \bar{D}$ it follows from (49)that $dt_{ij}/d\tau_k^t = 0$ and from (43) that $MEC^t = 0$. If $dD_{ij}/d\tau_k^t \neq 0$ then $dt_{ij}/d\tau_k^t \neq 0$ and $MEC_{\tau_k^t} \neq 0$. ■

This result implies that in cities where many of households do not really have the option to move to the inner city, e.g. due to high housing prices, or due to negative costs such as loss of neighbors, fear for crime etc., effects of both approaches are expected to differ significantly.

We can also derive some tentative conclusions concerning the number of commuting trips (workdays): Assume workdays are endogenous and the first-round effect of the toll on the VOT of a workday dominates indirect price effects via the markets. Then the VOT of a workday declines. If, in addition, substitution effects dominate, the number of workdays declines ($dD_{ij}/d\tau_k^t < 0$). In contrast, if working hours are endogenous, there is no direct effect of the toll on the VOT because there is only an income effect. With lump-sum tax recycling this effect is neutralized on average – if we neglect market based changes.

But household types facing high congestion tolls have a larger tax liability than commuters facing low tolls. As a consequence, working hours of highly taxed households might increase ($dh_{ij}/d\tau_k^t > 0$, if $\tau_k^t D_{ij} > \left|\tau^{ls}\right|$) and those of low taxed households decline ($dh_{ij}/d\tau_k^t < 0$, if $\tau_k^t D_{ij} < \left|\tau^{ls}\right|$). In addition, households can avoid high net taxation by relocating. This implies a decline in traveling on highly congested routes and an increase in traveling on less congested routes. Assume congestion is high on the city-city and suburb-city link, then we would expect spatial resorting from households of type ii (city-city) to ij (city-suburb).

Furthermore, because in the end relocation adds up to zero $\left(\sum_{ij}\Psi_{ij} = 1\right)$, the effect of relocation on revenues from other taxes is expected to be low. Hence, responses of labor supply mainly determine the sign of the tax interaction term (45). Because the change in labor supply as a response to congestion tolls is theoretically ambiguous in the workdays approach (due to countervailing substitution and income effects), the tax interaction effect and associated with it its impact on welfare is likely to be different across labor supply approaches.

Referring to congestion we know that workdays are complementary to the number of commuting trips. Hence, the decline in workdays lowers commuting. However, as the level of congestion declines, commuting costs decline and the number of workdays increase. This induces additional congestion, diminishing the returns from internalization. Therefore, in the workdays approaches welfare is expected to increase less than in workhours approaches (Hi, Hh) due to the internalization effect.

From setting the marginal welfare change to zero and solving for τ_k^t we can derive the optimal Pigouvian toll in zone k :

$$\left(\tau_k^t\right)^* = \underbrace{\frac{MEC^t}{Adj^t}\left(-\frac{dF}{d\tau_k^t}\right)}_{(+)} + \underbrace{\frac{TI^t}{Adj^t}}_{(-)} + \underbrace{\frac{RE^t}{Adj^t}}_{(?)}. \tag{50}$$

This formula implies that optimal congestion tolls are spatially differentiated except for the unlikely case that the sum of the terms are equal for each tax. Because traffic flows and labor supply decline with a marginal increase in the toll, the first two terms in the optimal tax formula (50) are of opposite sign. Nothing can be said about redistribution. Hence, optimal tax rates are ambiguous. If redistribution is avoided due to transfers equalizing marginal utility of incomes, RE vanishes. Then, if congestion would be the only distortion (neither further externalities nor distortionary taxes) the Pigouvian tolls represent the first best solution.

3.3 Conclusions from theory

As theory shows welfare effects of transportation policy do not only depend on marginal congestion costs but also on tax interaction, tax recycling and redistribution effects. Further, similar formula can be derived for miles taxes and a cordon toll. In case of land-use type regulation, the tax distortion due to the tax instrument does not exist and, instead, a land market distortion is added that does not directly depend on labor supply (see Appendix C.3). Hence, the effects of the labor supply approach are expected to be much smaller under land-use regulation. In general, the magnitude and the direction of the policies considered might depend on the labor supply approach modeled.

4 Simulations

In the following we provide a wide range of simulations to verify the impacts of differences in the labor supply approaches considered. The theoretical analysis is now extended to a spatial urban computable general equilibrium model involving the interactions between city households, firms, absentee landowners, and the (city) government. The simulation model is structurally and formally identical to the theoretical model with some exceptions. We have to specify utility and production functions, also allow for absentee landownership and close the model with a current account. Due to the similarity, we now only explain the novel model features and specify functional forms.

Our strategy is as follows: We first simulate welfare changes for the different labor supply approaches including further variations in important model specifications. This we use to compare the six models and to draw first conclusions. To find more conclusions we, afterwards, present more detailed results for a case where welfare effects are relatively close to each other.

4.1 Functional forms and model closure

In the inhomogeneous leisure approach the concrete utility function of household type $\{ij\}$ is

$$U_{ij} = u\left(z_{ij}, q_{ij}, \mathcal{L}_{ij1}, \mathcal{L}_{ij2}\right) + \varepsilon_{ij} = \alpha^{z} \ln Z_{ij} + \alpha^{q} \ln q_{ij} + \alpha_1^{\mathcal{L}} \ln\left(\ell_{ij} D_{ij}\right) + \alpha_2^{\mathcal{L}} \ln\left(l_{ij} L_{ij}\right) + \varepsilon_{ij}, \tag{51}$$

whereas in the homogeneous leisure approach it is

$$U_{ij} = u\left(z_{ij}, q_{ij}, \mathcal{L}_{ij1} + \mathcal{L}_{ij2}\right) + \varepsilon_{ij} = \alpha^z \ln Z_{ij} + \alpha^q \ln q_{ij} + \alpha^{\mathcal{L}} \ln\left(\ell_{ij} D_{ij} + l_{ij} L_{ij}\right) + \varepsilon_{ij}, \quad (52)$$

where $Z_{ij} = \left(\sum_k (z_{ijk})^\eta\right)^{1/\eta}$ represents the CES subutility function for consumption reflecting spatial taste variety in shopping (Dixit and Stiglitz, 1977). Hence, consumers want to shop everywhere (index k denotes the shopping location), but the number of trips made to stores/retailers at a particular location attenuates with an increase in the full cost of that trip, where $1/(1-\sigma)$ is the elasticity of substitution regarding shopping locations. α^z, α^q, and $\alpha^{\mathcal{L}}$ denote preferences for consumption of general goods, housing, and leisure, respectively. In the inhomogeneous leisure approach, the preference for leisure is differentiated between preference for leisure on workdays $\left(\alpha_1^{\mathcal{L}}\right)$ and on leisure days $\left(\alpha_2^{\mathcal{L}}\right)$.

In each zone i a sufficiently large number of firms produce zone-specific commodities X_i by applying a Cobb-Douglas technology that combines land and labor.

$$X_i = B_i Q_i^{\omega_i^Q} M_i^{\omega_i^M}. \quad (53)$$

B is the the productivity (scale-) parameter, ω_i^Q is the zone-specific output elasticity with respect to land, and ω_i^M is the zone-specific output elasticity with respect to labor. We assume constant returns to scale, thus $\mu_i + \delta_i = 1 \, \forall i$.

In line with Anas and Xu (1999) as well as Anas and Rhee (2006) the time t_i needed to travel one mile in zone i is determined by the BPR (bureau of public roads) congestion function

$$t_i = g_0 \left[1 + g_1 \left(\frac{F_i}{K_i}\right)^{g_2}\right], \quad (54)$$

where g_1, $g_2 > 0$; g_i is the inverse of the free of congestion traffic speed; F_i is traffic flow in zone i and $K_i = \kappa_i s_i A_i$ denotes the exogenously given road capacity (see (35)). Since $T_i = t_i F_i$ hours per mile are spent by the traffic in zone i where F_i is overall zone-specific traffic flow, the marginal social time cost is $\partial T_i / \partial F_i = t_i' F_i + t_i$ and, accordingly, the congestion externality [hours/mile] is

$$t_i' = g_0 g_1 g_2 \left(\frac{F_i}{K_i}\right)^{g_2}. \quad (55)$$

Furthermore, because we allow for absentee landownership, financial outflows to the absentee landowners must be balanced by zone-specific export quantities Γ_i determined by a 'balance of payment'. The 'balance of payment'

$$p_i\Gamma_i = \phi_i \left[(1-\Theta)\sum\nolimits_{i=1}^{2} r_i A_i\right] \tag{56}$$

ensures that land rents paid to absentee landowners (right-hand side) equal the value of exported commodities, where Θ is the share of residential land owned by urban households. Distributing aggregate financial outflows $[\cdot]$ to zone i by setting the export share of zone i at ϕ_i,where $\phi_i > 0$ and $\sum\nolimits_{i=1}^{2}\phi_i = 1$, allows determining zone-specific export quantities Γ_i.[8]

Because of export flows we need to adjust the zone-specific good market clearing condition (displayed in (38)) by adding export quantities (outside demand) on the demand side, yielding

$$X_k = N\sum_i\sum_j \Psi_{ij} Z_{ijk} + \Gamma_k. \tag{57}$$

Absentee landowners are assumed to use their rent dividend income, $Y^A = (1-\Theta)\sum\nolimits_i r_i A_i$, to buy commodities produced and supplied in the city at mill price p_i. Assuming that their preferences are represented by a Cobb-Douglas utility function with uniform expenditure shares across the city zones, the utility function is $U_A = u_A\left(z_1^A, z_2^A\right) = (1/2)\sum_i \ln z_i^A$. Maximizing utility subject to the monetary budget constraint then gives indirect utility $V_A = \ln\frac{1}{2} + \ln Y^A - \frac{1}{2}\left(\sum_i \ln p_i\right)$.

4.2 Parameters and benchmark simulation

We choose parameters to reproduce characteristics of a prototype medium-sized U.S. metropolitan area. Table 3 displays the parameter values used to simulate the benchmark (pre-policy) urban economy for the inhomogeneous as well as the homogeneous leisure approaches, and Table 4 shows the (endogenous) outcome of the benchmark simulation in the inhomogeneous leisure approaches.[9] We consider the polycentric as well as a monocentric city, where the CBD allows for mixed land-use while suburbs are residential areas.

[8] For simplicity we assume that commodities can be exported at zero transport costs.

[9] We first simulated the hybrid labor supply approach where workdays per year as well as workhours per day are endogenously determined. Subsequently, the number of workdays (workhours) was then used as exogenous parameter in workhours (workdays) approach, thereby resulting in the same benchmark. Therefore benchmark (pre-policy) outcomes presented in Table 4 apply to the inhomogeneous hybrid, workdays and workhours approach. We refrain from also discussing the benchmark of the homogeneous leisure approach since outcomes are basically comparable.

Table 3: Benchmark parameters

Description	Notation	Value
City characteristics		
Total available land area [square mile] city/suburb	A_i	58/232
Travel distance [miles] city–city	m_{11}	8
Travel distance [miles] city–suburb	m_{12}	24 (–)[1]
Travel distance [miles] suburb–city	m_{21}	24
Travel distance [miles] suburb–suburb	m_{22}	16 (–)[1]
Share of land allocated to roads city/suburb	s_i	0.45/0.20
Consumption good price in the city (numeraire)	p_1	50 $
Export share zone i	ϕ_i	$\phi_i = 1/2\ \forall i\ (\phi_1 = 1)$[1]
Households		
Number of households/residents/workers (full city)	N	$500,000$
Time endowment (days per year)	E	315
Time endowment (hours per day)	e	16
Preference consumption/shopping	α^z	0.37
Preference housing	α^q	0.27
Preference (homogeneous) leisure	$\alpha^{\mathcal{L}}$	0.36
Preference (inhomogeneous) leisure on workdays	$\alpha_1^{\mathcal{L}}$	0.26
Preference (inhomogeneous) leisure on leisure days	$\alpha_2^{\mathcal{L}}$	0.10
Share of shopping trips on workdays	β	0.50
Taste for shopping variety	η	0.6 (–)[1]
Spatial location taste heterogeneity	Λ	3
Share urban landownership	Θ	0.3
Labor tax rate	τ^w	0.35
Firms		
Labor cost share (output elasticity) city/suburb	ω_i^M	0.90/0.70 (0.90/–)[1]
Land cost share (output elasticity) city/suburb	ω_i^Q	0.10/0.30 (0.10/–)[1]
Scale (productivity) parameter production function	B	0.70 (–)[1]
Transport		
Free flow travel time per mile	g_0	$1/40\ h$
Parameter congestion function	g_1	2.0
Parameter congestion function	g_2	5.0
Road capacity scale parameter	κ	0.68 (1.30)[1]

[1] In parentheses: monocentric city parameters

We assume a medium-sized U.S. metropolitan area inhabited by $N = 500,000$ households. The total available land area $\sum_i A_i$ is taken to be 290 square miles. Assuming an average household size of 2.5 (U.S. Census Bureau, 2012) this implies an overall population density of around 4300 persons per square mile. We reasonably assume that the road network is denser in the city compared to the suburbs and thus set the shares of land allocated roads at $s_1 = 0.45$ and $s_2 = 0.20$.

Travel distances are lowest for intra-city level (8 miles per one-way trip) and highest for inter-urban travel (24 miles per one-way trip). Along with evidence on parameters for the BPR congestion function (Small and Verhoef, 2007), this gives realistic travel and congestion patterns in the urban area. Average one-way commuting time is 31 minutes

Table 4: Outcome of the benchmark simulation (inhomogeneous leisure approach)

	Polycentric City
Time allocation	
Workdays per year	263
Leisure days per year	52
Hours on a workday spent working/leisure	8.3/5.8
Hours on a workday spent/commuting/shopping	1.1/0.8
Hours on a leisure day spent leisure/shopping	12.0/4.0
Total labor supply [hours/year]	2187
Total leisure demand [hours/year]	2164
Total commuting time on workdays [hours/year]	272
Total shopping time [hours/year]	417
Travel/Transport/Traffic	
Travel time delay [hours/year]	31
Marginal external congestion cost [$-cents/mile]	22
Total travel time [hours/year]	689
One-way commuting time [minutes]	31
Value of time of one hour on a workday [$/hour]	13.87
Value of time of one hour on a leisure day [$/hour]	12.97
Commuting trip pattern [million/year] city–city	25.4
Commuting trip pattern [million/year] city–suburb	19.3
Commuting trip pattern [million/year] suburb–city	45.0
Commuting trip pattern [million/year] suburb–suburb	41.6
Households	
Gross income [$/year]	61,071
Consumption (shopping) [trips/year]	472
Average housing demand [sqr feet]	7778
Urban Economy	
Total urban production [million units]	556.7
Urban GDP [billion $/year]	29.1
Rent city/suburb [$/sqr feet*year]	5.95/2.22
Wage rate city/suburb [$/hour]	22.81/19.65
Government	
Labor tax revenue [million $/year]	8171
Lump-sum tax revenue [million $/year]	–974
Infrastructure costs [million $/year]	7197
Location	
Households – city	168,687
Households – suburb	331,313
Jobs – city	268,099
Jobs – suburb	231,901

per trip,[10] total annual time delay per commuter is 31 hours per year[11] and averaged marginal external cost amounts to 22.$-cents/mile.[12]

Parameters in the utility function were set to obtain real-world expenditure shares for consumption and housing, and, in particular to reproduce time allocation patterns according to the American Time Use Survey. For example, pure time spent working on a working day amounts to 8.3 hours in the benchmark[13] while time spent in leisure activities is 5.8 hours. The remaining around 2 hours are used for traveling. The distribution of the annual time endowment E is 263/52. In the benchmark the number of shopping trips per year is larger than the number of commutes reflecting empirical evidence on the increasing importance of-non-work related trips in regard to individual mobility patterns (Anas, 2007).

