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Georg Hirte
Stefan Tscharaktschiew

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The Impact of Anti-congestion Policies and the Role of Labor-Supply Margins

Georg Hirte[†]
TU Dresden

Stefan Tscharaktschiew[‡]
TU Dresden

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Abstract

Transportation economists apply different labor supply models when studying anti-congestion policy: (i) endogenous working hours; (ii) endogenous workdays but given daily working hours; (iii) labor supply as a residual. We study whether the outcome of anti-congestion policies that change the relative cost of labor supply margins, and, thus, may affect decisions on working hours and working days, is robust against the model applied. In particular, we focus on welfare implications in the presence of other taxes when there is a congestion externality. We find surprisingly strong differences in quantity and sign. Further, we develop a clear recommendation for future research on issues that include decisions on commuting trips. Researchers shall apply both a model of endogenous working hours that provides an upper limit and a model of endogenous workdays that provide a lower limit of results for welfare changes, optimal policies and two optimal tax components (Pigouvian and Ramsey terms).

JEL classification: H2, H3, J2, R1, R4

Keywords: Public Economics; Tax Design; Time Allocation; Labor Supply; Pigouvian Tax; Urban Economics; CGE; Spatial Modeling; Transportation; Transportation Economics; Transport Policy, Congestion

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[†]Corresponding author: Technische Universität Dresden, "Friedrich List" Faculty of Transport and Traffic Sciences, Institute of Transport and Economics, D-01062 Dresden, Germany. e-mail: georg.hirte@tu-dresden.de

[‡]Technische Universität Dresden, Institute of Transport and Economics.

1 Introduction

Intensive and extensive margins of labor supply are imperfect substitutes and, thus, distinct decision variables of workers (Hanoch, 1976; Blank, 1988).[1] This is usually traced back to fixed costs of the extensive margin (participation, Cogan, 1981; Hamermesh, 1996).[2] These findings initiated new research on optimal income taxation where the extensive margin, usually modeled as a discrete choice (Cogan, 1981), plays a decisive role (Diamond, 1980; Saez, 2002; Laroque, 2005) [3]. Extensions to tax and welfare reforms confirm this relevance owing to first-order effects that result from participation responses (Eissa and Hoynes, 2004)[4].

Much less is known about other margins. There is tentative evidence that commuting costs, that add to fixed costs of workdays[5], affect daily working hours (Gutiérrez-i-Puigarnau and van Ommeren, 2010; Gimenez-Nadal et al., 2016), but evidence concerning the impact on workdays is inconclusive (Gutiérrez-i-Puigarnau and van Ommeren, 2010; Van Ommeren and Gutiérrez-i-Puigarnau, 2011). Rather limited is research on workday elasticities (Dechter, 2013). Given that, researchers feel free in modeling labor supply even if policies considered affect the costs of workdays. They assume that labor supply and leisure demand is constant (Anas and Rhee, 2007; Parry and Small, 2009)[6], is the residual of time endowment net of travel time (Brueckner, 2005)[7] or is a decision variable where the endogenous margin is either working hours[8] (Verhoef and Nijkamp, 2002; Parry and Small, 2005)[9] or workdays (Arnott, 2007; De Borger and Wuyts, 2009).[10]

Given this variety, there is a surprising lack of knowledge of how policy evaluation is affected by labor supply modeling (LSM)[11]. As we argue below, this is a reason for concern. We explore this issue and ask whether policy evaluation is robust against the modeling of leisure demand and supply of workdays and working hours.

But why should modeling those margins be important considering that labor supply

[1]See also Hanoch (1980a), Hanoch (1980b), Hamermesh (1996). Blundell and MaCurdy (1999) and Heckman (1993) report a strong influence of the extensive margin on observed labor supply. Blundell et al. (2011a,b) provide the margins for the US, UK and France. Labor supply elasticities differ among extensive and intensive margins (recent reviews by Chetty, Guren, Manoli and Weber, 2012; Keane, 2011; Chetty, 2012) and among the life-cycle (Keane and Wasi, 2016).

[2]Costs of the extensive margin are, e.g., application costs, relocation costs, tax declaration costs, costs of searching for child care or changes in social security contributions or claims.

[3]See also Kleven and Kreiner (2006). A recent review is Piketty and Saez (2014).

[4]See also Immervoll et al. (2007); Eissa et al (2008).

[5]Fixed costs of days are, for instance, commuting costs, taxes on traveling, parking fees, child transport costs or child care costs.

[6]See De Borger and Wouters (1998); Calthrop et al. (2000); Martin (2001); Kwon (2005); Bento et al. (2006); Brueckner (2007); McDonald (2009); Parry and Timilsina (2010); Kono et al. (2012); De Lara et al. (2013).

[7]Further, Sullivan (1983a,b,c); Wrede (2001); Rossi-Hansberg (2004); De Borger and Wuyts (2011a); Fetene et al. (2016).

[8]This includes all models that do not explicitly distinguish between margins. If fixed costs of the margins differ, these models imply that some margins, e.g. workdays, are fixed.

[9]See also White (1977, 1988); Hotchkiss and White (1993); Parry (1995); Anas and Kim (1996); Parry and Bento (2002); De Palma and Lindsey (2004); Anas and Rhee (2006); West and Williams (2007); Van Ommeren and Fosgerau (2009); Fujishima (2011); Olwert and Guldmann (2012); Tscharaktschiew (2014, 2015).

[10]Others include Calthrop (2001); Parry and Bento (2001); De Borger and Van Dender (2003); Van Dender (2003); Berg (2007); Pilegaard and Fosgerau (2008); Rhee (2008, 2009); De Borger and Wuyts (2011b); Tscharaktschiew and Hirte (2010a,b, 2012); Hirte and Tscharaktschiew (2013a,b, 2015); Nitzsche and Tscharaktschiew (2013).

[11]The abbreviation 'LSM' refers to 'labor supply model' as well as 'labor supply modeling' depending on the context.

elasticities are small for some groups of workers?[12] The answer is that there are many groups whose number of workdays (workweeks) per year is variable since they decide on participation, parental leave, sabbaticals, overtime, part-time or use worktime accounts.[13] With that in mind, we expect to find a systematic influence of LSM since pricing instruments such as fuel taxes, congestion tolls and cordon tolls affect the workday costs but not those of daily working hours. If workdays are not explicitly modeled in such cases substitution effects between the margins are neglected. Further differences among the LSMs result from the time perspective. Modeling fixed or residual labor supply implies a short-term perspective though many studies making these assumptions look at the long term (e.g., spatial patterns).

Our research strategy is as follows: We, first, introduce six LSMs and show how the value of time (VOT) differs between them, thereby focusing on two margins: daily working hours and annual workdays.[14] We distinguish the case that working hours are endogenous but workdays are fixed (the *workhours* approach, WH), that there is a workday choice but working hours are exogenous (the *workdays* approach, WD), and the case of a *hybrid* model (HY) – which has never been applied to policy evaluation – where workers decide on both working hours and workdays (based on Hanoch, 1976; Oi, 1976; Deaton and Muellbauer, 1980). In each case, we model leisure as either homogeneous or inhomogeneous across types of day. This adds to the literature on the VOT (see the review by Small, 2012) which does not yet derive VOTs in case both working and non-working days are endogenous.[15]

After that, we implement different margins of labor supply in the well-known approach provided by Parry and Small (2005) used to derive and calculate optimal fuel taxes. This allows us to derive the impact of labor supply margins on the components of the optimal tax. We apply Monte Carlo simulations to explore how the optimal fuel taxes depend on the elasticities of the different margins of labor supply and how they interact with other parameters. This reveals that magnitudes as well as signs of the Ramsey components depend on the specific labor supply model. We, further, show that the endogenous working hours model provides an upper limit while the endogenous working day approach gives the lower limit of the optimal fuel tax and the Ramsey tax component.

In the next stage, we use this result when moving on to a spatial general equilibrium framework (Anas and Xu, 1999) that we apply to study the effect of anti-congestion policies in an urban economy.[16] Here, workers adjust labor supply along the two margins and may choose to relocate. The latter strongly affects travel costs and wages, thus adding discrete changes in labor supply. To discriminate between decisions on hours and days, we focus on policies that affect the fixed costs of workdays. These are policies aimed at curbing traffic congestion: (1) Pigouvian congestion tolls, (2) cordon tolls, (3) miles tax, (4) enhancing infrastructure capacity, and (5) land-use type regulation (zoning). We analytically derive welfare changes and show how the labor supply modeling affect the welfare components before we apply simulations to identify signs and quantify the effects. We find that the labor supply modeling affect magnitude as well as sign and, further, confirm that the workhours

[12] A recent review is (Blundell et al., 2013). More references see below.

[13] The groups differ across countries (Bick, Brüggemann et al., 2016).

[14] Annual workdays also reflect participation decisions (see Blundell et al., 2013).

[15] Only few studies consider time use on working and non-working days (Gronau, 1986) or multiday time allocation of non-working activities between both types of days (Yamamoto and Kitamura, 1999). However, days are fixed in these studies.

[16] The other non-monocentric model available is Lucas and Rossi-Hansberg (2002). They consider agglomeration effects that we neglect here, though they are modeled in the Anas-Xu-world, too (Rhee et al., 2014). The Anas-Xu model with fixed workdays is applied to congestion policies by Anas and Hiramatsu (2012, 2013). A minor reason for using a spatial approach is that more than half of the literature cited above applies spatial models.

model (WH) provides an upper limit of the results while the workdays approach (WD) provides a lower limit. Interestingly, results of zoning do hardly depend on LSM.[17]

Our results offer a strategy for the choice of LSM. In general, we suggest that both WH and WD should be applied whenever a policy asymmetrically affects the fixed costs of the margins because these span the interval of results. This strategy is useful as a shortcut given the missing knowledge on elasticities in a hybrid model. Of course, the hybrid model (HY) should be preferred if elasticities are well specified.

The paper is organized as follows. First, we introduce LSMs and derive VOTs. Next, we apply the Parry and Small approach to calculate optimal fuel taxes. In Section 4 we derive welfare effects of anti-congestion policies – choosing Pigouvian tolls as the example – and study how they depend on LSMs in the spatial, general equilibrium model. Subsequently, we use numerical simulations to find magnitude and sign of the effects of this and other policies considered. Eventually, we finish with some conclusions.

2 Labor supply approaches and VOT

Let us set the scene. We introduce the six LSMs, derive the value of time (VOT) and value of travel time savings (VTTS)[18] to see the difference between the LSMs. Thereby, ℓ denotes leisure on a workday D, l is leisure on a non-working day L, h is daily working hours, e is daily time endowment, and E is days per year. If leisure is homogeneous, leisure $\mathcal{L}$ is the sum of leisure on workdays $\mathcal{L}_1 \equiv \ell D$ and leisure on non-working days $\mathcal{L}_2 \equiv lL$, while both are distinct arguments of utility otherwise. If traveling affects utility (De Serpa, 1971), the well behaved utility function is

$$\text{(a)} \quad u = u\left(z, \mathcal{L}_1, \mathcal{L}_2, t^z z, tD\right), \qquad \text{(b)} \quad u = u\left(z, \mathcal{L}, t^z z, tD\right), \tag{1}$$

where z is consumption assumed to be equivalent to the number of shopping trips[19]. t^z and t are two-way shopping travel and commuting time per trip[20]. A worker's monetary budget constraint is $(p + c^z)z = (w^n h - c)\, D$, where p is the price of z, c^z and c are monetary two-way travel costs per shopping trip and commuting trip respectively, $w^n = w\,(1 - \tau^w)$ is the hourly net wage, w is the hourly wage and τ^w is the wage tax rate. The time constraints on workdays and non-working days in annual terms are $eD = (h + t)\, D + \ell D + bt^z z$ and $eL = lL + (1 - b)\, t^z z$ where b is the share of shopping on workdays and $E = D + L$ is the annual days restriction.

HY is the *general model* where workers choose both daily working hours and annual workdays (hybrid model). We distinguish (1a) HY with inhomogeneous leisure and (1b) HY with homogeneous leisure.

1a) Concerning HY with *inhomogeneous leisure*, maximization of (a) in Eq. (1) w. r. t. z, ℓ, D, h, l, and L subject to the budget constraints implies

$$\text{VOT}_h\text{:} \quad \frac{\mu}{\lambda} = w^n, \quad \text{VOT}_l\text{:} \quad \frac{\rho}{\lambda} = w^n - \frac{\nu_t t + c}{e}, \tag{2}$$

[17] This indicates that the current state of knowledge in the literature that zoning approximates Pigouvian tolls (e.g., Rhee et al., 2014) may hold only for a specific LSM.

[18] Becker (1965); Johnson (1966); Oort (1969), and De Serpa (1971) develop the theory of time evaluation. Recent works include Jara-Díaz (2007); Small and Verhoef (2007), and Jara-Díaz (2008) (see the review by Small, 2012).

[19] If there is no further restriction, people always fill up the car at each shopping trip to exploit economies of scale in shopping trips.

[20] By assuming that travel time of shopping and commuting enters utility as distinct arguments, VTTS of both types of traveling may differ. While there is some evidence that this is the case, there is no clear tendency on average (see the review of Mackie et al., 2001; the meta-analysis of Abantes and Wardman, 2011).

where λ, μ, ρ are the Lagrangian multipliers of the budget constraint and the time restrictions on workdays and non-working days. ν_t is the VTTS of commuting ($\nu_t \equiv w^n - \frac{u_t}{\lambda}$), where $\frac{u_t}{\lambda}$ is the disutility of traveling (Small, 2012). VOT_h – the "value of time as a resource" (De Serpa, 1971) on workdays – equals the hourly net wage. VOT_l is the VOT as a resource on a non-working day not yet found in the literature. It represents the opportunity costs of an hour on a nonworking day, i.e. the hourly net wage minus average fixed costs of a workday: average generalized commuting costs arising when turning the non-working day into a workday. Owing to these costs VOTs differ.

1b) In HY with *homogeneous leisure* we use (b) in Eq. (1). Due to economies of scale workers want to use all available daily time for working and none for leisure. To avoid this, we constraint leisure to $\ell \geq \bar{\ell}$.[21]

2a) In WH with *inhomogeneous leisure* workdays are constant ($\bar{D}$ substitutes D), there is no annual day restriction and we use (a) in Eq. (1).

2b) In WH with *homogeneous leisure* we use (b) in Eq. (1), $\bar{D}$ substitutes D and there is no annual day restriction.

3a) In WD with *inhomogeneous leisure* daily working hours are fixed ($\bar{h}$ substitutes h) and (a) is used in Eq. (1).

3b) In WD with *homogeneous leisure* we use (b) in Eq. (1) and $\bar{h}$.

Table 1: Time values in different labor supply approaches

Approach	u	VOT_h: $\frac{\mu}{\lambda}$	VOT_l: $\frac{\rho}{\lambda} = \frac{1}{e}\frac{\gamma}{\lambda}$	VTTS: ν_t
HY inhomog.	$u(\ldots,\mathcal{L}_1,\mathcal{L}_2)$	w^n	$w^n - \frac{\nu_t t + c}{e}$	$w^n - \frac{u_t}{\lambda}$
homog.	$u(\ldots,\mathcal{L})$	w^n	$w^n - \frac{\nu_t t + c}{e - \bar{\ell}}$	$w^n - \frac{u_t}{\lambda}$
WH inhomog.	$u(\ldots,\mathcal{L}_1,\mathcal{L}_2)$	w^n	$\frac{\rho}{\lambda}$	$w^n - \frac{u_t}{\lambda}$
homog.	$u(\ldots,\mathcal{L})$	w^n	w^n	$w^n - \frac{u_t}{\lambda}$
WD inhomog.	$u(\ldots,\mathcal{L}_1,\mathcal{L}_2)$	$\frac{\mu}{\lambda}$	$\frac{\mu}{\lambda} + \left(w^n - \frac{\mu}{\lambda}\right)\frac{\bar{h}}{e} - \frac{\nu_t t + c}{e}$	$\frac{\mu}{\lambda} - \frac{u_t}{\lambda}$
homog.	$u(\ldots,\mathcal{L})$	$w^n - \frac{\nu_t t + c}{\bar{h} + t}$	$w^n - \frac{\nu_t t + c}{\bar{h} + t}$	$w^n - \frac{u_t}{\lambda}$

VOT of hours on workdays (VOT_h), VOT of hours on non-working days (VOT_l). VTTS value of travel time savings for commuting trips. HY hybrid model, WH workhours model, WD workdays model.

Table 1 displays the VOTs and VTTS of the LSMs. The VOT on a workday, VOT_h, equals the net wage w^n whenever daily hours are endogenous (HY, WH). In WD with inhomogeneous leisure, the restriction for leisure is binding and VOT_h is the shadow price $\frac{\mu}{\lambda}$. In case of homogeneous leisure only workdays are endogenous in WD and VOT_h is the daily available wage income in terms of time spent working plus commuting.

The VOT on non-working days, VOT_l, depends on average commuting costs if workdays are endogenous (HY, WD). In general, average costs depend on the hours available for time use decisions. In HY with homogeneous leisure, e.g., less time is available for working on account of the binding leisure restriction. A policy that affects generalized

[21] $\ell = \bar{\ell}$, as we show in Appendix A

travel costs changes VOT_l only in HY and WD with inhomogeneous leisure, affects both VOTs in a symmetric way in WD with homogeneous leisure, but is neutral for both VOTs in WH. Changes in wage taxes affect both VOTs, but in inhomogeneous models and the homogeneous HY approach in a different way.[22]

3 Optimal fuel taxes and the margins of labor supply

Next, we calculate optimal fuel taxes in the well-known approach of Parry and Small (2005). We derive the optimal tax formula to understand the role of the margins of labor supply. Then, we apply Monte Carlo simulations to examine the role of the elasticities of the labor supply margins. This is particularly valuable since to our knowledge estimates of the compensated elasticity of workdays are not yet available.[23] We choose the approach of Parry and Small (2005) (PS, henceforth) to explore analytically and by Monte Carlo simulations how LSMs affect the optimal tax rate and its components and how the results depend on labor supply elasticities and other parameters. Thereby we consider the homogeneous leisure, workhours model (WH), the inhomogeneous leisure, workdays approach (WD) and the inhomogeneous leisure, hybrid approach (HY).

We start with the PS model but decompose miles into non-commuting and commuting miles and leisure into leisure on workdays and leisure on non-workdays. The well-behaved utility function is

$$U = u\left[\varphi\left[(Z, M^o, T^o, G)\right], M^D, T^D, \mathcal{L}_1, L\right] - \phi\left(P\right) - \delta\left(A\right) \tag{3}$$

where Z is consumption, M^o is annual vehicle miles traveled (VMT), T^0 is total travel time both except for commuting, and G is public expenditure.

We follow PS and assume that M^o is produced through fuel consumption F^o and other monetary travel costs C^o ($M^o = M^o(F^o, C^o)$). We add total commuting time $T^D = tM^D$ with t as travel time per VMT and $M^D = mD$ as commuting miles traveled, where $m = m\left(f, c\right)$ is average miles on a two-way commuting trip depending on fuel consumption f and monetary costs c per trip. Z, M^o, T^o, G (see PS) and m are assumed to be weakly separable from leisure decisions.[24] $\mathcal{L}_1 = \ell D$, ℓ, D and L are defined above.[25] Aggregate miles traveled are $M = M^o + M^D$ and aggregate travel time is $T = T^o + T^D$. $\phi\left(P\right)$ and $\delta\left(A\right)$ are externalities of pollution P and accidents A both depending on M. Further, M^o is traveled only on workdays.