We assume that the labor cost share of city firms is higher whereas the land cost share is lower compared to suburban firms. This is to reflect that land intensive firms usually prefer to produce at suburban locations while labor intensive (management related) jobs are more heavily concentrated in the city. Along with residential and employment location decisions of workers, this gives reasonable wage and rent profiles. For example, the average wage rate in the whole urban area amounts to 21.34 $/hour (22.81 $/hour in the city and 19.65 $/hour in the suburbs).[14]

The spatial location taste heterogeneity parameter was adjusted in such a way so that population and employment densities peak in the city and that the job–housing balance (ratio of the number of jobs in zone i to the number of employed persons in zone i) exceeds unity in the city and falls short of unity in the suburbs.[15]

[10] For comparison, average one-way commuting time in U.S. MSAs is as follows (U.S. Census Bureau, 2011): 35 min (New York-Northern New Jersey-Long Island, NY-NJ-PA); 33 min (Washington-Arlington-Alexandria, DC-VA-MD-WV); 31 min (Chicago-Naperville-Joliet, IL-IN-WI); 30 min (Winchester, VA-WV); 30 min (Riverside-San Bernardino-Ontario, CA).

[11] According to the 2012 Urban Mobility Report the yearly (2011) delay per auto commuter amounted to 29 hours (on average) in medium sized MSAs; 23 hours in small MSAs (less than 500,000 population); and 37 hours in large MSAs (over 1 million and less than 3 million population).

[12] Parry and Small (2009) report peak-period marginal external congestion of 21 $-cents/mile for Washington, DC and 26 $-cents/mile for Los Angeles.

[13] The U.S. Department of Labor/Bureau of Labor Statistics (2013a) reports average workhours of employed full time persons who worked on an average weekday of 8.5 (only men: 8.8; only women 8.1).

[14] For comparison, according to the U.S. Department of Labor/Bureau of Labor Statistics (2013b), the mean hourly wage rate for all occupations amounted to $22.33 $/hour in May 2013.

[15] For empirical evidence see, e.g. Cox (2013), Levine (1998), or Sultana (2002).

4.3 Effects of policies – numerical results

4.3.1 Overview

We run simulations in regard to five transportation policies: (1) introduction of a Pigouvian congestion toll, (2) a road infrastructure capacity expansion, (3) a miles tax of 0.05 $/mile, (4) a cordon toll of $10 for entering the city, and (5) land-use type regulation implying an increase in residential land in the city by 4 percentage points and a decline in suburbs by 4 percentage points. We consider these policies to be of reasonable size. For each policy we consider all six labor supply approaches and in addition, differentiate with respect to revenue recycling (lump-sum vs. labor tax recycling) and landownership (mixed landownership, only absentee landowners and only local landowners). Table 5 displays equivalent variations (EV) of these policies in comparison to the benchmark in million USD per year. To get an idea of the size of the effects note that 100 million $ is about 1.4% of benchmark net tax revenue and 0.3% of benchmark urban GDP.

Table 5: Simulation overview - welfare effects of policies (million dollars per year)

					Inhomogeneous leisure				Homogeneous leisure		
	Policy	Recycling	Landownership	Version	Hours Hi	Hybrid Yi	Days Di	Version	Hours Hh	Hybrid Yh	Days Dh
1	Congestion toll	Lump-sum tax	Mixed	1a	43	16	-17	6a	30	-107	-109
2	Congestion toll	Lump-sum tax	Absentee	1b	56	26	-17	6b	76	-140	-155
3	Congestion toll	Lump-sum tax	Urban	1c	17	4	-10	6c	2	-15	-16
4	Congestion toll	Labor tax	Mixed	1d	202	199	13	6d	177	20	4
5	Congestion toll	Labor tax	Absentee	1e	217	215	16	6e	325	63	24
6	Congestion toll	Labor tax	Urban	1f	127	122	5	6f	15	1	-1
7	Road capacity	Lump-sum tax	Mixed	2a	-499	-476	-633	7a	-521	-494	-507
8	Road capacity	Lump-sum tax	Absentee	2b	-420	-384	-589	7b	-368	-350	-385
9	Road capacity	Lump-sum tax	Urban	2c	-732	-730	-748	7c	-808	-764	-755
10	Road capacity	Labor tax	Mixed	2d	-706	-709	-669	7d	-757	-699	-715
11	Road capacity	Labor tax	Absentee	2e	-580	-571	-620	7e	-552	-494	-535
12	Road capacity	Labor tax	Urban	2f	-1038	-1047	-785	7f	-1139	-1079	-1070
13	Miles tax	Lump-sum tax	Mixed	3a	4	-4	-6	8a	3	-41	-46
14	Miles tax	Lump-sum tax	Absentee	3b	6	-2	-5	8b	5	-33	-40
15	Miles tax	Lump-sum tax	Urban	3c	1	-3	-6	8c	1	-40	-45
16	Miles tax	Labor tax	Mixed	3d	50	49	2	8d	53	3	0
17	Miles tax	Labor tax	Absentee	3e	47	46	3	8e	58	7	3
18	Miles tax	Labor tax	Urban	3f	46	45	1	8f	32	-1	-2
19	Cordon toll	Lump-sum tax	Mixed	4a	9	-11	-27	9a	3	-122	-143
20	Cordon toll	Lump-sum tax	Absentee	4b	12	-7	-27	9b	14	-91	-121
21	Cordon toll	Lump-sum tax	Urban	4c	2	-12	-24	9c	1	-126	-149
22	Cordon toll	Labor tax	Mixed	4d	123	121	-7	9d	128	3	-19
23	Cordon toll	Labor tax	Absentee	4e	115	111	-7	9e	140	12	-12
24	Cordon toll	Labor tax	Urban	4f	113	109	-8	9f	81	-18	-31
25	LUR	Lump-sum tax	Mixed	5a	-16	-6	-74	10a	-54	-12	-57
26	LUR	Lump-sum tax	Absentee	5b	8	20	-38	10b	30	63	-9
27	LUR	Lump-sum tax	Urban	5c	-206	-207	-195	10c	-201	-202	-198
28	LUR	Labor tax	Mixed	5d	-121	-125	-91	10d	-104	-125	-102
29	LUR	Labor tax	Absentee	5e	-61	-46	-65	10e	-66	-44	-69
30	LUR	Labor tax	Urban	5f	-647	-660	-242	10f	-667	-670	-533

Congestion toll: Endogenous Pigouvian congestion toll on urban commuting trips
Road capacity expansion: 10% increase in urban road infrastructure capacity
Miles tax: 0.05 $/mile on urban commuting trips ($\approx$ 1.15 $/gallon assuming average fuel economy 23 miles/gallon)
Cordon toll: Commuter is charged $ 10 for entering the city zone
LUR: land-use type regulation (zoning): increasing (decreasing) the residential land share by 4 percentage-points in the city (suburbs)
100 million $ per year is about 1.4% of benchmark net tax revenue and 0.3% of benchmark urban GDP (291 million $ is 1% of GDP)

These data reveal several results for the polycentric city[16]

- In only 15 out of the 30 variants (or 32 out of 60 if we consider model versions) calculated for each of the labor supply approaches the sign of the welfare change is uniform. This shows, that not only the magnitude but also the direction of the policy effect depends on the labor supply approach chosen.
  - for example considering price based policies, in the homogeneous leisure approach and with lump-sum tax funding, large losses in approaches with endogenous workdays (Dh, Yh) turn into gains when workdays become fixed (Hh).
- In almost all scenarios, welfare effects of the hybrid approach are in between both 'extreme' labor supply approaches.
- Labor tax recycling produces higher benefits than lump sum tax recycling. The reason is the positive tax recycling effect (see above).
- Considering economic instruments (price based policies),
  - in the inhomogeneous leisure approach and with labor tax recycling, EVs in the hybrid (Yi) and the workhours (Hi) approach are very similar, while
  - in the homogeneous leisure approach and with lump-sum tax recycling, EVs in the hybrid (Yh) and the workdays (Dh) approach produce almost the same welfare effects.
- Considering planning instruments (road capacity expansion and LUR), all labor supply approaches result in similar welfare effects.

[16] By adjusting a few parameter values (see Table 3) we also calculated the effects for a mononectric city. We find that the basic impacts of labor supply modeling on policy effects we discuss hereafter for the polycentric city also hold for the monocentric city. The main difference is that welfare differentials caused by variations in labor supply modeling are stronger in the monocentric city case. Therefore, certain patterns found for the polycentric city tend to be even more robust in the monocentric city case. The reason is that in the monocentric city with mixed land-use in the CBD only the choice sets ii (city-city), and ji (suburb-city) are feasible. In this case households will respond to policies (e.g. congestion tolls) by relocating to the CBD in the workours approaches (Hi, Hh), but by both – relocating to the city and changing labor days – in the other approaches. In contrast, in a polycentric urban area even the choice set jj (suburb-suburb) is feasible, making the workhours approach less restrictive. In the monocentric city the impacts of the different labor supply approaches are therefore more distinctive than in the polycentric city case. We therefore restrict our exposition to the polycentric city case, keeping in mind that our conclusions on the importance of labor modeling also hold for the monocentric city case.

– for example, road capacity expansion is unambiguously welfare reducing across all labor supply approaches and regardless of whether leisure is homogeneous or inhomogeneous. Here, the negative effect of financing is dominant.

To get a clearer idea why this happens, we now look into some details of the results. We first study the inhomogeneous case with lump-sum tax recycling which provides the smallest differences among the different models.

4.3.2 Detailed effects

In order to figure out fundamental characteristics that drive the differences among the labor supply approaches, let us exemplarily pick up case 1a, i.e. the case of introducing the Pigouvian congestion toll with lump-sum tax recycling in the inhomogeneous leisure case.[17] Table 6 displays the simulation results where numbers are deviations from the benchmark printed in column 2).

Before we refer to the differences in the effects that can be traced back to the different labor supply approaches, let us discuss some general effects of the congestion toll policy which should be consistent with intuition and, of course, the effects suggested by the literature. Let us check this through two indicators: the toll induced change in congestion levels and changes in location decisions.

First, in all approaches, introducing congestion pricing reduces congestion levels, travel time delays and marginal congestion costs decline (see row (10) and (11)). The congestion toll is highest (7.33 $/trip) where most commutes appear (trips originating in the suburbs and terminating in the city) whereas it is almost zero in the reverse direction. Second, levying congestion tolls increases population densities in the city where the majority of jobs exists. Commuters urbanize in order to economize on higher commuting costs which is consistent with the classical urban economics theory (see row (35)). We also find that in contrast to residents, jobs suburbanize since land used as input by firms becomes relatively cheaper in the suburbs (see row (38)). This is consistent with the literature dealing with polycentric cities (see Anas and Xu, 1999).

Now let discuss differences in the effects of the policy that stem from differences in the way labor supply is modeled.

As can be seen, though labor supply effects are small in magnitude, the total number

[17] Detailed effects of the other policies and with same charatersistics (i.e. versions 2a, 3a, 4a, 5a according to the nomenclature in Table 5) are listed in Tables 10-13 in Appendix D.

Table 6: Policy effects of Pigouvian congestion tolls with inhomogenous leisure

Pigouvian congestion toll - Case 1a	Benchmark	Hours Hi	Hybrid Yi	Days Di
Time allocation				
(1) Workdays per year	263	0	−1	−1
(2) Leisure days per year	52	0	+1	+1
(3) Hours on a workday spent working/leisure	8.3/5.8/	0/0	+0.1/0	0/+0.1
(4) Hours on a workday spent/commuting/shopping	1.1/0.8	0/0	−0.1/0	−0.1/0
(5) Hours on a leisure day spent leisure/shopping	12.0/4.0	+0.1/−0.1	+0.1/−0.1	+0.1/−0.1
(6) Total labor supply [hours/year]	2187	+6	−2	−6
(7) Total leisure demand [hours/year]	2164	+3	+12	+17
(8) Total commuting time on workdays [hours/year]	272	−6	−8	−7
(9) Total shopping time [hours/year]	417	−3	−3	−4
Travel/Transport/Traffic				
(10) Travel time delay [hours/year]	31	−5	−5	−5
(11) MECC [$-cents/mile]	22	−3	−4	−3
(12) Total travel time [hours/year]	689	−9	−10	−11
(13) One-way commuting time [minutes]	31	−1	−1	−1
(14) VOT of one hour on a workday [$/hour]	13.87	−0.16	−0.15	−0.35
(15) Commuting trips [million/year] city–city	25.4	+0.4	+0.3	+0.4
(16) Commuting trips [million/year] city–suburb	19.3	+0.6	+0.5	+0.2
(17) Commuting trips [million/year] suburb–city	45.0	−2.0	−2.2	−1.9
(18) Commuting trips [million/year] suburb–suburb	41.6	+1.0	+0.8	+0.8
(19) Congestion toll [$/trip] city–city	0.0	1.54	1.51	1.50
(20) Congestion toll [$/trip] city–suburb	0.0	0.16	0.15	0.14
(21) Congestion toll [$/trip] suburb–city	0.0	7.33	7.22	7.35
(22) Congestion toll [$/trip] suburb–suburb	0.0	2.13	2.09	2.04
Households				
(23) Gross income [$/year]	61,071	−460	−632	−1,136
(24) Consumption (shopping) [trips/year]	472	0	−1	−2
(25) Average housing demand [sqr feet]	7778	−55	−58	−77
Urban Economy				
(26) Total urban production [million units]	556.7	+0.1	−0.4	−1.5
(27) Urban GDP [billion $/year]	29.1	−0.2	−0.3	−0.5
(28) EV [million $/year]	–	+43	+16	−17
(29) Rent city/suburb [$/sqr feet*year]	5.95/2.22	+0.12/−0.05	+0.09/−0.05	+0.08/−0.08
(30) Wage rate city/suburb [$/hour]	22.81/19.65	−0.05/−0.39	−0.04/−0.36	−0.04/−0.62
Government				
(31) Labor tax revenue [million $/year]	8171	−65	−87	−155
(32) Lump-sum tax revenue [million $/year]	–974	−817	−804	−791
(33) Congestion toll revenue [million $/year]	0	+897	+880	+890
(34) Infrastructure costs [million $/year]	7197	+15	−13	−56
Location				
(35) Households – city	168,687	+3,745	+3,687	+2,882
(36) Households – suburb	331,313	−3,745	−3,687	−2,882
(37) Jobs – city	268,099	−6,356	−6,313	−4,971
(38) Jobs – suburb	231,901	+6,356	+6,313	+4,971

of working hours per year increases in the workhours approach whereas it decreases in the hybrid (Yi) and the workdays (Di) approach. The latter effect of a decrease in total labor supply is driven by the reduction in workdays as response to the congestion toll and thus to higher commuting costs. This implies that in both labor supply approaches where workdays are endogenous, (Yi and Di) the substitution effect (leisure becomes cheaper due to the toll, see also Table 1) outweighs the income effect (leisure is a normal good), causing an overall reduction in labor supply. In addition, working hours per day increase which is consistent with theory (see also Gutiérrez-i-Puigarnau and van Ommeren, 2010) because workers have an incentive to reduce the number of workdays to avoid additional commuting costs, and then to increase daily supply to avoid a reduction in income.