Assuming that $p_Z = 1 = w$, the monetary budget constraint $(Z + p_F F + C = I, I \equiv (1-\tau^w)\,H)$ states that expenditures on consumption, fuel $F = F^o + fD$ and monetary travel costs $C = C^o + cD$ equal net income from working with the wage tax rate τ^w and annual hours of work $H \equiv hD$. $p^F = q^F + \tau^F$ is the gross price of fuel, q_F the net price and τ^F the fuel tax rate. The time constraint on workdays is $H + \mathcal{L}_1 + T = eD$, and the annual days constraint $E = D + L$. In analogy to PS, we can derive the optimal fuel tax

[22] Adding heterogeneity of households, these VOTs become heterogeneous too (Small et al., 2005). This is considered in the simulation below.

[23] Dechter (2013) provides only estimates of the uncompensated elasticity of workdays.

[24] This assumption is required to apply the PS framework with all its power. It implies that the choice of m – route choice, mode choice, car type choice, residence location choice – does not depend on the number of commutes D.

[25] Since time endowment e on a non-working day is constant we can use L instead of $\mathcal{L}_2 = eL$.

for HY[26] (see Appendix A):

$$\tau^F = \overbrace{MEC/(1+MEB)}^{\text{adjusted Pigouvian tax } (\approx \text{PS})} + \left[\overbrace{\frac{(1-\eta_{MI})\,\varepsilon^c_{Hw}}{\eta_{FF}}}^{\text{Ramsey annual (PS)}} \overbrace{-\frac{\sigma_m \varepsilon^c_{Dw}}{\eta_{FF}}}^{\text{Ramsey days}} \right] \frac{\tau^w p^F}{1-\tau^w} \tag{4}$$

$$+ \beta \frac{M}{F} E^c \left[\overbrace{\varepsilon_{Hw} - (1-\eta_{MI})\,\varepsilon^c_{Hw}}^{\text{congestion feedback (PS)}} + \overbrace{\sigma_m \varepsilon^c_{Dw}}^{\text{feedback commuting}} \right] \frac{\tau^w}{1-\tau^w},$$

$$\beta = \frac{\eta_{MF}}{\eta_{FF}}; \qquad \sigma_m = \frac{M^D}{M}; \qquad \eta_{MI} \equiv (1-\sigma_m)\,\eta_{M^oI} + \sigma_m \eta_{mI}. \tag{5}$$

MEC are marginal external costs and MEB is the marginal excess burden of taxation as defined by PS[27], ε^c_{Hw} and ε^c_{Dw} are the compensated wage elasticities of aggregate labor supply and workdays, ε_{Hw} is the uncompensated wage elasticity of aggregate working hours, η_{MI} is the aggregate income elasticity of VMT, η_{mI} the income elasticity of commuting miles given the number of workdays, η_{M^oI} is the income elasticity of non-commuting miles, η_{FF} the own price elasticity of fuel consumption, and σ_m the share of commuting miles on aggregate VMT. All elasticities are expressed as positive numbers. E^c is the congestion externality

$$E^c = \nu M t' = \nu^o M^o t' + \nu^t m D t', \tag{6}$$

where $\nu^o = 1 - \tau^w - \frac{u_{To}}{\lambda}$ and $\nu^t = 1 - \tau^w - \frac{u_{TD}}{\lambda}$ are the VTTS of non-commuting and commuting VMT, respectively.

According to PS, the optimal fuel tax (4) depends on three components: the adjusted Pigouvian term (first term on the right-hand side), the Ramsey term (second row) and the congestion feedback (second term). We add another Ramsey term ('Ramsey days') and another congestion feedback ('feedback commuting'). These account for the compensated effects of commuting trips owing to their complementarity to workdays.

The adjusted Pigouvian term is almost constant because we use fixed elasticities for the externalities such that the Pigouvian term does not explicitly depend on D.

The Ramsey term captures the efficiency gain from the wage tax reduction (revenue recycling) and the efficiency loss from the reduction in labor supply due to the fuel tax (tax interaction). In PS, the latter is the effect of the change in income from the compensated labor supply response on VMT, while, here, the compensated response of workdays adds a compensated effect on commuting trips. This exacerbates the negative tax interaction effect.

The congestion feedback effect arises since higher travel costs mitigates congestion which eventually leads to more labor supply. PS measure it through the income effect on VMT and labor supply initiated by the compensated change in labor supply. The new term we add is the effect of the compensated supply of workdays which impacts VMT through its complementarity with commuting trips.

Both new effects vanish if $\varepsilon^c_{Dw} = 0$ and reach a maximum at $\varepsilon^c_{Dw} = \varepsilon^c_{Hw}$ the upper limit for ε^c_{Dw}. If $\varepsilon^c_{Dw} = 0$ and there is weak separability between travel and leisure, the taxed good (miles) is a weak substitute for leisure and, thus, should be taxed relatively heavy,

[26] The optimal fuel tax for WH and WD can be found by assuming $\varepsilon^c_{Dw} = 0$ or $\varepsilon^c_{Dw} = \varepsilon^c_{Hw}$.

[27] $MEC = E^{P_F} + \left(E^c + E^{P_M} + E^A\right)\beta \frac{M}{F}$; $\quad MEB_H = \frac{\tau_w\, \varepsilon_{Hw}}{1-\tau_w(1+\varepsilon_{Hw})}$. E^{P_F}, E^{P_M} are pollution externalities from fuel consumption and miles and E^A denotes externalities from accidents as defined by PS (see Appendix B).

provided $\eta_{mI} < 1$ (PS). If $\varepsilon^c_{Dw} > 0$ the new Ramsey term absolutely exceeds the new congestion feedback and the optimal fuel tax is below the PS fuel tax, the more the higher ε^c_{Dw}. Then the taxed good is increasingly substitutable to leisure and tax interaction may exceed revenue recycling.[28]

In a first experiment, we calculate the US and UK optimal fuel tax and their components for HY and vary the Hicksian elasticity of workdays ε^c_{Dw} from $\varepsilon^c_{Dw} = 0$ (WH) to $\varepsilon^c_{Dw} = \varepsilon^c_{Hw}$ (WD). Basic elasticities and parameters are taken from PS. We add the annual share of commuting on VMT, which is 0.28 (0.275) for the US (UK),[29] and choose $\varepsilon^c_{Dw} = 0.2$ as benchmark.[30][31]

Table 2: Fuel taxes with variation of Hicks elasticity of days (HY)

	US				UK			
ε^c_{Dw}	τ^F	Pigou	Ramsey	CongF	τ^F	Pigou	Ramsey	CongF
0.00*	101	74	26	1	134	104	23	7
0.10	96	74	20	1	125	103	14	8
0.20	90	73	15	2	116	101	5	10
0.30	85	72	10	2	108	100	-3	11
0.35**	82	72	7	2	104	99	-7	12

*$\varepsilon^c_{Dw} = 0$ is WH. **$\varepsilon^c_{Dw} = 0.35 = \varepsilon^c_{Hw}$ is WD. Source: own calculations.

Since the endogeneity of workdays adds an tax interaction term, the optimal fuel tax and the Ramsey term decline when the workday elasticity increases (see Table 2). The optimal fuel tax for the US (UK) is between 81 and 100% (78 and 100%) of the PS fuel tax.[32] The Ramsey term varies strikingly. It is between 100 and 27% (100 and −35%) of the PS results for US (UK). WH ($\varepsilon^c_{Dw} = 0$) provides the maximum and WD ($\varepsilon^c_{Dw} = \varepsilon^c_{Hw} = 0.35$) the minimum of the optimal fuel tax and the Ramsey component and, vice versa, for the congestion feedback.

Analytically, the strength of the effects depends on the interaction of the Hicksian workdays elasticity with other parameters that are not exactly known. We study this interaction by Monte Carlo simulations where six central parameters are varied: ε^c_{Dw}, ε^c_{Hw},

[28]This is in contrast to the findings of the early double-dividend literature where the negative tax interaction effect always dominates the positive revenue recycling effect (Parry, 1995, 1997). Three reasons have been reported why the recycling effect may dominate (Bovenberg and Goulder, 2002): first, the initial labor tax is not optimal so that the Ramsey component matters (Parry and Small, 2005), second, there are general equilibrium changes in prices since the reduction of the externality capitalizes in land rents (Bento et al., 2006) and, third, the taxed good is at most a weak substitute for leisure (Deaton, 1981; Parry and Small, 2005). The second effect is significant in the spatial model above but does not work here.

[29]From NTHS we calculate the averages of 2001 and 2009 VMT per year (2259.95 billion miles/year) and annual commuting VMT (628.579 billion miles/year) (Federal Highway Administration, 2015). From this we calculate the share of non-commuting miles on all VMT which is 0.72. For the UK, average annual VMT per 4-wheel car in total and for commuting are 9,100 and 2,500 miles/year in 2004, respectively (National Travel Survey, see Department of Transport, 2015). Hence, the share of non-commuting miles on all VMT is 0.725.

[30]Chetty (2012) estimates average Hicksian intensive and extensive elasticities of 0.33 and 0.25, respectively. Applying the ratio of both implies that 0.15 is the Hicksian extensive elasticity under the PS assumptions of an aggregate Hicksian elasticity of 0.35. However, since decisions on days reflect the extensive margin but also a part of the intensive margin in the empirical literature we use 0.2 as our preferred value for the Hicksian elasticity of days.

[31]Table C.1 displays the main parameters used in the Monte Carlo simulation.

[32]Because we are interested in the effects of LSMs on the findings we stick to the original PS data and calculations and do not make an update based on other studies (e.g., Bento et al., 2009; Lin and Prince, 2009; Parry and Small, 2009).

ε_{Hw}, β, η_{FF}[33], and η_{MI}. We randomly draw 10,000 values of Hicksian and Marshallian elasticities from their empirical distributions.[34] Since there are no estimates of ε^c_D we randomly draw it for each run from a uniform distribution over the interval from zero to the drawn Hicksian elasticity as its upper ceiling. The other parameters – η_{FF}, η_{MI}, β – are randomly drawn from a gamma distribution fitted to the mean and interval of these elasticities taken from PS.

Table 3: Monte Carlo simulation of optimal fuel taxes

US	(1)	(2)	(3)	**UK**	(4)	(5)	(6)
	WH	HY	WD		WH	HY	WD
	optimal fuel tax				optimal fuel tax		
¢/gallon[a]	probability			¢/gallon[a]	probability		
40	0.03	0.05	0.07	50	0.08	0.11	0.14
75	0.27	0.33	0.40	100	0.33	0.38	0.45
100	0.51	0.58	0.65	150	0.58	0.64	0.71
150	0.81	0.86	0.92	200	0.75	0.81	0.86
200	0.91	0.94	0.97	280	0.89	0.93	0.96
median	99[a]	92[a]	85[a]	median	132[a]	120[a]	108[a]
	Ramsey term				Ramsey term		
¢/gallon[a]	probability			¢/gallon[a]	probability		
0	0.06	0.14	0.27	0	0.23	0.38	0.54
5	0.26	0.40	0.57	5	0.38	0.53	0.70
15	0.54	0.66	0.79	15	0.57	0.70	0.82
50	0.81	0.87	0.93	50	0.80	0.87	0.93
100	0.90	0.94	0.97	100	0.89	0.93	0.97
median	13[a]	8[a]	4[a]	median	11[a]	4[a]	-1[a]

[a] ¢/gallon. Monte Carlo results of US and UK optimal fuel tax. Source: own calculations.

Table 3 shows that optimal fuel taxes and Ramsey terms differ across LSMs. Columns (1)-(3) and (4)-(6) display cumulative probabilities for both in WH, HY and WD. For instance, according to column (1) the probability that the "true" optimal tax is not above 100 ¢/gallon is 51% which rises to 65% in WD (column (3)).

If travel is a weak substitute for leisure the Ramsey term is positive since the revenue recycling term dominates. The probability of a negative Ramsey term is 6-27% for the US and 23-54% for the UK. The tax interaction term dominates with a higher probability in WD than WH. As argued above, this is mainly due to the increase in the substitutability of leisure and fuel (travel). Differences in the optimal fuel tax are almost entirely determined by those in the Ramsey term. Variations in the outcome are huge showing the uncertainty concerning the optimal fuel tax.

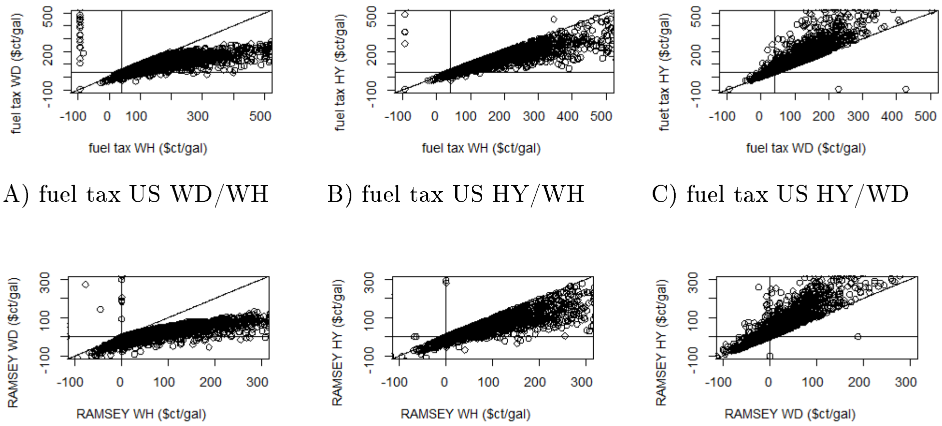
Figure 1 provides pairwise plots of the US-results of the three LSMs.[35] Panels A) and D) show that the optimal fuel tax and the Ramsey term results of WD (vertical axis) are below those of WH (horizontal axis), and panels B) and E) confirm this for HY, too. Hence, WH gives the upper limit of the results independently of elasticities. Panels C) and

[33] As β is the ratio of η_{MF} and η_{FF}, η_{MF} is implicitly adjusted, too.

[34] We collected 129 estimates of various labor supply elasticities from well-known surveys: Pencavel (1986); Blundell and MaCurdy (1999); Keane (2011); Chetty et al. (2011, 2012); Chetty (2012). We added some recent estimates since they provide also estimates of the Hicksian elasticity of extensive labor supply (participation) or Marshallian elasticities of workdays or daily working hours (Dechter, 2013; Bargain et al., 2014). Since estimates of the elasticities are scarce we assume that each estimate is the mean of a normally distributed elasticity that we consider when drawing values. We randomly get 10,000 values from the adjusted empirical elasticities and exclude Hicksian elasticities below zero and Marshallian elasticities exceeding Hicksian elasticities.

[35] The results for the UK look very similar. See Figure C.1

Figure 1: Comparison of LSMs in case of US



A) fuel tax US WD/WH B) fuel tax US HY/WH C) fuel tax US HY/WD

D) Ramsey US WD/WH E) Ramsey US HY/WH F) Ramsey US HY/WD

Pairwise plots of optimal fuel taxes (upper panels; vertical and horizontal lines represent the US fuel tax in 2005: 40 ¢/gallon) and Ramsey tax terms (lower panels) for the US for the LSMs. Each dot represents the results for the identical parameter constellation. Panels A) and D): WD vs. WH, WH is the upper limit for WD. Panels B) and E): HY vs. WH, WH is the upper limit for HY. Panel C) and F): HY vs. WD, WD is the lower limit for HY. A few parameter combinations produce irregularities (division by zero etc.) Source: own calculations.

F) show that WD forms the lower boundary of HY.

4 Welfare effects of congestion policies

Next, we study the working mechanism of the LSMs in a spatial general equilibrium and derive welfare effects and optimal Pigouvian congestion tolls. This study allows us to discuss policies that are usually discussed in the context of cities. However, we face a specific problem. Applying Monte Carlo simulations with different elasticities in the spatial city model implies to generate several thousand benchmarks – one for each draw of elasticities – which would make cross-comparisons almost impossible and, by the way, would also be extremely time consuming. Further, there are hardly any estimates of the elasticity of working days so that we cannot use a specific elasticity when modeling the hybrid labor supply approach. Instead, our strategy is relied to the findings of the above Monte Carlo simulation. We apply the workdays as well as the workhours model to generate the upper and lower ceilings of the welfare effects of anti-congestion policies. The result is robust if both provide the same sign of the welfare change for a specific policy. This approach can be easily adapted in simulation studies.

To see whether LSM matters, we study five anti-congestion policies usually discussed and perform 24 simulations for each policy. We distinguish WH and WD each with homogeneous and inhomogeneous leisure, vary tax recycling and change landlord modeling. The latter shows whether LSM impacts may also depend on other modeling parts of a simulation model. The set of policies considered in the simulations involve: Pigouvian congestion tolls, cordon toll, miles tax, investment in road capacities, and zoning. In the next subsection we adopt the congestion toll policy to provide some basic findings. Afterwards, we provide simulations of the full set of policies and model variants.

4.1 The spatial model and welfare effects

The urban area consists of J zones of mixed land use where local competitive firms produce local composite goods. We assume that congestion is present only during peak hours where commuting takes place while off-peak shopping trips are uncongested. Commuting time per unit of two-way distance m_{ij} from i to j, $t_{ij} = t_{ij}(f_{ij})$ depends, thus, on peak traffic volume-capacity ratio f_{ij}, while off-peak travel time per two-way shopping distance m_{ik} is fixed at t_{ik}, thus:

$$t_{ij} \equiv m_{ij} t_{ij}(f_{ij}), \qquad t_{ik}^{z} \equiv m_{ik} t_{ik}. \tag{7}$$

In the first stage, workers decide on quantities given location ij, while they choose residence and working locations i and j in a multinomial logit framework in the second stage. The random utility functions of a type ij worker is the sum of deterministic utility u_{ij} and ε_{ij}, an idiosyncratic preference for location ij (Anas and Xu, 1999)[36] and differs in the inhomogeneous and homogeneous leisure case:

$$U_{ij}^{inh} = u_{ij}(z_{ij1,\ldots,}z_{ijJ}, q_{ij}, \mathcal{L}_{1ij}, \mathcal{L}_{2ij}) + \varepsilon_{ij}, \tag{8}$$

$$U_{ij}^{\mathrm{hom}} = u_{ij}(z_{ij1,\ldots,}z_{ijJ}, q_{ij}, \mathcal{L}_{ij}) + \varepsilon_{ij}. \tag{9}$$

z_{ijk} is spatially differentiated consumption of zone k's good, q_{ij} is housing demand, $\mathcal{L}_{1ij} \equiv \ell_{ij} D_{ij}$ and $\mathcal{L}_{2ij} \equiv l_{ij} L_{ij}$ are leisure on workdays and on non-working days.