Furthermore, even though households urbanize as a response to congestion tolls in all labor supply approaches, there is a significant difference. The relocation effect is weakest in the workdays approach where workers can respond to congestion not only by relocation, e.g. changing the residential location to avoid commuting pattern suburb-city, but can also adjust the number of commuting trips. In contrast, the relocation effect is strongest in the workhours approach, where the only choice for commuters to avoid paying the toll is to relocate, thus avoiding highly tolled commuting patterns. That is, the more flexible commuters may adjust commuting trips, the weaker relocation effects, or to put it in another way, relocation is stronger in labor supply approaches with endogenous working hours.

Interestingly, the decline in congestion levels is almost the same across all labor supply approaches. Travel time delays decline by about 16% (see row (10)) and marginal external congestion costs by about 15% (see row (11)) in all approaches. This implies that stronger relocation effects (Hi) almost exactly offset the additional adjustment in workdays in the other approaches (Yi, Di). Hence, concerning congestion the labor supply regime doesn't matter provided relocation is considered. There is also no clear pattern of differences in toll rates across the three labor supply approaches. The reason is that the Pigouvian toll in the simulation is equal to the marginal congestion cost at equilibrium and thus distribution and tax interaction effects present in the optimal toll formula (50) are not able to generate significant toll differences. A general result is therefore that a Pigouvian toll is unambiguously an effective instrument for lowering congestion externalities in the long term regardless of how commuters are able to adjust their labor supply.[18]

Comparing welfare effects of the policy (see row (28)) it can be seen that case 1a is

[18] Note that Table 6 refers to simulation 1a (see Table 5), i.e. lumps-sum tax recycling with mixed landownership. However, effetcs on congestion are similar across all congestion toll policy simualtions.

one of the cases where welfare effects differ not only in magnitude between labor supply approaches, but, more importantly, also with respect to the direction. In the workdays approach, the Pigouvian toll reduces welfare, while in the other approaches it enhances welfare. As a consequence, recycling revenues from congestion pricing efficiently through cuts in distortionary labor taxes is not a requirement to generate positive welfare effects in the inhomogeneous workhours and hybrid approach, but it is in the inhomogeneous workdays approach.

4.3.3 Generalization of findings

Recall that one of the main conclusions derived from Table 5 was that when considering price based policies,

- in the inhomogeneous leisure approach and with labor tax recycling, welfare effects in the hybrid (Yi) and the workhours (Hi) approach are very similar, while
- in the homogeneous leisure approach and with lump-sum tax recycling, welfare effects in the hybrid (Yh) and the workdays (Dh) approach produce almost the same welfare effects.

Because these conclusions are drawn from specific policies, e.g. a miles tax of 0.05 $/mile or a cordon toll of $10 per trip, it is essential to analyze whether these findings hold for a wide range of policies as well. Figure 1 presents the welfare effects different levels of the miles tax and cordon toll rate. The run of the welfare curves suggest that indeed findings are quite robust. The figure also reveals that optimal policy levels are usually higher in the workhours approach, while at the optimal policy level, welfare gains are larger (respectively there are welfare gains at all).

4.3.4 Recommendations

Given the missing empirical evidence on the actual labor supply behavior, the hybrid approach is suggested to be the 'best' choice because it takes into account endogenous working hours as well as endogenous workdays and thus avoids the restrictive assumption of fixed working hours or fixed workdays. A comparison of its results with those of the workhours and the workdays approaches reveals which kind of labor supply adjustment is more significant when applying a specific policy. Based on the results of our analyses we derive some recommendations on which of the modeling approaches might provide a useful shortcut to the hybrid approach.

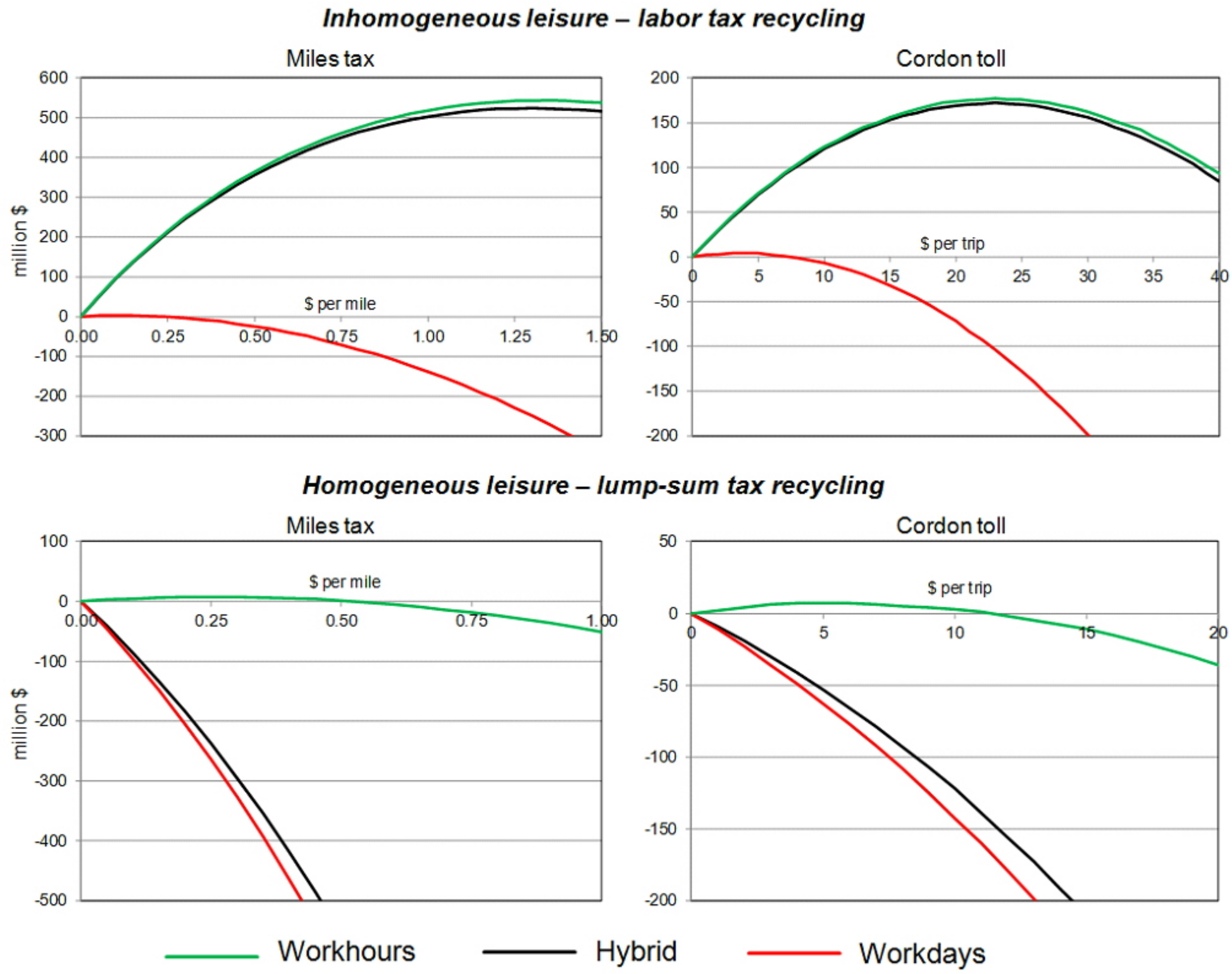

Figure 1: Welfare effects of congestion pricing policies

Economics instruments, homogeneous leisure

The above results suggest that with homogeneous leisure Dh is a good approximation of Yh while Hh provides results that strongly deviate from both approaches. However, welfare variations around the optimal policies are small in Hh, so that the findings of Yh or Dh concerning optimal taxes are also acceptable from the point of view of the Hh approach. Because Yh considers both endogenous working hours and endogenous workdays, it is the more general approach. Given the missing empirical evidence on the actual behavior concerning labor supply, the Yh approach should be the first choice. Since in the case of homogeneous leisure the Dh approach provides a very close welfare approximation of the Yh approach, we recommend applying the Dh approach in studies on tax policies when leisure is homogeneous.

Economics instruments, inhomogeneous leisure, lump-sum tax recycling

Here Yi provides findings in between the pure workdays and the pure workhours approaches. We therefore recommend to apply hybrid models. However, the impact of tax policies is lower than with the homogeneous approaches (see Table 5) because leisure on leisure days is a weaker substitute to leisure on workdays and, thus, labor supply responses are likely to be smaller. For this reason, possible misinterpretation occurring when applying either approach are likely to be relatively small. Accordingly, the modeler is free to decide.

Economics instruments, inhomogeneous leisure, labor tax recycling

Here Yi and Hi approaches deliver very similar results. As a consequence, we recommend applying either the hybrid or the workhours approach.

Planning instruments

As regards planning instruments (LUR or road capacity expansion) one can state that all labor supply approaches are relatively coequal. Due to the absence of tolls/taxes, there is no direct effect of the policy on VOTs such that differences among the labor supply approaches hardly evolute. This applies to the homogeneous as well as inhomogeneous leisure assumption. Concerning land-use type regulation ζ we see this from the optimal regulation formula (see Appendix C.3), where labor supply only enters the tax interaction effect TI directly, while the land market distortion effect of the land-use type regulation, i.e. the third term on the right-hand side, does not depend directly on labor supply

$$\frac{1}{\lambda}\frac{dW}{d\zeta_k} = MEC_{\zeta k}\left(-\frac{dF}{d\zeta_k}\right) + TI_{\zeta k} + N\sum_i \left(r_i^q - r_i^Q\right)(1-s_i)\,A_i + RE_{\zeta k}.$$

Congestion

If the only aim is to examine consequences of the policies on congestion, each of the approaches can be applied because they provide very similar results (but note that the causes yielding these results are different).

Land use (spatial effects)

Concerning land-use and location decisions, findings are very different. Approaches with endogenous working hours (Hi, Hh, Yi, Yh) are characterized by much stronger spatial resorting than the pure workdays approach (Di, Dh).

5 Conclusions

Modeling labor supply is an important issue in transportation and urban economics because it determines some basic margins of adjustments with respect to transport policies. In our application to congestion policies we found to our surprise that the different labor supply approaches provide very similar effects on commuting and congestion even though welfare effects and effects on other economic variables may differ considerably. Hence, if one wants to examine effects of policies on congestion only, either a pure workhours or a workdays approach is a useful shortcut in a spatial model. We expect that this is true in other transportation issues such as emissions, noise, infrastructure financing, or accidents.

Most importantly, we have shown that in many cases the modeling of labor supply might affect not only the magnitude but even the direction of policy induced welfare effects. While theory is not concerned with the size of the effect, which also varies a lot, a change in the direction is a critical outcome. A finding that is even more pronounced if we consider a monocentric city with mixed land-use in the CBD. In light of these findings we need a decision rule on which of the labor supply approaches is the most appropriate to apply.

Given the missing empirical evidence on the actual labor supply behavior, the hybrid approach is suggested to be a useful choice because it takes into account endogenous working hours as well as endogenous workdays, thereby avoiding extreme assumptions such as fixed working hours or fixed workdays. According to our simulation results all three approaches provide similar findings when applied to planning instruments (land-use-restriction and road capacity expansion) and, thus, the modeler is free which one to apply. The same applies to inhomogeneous leisure and lump-sum tax recycling if we consider tax policies. If leisure is homogeneous – the usual assumption made in urban and transportation policy papers – the workdays approaches seems to be an approximation of the hybrid approach. In contrast, the workhours approach seems to be a better approximation to the hybrid approach than the workdays approach when considering economic instruments with labor tax recycling and under the assumption that leisure is inhomogeneous. We expect that our findings also hold in tendency when we extend to model to include other distortionary taxes, other trip purposes during the peak or mode choice.

Our analyses underline the importance of generating knowledge on how employees adjust their labor supply as a response to transport policy. Unfortunately there are hardly robust empirical findings. Hence, there is a need of data usually not fully documented in micro data on labor markets, because households can vary their workdays by being ill, working overtime to reduce workdays, by not fully utilizing all leave days, working part-time, by increasing or decreasing the number of days not working when changing jobs, or by telecommuting. This is usually not found in labor contracts or not documented in micro data. Our study makes clear that there is need to develop such a data base because it is crucial for policy research in some fields to know more about labor supply choices. This might also concern time-use studies, decisions on child care, studies on worktime flexibility etc.

Of course, our analyses simplifies in different ways. First, we do not consider telecommuting which softens the close link between workdays and commuting. We also do not consider tax deductions of commuting costs that might lower the reduction in the VOTs due to road charges (e.g. Hirte and Tscharaktschiew, 2013a). Further, mode and route choice could also weaken the strong effect on workdays. Nonetheless, given the weak empirical research and the danger of deriving misleading findings, it could be a promising strategy to apply a hybrid approach that relies on more flexible margins of adjustments.

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A Literature review (policy papers and labor supply approaches)

Table 7: Literature review: studies with endogenous workhours per day and fixed workdays

Paper	Research questions / Policy issues
Anas (2002)*	Impacts of spatial segregation on urban economies
Anas and Kim (1996)*	Scale economies in shopping/interactions with congestion
Anas and Rhee (2006)*	Congestion tolls vs. urban growth boundaries
Anas and Xu (1999)*	Spatial effects of congestion tolls
De Borger and Wuyts (2011a)	Preferential tax treatment of company cars
De Palma and Lindsey (2004)	Importance of traveler heterogeneity for congestion pricing
Fujishima (2011)*	Cordon pricing and area pricing in a dispersed city
Hotchkiss and White (1993)*	Spatial distribution of different household types
Olwert and Guldmann (2012)*	Zoning and infrastructure policies in cities
Parry and Bento (2002)	Interaction of congestion with other transport related distortions
Van Ommeren and Fosgerau (2009)	Estimating workers' marginal costs of commuting
Verhoef and Nijkamp (2002)*	Interactions between environmental/agglomeration externalities
West and Williams (2007)	Optimal gasoline tax and leisure
White (1988)*	Residential/job location patterns in a decentralized city
White (1977)*	Location choice and household heterogeneity

* Spatial model (incorporating location decisions of households and/or firms)

Table 8: Literature review: Studies with endogenous workdays and fixed workhours per day

Paper	Research questions / Policy issues
Arnott (2007)	Congestion pricing and positive agglomeration externalities
Berg (2007)	Greenhouse gas transportation policies in Sweden
Calthrop (2001)	Relationship congestion toll/labor tax/commuting subsidy
De Borger and Van Dender (2003)	Transport tax reform, value of time and congestion costs
De Borger and Wuyts (2009)	Congestion taxes in the presence of employer-paid parking
De Borger and Wuyts (2011b)[1]	Congestion tolls under wage bargaining and telecommuting
Fosgerau and Pilegaard (2007)	Deriving cost-benefit rules for transport projects
Hirte and Tscharaktschiew (2013a)*	Tax deduction of commuting expenses
Hirte and Tscharaktschiew (2013b)*	Subsidies on electric vehicles
Lin and Prince (2009)[2]	Optimal gasoline tax in the California
Nitzsche and Tscharaktschiew (2013)*	Speed limits in cities
Parry and Bento (2001)	Interactions between congestion tolls and labor taxes
Parry and Small (2005)[2]	Optimal gasoline tax in the US/UK
Parry (2011)[2]	Optimal fuel taxes in the US
Rhee (2008)*[1]	Telecommuting and spatial commuting patterns in cities
Rhee (2009)*[1]	Effects of telecommuting on city size and urban sprawl
Tscharaktschiew (2014)[2]	Optimal gasoline tax in Germany
Tscharaktschiew and Hirte (2010a)*	Household structure heterogeneity and urban economies
Tscharaktschiew and Hirte (2010b)*	Carbon emission pricing in urban areas
Tscharaktschiew and Hirte (2012)*	Subsidies to urban passenger transport
Van Dender (2003)	Differentiating tolls between commuting and leisure trips
Verhoef (2005)*	Second-best congestion pricing in a monocentric city

[1] Studies dealing with telecommuting issues: modeling approach ‘days’ refers to the on-site-work labor option
[2] Studies do not explicitly model workdays, but labor supply responds to changes in travel costs
* Spatial model (incorporating location decisions of households and/or firms)

Table 9: Literature review: Studies with fixed labor supply or labor supply as residual

Paper	Research questions / Policy issues
Anas and Hiramatsu (2012)*	Effects of cordon tolling
Anas and Hiramatsu (2013)*	Effects of gasoline price on an urban economy
Anas and Liu (2013)*	RELU-TRAN
Anas and Rhee (2007)*	Urban growth boundaries and congestion toll
Arnott et al. (2008)*	Pollution, land use
Bento et al. (2006)	Effects of anti-sprawl policies
Brock and Wrede (2005)*	Subsidies for short and long distance commuting
Borck and Wrede (2008)*	Commuting subsidies and travel mode choice
Borck and Wrede (2009)*	Political economy of transport subsidies
Brueckner (2005)*	Transport subsidies, transport system choice and urban sprawl
Brueckner (2007)*	Urban growth boundaries and congestion toll
Brueckner et al. (2002)*	Job matching and urban location
Calthrop et al. (2000)	Parking policies and road pricing
De Borger and Wouters (1998)	Optimal subsidies and supply of transit
De Lara et al. (2013)*	Congestion pricing and spatial structure
De Salvo (1977)	Household behaviour in a monocentric city
Kono et al. (2013)*	Regulation on building size and city boundary
Kwon (2005)	Commuting costs and income
Martin (2001)*	Spatial mismatch and commuting subsidies
McDonald (2009)*	Congestion in a monocentric city
Parry (1995)	Pollution taxes and tax revenue recycling
Parry and Small (2009)	Urban transit subsidies
Parry and Timilsina (2010)	Passenger transport pricing policies
Ross and Zenou (2009)	Wages and spatial distribution of unemployment
Sullivan (1983a,b)	Congestion and congestion pricing
Rhee et al. (2014)*	Land use/transport policies with congestion and agglomeration
Wrede (2001)	Tax deduction of commuting expenses
Wrede (2009)	Labor tax and commuting subsidies

* Spatial model (incorporating location decisions of households and/or firms)

B First-order conditions (FOCs)

B.1 FOCs (Yi)

The Lagrangian in the inhomogeneous hybrid approach is

$$\mathcal{L} = u\left(z, q, \underset{\ell D}{\mathcal{L}_1}, \underset{eL}{\mathcal{L}_2}\right) + \lambda\left\{\left(w^n h - c\right) D + I - \left(p + c^z\right) z - rq\right\} + \gamma\left\{E - L - D\right\}$$
$$+ \mu\left\{eD - \left(h + t\right) D - \ell D - t^z z\right\}$$

The first-order conditions then are (we define $u_{\mathcal{L}_2} \equiv \rho$)

$$\frac{\partial \mathcal{L}}{\partial z}\colon u_z = \lambda\left(p + c^z\right) + \mu t^z \tag{58}$$
$$\frac{\partial \mathcal{L}}{\partial q}\colon u_q = \lambda r \tag{59}$$
$$\frac{\partial \mathcal{L}}{\partial L}\colon u_{\mathcal{L}_2} e = \gamma \rightarrow \gamma = \rho e \tag{60}$$
$$\frac{\partial \mathcal{L}}{\partial \ell}\colon u_{\mathcal{L}_1} D = \mu D \rightarrow u_{\mathcal{L}_1} = \mu \tag{61}$$
$$\frac{\partial \mathcal{L}}{\partial D}\colon u_{\mathcal{L}_1} \ell = -\lambda\left(w^n h - c\right) + \gamma - \mu\left(e - h - t - \ell\right) \tag{62}$$
$$\frac{\partial \mathcal{L}}{\partial h}\colon \lambda w^n D = \mu D \rightarrow \frac{\mu}{\lambda} = w^n \tag{63}$$

Consolidating and (**??**) yields

$$\gamma = \rho e \rightarrow \frac{\gamma}{\lambda} = e\frac{\rho}{\lambda}$$

Substituting (61) into (62) yields

$$\mu \ell = -\lambda\left(w^n h - c\right) + \gamma - \mu\left(e - h - t - \ell\right) \tag{64}$$

implying the following results

$$\text{VOTh}^{Yi}\colon \quad \frac{\mu}{\lambda} = w^n = \frac{u_{\mathcal{L}_1}}{\lambda}$$
$$\text{VOTL}^{Yi}\colon \quad \frac{\gamma}{\lambda} = w^n\left(e - t\right) - c$$
$$\text{VOTl}^{Yi}\colon \quad \frac{\rho}{\lambda} = \frac{\gamma}{\lambda}\frac{1}{e} = \frac{w^n\left(e - t\right) - c}{e}$$

Applying this to (58) gives us

$$\frac{u_z}{\lambda} = \left(p + c^z\right) + \frac{\mu}{\lambda} t^z$$
$$= p + c^z + w^n t^z$$

B.2 FOCs (Yh)

By accounting for the additional restriction $\ell \geq \bar{\ell}$, the Lagrangian in the homogeneous hybrid approach becomes

$$\mathcal{L} = u\left(z, q, \underbrace{\mathcal{L}_1 + \mathcal{L}_2}_{\ell D + lL}\right) + \lambda\left\{(w^n h - c)\,D + I - (p + c^z)\,z - r^q q\right\} + \gamma\left\{E - L - D\right\}$$
$$+ \mu\left\{eD - (h+t)\,D - \ell D - t^z z\right\} + \rho\left\{eL - lL\right\} + \pi\left(\bar{\ell} - \ell\right) D$$

and the corresponding first-order conditions are

$$\frac{\partial \mathcal{L}}{\partial z}\colon u_z = \lambda\,(p + c^z) + \mu t^z \tag{65a}$$
$$\frac{\partial \mathcal{L}}{\partial L}\colon u_{\mathcal{L}} l = \gamma - \rho\,(e - l) \rightarrow (u_{\mathcal{L}} - \rho)\,l = \gamma - \rho e \rightarrow \gamma = \rho e \tag{65b}$$
$$\frac{\partial \mathcal{L}}{\partial l}\colon u_{\mathcal{L}} L = \rho L \rightarrow u_{\mathcal{L}} = \rho \tag{65c}$$
$$\frac{\partial \mathcal{L}}{\partial \ell}\colon u_{\mathcal{L}} D - \mu D - \pi D \leq 0 \rightarrow \; u_{\mathcal{L}} = \begin{cases} \mu & \text{if } \ell > \bar{\ell} \\ \mu + \pi & \text{if } \ell = \bar{\ell} \end{cases} \tag{65d}$$
$$\frac{\partial \mathcal{L}}{\partial D}\colon u_{\mathcal{L}} \ell = -\lambda\,(w^n h - c) + \gamma - \mu\,(e - h - t - \ell) - \pi\left(\bar{\ell} - \ell\right) \tag{65e}$$
$$\frac{\partial \mathcal{L}}{\partial h}\colon \lambda w^n D = \mu D \;\rightarrow \frac{\mu}{\lambda} = w^n \tag{65f}$$

We now have to distinguish two cases: $\ell > \bar{\ell}$ and $\ell = \bar{\ell}$.

If $\ell > \bar{\ell}$ then $\pi = 0$. From (65b)–(65d) it follows that $\gamma = \rho e = \mu e$ and $u_{\mathcal{L}} = \mu = \rho$. Further, due to (65f)

$$\frac{\rho}{\lambda} = \frac{\mu}{\lambda} = w^n, \; \frac{\gamma}{\lambda} = w^n e \tag{66}$$

Due to (65e) (and use $\mu e = \gamma$)

$$0 = -\lambda\,(w^n h - c) + \gamma \frac{(h+t)}{e}$$
$$\rightarrow \frac{\gamma}{\lambda} = \left(\frac{w^n h - c}{h + t}\right) e \rightarrow \frac{\mu}{\lambda} = \frac{w^n h - c}{h + t}$$

This should be equivalent to (65f), thus

$$\frac{\mu}{\lambda} = \frac{w^n h - c}{h + t} = w^n$$

This condition is only fulfilled if $c = t = 0$, i.e. if commuting is for free. Since for never consider cases with $c = t = 0$, we assume that $\ell > \bar{\ell}$ is not a useful solution.

If $\ell = \bar{\ell}$ then $\pi > 0$. From (65f) it follows

$$(\mu + \pi)\,\ell = -\lambda\,(w^n h - c) + \gamma - \mu\,(e - h - t - \ell)$$

Substituting $\mu/\lambda = w^n$ gives

$$0 = -\left(w^n h - c\right) + \frac{\gamma}{\lambda} - w^n\left(e - h - t\right) - \frac{\pi}{\lambda}\ell$$

which is equivalent to

$$\frac{\gamma}{\lambda} = w^n\left(e - t\right) - c + \frac{\pi}{\lambda}\ell \tag{67}$$

From (65b)–(65d) we get $\mu e = \gamma - \pi e$ and $\mu = \gamma/e - \pi$. Substituting μ in (65e) yields

$$0 = -\lambda\left(w^n h - c\right) + \gamma - \left(\frac{\gamma}{e} - \pi\right)\left(e - h - t\right) - \pi\ell$$

After rearranging, dividing by λ, and replacing γ by $\left(\mu + \pi\right)e$ we obtain

$$0 = -\left(w^n h - c\right) + \frac{\left(\mu + \pi\right)e}{\lambda} - \left(\frac{\left(\mu + \pi\right)}{\lambda}\right)\left(e - h - t\right) + \frac{\pi}{\lambda}\left(e - h - t - \ell\right)$$

Cancelling terms and solving for $\frac{\pi}{\lambda}$ gives

$$\frac{\pi}{\lambda} = -\frac{w^n t + c}{\left(e - \ell\right)} \tag{68}$$

Plugging (68) into 67 gives

$$\begin{aligned}\frac{\gamma}{\lambda} &= w^n\left(e - t\right) - c - \frac{w^n t + c}{\left(e - \ell\right)}\ell \\ &= w^n\left(e - t - \frac{t\ell}{e - \ell}\right) - c - \frac{c}{e - \ell}\ell \\ &= w^n\left(e - \frac{te}{e - \ell}\right) - \frac{ce}{e - \ell} \\ &= w^n e - \left(w^n t + c\right)\frac{e}{e - \ell}\end{aligned}$$

which is equivalent to $VOTL^{Yh}$ as indicated by (20).

C Welfare

C.1 Yi: endogenous leisure hours and endogenous leisure days

Hanoch (1975) and Oi (JPE, 1976) emphasize that leisure on a workday, ℓ, and leisure on a non-workday, l, are inhomogeneous and, thus, should be treated as different arguments in the utility function. To simplify the following discussion we assume that all shopping trips take place only on shopping days. We define deterministic utility as[19]

$$u\left(z_{ij1,\ldots,}z_{ijJ}, q_{ij}, \mathcal{L}_{1ij}, \mathcal{L}_{2ij}\right) \rightarrow u\left(z_{ijk}, q_{ij}, \mathcal{L}_{1ij}, \mathcal{L}_{2ij}\right), \tag{69}$$

[19] In the following it doesn't matter whether the residual leisure time on leisure days, ℓ_{ij}^{L}, is considered. Further, we could drop the weight for leisure hours on workdays in utility, $E - L_{ij}$.

where $\mathcal{L}_1 \equiv \ell_{ij}(E - L_{ij})$ and $\mathcal{L}_2 \equiv L_{ij} l_{ij}$. There is a monetary budget constraint, a daily time constraint for working days, another for leisure days and a yearly day restriction. Hence,

$$\sum_k (p_k + c^z_{ik}) z_{ijk} + r^q_i q_{ij} = \left(w^n_j h_{ij} - c_{ij}\right) D_{ij} + I \tag{70a}$$

$$eD_{ij} = (h_{ij} + t_{ij}) D_{ij} + \ell_{ij} D_{ij} + \sum_k t^z_{ik} z_{ijk} \tag{70b}$$

$$eL_{ij} = l_{ij} L_{ij} \tag{70c}$$

$$E = D_{ij} + L_{ij}, \tag{70d}$$

where ρ_i is the consumer price of the local consumption good in zone i, r the local housing price, $w^n h = (1 - \tau^w) w$ is the daily net wage at the working zone, where τ^w is the marginal wage tax rate, w is the wage.

$$c_{ij} \equiv \tau^m m_{ij} + \delta^c \tau^c + \sum_l \delta_{ij} \tau^t_l$$
$$c^z_{ik} \equiv \tau^m m_{ik} + \delta^c \tau^c$$

is the tax vector of commuting where τ^m is the miles tax, τ^c the cordon toll if applied, and τ^t_{ij} the congestion toll per trip from i to j, and I is non-labor income arising from shared land rents and lump sum subsidies $(-\tau^{ls})$. We assume that shopping is equally distributed across all days. There are no other monetary travel costs.

$$\sum_k (p_k + c^z_{ik}) z_{ijk} + r^q_i q_{ij} = \left(w^n_j h_{ij} - c_{ij}\right) D_{ij} + I$$
$$h_{ij} D_{ij} = (e - t_{ij}) D_{ij} - \ell_{ij} D_{ij} - \sum_k t^z_{ik} z_{ijk}$$
$$eL_{ij} = l_{ij} L_{ij}$$
$$E = D_{ij} + L_{ij},$$

Expanding

$$\begin{aligned}
\left(w^n_j h_{ij} - c^D_{ij}\right) D_{ij} &= \left(w^n_j h_{ij} - c_{ij}\right)(E - L_{ij}) \\
&= \left(w^n_j \left[(e - t_{ij}) - \ell_{ij} - \sum_k t^z_{ik} \frac{z_{ijk}}{(E - L_{ij})}\right] - c^D_{ij}\right)(E - L_{ij}) \\
&= \left\{w^n_j \left[(e - t_{ij}) - \ell_{ij}\right] - c_{ij}\right\}(E - L_{ij}) - w^n_j \sum_k t^z_{ik} z_{ijk} \\
&= \left[w^n_j (e - t_{ij}) - c_{ij}\right](E - L_{ij}) - w^n_j \ell_{ij}(E - L_{ij}) - w^n_j \sum_k t^z_{ik} z_{ijk} \\
&= \left[w^n_j (e - t_{ij}) - c_{ij}\right]\left(E - \frac{l_{ij}}{e} L_{ij}\right) - w^n_j \ell_{ij}(E - L_{ij}) - w^n_j \sum_k t^z_{ik} z_{ijk} \\
&= \left[w^n_j (e - t_{ij}) - c_{ij}\right] E - \left(w^n_j (e - t_{ij}) - c_{ij}\right) L_{ij} - w^n_j \ell_{ij} D_{ij} \\
&\quad - \sum_k w^n_j t^z_{ik} z_{ijk}
\end{aligned}$$

and rearranging gives us

$$\sum_k \left(p_k + c^z_{ik} + w^n_j\right) t^z_{ik} z_{ijk} + \left[w^n_j \left(e - t_{ij}\right) - c_{ij}\right] L_{ij} + w^n_j \ell_{ij} D_{ij} + r^q_i q_{ij} = \left[w^n_j \left(e - t_{ij}\right) - c_{ij}\right] E + I$$

The consolidated budget constraint is

$$\theta^A_{ij} E + I = \sum_k \rho^A_{ijk} z_{ijk} + r^q_i q_{ij} + w^n_j \left(E - L_{ij}\right) \ell_{ij} + \theta^A_{ij} L_{ij}, \tag{71}$$

where

$$\theta^A_{ij} \equiv w^n_j \left(e - t_{ij}\right) - c_{ij} \tag{72}$$

is the value of time (VOT) of workdays. The VOT of an hour on a workday is w^n_j which is $w^n_j D_{ij}$ in terms of days. δ^c is an indicator which is unity if $i \neq j$ and zero else.