Workers face a monetary budget constraint (10) and time constraints per workday (11), per non-work day (12) and of days (13):

$$\sum\nolimits_k (p_k + c_{ik}^z) z_{ijk} + r_i q_{ij} = \left(w_j^n h_{ij} - c_{ij}\right) D_{ij} + I \tag{10}$$

$$(h_{ij} + t_{ij} m_{ij}) D_{ij} + \ell_{ij} D_{ij} + b \sum\nolimits_k t_{ik}^z m_{ik} z_{ijk} = e D_{ij} \tag{11}$$

$$l_{ij} L_{ij} + (1-b) t_{ik}^z z_{ijk} = e L_{ij} \tag{12}$$

$$D_{ij} + L_{ij} = E, \tag{13}$$

where p_k is the price of zone k's good, c_{ij} (c_{ik}^z) are two-way monetary travel costs for a commuting (shopping) trip from i to j (k), r_i is the unit land price in zone i. Net income $I = ALR - \tau^{ls}$ is aggregate land rents per capita, ALR, minus head taxes, τ^{ls}, w_j^n is the net wage earned in zone j and b is defined above.

Based on indirect utility V_{ij}, each worker decides on his locations ij taking into account idiosyncratic preferences ε_{ij}. Assuming 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 a multinomial logit model (MNL) with location choice probabilities (McFadden, 1973) $\psi_{ij} = \exp(\Lambda V_{ij}) / \sum_{a,b} \exp(\Lambda V_{ab})$.

The representative firm at zone i demands land Q_i and labor M_i to produce the local good with a CRS function $X_i = f(Q_i, M_i)$. A wage tax at rate τ^w, congestion tolls of τ_{ij}^t on route ij and head taxes finance opportunity cost of roads $r_i s_i A_i$. s_i is the road share of land A_i. The public budget constraint is

$$\tau^w T^w + \sum\nolimits_{i,j} \tau_{ij}^t T_{ij}^t + \tau^{ls} N = \sum\nolimits_i r_i s_i A_i \tag{14}$$

with wage tax and congestion toll bases

$$T^w \equiv N \sum\nolimits_{i,j} \psi_{ij} w_j H_{ij}, \qquad T_{ij}^t \equiv F_{ij} = N \psi_{ij} D_{ij}, \tag{15}$$

[36] Note that travel time is not an argument of utility in (8) and (9). This simplifies calibration. Since disutility of travel is not directly affected by the policies considered it shall not affect the findings. Later on we move to the full concept (De Serpa, 1971).

where $H_{ij} = h_{ij} D_{ij}$ is annual working hours, F_{ij} is commuting traffic flow during on route ij. The volume-capacity ratio is $f_{ij} = F_{ij}/K_{ij}$, where road capacity $K_{ij} = \kappa_{ij} \sum_i s_i A_i$ is proportional to road area with κ_{ij} as capacity scale parameter.[37] Clearing local land, labor and consumer goods markets implies:

$$A_i = Q_i + N \sum\nolimits_j \psi_{ij} q_{ij} + s_i A_i, \tag{16}$$

$$M_j = N \sum\nolimits_i \psi_{ij} H_{ij}, \qquad X_k = N \sum\nolimits_{i,j} \psi_{ij} z_{ijk}. \tag{17}$$

Aggregate land rents earned per capita are $ALR \equiv \frac{1}{N} \sum_i r_i A_i$.

Welfare is the expected value of the maximized utilities (McFadden, 1973):

$$W = E\left[\max_{(ij)} \left(V_{ij} + \varepsilon_{ij}\right)\right] = \frac{1}{\Lambda} \ln \sum\nolimits_{i,j} \exp\left(\Lambda V_{ij}\right). \tag{18}$$

implying marginal welfare changes w.r.t. the congestion toll on route hk of

$$\frac{\mathrm{d}W}{\mathrm{d}\tau_{hk}^t} = N \sum\nolimits_{i,j} \psi_{ij} \frac{\mathrm{d}V_{ij}}{\mathrm{d}\tau_{hk}^t}. \tag{19}$$

After applying the envelope theorem to $\frac{\mathrm{d}V_{ij}}{\mathrm{d}\tau_{hk}^t}$ (Yu and Rhee, 2011; Rhee et al., 2014)[38], using (14), (16), (17) and the zero profit conditions and assuming head-tax revenue recycling (see Appendix D), (19) becomes:[39]

$$\frac{1}{\lambda} \frac{\mathrm{d}W}{\mathrm{d}\tau_{hk}^t} = \left(MEC_{hk}^t - \tau_{hk}^t \frac{Adj_{hk}^t}{-\mathrm{d}F/\mathrm{d}\tau_{hk}^t}\right)\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_{hk}^t}\right) + TI_{hk}^t + RE_{hk}^t, \tag{20}$$

where the average marginal utility of income (MUI) is defined as $\lambda \equiv \sum_{i,j} \psi_{ij} \lambda_{ij}$, overall traffic is $F = \sum_{i,j} F_{ij}$ and changes in average marginal external congestion costs (MEC)[40] are

$$MEC_{hk}^t = \sum_{i,j} \psi_{ij} D_{ij} w_j^n t'_{ij} \frac{dF_{ij}/d\tau_{hk}^t}{dF/d\tau_{hk}^t}. \tag{21}$$

Changes in traffic on route ij and in overall traffic are

$$\frac{\mathrm{d}F_{ij}}{\mathrm{d}\tau_{hk}^t} = N\left(\psi_{ij} \frac{\mathrm{d}D_{ij}}{\mathrm{d}\tau_{hk}^t} + D_{ij} \frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau_{hk}^t}\right), \qquad \frac{\mathrm{d}F}{d\tau_{hk}^t} = \sum_{i,j} \frac{\mathrm{d}F_{ij}}{\mathrm{d}\tau_{hk}^t}. \tag{22}$$

The adjustment term denotes the change in the link-specific toll tax base:

$$Adj_{hk}^t \equiv -N\left(\psi_{hk} \frac{\mathrm{d}D_{hk}}{\mathrm{d}\tau_{hk}^t} + D_{hk} \frac{\mathrm{d}\psi_{hk}}{\mathrm{d}\tau_{hk}^t}\right). \tag{23}$$

The marginal welfare effect (20) is the sum of Pigouvian (first term on RHS), tax interaction, TI, and redistribution effects, RE.[41] The latter arises due to differences in MUIs across worker types ij (spatial heterogeneity). TI and RE are

$$\begin{aligned} TI_{hk}^t \equiv\ & \tau^w N \sum_{i,j} \left(\psi_{ij} w_j \frac{\mathrm{d}H_{ij}}{\mathrm{d}\tau_{hk}^t} + w_j H_{ij} \frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau_{hk}^t}\right) \\ & + N\left[\psi_{hk} D_{hk} + \sum_{i,j|ij \neq hk} \tau_{ij}^t \left(\psi_{ij} \frac{\mathrm{d}D_{ij}}{\mathrm{d}\tau_{hk}^t} + D_{ij} \frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau_{hk}^t}\right)\right] \end{aligned} \tag{24}$$

[37] κ_{ij} may indicate quality of infrastructure on route ij.

[38] This is equivalent to applying Roy's identity

[39] Similar formulae can be derived for all other LSMs.

[40] Since K_{ij} is constant $\frac{\mathrm{d}t_{ij}}{\mathrm{d}F_{ij}} = \frac{\partial t_{ij}}{\partial f_{ij}} \frac{\partial f_{ij}}{\partial F_{ij}} = \frac{\partial t_{ij}}{\partial f_{ij}} \frac{1}{K_{ij}}$. We define $t'_{ij} \equiv \frac{\partial t_{ij}}{\partial f_{ij}} \frac{1}{K_{ij}}$.

[41] In the case of wage tax recycling a positive tax recycling effect has to be added (Parry, 1995).

$$RE_{hk}^t \equiv MEC_{hk}^t \left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_{hk}^t}\right)(\phi_{hk}^{mec}-1) + Y_{hk}^t\left(\phi_{hk}^{y}-1\right) \tag{25}$$
$$- N\psi_{hk}D_{hk}\left(\phi_{hk}^{toll}-1\right) - \tau^w N\left(\sum_{i,j}\psi_{ij}H_{ij}\frac{\mathrm{d}w_j}{\mathrm{d}\tau_{hk}^t}\right)\left(\phi_{hk}^{wtax}-1\right).$$

The distributional characteristics ϕ (Feldstein, 1972) represent the ratios of changes in congestion externalities (ϕ_{hk}^{mec}), income net of consumption and housing expenditure (ϕ_{hk}^{y}), the toll base (ϕ^{toll}) and wage tax revenue (ϕ_{hk}^{wtax}) evaluated at individual MUIs to those evaluated at average MUI. If MUIs are identical, ϕ_s are unity and RE_{hk}^t vanishes (ϕ is defined in Appendix D).

From (20) in connection with (21) - (24) we deduce the following:

Remark 1 *Decision on workdays directly affect all components of the welfare change (WD or HY model), while decisions on daily working hours (WH or HY model) have a direct impact only on the tax interaction term.*

Remark 2 *(No relocation). Assume relocation is not allowed. Then, MEC cannot change if workdays are constant.*[42]

An even stronger result can be derived for pure workhours models (WH): if there is no relocation, changes in MECs are always zero owing to given workdays. In this case or if redistribution is sufficiently moderate, welfare declines due to the negative tax interaction term.

We can draw some conclusions on the number of commuting trips (workdays): first, a higher toll lowers VOT_l in WD.[43] If substitution effects dominate $\mathrm{d}D_{ij}/\mathrm{d}\tau_{hk}^t < 0$. Second, there is only an income effect in WH since the toll does not directly affect the VOTs. With head tax recycling this effect is offset on average, provided we neglect market based changes. However, worker types facing high tolls have a larger tax liability than those paying low tolls. Therefore, working hours of highly taxed workers increase ($\mathrm{d}h_{ij}/\mathrm{d}\tau_{hk}^t > 0$, if $\tau_{hk}^t D_{ij} > \left|\tau^{ls}\right|$) while they decline for low taxed workers ($\mathrm{d}h_{ij}/\mathrm{d}\tau_{hk}^t < 0$, if $\tau_{hk}^t D_{ij} < \left|\tau^{ls}\right|$). In addition, workers can avoid high net taxation through relocation. This results in less traffic on highly congested routes. If congestion is high on the intra-city and suburb-city links, we expect resorting to city-suburb and intra-suburban links.

Third, the decline in workdays diminishes congestion. This raises VOT_l in some of the LSMs inducing additional travel and congestion. Due to this congestion feedback, welfare can be expected to increase in WD less than in WH in case of an increase in congestion tolls.

By setting the marginal welfare change to zero and solving for τ_{hk}^t we can derive the optimal toll on route hk

$$\left(\tau_{hk}^t\right)^* = \underbrace{\frac{MEC_{hk}^t}{Adj_{hk}^t}\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_{hk}^t}\right)}_{(+)} + \underbrace{\frac{TI_{hk}^t}{Adj_{hk}^t}}_{(-)} + \underbrace{\frac{RE_{hk}^t}{Adj_{hk}^t}}_{(?)}. \tag{26}$$

The optimal congestion tolls are spatially differentiated except for the unlikely case that the sum of the terms is equal for each tax. Because traffic flows and labor supply decline

[42]If $\mathrm{d}\psi/\mathrm{d}\tau_{hk}^t = 0$ and if $D = \bar{D}$ it follows from (22) that $\mathrm{d}t_{ij}/\mathrm{d}\tau_{hk}^t = 0$ and from (21) that $MEC_{hk}^t = 0$. If $\mathrm{d}D_{ij}/\mathrm{d}\tau_{hk}^t \neq 0$ then $\mathrm{d}t_{ij}/\mathrm{d}\tau_{hk}^t \neq 0$ and $MEC_{\tau_{hk}^t}^t \neq 0$.

[43]We implicitly assume that the first round effect of the toll on the VOT exceeds market induced feedback on wages and travel time if these run into the opposite direction.

w.r.t. the toll, the first two terms in (26) are of opposite sign. Nothing can be said about redistribution. Hence, optimal tax rates are ambiguous.

Similar formulae can be derived for miles taxes and a cordon toll. In case of zoning[44], the tax-interaction effect does not exist but a land market distortion is added (see Appendix D; see also Rhee et al., 2014). Since the latter does not directly depend on labor supply, LSM is less important under zoning.

Our results will likely hold in a similar way when the approach is extended. First, each relocation implies the use of another $\{i, j\}$. The same happens if we fix locations and allow for mode or route choice (De Palma and Lindsey, 2004). Travel time is also affected if workers avoid peak hours by timing their work (Arnott et al., 1990; Hamermesh, 1999; Winston, 2008).

Second consider telecommuting (e.g., Rhee, 2008). As commuting costs are fixed costs of a workday spent away from home, people would prefer to maximize telecommuting days c.p. If leisure is homogeneous the choices of hours and telecommuting days are equivalent and implicitly included in our model.

Third, adding a decision on weeks per year or participation (Anas and Liu, 2007) is straightforward. Assume there are fixed costs of a working week. This will also affect commuting and, thus, the Pigouvian and the tax interaction terms in a very similar way compared to the decision on days.

5 Simulations

Below we present the simulations. The numerical model is almost identical to the above model apart from some minor adjustments. We specify functions and landownership and add a current account.

5.1 Functional forms and model closure

We define the random utility functions of worker type ij in the inhomogeneous and the homogeneous case, respectively

$$\begin{aligned} U_{ij}^{inh} &= \alpha^z \ln Z_{ij} + \alpha^q \ln q_{ij} + \alpha_1^{\mathcal{L}} \ln(\ell_{ij} D_{ij}) + \alpha_2^{\mathcal{L}} \ln(l_{ij} L_{ij}) + \varepsilon_{ij}, \\ U_{ij}^{\hom} &= \alpha^z \ln Z_{ij} + \alpha^q \ln q_{ij} + \alpha^{\mathcal{L}} \ln(\ell_{ij} D_{ij} + l_{ij} L_{ij}) + \varepsilon_{ij}, \end{aligned}$$

where $Z_{ij} = \left(\sum_k (z_{ijk})^\eta\right)^{1/\eta}$ is the CES subutility for consumption of local goods (Dixit and Stiglitz, 1977), $1/(1-\eta)$ is the elasticity of substitution and the αs are expenditure shares. Each local representative firm produces a local commodity X_i with a constant returns to scale CD technology $X_i = B_i Q_i^{\omega_i^Q} M_i^{\omega_i^M}$, $\omega_i^Q + \omega_i^M = 1$, using land Q_i and labor M_i, where B, ω_i^Q and ω_i^M are parameters.

We use the BPR (bureau of public roads) congestion function (e.g., Anas and Xu, 1999)[45] to compute travel time t_{ij} on link ij. The current account $\sum_i p_i \Gamma_i = [(1-\Theta)\sum_i r_i A_i]$ states that the value of exports, with Γ_i as the exported goods, equals land rents paid to

[44] Zoning is known to be almost equivalent to congestion tolls (Pines and Sadka, 1985; Rhee et al., 2014).

[45] $t_{ij} = g_0 \left[1 + g_1 \left(\frac{F_{ij}}{K_{ij}}\right)^{g_2}\right]$ where $g_1 > 0$, $g_2 \geq 1$. g_0 is the inverse of the free of congestion traffic speed. Since a total of $T_{ij} = t_{ij} F_{ij}$ hours is spent on link ij, the marginal social time of traveling is $\partial T_{ij}/\partial F_{ij} = t'_{ij} F_{ij} + t_{ij}$. The congestion externality is $t'_{ij} F_{ij} = g_0 g_1 g_2 \left(\frac{F_{ij}}{K_{ij}}\right)^{g_2}$.

absentee landowners. Θ is the local landlords' share of land.[46] Clearings of local good markets require $X_k = N \sum_{i,j} \psi_{ij} Z_{ijk} + \Gamma_k$.

5.2 Parameters and benchmark simulation

We calibrate a city with two zones, named City and Suburb, so that it approximates a stylized medium-sizedd MSA (parameters see Table 4). Table 5 displays the benchmark figures for the inhomogeneous leisure case.[47] $N = 500,000$ workers live in the city on 290 square miles of land. We assume an average household size of 2.5 (U.S. Census Bureau, 2012) so that the average population density is 4300 persons per square mile. The shares of land allocated to roads is set at $s_1 = 0.45$ and $s_2 = 0.20$ to get a higher network density in the City. The average intra-City (intra-Suburb) travel distance is 8 (16) miles per one-way trip and the average distance of inter-urban (inter-zone) trips is 24 miles. Along with the chosen parameter values for the BPR congestion function (Small and Verhoef, 2007) this delivers realistic travel and congestion patterns. Average one-way commuting time is 31 minutes,[48] total annual time delay per commuter is 31 hours[49] and averaged MEC are 22 ¢ /mile.[50]

Utility parameters provide real expenditure shares for consumption and housing, and reproduce time allocation patterns from the American Time Use Survey. Pure time spent working (leisure time) on a workday is 8.3 (5.8) hours[51] while 2 hours are used for traveling. The annual number of workdays (non-workdays) is 263 (52). The number of shopping trips exceeds the number of commutes (Anas, 2007).

We assume a higher (lower) labor (land) cost share in City's firms, so that labor intensive firms locate in the City but land intensive firms in the Suburb. This results in reasonable wage and rent profiles. The average wage rate is 21.34 \$/hour (City: 22.81 \$/hour; Suburb: 19.65 \$/hour).[52] The location parameters imply a population and employment density peak in the City where the job–housing ratio exceeds unity while it falls short of unity in the Suburb (Cox, 2013; Levine, 1998; Sultana, 2002).

5.3 Effects of policies – numerical results

We run simulations for five anti-congestion policies: (1) introduction of a Pigouvian congestion toll, (2) an expansion of road capacity by 10 %, (3) a miles tax of 5 cents per mile, (4) a cordon toll of \$10 for entering the city, and (5) zoning that increases residential land in the City and declines it in the Suburb by 4 percentage points each. We apply four LSMs to each policy and, in addition, differentiate with respect to revenue recycling

[46] For simplicity, we assume that commodities can be exported at zero transport costs. Export demands are derived from a CD utility function of the outside world (absentee landlords) over all local goods with uniform expenditure shares.

[47] The benchmark of the LSMs with homogeneous leisure, which is separately calculated, is very similar.

[48] Average one-way commuting time in MSAs (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).

[49] According to the 2012 Urban Mobility Report (Schrank et al., 2012), the average annual delay per auto commuter was 29 hours in medium MSAs in 2011; 23 hours in small MSAs (population $\leq$ 500,000); and 37 hours in large MSAs (population 1 to 3 million).

[50] Parry and Small (2009) report peak-period MEC of 21 ¢/mile for Washington, DC and 26 ¢ /mile for Los Angeles.

[51] The U.S. Department of Labor (2013a) reports an average of 8.5 workhours of employed full time persons on an average weekday (men: 8.8; women 8.1).

[52] The mean hourly wage is 22.33 \$/hour in May 2013 (U.S. Department of Labor, 2013b).