The full consumer price of shopping in zone k is

$$\rho^A_{ijk} \equiv p_k + c^z_{ik} + w^n_j t^z_{ik}$$

For later reference we have

$$d\theta^A_{ij} = \left(e - t_{ij}\right) dw^n_j - w^n_j dt_{ij} - dc_{ij} \tag{73}$$

$$d\rho^A_{ijk} = dp_k + dc^z_{ik} + t^z_{ik} dw^n_j \tag{74}$$

Maximizing deterministic utility w.r.t. z, q, ℓ and L to obtain the FOCs in terms of days

$$\frac{u_{z_{ijk}}}{u_{z_{ijl}}} = \frac{\rho_{ijk}}{\rho_{ijl}}, \qquad \frac{u_{\ell_{ij}}}{u_{z_{ijk}}} = \frac{w^n_j D_{ij}}{\rho_{ijk}}, \qquad \frac{u_{L_{ij}}}{u_{z_{ijk}}} = \frac{\theta^A_{ij}}{\rho_{ijk}}, \qquad \frac{u_{l_{ij}}}{u_{z_{ijk}}} = \frac{\theta^A_{ij}/e}{\rho_{ijk}} \qquad \frac{u_{q_{ij}}}{u_{z_{ij}}} = \frac{r^q_i}{\rho_{ijk}} \tag{75}$$

Using (4)-(6d) gives indirect utility. Since all prices depend on the policy parameter ζ, τ or τ^c we write

$$V_{ij}\left(\tau^t_i, \tau^m, \tau^c\right) = \left\{ \max u\left(z_{ijk}, q_{ij}, \mathcal{L}_{1ij}, \mathcal{L}_{2ij}\right) + \lambda \left[\theta^A_{ij} E_{ij} + I - w^n_j \left(E - L_{ij}\right) \ell_{ij} - \theta^A_{ij} L_{ij} - \sum_k \rho^A_{ijk} z_{ijk} - r^q_i q_{ij}\right] \right. \tag{76}$$

For later use we totally differentiate ν w.r.t. policy parameters and apply the envelope theorem (see Rhee et al., 2014), yielding

$$\frac{1}{\lambda_{ij}} \frac{dV_{ij}}{d\tau^t_l} = \left(E_{ij} - \frac{l_{ij} L_{ij}}{e}\right) \frac{d\theta^A_{ij}}{d\tau^t_l} - \left(E - L_{ij}\right) \ell_{ij} \frac{dw^n_j}{d\tau^t_l} + \frac{dARL}{d\tau^t_l} - \frac{d\tau^{ls}}{d\tau^t_l} - \sum_k z_{ijk} \frac{d\rho^A_{ijk}}{d\tau^t_l} - q_{ij} \frac{dr^q_i}{d\tau^t_l}$$

Substituting

$$
\begin{aligned}
\frac{1}{\lambda_{ij}}\frac{dV_{ij}}{d\tau_l^t} = {} & (E_{ij}-L_{ij})\left((e-t_{ij})\frac{dw_j^n}{d\tau_l^t} - w_j^n\frac{dt_{ij}}{d\tau_l^t} - \frac{dc_{ij}}{d\tau_l^t}\right) - (E-L_{ij})\,\ell_{ij}\frac{dw_j^n}{d\tau_l^t} \\
& + \frac{dARL}{d\tau_l^t} - \frac{d\tau^{ls}}{d\tau_l^t} - q_{ij}\frac{dr_i^q}{d\tau_l^t} - \sum_k z_{ijk}\frac{dp_k}{d\tau_i^t} - \sum_k z_{ijk}\frac{dc_{ik}^z}{d\tau_l^t} \\
& - \beta\left(\sum_k t_{ik}^z z_{ijk}\right)\frac{dw_j^n}{d\tau_l^t}
\end{aligned}
$$

and rearranging yields

$$
\begin{aligned}
\frac{1}{\lambda_{ij}}\frac{dV_{ij}}{d\tau_l^t} = {} & \left\{(E-L_{ij})(e-t_{ij}) - (E-L_{ij})\,\ell_{ij} - \left(\sum_k t_{ik}^z z_{ijk}\right)\right\}\frac{dw_j^n}{d\tau_l^t} \\
& - (E-L_{ij})\,w_j^n\frac{dt_{ij}}{d\tau_l^t} \\
& - (E-L_{ij})\frac{dc_{ij}}{d\tau_l^t} - \sum_k z_{ijk}\frac{dc_{ik}^z}{d\tau_l^t} \\
& + \frac{dARL}{d\tau_l^t} - \frac{d\tau^{ls}}{d\tau_l^t} - q_{ij}\frac{dr_i^q}{d\tau_l^t} - \sum_k z_{ijk}\frac{dp_k}{d\tau_i^t}.
\end{aligned}
$$

Substitute $eE = eD_{ij} + eL_{ij}$ and $eL_{ij} = l_{ij}L_{ij}$ to obtain

$$
\begin{aligned}
\frac{1}{\lambda_{ij}}\frac{dV_{ij}}{d\tau_l^t} = {} & \left[D_{ij}(e-t_{ij}-\ell_{ij}) - \left(\sum_k t_{ik}^z z_{ijk}\right)\right]\frac{dw_j^n}{d\tau_l^t} \\
& - w_{ij}^n D_{ij}\frac{dt_{ij}}{d\tau_l^t} - D_{ij}\frac{dc_{ij}}{d\tau_l^t} - \sum_k z_{ijk}\frac{dc_{ik}^z}{d\tau_l^t} \\
& + \frac{dARL}{d\tau_l^t} - \frac{d\tau^{ls}}{d\tau_l^t} - q_{ij}\frac{dr_i^q}{d\tau_l^t} - \sum_k z_{ijk}\frac{dp_k}{d\tau_i^t}.
\end{aligned}
$$

Substitute $h_{ij}D_{ij} = (e-t_{ij}-\ell_{ij})\,D_{ij} - \beta\sum_k t_{ik}^D z_{ijk}$ this is

$$
\begin{aligned}
\frac{1}{\lambda_{ij}}\frac{dV_{ij}}{d\tau_l^t} = {} & h_{ij}D_{ij}\frac{dw_j^n}{d\tau_l^t} - w_{ij}^n D_{ij}\frac{dt_{ij}}{d\tau_l^t} - D_{ij}\frac{dc_{ij}}{d\tau_l^t} - \sum_k z_{ijk}\frac{dc_{ik}^z}{d\tau_l^t} \\
& + \frac{dARL}{d\tau_l^t} - \frac{d\tau^{ls}}{d\tau_l^t} - q_{ij}\frac{dr_i^q}{d\tau_l^t} - \sum_k z_{ijk}\frac{dp_k}{d\tau_i^t}.
\end{aligned} \tag{77}
$$

Since $dc^z_{ij}/d\tau^t_l = 0$ and $dc_{ij}/d\tau^t_l = 1$

$$\frac{1}{\lambda_{ij}}\frac{dV_{ij}}{d\tau^t_i} = h_{ij}D_{ij}\frac{dw^n_j}{d\tau^t_i} - w^n_{ij}D_{ij}\frac{dt_{ij}}{d\tau^t_i} - D_{ij} + \frac{dARL}{d\tau^t_i} - \frac{d\tau^{ls}}{d\tau^t_i} - q_{ij}\frac{dr^q_i}{d\tau^t_i} - \sum_k z_{ijk}\frac{dp_k}{d\tau^t_i}. \tag{78}$$

$$\frac{1}{\lambda_{ji}}\frac{dV_{ji,j\neq i}}{d\tau^t_i} = h_{ji}D_{ji}\frac{dw^n_i}{d\tau^t_i} - w^n_i D_{ji}\frac{dt_{ji}}{d\tau^t_i} - D_{ji} + \frac{dARL}{d\tau^t_i} - \frac{d\tau^{ls}}{d\tau^t_i} - \sum_k z_{jik}\frac{dp_k}{d\tau^t_i} - q_{ji}\frac{dr^q_j}{d\tau^t_i} \tag{79}$$

For other policies we obtain

$$\frac{1}{\lambda_{ij}}\frac{dV_{ij}}{d\tau^m} = h_{ij}D_{ij}\frac{dw^n_j}{d\tau^m} - w^n_j D_{ij}\frac{dt_{ij}}{d\tau^m} - m_{ij}D_{ij} - \sum_k m_{ik}z_{ijk} + \frac{dARL}{d\tau^m} - \frac{d\tau^{ls}}{d\tau^m} - \sum_k z_{ijk}\frac{dp_k}{d\tau^m} - q_{ij}\frac{dr^q_i}{d\tau^m} \tag{80}$$

$$\frac{1}{\lambda_{ij}}\frac{dV_{ij}}{d\tau^c} = D_{ij}h_{ij}\frac{dw^n_j}{d\tau^c} - w^n_j D_{ij}\frac{dt_{ij}}{d\tau^c} - \delta^c D_{ij} - \sum_{k\neq i} z_{ijk} + \frac{dARL}{d\tau^c} - \frac{d\tau^{ls}}{d\tau^c} - \sum_k z_{ijk}\frac{dp_k}{d\tau^c} - q_{ij}\frac{dr^q_i}{d\tau^c} \tag{81}$$

$$\frac{1}{\lambda_{ij}}\frac{dV_{ij}}{d\zeta} = D_{ij}h_{ij}\frac{dw^n_j}{d\zeta} - w^n_j D_{ij}\frac{dt_{ij}}{d\zeta} + \frac{dARL}{d\zeta} - \frac{d\tau^{ls}}{d\zeta} - \sum_k z_{ijk}\frac{dp_k}{d\zeta} - q_{ij}\frac{dr^q_i}{d\zeta}, \tag{82}$$

where ARL is aggregate land rent and δ^c is an indicator set to unity if $i \neq j$ and zero otherwise.

C.1.1 Closing the model

Each household decides on its spatial choice set ij that maximizes its expected utility. Since ε_{ij} is stochastically distributed among households for each ij, a household's probability for choosing ij is $\psi_{ij} = \Pr\left[V_{ij} + \varepsilon_{ij} > V_{\tilde{ij}} + \varepsilon_{\tilde{ij}}, \forall\, \tilde{ij} \neq ij\right]$. We assume that ε_{ij} is i.i.d. Gumbel distributed with zero mean, variance σ^2 and dispersion parameter $\Lambda = \pi/\left(\sigma\sqrt{6}\right)$. This implies that the choice probabilities are given by the multinominal logit model (e.g. Small and Rosen, 1981, Anas and Rhee, 2006)

$$\psi_{ij} = \frac{\exp\left(\Lambda V_{ij}\right)}{\sum_{a=1}^{J}\sum_{b=1}^{J}\exp\left(\Lambda V_{ab}\right)}, \qquad \forall i, j. \tag{83}$$

Production Output of local consumption goods is $X_i = f\left(Q_i, L_i\right)$. It is produced by a representative firm applying a CRS production function with land demand Q_i and labor demand

L_i. Applying Euler's theorem, we have

$$X_i = f_Q Q_i + f_M M_i$$

respectively

$$dX_i = f_Q dQ_i + f_M dM_i$$

after multiplying by p_i

$$\begin{aligned} p_i dX_i &= p_i f_Q dQ_i + p_i f_M dM_i \\ &= r_i^Q dQ_i + w_i dM_i \end{aligned} \tag{84}$$

since we get from profit maximization

$$p_i f_Q = r_i^Q, \qquad p_i f_M = w_i.$$

Totally differentiate zero profits $p_i X_i = w_i L_i + r_i^Q Q_i$ to obtain

$$p_i dX_i + X_i dp_i = w_i dL_i + M_i dw_i + r_i^Q dQ_i + Q_i dr_i^Q.$$

Plugging in (84) yields

$$X_i dp_i = M_i dw_i + Q_i dr_i^Q. \tag{85}$$

Government The consolidated government levies a wage tax with rate τ^w, a miles (distance) tax τ^m per unit of distance, Pigouvian congestion tolls τ_i^t and a cordon toll for entering zone 1 with rate τ^c. It grants lump sum transfers $T^{ls} = N\tau^{ls}$ and pays opportunity costs of infrastructure capacity $r_i s_i A_i$, where s_i is the share of infrastructure on land. We assume that opportunity costs of land are given by the highest land use price. The government budget constraint is

$$\tau^w T^w + \sum_i \tau_i^t T_i^t + \tau^m T^m + \tau^c T^c + N\tau^{ls} = \sum_i r_i s_i A_i \tag{86}$$

where the tax bases are (assuming there are no shopping trip costs)

$$T^w = N \sum_i \sum_j \psi_{ij} w_j h_{ij} D_{ij} \tag{87}$$

$$T_i^t = N \sum_j \psi_{ij} D_{ij} + N \sum_{j \neq i} \psi_{ji} D_{ji} \tag{88}$$

$$T^m = N \sum_i \sum_j \psi_{ij} m_{ij} D_{ij} + N \sum_i \sum_j \psi_{ij} \sum_k m_{ik} z_{ijk} \tag{89}$$

$$T^c = N \sum_i \sum_{j \neq i} \psi_{ij} D_{ij} + N \sum_i \sum_j \psi_{ij} \sum_{k \neq i} z_{ijk}. \tag{90}$$

Differentiating the government budget constraint (86) w.r.t. to τ_k^t yields

$$\begin{aligned}
\frac{d\tau^{ls}}{d\tau_k^t} &= \sum s_i A_i \frac{dr_i}{d\tau_k^t} - \frac{1}{N} T_k^t - \frac{1}{N} \sum_j \tau_j^t \frac{dT_j^t}{d\tau_k^t} - \frac{\tau^w}{N} \frac{dT^w}{d\tau_k^t} \\
\frac{d\tau^{ls}}{d\tau^m} &= \sum s_i A_i \frac{dr_i}{d\tau^m} - \frac{1}{N} T^m - \frac{1}{N} \frac{dT^m}{d\tau^m} - \frac{\tau^w}{N} \frac{dT^w}{d\tau^m} \\
\frac{d\tau^{ls}}{d\tau^c} &= \sum s_i A_i \frac{dr_i}{d\tau^c} - \frac{1}{N} T^c - \frac{1}{N} \tau^c \frac{dT^c}{d\tau^c} - \frac{\tau^w}{N} \frac{dT^w}{d\tau^c} \\
\frac{d\tau^{ls}}{d\zeta} &= \sum s_i A_i \frac{dr_i}{d\zeta} - \frac{\tau^w}{N} \frac{dT^w}{d\zeta} \\
\frac{d\tau^{ls}}{ds_k} &= r_k A_k + \sum s_i A_i \frac{dr_i}{ds_k} - \frac{\tau^w}{N} \frac{dT^w}{ds_k}
\end{aligned} \tag{91}$$

where we define capacity

$$K_i \equiv \kappa_i s_i A_i \tag{92}$$

and assume that only one congestion related policy is applied.

Market Clearing Private consumption plus public consumption add up to demand for urban goods. Because local goods are produced with a CRS production function where local labor is the only input, the local good markets are cleared too. The market clearing conditions of local labor markets are

$$M_i = N \sum_j \psi_{ji} h_{ji} D_{ji}, \qquad \forall i. \tag{93}$$

and those of the local land markets are

$$(1 - s_i) A_i = Q_i + N \sum_j \psi_{ij} q_{ij}, \qquad \forall i. \tag{94}$$

In the case of zoning there are two local land markets in each zone: one for residential use $\zeta_i (1 - s_i) A_i = N \sum_j \psi_{ij} q_{ij}$ and the other for business use: $(1 - \zeta_i)(1 - s_i) A_i = Q_i$.

Eventually, the population has to be fully distributed across the city. This is achieved because $\sum_i \sum_j \psi_{ij} = 1$. There are six market clearing conditions plus the government budget constraint and seven unknowns: $\{r_1, r_2, p_1, p_2, w_1, w_2, \tau^{ls}\}$.

For later use we totally differentiate the market clearing conditions to have

$$dX_i = N \sum_j \sum_k (\psi_{ij} dz_{ijk} + z_{ijk} d\psi_{ij}) \tag{95}$$

$$dM_i = N \sum_j (\psi_{ji} h_{ji} dD_{ji} + \psi_{ji} D_{ji} dh_{ji} + h_{ji} D_{ji} d\psi_{ji}) \tag{96}$$

$$dA_i = dQ_i + N \sum_j (\psi_{ij} dq_{ij} + q_{ij} d\psi_{ij}) + A_i ds_i = 0 \tag{97}$$

With LUR we have $(\zeta\left(1-s_i\right)A_i=\sum\psi_{ij}q_{ij},\ (1-\zeta)\left(1-s_i\right)A_i=Q_i)$. Then

$$N\sum_j\left(\psi_{ij}\frac{dq_{ij}}{d\zeta}+q_{ij}\frac{d\psi_{ij}}{d\zeta}\right)=\left(1-s_i\right)A_i$$

$$\frac{dQ_i}{d\zeta}=-\left(1-s_i\right)A_i$$

$$\frac{dQ_i}{d\zeta}=N\sum_j\left(\psi_{ij}\frac{dq_{ij}}{d\zeta}+q_{ij}\frac{d\psi_{ij}}{d\zeta}\right). \tag{98}$$

We define aggregate land rents (ARL)

$$ALR\equiv N\sum_i\sum_j\psi_{ij}r_i^q q_i+\sum r_i^Q Q_i+\sum_i r_i s_i A_i \tag{99}$$

to obtain

$$\frac{dALR}{d\chi_{(k)}}=N\sum_i\sum_j\left(\psi_{ij}r_i^q\frac{dq_i}{d\chi_{(k)}}+\psi_{ij}q_i\frac{dr_i^q}{d\chi_{(k)}}+r_i^q q_i\frac{d\psi_{ij}}{d\chi_{(k)}}\right)+\sum_i\left(r_i^Q\frac{dQ_i}{d\chi_{(k)}}+Q_i\frac{dr_i^Q}{d\chi_{(k)}}\right)$$
$$+r_kA_k\frac{ds_k}{d\chi_{(k)}}+\sum_i s_iA_i\frac{dr_i}{d\chi_{(k)}}. \tag{100}$$

C.2 Marginal welfare changes with lump sum recycling

We use the hybrid approach Yh as our benchmark because it is the most general model without any restrictions on the choice of leisure. Welfare

$$W=E\left[\max_{(ij)}\left(V_{ij}+\varepsilon_{ij}\right)\right]=\frac{1}{\Lambda}\ln\sum_i\sum_j\exp\left(\Lambda V_{ij}\right). \tag{101}$$

We maximize welfare subject to the public budget constraint and the market clearing conditions by choosing congestion tolls τ_k^t, for each zone k.

Instead of using the Lagrangian approach we simplify derivations by proceeding in the following way. We derive welfare changes of a small change in investment. Next, we set this to zero to find the optimum and subsequently put in all restrictions (Rhee et al. 2014, or Hirte and Tscharaktschiew, 2013).

The derivation of the expected welfare function w.r.t. to any policy instrument is

$$\frac{dW}{d\tau_k^t}=N\sum_i\sum_j\psi_{ij}\frac{dV_{ij}}{d\tau_k^t} \tag{102}$$

Plugging (78) into (102) yields for the congestion toll

$$\frac{dW}{d\tau_k^t} = -N\sum_i\sum_j \psi_{ij}\lambda_{ij}w_j^n D_{ij}\frac{dt_{ij}}{d\tau_k^t} \tag{103}$$
$$- N\sum_i\sum_j \psi_{ij}\lambda_{ij}\delta^k D_{ij} + N\left(1-\tau^w\right)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\tau_k^t}$$
$$- N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\tau_k^t} - N\sum_i\sum_j \psi_{ij}\lambda_{ij}q_{ij}\frac{dr_i^q}{d\tau_k^t} + N\lambda\frac{dALR}{d\tau_k^t} - N\lambda\frac{d\tau^{ls}}{d\tau_k^t}$$

where the indicator δ^k is unity if i or j equals k and zero otherwise and with the average marginal utility of income defined as

$$\lambda \equiv \sum_i\sum_j \Psi_{ij}\lambda_{ij}. \tag{104}$$

For the emission tax we get from differentiating (80) w.r.t. the miles tax rate

$$\frac{dW}{d\tau^m} = -N\sum_i\sum_j \psi_{ij}\lambda_{ij}w_j^n D_{ij}\frac{dt_{ij}}{d\tau^m} \tag{105}$$
$$- N\sum_i\sum_j \psi_{ij}\lambda_{ij}\left(m_{ij}D_{ij} + \sum_k m_{ik}z_{ijk}\right) + N\left(1-\tau^w\right)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\tau^m}$$
$$- N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\tau^m} - N\sum_i\sum_j \psi_{ij}\lambda_{ij}q_{ij}\frac{dr_i^q}{d\tau^m} + N\lambda\frac{dALR}{d\tau^m} - N\lambda\frac{d\tau^{ls}}{d\tau^m}.$$

The differential of (81) w.r.t. the cordon toll is

$$\frac{dW}{d\tau^c} = -N\sum_i\sum_j \psi_{ij}\lambda_{ij}w_j^n D_{ij}\frac{dt_{ij}}{d\tau^c} \tag{106}$$
$$- N\sum_i\sum_j \psi_{ij}\lambda_{ij}\left(\delta^c D_{ij} + \sum_{k\neq i} z_{ijk}\right) + N\left(1-\tau^w\right)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\tau^c}$$
$$- N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\tau^c} - N\sum_i\sum_j \psi_{ij}\lambda_{ij}q_{ij}\frac{dr_i^q}{d\tau^c} + N\lambda\frac{dALR}{d\tau^c} - N\lambda\frac{d\tau^{ls}}{d\tau^c}.$$

For land-use regulation ζ_i, we have (from (82))

$$\frac{dW}{d\zeta_k} = -N\sum_i\sum_j \psi_{ij}\lambda_{ij}w_j^n D_{ij}\frac{dt_{ij}}{d\zeta_k} \tag{107}$$
$$+ N\left(1-\tau^w\right)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\zeta_k}$$
$$- N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\zeta_k} - N\sum_i\sum_j \psi_{ij}\lambda_{ij}q_{ij}\frac{dr_i^q}{d\zeta_k} + N\lambda\frac{dALR}{d\zeta_k} - N\lambda\frac{d\tau^{ls}}{d\zeta_k}.$$

Exchanging ζ_i with s_i gives the welfare change with road capacity expansion.

Using (100) and (91) expands (103)

$$\frac{dW}{d\tau_k^t} = -N\sum_i\sum_j \psi_{ij}\lambda_{ij}w_j^n D_{ij}\frac{dt_{ij}}{d\tau_k^t} - N\sum_i\sum_j \psi_{ij}\lambda_{ij}\delta^k D_{ij}$$
$$+ N(1-\tau^w)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\tau_k^t} - N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\tau_k^t} - N\sum_i\sum_j \psi_{ij}\lambda_{ij}q_{ij}\frac{dr_i^q}{d\tau_k^t}$$
$$+ \lambda N\sum_i\left(\psi_{ij}r_i^q\frac{dq_i}{d\tau_k^t} + \psi_{ij}q_i\frac{dr_i^q}{d\tau_k^t} + r_i^q q_i\frac{d\psi_{ij}}{d\tau_k^t}\right) + \lambda\sum_i\left(r_i^Q\frac{dQ_i}{d\tau_k^t} + Q_i\frac{dr_i^Q}{d\tau_k^t}\right) + \lambda\sum_i s_iA_i\frac{dr_i}{d\tau_k^t}$$
$$- \lambda\sum s_iA_i\frac{dr_i}{d\tau_k^t} + \lambda T_k^t + \lambda\sum_j \tau_j^t\frac{dT_j^t}{d\tau_k^t} + \lambda\tau^w\frac{dT^w}{d\tau_k^t}$$

Substituting (91) yields

$$\frac{1}{\lambda}\frac{dW}{d\tau_k^t} = -\frac{N}{\lambda}\sum_i\sum_j \psi_{ij}\lambda_{ij}D_{ij}w_j^n\frac{dt_{ij}}{d\tau_k^t} - \frac{N}{\lambda}\sum_i\sum_j \psi_{ij}\lambda_{ij}\delta^k D_{ij} \tag{108}$$
$$+ \frac{N}{\lambda}(1-\tau^w)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\tau_k^t} - \frac{N}{\lambda}\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\tau_k^t} - \frac{N}{\lambda}\sum_i\sum_j \psi_{ij}\lambda_{ij}q_i\frac{dr_i^q}{d\tau_k^t}$$
$$+ N\sum_i\left(\psi_{ij}r_i^q\frac{dq_i}{d\tau_k^t} + \psi_{ij}q_i\frac{dr_i^q}{d\tau_k^t} + r_i^q q_i\frac{d\psi_{ij}}{d\tau_k^t}\right) + \sum_i\left(r_i^Q\frac{dQ_i}{d\tau_k^t} + Q_i\frac{dr_i^Q}{d\tau_k^t}\right) + \sum_i s_iA_i\frac{dr_i}{d\tau_k^t}$$
$$- \sum s_iA_i\frac{dr_i}{d\tau_k^t} + \underbrace{\left(N\sum_j \psi_{kj}D_{kj} + N\sum_{j\neq k}\psi_{jk}D_{jk}\right)}_{\sum_i\sum_j \psi_{ij}\delta^k D_{ij}}$$
$$+ N\sum_i \tau_i^t\left[\sum_j\left(\psi_{ij}\frac{dD_{ij}}{d\tau_k^t} + D_{ij}\frac{d\psi_{ij}}{d\tau_k^t}\right) + N\sum_{j\neq i}\left(\psi_{ji}\frac{dD_{ji}}{d\tau^k} + D_{ji}\frac{d\psi_{ji}}{d\tau^k}\right)\right]$$
$$+ \tau^w N\sum_i\sum_j\left(\psi_{ij}w_jh_{ij}\frac{dD_{ij}}{d\tau_k^t} + \psi_{ij}w_jD_{ij}\frac{dh_{ij}}{d\tau_k^t} + w_jh_{ij}D_{ij}\frac{d\psi_{ij}}{d\tau_k^t} + \psi_{ij}h_{ij}D_{ij}\frac{dw_j}{d\tau_k^t}\right).$$

It is convenient to define the marginal external costs of congestion ($\frac{dt_{ij}}{d\tau} = t_i' + \eta_{ij}t_j'$) as

$$MEC_{\chi(k)} \equiv N\sum_i\sum_j \Psi_{ij}D_{ij}w_j^n\frac{dt_{ij}/d\chi_{(k)}}{dF/d\chi_{(k)}}, \tag{109}$$

where F is overall traffic flow.

After expanding (108) by λ times different terms, we have

$$\begin{aligned}\frac{1}{\lambda}\frac{dW}{d\tau_k^t} &= MEC_{tk}\left(-\frac{dF}{d\tau_k^t}\right) + MEC_{tk}\left(\frac{dF}{d\tau_k^t}\right)\left[\frac{mec_{tk}}{\lambda MEC_{tk}} - 1\right] \\ &- N\sum_i\sum_j \psi_{ij}\delta^k D_{ij}\left[\frac{N\sum_i\sum_j \psi_{ij}\lambda_{ij}\delta^k D_{ij}}{\lambda N\sum_i\sum_j \psi_{ij}\delta^k D_{ij}} - 1\right] \\ &+ Y_{tk}\left(\frac{y_{tk}}{\lambda Y_{tk}} - 1\right) \\ &+ N\sum_i\left(\psi_{ij}r_i^q\frac{dq_i}{d\tau_k^t} + \psi_{ij}q_i\frac{dr_i^q}{d\tau_k^t} + r_i^q q_i\frac{d\psi_{ij}}{d\tau_k^t}\right) + \sum_i\left(r_i^Q\frac{dQ_i}{d\tau_k^t} + Q_i\frac{dr_i^Q}{d\tau_k^t}\right) \\ &+ N\sum_i \tau_i^t\left[\sum_j\left(\psi_{ij}\frac{dD_{ij}}{d\tau_k^t} + D_{ij}\frac{d\psi_{ij}}{d\tau_k^t}\right) + N\sum_{j\neq i}\left(\psi_{ji}\frac{dD_{ji}}{d\tau^k} + D_{ji}\frac{d\psi_{ji}}{d\tau^k}\right)\right] \\ &+ \tau^w N\sum_i\sum_j\left(\psi_{ij}w_j h_{ij}\frac{dD_{ij}}{d\tau_k^t} + \psi_{ij}w_j D_{ij}\frac{dh_{ij}}{d\tau_k^t} + w_j h_{ij}D_{ij}\frac{d\psi_{ij}}{d\tau_k^t}\right),\end{aligned} \tag{110}$$

where we applied the definitions for price induced changes in average market income minus expenditure, Y, the sum of individual utility values of price induced changes in market income minus expenditures, and the sum of individual utility values of marginal external congestion costs

$$Y_{tk} \equiv N\sum_i\sum_j \psi_{ij}h_{ij}D_{ij}\frac{dw_j}{d\tau_k^t} - N\sum_i\sum_j\sum_l \psi_{ij}z_{ijl}\frac{dp_l}{d\tau_k^t} - N\sum_i\sum_j \psi_{ij}q_i\frac{dr_i^q}{d\tau_k^t} \tag{111}$$

$$y_{tk} \equiv N\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\tau_k^t} - N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\tau_k^t} - N\sum_i\sum_j \Psi_{ij}\lambda_{ij}q_i\frac{dr_i^q}{d\tau_k^t} \tag{112}$$

$$mec_{tk} \equiv N\sum_i\sum_j \Psi_{ij}\lambda_{ij}D_{ij}w_j^n\frac{dt_{ij}/d\tau^k}{dF/d\tau_k^t}. \tag{113}$$