Table 4: Benchmark parameters

Description	Symbol	Value
	City characteristics	
Land area [square mile] City|Suburb	A_i	58|232
Travel distance [miles] ij	$m_{11}\|m_{12}\|m_{21}\|m_{22}$	8|24|24|1
Share of road area City|Suburb	s_i	0.45|0.20
Price of goods in the City (numeraire)	p_1	50
Export share zone i	ϕ_i	1/2
	Households	
Number of workers (full city)	N	500,000
Time endowment [annual days|daily hours]	$E\|e$	315|16
Full expenditure share consumption	α^z	0.37
Share housing	α^q	0.27
Share (homogeneous) leisure	$\alpha^{\mathcal{L}}$	0.36
Share (inhomog.) leisure on workdays	$\alpha_1^{\mathcal{L}}$	0.26
Share (inhomog.) leisure on non-work days	$\alpha 2^{\mathcal{L}}$	0.10
Share of shopping trips on workdays	b	0.50
Taste for shopping variety	η	0.6
Spatial location taste heterogeneity	Λ	3
Share urban landownership	Θ	0.3
Labor tax rate	τ^w	0.35
	Firms	
Labor cost share City|Suburb	ω_i^M	0.90|0.70
Land cost share City|Suburb	ω_i^Q	0.10|0.30
Scale parameter production function	B	0.70
	Transport	
Free flow travel time [hours/mile]	g_0	1/40
Parameters congestion function	$g_1\|g_2$	2.0|5.0
Road capacity scale parameter	κ	0.68

Parameters in the benchmark model. Own choices.

(head tax vs. wage tax recycling) and landownership (mixed landownership, only absentee landowners and only local landowners).

Table 6 shows equivalent variations (EV) in million USD per year. Surprisingly, the signs change across the LSMs in half of the 30 variants. For example, if leisure is homogeneous price based policies with head tax recycling cause losses when workdays are endogenous (WD) but gains when workdays are fixed (WH). A general outcome is that WH provides an upper limit but WD a lower limit of welfare effects of pricing policies within each homogeneity class.[53]

In general, benefits are higher under wage tax than head tax recycling due to the positive revenue recycling effect which results from the reduced wage tax (Parry, 1995). Considering planning instruments (road capacity expansion and zoning), all LSMs produce similar effects. Expansion of road capacity unambiguously diminishes welfare due to the negative effect of funding.

To get an idea why EVs differ we compare results of imposing Pigouvian congestion tolls with head tax recycling under homogeneous leisure versus wage tax recycling with inhomogeneous leisure (Case 1a and 1d in Table 7; others, see Appendix E). In general, tolls differ across routes (rows 6-9) and the Suburb-City toll is the highest (4.99–7.74,

[53]If leisure taxation is absent complements to leisure should be taxed more heavily (Corlett and Hague, 1953).

Table 5: Benchmark simulation - general model

	Value
Workdays per year|non-work days per year	263|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 non-work day spent leisure|shopping	12.0|4.0
Total labor supply|leisure demand [h/year]	2187|2164
Total commuting time|shopping time [hours/year]	272|417
Travel time delay|total travel time [hours/year]	31|689
Marginal external congestion cost [¢/mile]	22
One-way commuting time [minutes]	31
VOT of one hour on workday|non-work day [$/h]	13.87|12.97
Commuting trip pattern [million/year] ik	25.4|19.3|45.0|41.6
Gross income [$/year]	61,071
Consumption (shopping) [trips/year]	472
Average housing demand [sqr feet]	7778
Urban GDP [billion $/year]	29.1
hline Rent City/Suburb [$/sqr feet*year]	5.95|2.22
Wage rate City/Suburb [$/h]	22.81| 19.65
Labor tax|Lump-sum tax revenue [million $/year]	8171|−974
Infrastructure costs [million $/year]	7197
Households – City|Suburb	168,687|331,313
Jobs – City|Suburb	268,099|231,901

Benchmark characteristics of all LSMs with inhomogeneous leisure using parameters of Table 2. The benchmark of all LSMs with homogeneous leisure is similar. Source. own calculations.

rows 8a-8b). It is higher with wage tax recycling due to the additional revenue recycling induced by the the increase in the supply of working hours (rows 2-3) resulting from the tax reduction. This is the major reason why welfare increases (row 10b) whereas it declines with head tax recycling (row 10a). Further, even though households urbanize in all LSMs, relocation is weaker in WD (row 13b) where workers can respond to the toll by adjusting commuting trips. In contrast, the relocation effect is stronger in WH (row 13a), where commuters can avoid the toll only by relocating.[54] Interestingly, the reduction in MECC is similar across LSMs (row 4) which suggests that the missing opportunity of commuters to adjust the frequency of commuting trips in WH is almost exactly offset by more intense relocation. Further, people rely more on relocation in inhomogeneous leisure models where non-work and working days are less substitutable.

Next, we vary the magnitude of the policies. Figure 1 shows the welfare effects for different levels of the miles tax (LHS) and cordon toll rate (RHS) in terms of EVs (equivalent variations). The upper panels present results of wage tax recycling and inhomogeneous leisure and the lower panels results of head tax recycling and homogeneous leisure. Dotted graphs represent the workhours approach (WH), dashed graphs the workdays approach (WD) and solid graphs the hybrid approach (HY) which we add to illustrate HY in a specific case. Optimal tax and toll rates are higher under WH than under WD. Daily working hours vary stronger than workdays if leisure is inhomogeneous and there is wage tax recycling. In contrast, with homogeneous leisure and head tax recycling the revenue

[54]Levying congestion tolls raises population density in the City which is the main job center. Commuters urbanize to economize on higher commuting costs. This is consistent with classical urban economic theory. In contrast to residents, jobs suburbanize since land used as input by firms becomes relatively cheaper in the Suburb. This is consistent with the literature on polycentric cities (see Anas and Xu, 1999).

Table 6: Simulation overview - welfare effects of policies

	Policy	Recycling	Land-lord	Inhomogeneous leisure No.	WH	WD	Homogeneous leisure No.	WH	WD
1	Cong.toll[a]	head tax	mixed	**1a**	43	−17	**6a**	30	−109
2	Cong.toll	head tax	absentee	**1b**	56	−17	**6b**	76	−155
3	Cong.toll	head tax	urban	**1c**	17	−10	**6c**	2	−16
4	Cong.toll	wage tax	mixed	**1d**	202	13	**6d**	177	4
5	Cong.toll	wage tax	absentee	**1e**	217	16	**6e**	325	24
6	Cong.toll	wage tax	urban	**1f**	127	5	**6f**	15	−1
7	Road cap.[b]	head tax	mixed	**2a**	−499	−633	**7a**	−521	−507
8	Road cap.	head tax	absentee	**2b**	−420	−589	**7b**	−368	−385
9	Road cap.	head tax	urban	**2c**	−732	−748	**7c**	−808	−755
10	Road cap.	wage tax	mixed	**2d**	−706	−669	**7d**	−757	−715
11	Road cap.	wage tax	absentee	**2e**	−580	−620	**7e**	−552	−535
12	Road cap.	wage tax	urban	**2f**	−1038	−785	**7f**	−1139	−1070
13	Miles tax	head tax	mixed	**3a**	4	−6	**8a**	3	−46
14	Miles tax	head tax	absentee	**3b**	6	−5	**8b**	5	−40
15	Miles tax	head tax	urban	**3c**	1	−6	**8c**	1	−45
16	Miles tax	wage tax	mixed	**3d**	50	2	**8d**	53	0
17	Miles tax	wage tax	absentee	**3e**	47	3	**8e**	58	3
18	Miles tax	wage tax	urban	**3f**	46	1	**8f**	32	−2
19	Cord.toll[c]	head tax	mixed	**4a**	9	−27	**9a**	3	−143
20	Cord.toll	head tax	absentee	**4b**	12	−27	**9b**	14	−121
21	Cord.toll	head tax	urban	**4c**	2	−24	**9c**	1	−149
22	Cord.toll	wage tax	mixed	**4d**	123	−7	**9d**	128	−19
23	Cord.toll	wage tax	absentee	**4e**	115	−7	**9e**	140	−12
24	Cord.toll	wage tax	urban	**4f**	113	−8	**9f**	81	−31
25	Zoning	head tax	mixed	**5a**	−16	−74	**10a**	−54	−57
26	Zoning	head tax	absentee	**5b**	8	−38	**10b**	30	−9
27	Zoning	head tax	urban	**5c**	−206	−195	**10c**	−201	−198
28	Zoning	wage tax	mixed	**5d**	−121	−91	**10d**	−104	−102
29	Zoning	wage tax	absentee	**5e**	−61	−65	**10e**	−66	−69
30	Zoning	wage tax	urban	**5f**	−647	−242	**10f**	−667	−533

[a] Congestion toll. [b] Road capacities. [c] Cordon toll

Million USD per year. Congestion toll: Pigouvian congestion toll. Road capacity expansion: 10 % increase in infrastructure capacity. Miles tax: 5¢ /mile on commuting (\$\approx\$ 1.15 \$/gallon at average fuel economy, 23 miles/gallon). Cordon toll: \$ 10 for entering the City. LUR (zoning): increasing (decreasing) the residential land share by 4 percentage-points in the City (Suburbs). 100 million \$ per year is about 1.4 % of tax revenue and 0.3 % of GDP). Source: own calculations.