Next we define the distributional characteristics

$$\phi_{tk}^Y \equiv \frac{y_{tk}}{\lambda Y_{tk}}, \qquad \phi_{tk}^E \equiv \frac{mec_{tk}}{\lambda MEC_{tk}}, \qquad \phi_{tk}^T \equiv \left(\frac{N\sum_i\sum_j \psi_{ij}\lambda_{ij}\delta^k D_{ij}}{\lambda N\sum_i\sum_j \psi_{ij}\delta^k D_{ij}}\right) \tag{114}$$

to simplify (110)

$$\begin{aligned}\frac{1}{\lambda}\frac{dW}{d\tau_k^t} &= MEC_{tk}\left(-\frac{dF}{d\tau_k^t}\right) \\ &+ N\sum_i\sum_j \underbrace{\psi_{ij}h_{ij}D_{ij}}_{L_j}\frac{dw_j}{d\tau_k^t} - N\sum_i\sum_j\sum_l \underbrace{\psi_{ij}z_{ijl}}_{X_l}\frac{dp_l}{d\tau_k^t} + \sum_i Q_i\frac{dr_i^Q}{d\tau_k^t} \\ &+ N\sum_i\left(\psi_{ij}r_i^q\frac{dq_i}{d\tau_k^t} + r_i^q q_i\frac{d\psi_{ij}}{d\tau_k^t} + r_i^Q\frac{dQ_i}{d\tau_k^t}\right) \\ &+ N\sum_i\tau_i^t\left[\sum_j\left(\psi_{ij}\frac{dD_{ij}}{d\tau_k^t} + D_{ij}\frac{d\psi_{ij}}{d\tau_k^t}\right) + N\sum_{j\neq i}\left(\psi_{ji}\frac{dD_{ji}}{d\tau_k^t} + D_{ji}\frac{d\psi_{ji}}{d\tau_k^t}\right)\right] \\ &+ \tau^w N\sum_i\sum_j\left(\psi_{ij}w_jh_{ij}\frac{dD_{ij}}{d\tau_k^t} + \psi_{ij}w_jD_{ij}\frac{dh_{ij}}{d\tau_k^t} + w_jh_{ij}D_{ij}\frac{d\psi_{ij}}{d\tau_k^t}\right) \\ &+ MEC_{tk}\left(\frac{dF}{d\tau_k^t}\right)\left(\phi_{tk}^E - 1\right) + Y_{tk}\left(\phi_{tk}^Y - 1\right) - N\sum_i\sum_j\psi_{ij}\delta^k D_{ij}\left(\phi_{tk}^T - 1\right).\end{aligned} \tag{115}$$

The second row gives the average change in income minus expenditure due to changes in market prices. The third row represents behavioral changes in the land market and the fourth and fifth row display changes in tax revenue due to behavior responses. The last row represents redistribution effects due to differences in the MUI between household types. By inserting (97) and (85) (115) simplifies to

$$\begin{aligned}\frac{1}{\lambda}\frac{dW}{d\tau_k^t} &= \left(MEC_{tk} - \tau_k^t\frac{Adj_{tk}}{-dF/d\tau_k^t}\right)\left(-\frac{dF}{d\tau_k^t}\right) \\ &+ N\sum_{i\neq k}\tau_i^t\left[\sum_j\left(\psi_{ij}\frac{dD_{ij}}{d\tau_k^t} + D_{ij}\frac{d\psi_{ij}}{d\tau_k^t}\right) + N\sum_{j\neq i}\left(\psi_{ji}\frac{dD_{ji}}{d\tau^k} + D_{ji}\frac{d\psi_{ji}}{d\tau^k}\right)\right] \\ &+ \tau^w N\sum_i\sum_j\left(\psi_{ij}w_jh_{ij}\frac{dD_{ij}}{d\tau_k^t} + \psi_{ij}w_jD_{ij}\frac{dh_{ij}}{d\tau_k^t} + w_jh_{ij}D_{ij}\frac{d\psi_{ij}}{d\tau_k^t}\right) \\ &+ \underbrace{MEC_{tk}\left(\frac{dF}{d\tau_k^t}\right)\left(\phi_{tk}^E - 1\right) + Y_{tk}\left(\phi_{tk}^Y - 1\right) - N\sum_i\sum_j\psi_{ij}\delta^k D_{ij}\left(\phi_{tk}^T - 1\right)}_{RE_{tk}}.\end{aligned} \tag{116}$$

where the adjustment term giving the response of the tax base to its toll is

$$Adj_{tk} \equiv -\sum_i\sum_j\delta^k\left(\psi_{ij}\frac{dD_{ij}}{d\tau_k^t} + D_{ij}\frac{d\psi_{ij}}{d\tau_k^t}\right). \tag{117}$$

Defining the second and third row as the tax interaction term and the fourth row as the redistribution term yields (42)

$$\frac{1}{\lambda}\frac{dW}{d\tau_k^t} = \left(MEC_{tk} - \tau_k^t\frac{Adj_{tk}}{-dF/d\tau_k^t}\right)\left(-\frac{dF}{d\tau_k^t}\right) + TI_{tk} + RE_{tk}. \tag{118}$$

C.3 General case $u(z,q,\ell,L)$,(model Yh) no restriction - with land-use type regulation

For land-use regulation ζ_i, we start with (107)

$$\frac{dW}{d\zeta_k} = -N\sum_i\sum_j \psi_{ij}\lambda_{ij}w_j^n D_{ij}\frac{dt_{ij}}{d\zeta_k} + N\left(1-\tau^w\right)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\zeta_k}$$
$$- N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\zeta_k} - N\sum_i\sum_j \Psi_{ij}\lambda_{ij}q_{ij}\frac{dr_i^q}{d\zeta_k} + N\lambda\frac{dALR}{d\zeta_k} - N\lambda\frac{d\tau^{ls}}{d\zeta_k}.$$

Using (100) and (91) expands (103)

$$\begin{aligned}\frac{dW}{d\zeta_k} &= -N\sum_i\sum_j \psi_{ij}\lambda_{ij}w_j^n D_{ij}\frac{dt_{ij}}{d\zeta_k} \\ &+ N\left(1-\tau^w\right)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\zeta_k} - N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\zeta_k} - N\sum_i\sum_j \psi_{ij}\lambda_{ij}q_{ij}\frac{dr_i^q}{d\zeta_k} \\ &+ \lambda N\sum_i\left(\psi_{ij}r_i^q\frac{dq_i}{d\zeta_k} + \psi_{ij}q_i\frac{dr_i^q}{d\zeta_k} + r_i^q q_i\frac{d\psi_{ij}}{d\zeta_k}\right) + \lambda\sum_i\left(r_i^Q\frac{dQ_i}{d\zeta_k} + Q_i\frac{dr_i^Q}{d\zeta_k}\right) + \lambda\sum_i s_iA_i\frac{dr_i}{d\zeta_k} \\ &- \lambda\sum s_iA_i\frac{dr_i}{d\zeta_k} + \lambda\tau^w\frac{dT^w}{d\zeta_k}\end{aligned}$$

Substituting (91) yields

$$\begin{aligned}\frac{dW}{d\zeta_k} &= -N\sum_i\sum_j \psi_{ij}\lambda_{ij}w_j^n D_{ij}\frac{dt_{ij}}{d\zeta_k} \\ &+ N\left(1-\tau^w\right)\sum_i\sum_j \psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\zeta_k} - N\sum_i\sum_j\sum_l \psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\zeta_k} - N\sum_i\sum_j \psi_{ij}\lambda_{ij}q_{ij}\frac{dr_i^q}{d\zeta_k} \\ &+ \lambda N\sum_i\left(\psi_{ij}r_i^q\frac{dq_i}{d\zeta_k} + \psi_{ij}q_i\frac{dr_i^q}{d\zeta_k} + r_i^q q_i\frac{d\psi_{ij}}{d\zeta_k}\right) + \lambda\sum_i\left(r_i^Q\frac{dQ_i}{d\zeta_k} + Q_i\frac{dr_i^Q}{d\zeta_k}\right) \\ &+ \tau^w N\sum_i\sum_j\left(\psi_{ij}w_jh_{ij}\frac{dD_{ij}}{d\zeta_k} + \psi_{ij}w_jD_{ij}\frac{dh_{ij}}{d\zeta_k} + w_jh_{ij}D_{ij}\frac{d\psi_{ij}}{d\zeta_k} + \psi_{ij}h_{ij}D_{ij}\frac{dw_j}{d\zeta_k}\right).\end{aligned} \tag{119}$$

Marginal external costs of are

$$MEC_{\zeta_k} \equiv N\sum_i\sum_j \Psi_{ij}D_{ij}w_j^n\frac{dt_{ij}/d\zeta_k}{dF/d\zeta_k}, \tag{120}$$

After expanding (119) by λ times different terms, we have

$$\frac{1}{\lambda}\frac{dW}{d\zeta_k} = MEC_{\zeta k}\left(-\frac{dF}{d\zeta_k}\right) + MEC_{\zeta k}\left(\frac{dF}{d\zeta_k}\right)\left[\frac{mec_{\zeta k}}{\lambda MEC_{\zeta k}} - 1\right] \tag{121}$$
$$+ Y_{\zeta k}\left(\frac{y_{\zeta k}}{\lambda Y_{\zeta k}} - 1\right)$$
$$+ N\sum_i\left(\psi_{ij}r_i^q\frac{dq_i}{d\zeta_k} + \psi_{ij}q_i\frac{dr_i^q}{d\zeta_k} + r_i^q q_i\frac{d\psi_{ij}}{d\zeta_k}\right) + \sum_i\left(r_i^Q\frac{dQ_i}{d\zeta_k} + Q_i\frac{dr_i^Q}{d\zeta_k}\right)$$
$$+ \tau^w N\sum_i\sum_j\left(\psi_{ij}w_jh_{ij}\frac{dD_{ij}}{d\zeta_k} + \psi_{ij}w_jD_{ij}\frac{dh_{ij}}{d\zeta_k} + w_jh_{ij}D_{ij}\frac{d\psi_{ij}}{d\zeta_k}\right),$$

where we use the following definitions:

$$Y_{\zeta k} \equiv N\sum_i\sum_j\psi_{ij}h_{ij}D_{ij}\frac{dw_j}{d\zeta_k} - N\sum_i\sum_j\sum_l\psi_{ij}z_{ijl}\frac{dp_l}{d\zeta_k} - N\sum_i\sum_j\psi_{ij}q_i\frac{dr_i^q}{d\zeta_k}$$
$$y_{\zeta k} \equiv N\sum_i\sum_j\psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{dw_j}{d\zeta_k} - N\sum_i\sum_j\sum_l\psi_{ij}\lambda_{ij}z_{ijl}\frac{dp_l}{d\zeta_k} - N\sum_i\sum_j\psi_{ij}\lambda_{ij}q_i\frac{dr_i^q}{d\zeta_k}$$
$$mec_{\zeta k} \equiv N\sum_i\sum_j\psi_{ij}\lambda_{ij}D_{ij}w_j^n\frac{dt_{ij}/d\zeta_k}{dF/d\zeta_k}.$$

Next we define the distributional characteristics

$$\phi_{\zeta k}^Y \equiv \frac{y_{\zeta k}}{\lambda Y_{\zeta k}}, \qquad \phi_{\zeta k}^E \equiv \frac{mec_{\zeta k}}{\lambda MEC_{\zeta k}}$$

to simplify (110)

$$\frac{1}{\lambda}\frac{dW}{d\zeta_k} = MEC_{\zeta k}\left(-\frac{dF}{d\zeta_k}\right) \tag{122}$$
$$+ N\sum_i\sum_j\underbrace{\psi_{ij}h_{ij}D_{ij}}_{L_j}\frac{dw_j}{d\zeta_k} - N\sum_i\sum_j\sum_l\underbrace{\psi_{ij}z_{ijl}}_{X_l}\frac{dp_l}{d\zeta_k} + \sum_i Q_i\frac{dr_i^Q}{d\zeta_k}$$
$$+ \sum_i\left[Nr_i^q\left(\psi_{ij}\frac{dq_i}{d\zeta_k} + q_i\frac{d\psi_{ij}}{d\zeta_k}\right) + r_i^Q\frac{dQ_i}{d\zeta_k}\right]$$
$$+ \tau^w N\sum_i\sum_j\left(\psi_{ij}w_jh_{ij}\frac{dD_{ij}}{d\zeta_k} + \psi_{ij}w_jD_{ij}\frac{dh_{ij}}{d\zeta_k} + w_jh_{ij}D_{ij}\frac{d\psi_{ij}}{d\zeta_k}\right)$$
$$+ MEC_{\zeta k}\left(\frac{dF}{d\zeta_k}\right)\left(\phi_{\zeta k}^E - 1\right) + Y_{\zeta k}\left(\phi_{\zeta k}^Y - 1\right).$$

By inserting (97) and (85) (122) simplifies to (because $N\sum_j\left(\psi_{ij}\frac{dq_{ij}}{d\zeta} + q_{ij}\frac{d\psi_{ij}}{d\zeta}\right) = (1 - s_i)A_i$

and $\frac{dQ_i}{d\zeta} = -(1-s_i)A_i$)

$$\begin{aligned}\frac{1}{\lambda}\frac{dW}{d\zeta_k} &= MEC_{\zeta k}\left(-\frac{dF}{d\zeta_k}\right) \\ &+ \underbrace{N\sum_i\sum_j L_j\frac{dw_j}{d\zeta_k} - N\sum_i\sum_j\sum_l X_l\frac{dp_l}{d\zeta_k} + \sum_i Q_i\frac{dr_i^Q}{d\zeta_k}}_{=0,\text{ from production}} \\ &+ \sum_i\left(r_i^q - r_i^Q\right)(1-s_i)A_i \\ &+ \underbrace{\tau^w N\sum_i\sum_j\left(\psi_{ij}w_jh_{ij}\frac{dD_{ij}}{d\zeta_k} + \psi_{ij}w_jD_{ij}\frac{dh_{ij}}{d\zeta_k} + w_jh_{ij}D_{ij}\frac{d\psi_{ij}}{d\zeta_k}\right)}_{TI_{\zeta k}} \\ &+ \underbrace{MEC_{\zeta k}\left(\frac{dF}{d\zeta_k}\right)\left(\phi_{\zeta k}^E - 1\right) + Y_{\zeta k}\left(\phi_{\zeta k}^Y - 1\right)}_{RE_{\zeta k}}.\end{aligned} \tag{123}$$

Defining the second and third row as the tax interaction term and the fourth row as the redistribution term yields (42)

$$\frac{1}{\lambda}\frac{dW}{d\zeta_k} = MEC_{\zeta k}\left(-\frac{dF}{d\zeta_k}\right) + TI_{\zeta k} + N\sum_i\left(r_i^q - r_i^Q\right)(1-s_i)A_i + RE_{\zeta k}. \tag{124}$$

where

$$MEC_{\zeta k} \equiv N\sum_i\sum_j \Psi_{ij}D_{ij}w_j^n\frac{dt_{ij}/d\zeta_k}{dF/d\zeta_k} \tag{125}$$

$$TI_{\zeta k} \equiv \tau^w N\sum_i\sum_j\left(\psi_{ij}w_jh_{ij}\frac{dD_{ij}}{d\zeta_k} + \psi_{ij}w_jD_{ij}\frac{dh_{ij}}{d\zeta_k} + w_jh_{ij}D_{ij}\frac{d\psi_{ij}}{d\zeta_k}\right) \tag{126}$$

$$RE_{\zeta k} \equiv MEC_{\zeta k}\left(\frac{dF}{d\zeta_k}\right)\left(\phi_{\zeta k}^E - 1\right) + Y_{\zeta k}\left(\phi_{\zeta k}^Y - 1\right) \tag{127}$$

The optimal regulation requires

$$0 = MEC_{\zeta k}\left(-\frac{dF}{d\zeta_k}\right) + TI_{\zeta k} + N\sum_i\left(r_i^q - r_i^Q\right)(1-s_i)A_i + RE_{\zeta k} \to (\zeta_k)^* \tag{128}$$

Land-use type restrictions are considered to be a second-best remedy to congestion tolls (e.g. Rhee et al. 2014). They are spatially differentiated across locations and, thus, can drive people living in suburbs and working in the city to move to the city. By doing so, congestion on the suburb-city relation might decline, but it will increase in the city-city and city-suburb relation. It is not possible to derive general lessons from the equations. We only see, that marginal congestion costs are a component of the optimal LUR. The higher MEC the higher LUR. In that way, LUR is a device to lower congestion. On the other side LURs generate distortions in the land market by driving a wedge between residential and business land prices, cause tax interaction and redistribution effects. Hence, the optimal ζ cannot be determined from theory.

D Detailed tables

Table 10: Policy effects of road capacity expansion with inhomogeneous leisure

Road capacity expansion - Case 2a	Benchmark	Hours Hi	Hybrid Yi	Days Di
Time allocation				
Workdays per year	263	0	0	−1
Leisure days per year	52	0	+1	+1
Hours on a workday spent working/leisure	8.3/5.8	+0.2/−0.1	+0.2/−0.1	0/+0.1
Hours on a workday spent/commuting/shopping	1.1/0.8	−0.1/0	−0.1/0	−0.1/0
Hours on a leisure day spent leisure/shopping	12.0/4.0	+0.1/−0.1	0/0	+0.1/−0.1
Total labor supply [hours/year]	2187	+41	+47	+7
Total leisure demand [hours/year]	2164	−23	−31	+13
Total commuting time on workdays [hours/year]	272	−10	−8	−8
Total shopping time [hours/year]	417	−8	−8	−12
Travel/Transport/Traffic				
Travel time delay [hours/year]	31	−10	−10	−10
MEC [$-cents/mile]	22	−7	−7	−8
Total travel time [hours/year]	689	−18	−16	−20
One-way commuting time [minutes]	31	−1	−1	−1
VOT of one hour on a workday [$/hour]	13.87	−0.05	−0.06	−0.71
Commuting trips [million/year] city–city	25.4	−0.5	−0.4	−0.4
Commuting trips [million/year] city–suburb	19.3	−0.4	−0.4	−0.4
Commuting trips [million/year] suburb–city	45.0	+0.7	+0.8	+0.9
Commuting trips [million/year] suburb–suburb	41.6	+0.2	+0.4	+0.4
Households				
Gross income [$/year]	61,071	+1,247	+1,410	+375
Consumption (shopping) [trips/year]	472	−10	−10	−15
Average housing demand [sqr feet]	7778	−345	−342	−354
Urban Economy				
Total urban production [million units]	556.7	+6.3	+7.6	−0.4
Urban GDP [billion $/year]	29.1	+0.4	+0.5	0
EV [million $/year]	–	−499	−476	−633
Rent city/suburb [$/sqr feet*year]	5.95/2.22	+0.36/+0.06	+0.38/+0.07	+0.28/+0.02
Wage rate city/suburb [$/hour]	22.81/19.65	−0.15/−0.01	−0.16/−0.03	−0.12/+0.01
Government				
Labor tax revenue [million $/year]	8171	+119	+139	+6
Lump-sum tax revenue [million $/year]	–974	+964	+970	+959
Infrastructure costs [million $/year]	7197	+1083	+1309	+965
Location				
Households – city	168,687	−3,556	−3,532	−3,706
Households – suburb	331,313	+3,556	+3,532	+3,706
Jobs – city	268,099	+603	+613	+686
Jobs – suburb	231,901	−603	−613	−686

Table 11: Policy effects of a miles tax with inhomogeneous leisure

Miles Tax - Case 3a	Benchmark	Hours Hi	Hybrid Yi	Days Di
Time allocation				
Workdays per year	263	0	−1	−1
Leisure days per year	52	0	+1	+1
Hours on a workday spent working/leisure	8.3/5.8	0/0	0/0	0/0
Hours on a workday spent/commuting/shopping	1.1/0.8	0/0	0/0	0/0
Hours on a leisure day spent leisure/shopping	12.0/4.0	0/0	+0.1/−0.1	+0.1/−0.1
Total labor supply [hours/year]	2187	+1	−1	−2
Total leisure demand [hours/year]	2164	0	+3	+3
Total commuting time on workdays [hours/year]	272	0	−1	−1
Total shopping time [hours/year]	417	−1	−1	−1
Travel/Transport/Traffic				
Travel time delay [hours/year]	31	0	−1	0
MEC [$-cents/mile]	22	0	0	0
Total travel time [hours/year]	689	−1	−1	−2
One-way commuting time [minutes]	31	0	0	0
VOT of one hour on a workday [$/hour]	13.87	0	0	−0.01
Commuting trips [million/year] city–city	25.4	+0.2	+0.2	+0.2
Commuting trips [million/year] city–suburb	19.3	−0.1	−0.2	−0.2
Commuting trips [million/year] suburb–city	45.0	−0.2	−0.2	−0.2
Commuting trips [million/year] suburb–suburb	41.6	+0.1	0	0
Households				
Gross income [$/year]	61,071	+19	−32	−55
Consumption (shopping) [trips/year]	472	0	0	0
Average housing demand [sqr feet]	7778	−3	−4	−5
Urban Economy				
Total urban production [million units]	556.7	+0.2	−0.2	−0.3
Urban GDP [billion $/year]	29.1	∼0	∼0	∼0
EV [million $/year]	–	+4	−4	−6
Rent city/suburb [$/sqr feet*year]	5.95/2.22	+0.01/0	+0.01/0	+0.01/0
Wage rate city/suburb [$/hour]	22.81/19.65	−0.01/0	−0.01/+0.01	−0.01/0
Government				
Labor tax revenue [million $/year]	8171	+2	−4	−7
Lump-sum tax revenue [million $/year]	–974	−237	−238	−237
Miles tax revenue [million $/year]		+241	+240.5	+241
Infrastructure costs [million $/year]	7197	+6	−2	−4
Location				
Households – city	168,687	+155	+148	+84
Households – suburb	331,313	−155	−148	−84
Jobs – city	268,099	+9	+1	+21
Jobs – suburb	231,901	−9	−1	−21

Table 12: Policy effects of a cordon toll with inhomogeneous leisure

Cordon Toll - Case 4a	Benchmark	Hours Hi	Hybrid Yi	Days Di
Time allocation				
Workdays per year	263	0	−1	−1
Leisure days per year	52	0	+1	+1
Hours on a workday spent working/leisure	8.3/5.8	0/0	+0.1/0	0/+0.1
Hours on a workday spent/commuting/shopping	1.1/0.8	0/0	−0.1/0	−0.1/0
Hours on a leisure day spent leisure/shopping	12.0/4.0	0/0	+0.1/−0.1	+0.1/−0.1
Total labor supply [hours/year]	2187	+3	−2	−4
Total leisure demand [hours/year]	2164	+3	+10	+8
Total commuting time on workdays [hours/year]	272	−6	−7	−7
Total shopping time [hours/year]	417	0	0	−1
Travel/Transport/Traffic				
Travel time delay [hours/year]	31	−3	−4	−3
MEC [$-cents/mile]	22	−2	−2	−2
Total travel time [hours/year]	689	−6	−8	−8
One-way commuting time [minutes]	31	−1	−1	−1
VOT of one hour on a workday [$/hour]	13.87	−0.04	−0.03	−0.08
Commuting trips [million/year] city–city	25.4	+1.1	+1.0	+1.0
Commuting trips [million/year] city–suburb	19.3	−1.2	−1.2	−1.3
Commuting trips [million/year] suburb–city	45.0	−1.7	−1.9	−1.7
Commuting trips [million/year] suburb–suburb	41.6	+1.8	+1.7	+1.6
Households				
Gross income [$/year]	61,071	−53	−185	−392
Consumption (shopping) [trips/year]	472	0	0	−1
Average housing demand [sqr feet]	7778	−5	−8	−14
Urban Economy				
Total urban production [million units]	556.7	+0.5	−0.6	−1.0
Urban GDP [billion $/year]	29.1	0	−0.1	−0.2
EV [million $/year]	–	0.009	−0.011	−0.027
Rent city/suburb [$/sqr feet*year]	5.95/2.22	+0.1/0	−0.01/−0.01	−0.02/−0.01
Wage rate city/suburb [$/hour]	22.81/19.65	−0.01/−0.09	−0.01/−0.08	−0.01/−0.20
Government				
Labor tax revenue [million $/year]	8171	−8	−24	−52
Lump-sum tax revenue [million $/year]	–974	−608	−610	−603
Cordon toll revenue [million $/year]		+614	+612	+613
Infrastructure costs [million $/year]	7197	−2	−19	−42
Location				
Households – city	168,687	−413	−419	−610
Households – suburb	331,313	+413	+419	+610
Jobs – city	268,099	−2,792	−2,725	−2,044
Jobs – suburb	231,901	+2,792	+2,725	+2,044

Table 13: Policy effects of land-use type regulation (LUR) with inhomogeneous leisure

LUR - Case 5a	Benchmark	Hours Hi	Hybrid Yi	Days Di
Time allocation				
Workdays per year	263	0	−1	−1
Leisure days per year	52	0	+1	+1
Hours on a workday spent working/leisure	8.3/5.8	0.1/0	+0.1/0	0/+0.1
Hours on a workday spent/commuting/shopping	1.1/0.8	−0.1/0	−0.1/0	−0.1/0
Hours on a leisure day spent leisure/shopping	12.0/4.0	+0.1/−0.1	0/0	+0.1/−0.1
Total labor supply [hours/year]	2187	+22	+24	−19
Total leisure demand [hours/year]	2164	−12	−15	+30
Total commuting time on workdays [hours/year]	272	−4	−4	−4
Total shopping time [hours/year]	417	−5	−5	−7
Travel/Transport/Traffic				
Travel time delay [hours/year]	31	−4	−3	−3
MEC [$-cents/mile]	22	−3	−3	−3
Total travel time [hours/year]	689	−10	−9	−11
One-way commuting time [minutes]	31	0	0	0
VOT of one hour on a workday [$/hour]	13.87	−0.34	−0.35	−0.63
Commuting trips [million/year] city–city	25.4	+1.2	+1.2	+1.1
Commuting trips [million/year] city–suburb	19.3	+1.1	+1.1	+1.1
Commuting trips [million/year] suburb–city	45.0	−1.3	−1.2	−1.2
Commuting trips [million/year] suburb–suburb	41.6	−0.9	−0.9	−0.8
Households				
Gross income [$/year]	61,071	−749	−680	−1,106
Consumption (shopping) [trips/year]	472	−4	−4	−6
Average housing demand [sqr feet]	7778	−388	−388	−388
Urban Economy				
Total urban production [million units]	556.7	+5.5	+6.1	+2.5
Urban GDP [billion $/year]	29.1	−0.4	−0.4	−0.6
EV [million $/year]	–	−16	−6	−74
Rent city: housing/business [$/sqr feet]	5.95	−0.47/+1.89	−0.46/+1.89	−0.50/+1.84
Rent suburb: housing/business [$/sqr feet]	2.22	+0.06/−0.27	+0.00/−0.27	+0.04/−0.26
Wage rate city/suburb [$/hour]	22.81/19.65	−0.69/−0.35	−0.69/−0.35	−0.68/−0.33
Government				
Labor tax revenue [million $/year]	8171	−65	−87	−155
Lump-sum tax revenue [million $/year]	–974	−817	−804	−791
Infrastructure costs [million $/year]	7197	+15	−13	−56
Location				
Households – city	168,687	+8,398	+8,475	+8,209
Households – suburb	331,313	−8,398	−8,475	−8,209
Jobs – city	268,099	−770	−768	−817
Jobs – suburb	231,901	+770	+768	+817

E List of Variables

Travel and transport		**Closing the model**	
m_i	two-way distance in zone i	Ψ_{ij}	choice probability of type ij
m_{ij}	two-way distance of household ij	V_{ij}	deterministic indirect utility
δ_{ij}	indicator of whether to travel in the other zone	X_i	local production of consumption goods
F_i	traffic flow in zone i	Q_i	office space demand in i
f_i	trafficdensity in zone i	M_i	local labor demand in i
K_i	road capacity in zone i	A_i	local land supply
t_{ij}	travel time for two-way trip ij	s_i	share of land used for roads
t_i	travel time in zone i	κ	road capacity per unit of land
t^z_{ik}	two-way travel time for shopping trip from i to k		
Individual choice			
u_{ij}	direct utility of household ij	**Government variables**	
$\mathcal{L}_{1ij}$	leisure on workday	τ^w	wage tax rate
$\mathcal{L}_{2ij}$	leisure on leisure days	τ^m	distance tax rate
z_{ijk}	shopping of household ij in zone k	τ^t_k	congestion toll in i
p_{ijk}	mill price for shopping	τ^c	cordon toll
w^n_j	net wage earned in zone j	τ^{ls}	lump-sum tax
h_{ij}	hours spent working per day	T^{ls}	lump sum tax base
c_{ij}	monetary travel costs for two-way trip ij incl. taxes	T^w	labor tax base
I	non wage income	T^m	miles tax base
e	hours endowment per day	T^c	cordon toll base
D_{ij}	workdays per year	T^t_i	congestion toll base in i
ℓ_{ij}	leisure hours on a workday	N	number of households in the city
β	share of shopping trips on a workday	ζ_i	land-use: share of residential land in i
L_{ij}	leisure days	ALR	aggregate land rent
l_{ij}	leisure hours on a leisure day		
E	days per year	λ	average MUI
λ_{ij}	MUI of household ij	MEC	marginal external costs
γ	Lagrangian multiplier of a day	RE	redistribution
μ	Lagrangian multiplier of time on a workday	ϕ	distributional characteristics
ρ	Lagrangian multiplier of time on a leisure day	δ^k	indicator: if relevant
P_{ijk}	full consumer price for shopping in k	Adj	adjustment: distortion of the tax
q_{ij}	housing demand of household ij	T_i	tax interation effect
r_i	housing price in i		

Table 14: List of variables