Table 7: Policy effects of Pigouvian congestion tolls

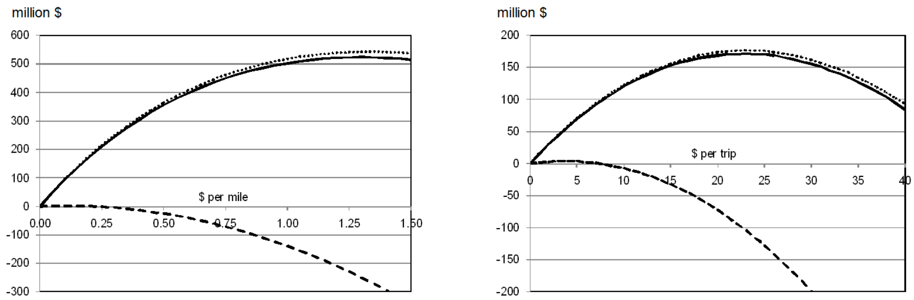
Case 1a – head tax recycling		Inhomogeneous leisure		Homogeneous leisure	
		WH	WD	WH	WD
1a	Workdays per year	0	−1	0	−4
2a	Daily working hours	0	0	+0.02	+0.02
3a	Total labor supply [h/year]	+6	−6	+4	−31
4a	MECC [¢/mile]	−3	−3	−3	−3
5a	VOT on a workday [$/h]	−0.16	−0.35	−0.11	−0.59
6a	Toll [$/trip] City–City	+1.54	+1.50	+1.37	+1.09
7a	Toll [$/trip] City–Suburb	+0.16	+0.14	+0.12	+0.09
8a	Toll [$/trip] Suburb–City	+7.33	+7.35	+6.01	+4.99
9a	Toll [$/trip] Suburb–Suburb	+2.13	+2.04	+1.74	+1.36
10a	EV [million $/year]	+43	−17	+30	−109
11a	Labor tax revenue [m $/y]^a	−65	−155	−48	−182
12a	Head tax revenue [m $/y]^a	−817	−791	−653	−508
13a	Workers in the City	+3,745	+2,882	+2,988	+1,870
14a	Jobs in the City	−6,356	−4,971	−5,155	−3,598
Case 1d – wage tax recycling		Inhomogeneous leisure		Homogeneous leisure	
		WH	WD	WH	WD
1b	Workdays per year	0	0	0	0
2b	Daily working hours	+0.2	0	+0.1	0
3b	Total labor supply [h/year]	+51	+2	+45	+2
4b	MECC [¢/mile]	−2	−3	−2	−2
5b	VOT on a workday [$/h]	+0.57	−0.33	+0.46	−0.20
6b	Toll [$/trip] City–City	1.68	1.57	1.46	1.24
7b	Toll [$/trip] City–Suburb	0.16	0.14	0.13	0.10
8b	Toll [$/trip] Suburb–City	7.74	7.52	6.28	5.49
9b	Toll [$/trip] Suburb–Suburb	2.22	2.06	1.79	1.52
10b	EV [million $/year]	+202	+13	+177	+4
11b	Labor tax revenue [m $/y]^a	−778	−923	−592	−652
12b	Head tax revenue [m $/y]^a	0	0	0	0
13b	Workers in the City	+4,109	+3,171	+3,247	+2,322
14b	Jobs in the City	−5,618	−4,380	−4,540	−3,316

a) million $ per year. Results of the simulation of the introduction of Pigouvian congestion tolls with head tax revenue recycling and mixed landownership. Source: own calculations.

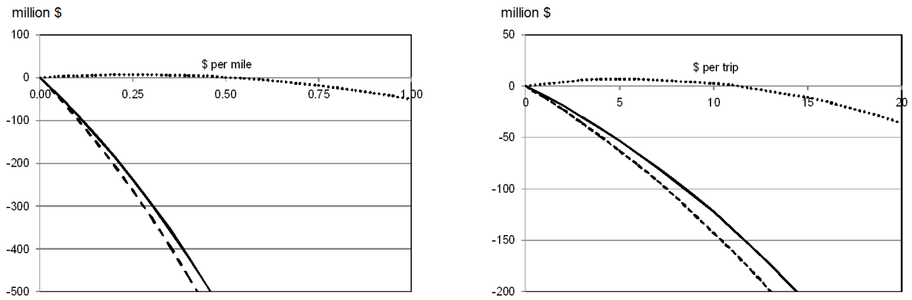
recycling effect is absent and optimal taxes are lower. Obviously, WD and WH span the interval of the effects of pricing policies.

Figure 2: Welfare effects of congestion pricing policies

Inhomogeneous leisure – wage tax recycling



Homogeneous leisure – head tax recycling



The figure draws welfare changes in the whole urban area (equivalent variations in million US-$) for different levels of the miles tax (LHS) and cordon tolls (RHS). The upper panels display results for wage tax recycling and inhomogeneous leisure and the lower panels results for head-tax recycling and homogeneous leisure. Dotted graphs represent the workhours approach (WH), dashed graphs the workdays approach (WD) and solid graphs the hybrid approach (HY). Optimal tax and toll rates in WH are much higher than in WD. Source: own calculations.

A note is in order. We applied the same benchmark to study the effects of the different policies and modeling features. This implies that we used specific labor supply elasticities (see Appendix E.5).[55]

6 Conclusions

How to model labor supply is a crucial decision when evaluating economic policies that change fixed costs of labor supply margins. It is crucial because it may affect both magnitudes and signs of welfare effects and its components as well as the optimal level of pricing instruments. That is why we need a decision rule for selecting the appropriate labor supply model.

Given that we do not know enough on elasticities of workdays or weeks, we suggest a simple rule of thumb, which is: use the workhours as well as the workdays approach to span the interval of results. The former provides the upper limit and the latter the lower limit

[55]We do not fix average labor supply elasticities to avoid calibrating 150 different models. Instead we use the same calibrated benchmark for all simulations within each homogeneity group. Elasticities are then endogenous but almost constant.

of optimal instrument levels and changes in welfare and its most important components which are induced by the policies considered. If the issue is to determine whether results are below (above) a threshold, applying only the workhours (workdays) model is sufficient if its outcome is below (above) the threshold. If elasticities are known, using the hybrid approach is the best choice because it avoids extreme assumptions of either fixed days or fixed daily hours. Concerning the homogeneity assumption of leisure, the finding is less clear. In many cases the inhomogeneous leisure assumption provides the upper limits of the results in the workhours model and the homogeneous leisure assumption the lower limit of the results under the workdays approach.

In our application to congestion policies we find that the different labor supply approaches results in very similar effects on commuting and congestion even though welfare effects and effects on other economic variables may differ considerably. The reason for this finding is that agents are flexible enough to avoid fixed costs of workdays, for instance, by relocating. As a consequence, either a pure workhours approach or a workdays approach may be a useful shortcut if one wants to examine effects of policies on congestion only, provided travel can respond sufficiently. According to our results, all three approaches provide similar findings when applied to planning instruments (land-use restriction and road-capacity expansion) and, thus, one is free to apply any of the LSMs when examining these instruments.

Our analyses simplifies in several ways. We expect equivalent results when considering other trip purposes, the possibility to shift travel time away from the peak, mode choice or route choice, as well as other extensions of the model such as heterogeneity of skills, accidents, noise, pollution, or emission of greenhouse gases.

In general, our results emphasize that magnitude as well as sign may depend on labor supply modeling. Hence, adding a decision on days or weeks may be appropriate if their marginal costs differ from those of the other margins. Given the danger of deriving misleading findings, our analysis underlines the importance of studying the actual responses of employees in medium or long-term workdays, daily working hours, workweek and worktiming to economic policies which change fixed costs of the labor supply margins. Unfortunately, there is hardly any empirical research on those topics. An exception is the literature on income taxes with respect to hours of work and participation which, however, does not consider workday decisions.

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References

Abrantes, Pedro A.L., and Mark. R. Wardman. 2011. Meta-analysis of UK values of travel time: An update. Transportation Research Part A 45: 1/17.

Anas, Alex. 2007. A unified theory of consumption, travel and trip chaining. Journal of Urban Economics, 62 (2): 162–186.

Anas, Alex, and Tomoru Hiramatsu. 2013. The economics of cordon tolling: General equilibrium and welfare analysis. Economics of Transportation, 2 (1): 18–37.

Anas, Alex, and Tomoru Hiramatsu. 2012. The effect of the price of gasoline on the urban economy: From route choice to general equilibrium. Transportation Research Part A: Policy and Practice, 46 (6): 855–873

Anas, Alex, and Ikki Kim. 1996. General Equilibrium Models of Polycentric Urban Land Use with Endogenous Congestion and Job Agglomeration. Journal of Urban Economics, 40 (2): 232–256.

Anas, Alex, and Yu Liu. 2007. A regional economy, land use, and transportation model (RELUTRAN ©): Formulation, algorithm design, and testing. Journal of Regional Science, 47 (3): 415–455.

Anas, Alex, and Hyok-Joo Rhee. 2006. Curbing excess sprawl with congestion tolls and urban boundaries. Regional Science and Urban Economics, 36 (4): 510–541.

Anas, Alex, and Hyok-Joo Rhee. 2007. When are urban growth boundaries not second-best policies to congestion tolls? Journal of Urban Economics, 61 (2): 263–286.

Anas, Alex, and Rong Xu. 1999. Congestion, land use, and job dispersion: A general equilibrium model. Journal of Urban Economic,. 45 (3): 451–473.

Arnott, Richard. 2007. Congestion tolling with agglomeration externalities. Journal of Urban Economics, 62 (2): 187–203.

Arnott, Richard, André De Palma, and Robin Lindsey. 1990. Economics of a bottleneck. Journal of Urban Economics 27: 111-130.

Bargain, Olivier, Kristian Orsini, and Andreas Peichl, 2014. Comparing labor supply elasticities in Europe and the United States. Journal of Human Resources 49 (3): 723-838.

Becker, Gary S. 1965. A theory on the allocation of time. The Economic Journal 75 (299): 493-517.

Bento, Antonio M., Sofia F. Franco, and Daniel Kaffine. 2006. The efficiency and distributional impacts of alternative anti-sprawl policies. Journal of Urban Economics, 59 (1): 121–141.

Bento, Antonio, Sofia Franco, and Daniel Kaffine. 2011. Is there a double-dividend from anti-sprawl policies? Journal of Environmental Economics and Management 61(2):135-52.

Bento, Antonio M., Lawrence H. Goulder, Mark R. Jacobsen, and Roger H. von Haefen, 2009. Distributional and efficiency impacts of increased US gasoline taxes. American Economic Review, 99(3): 667-699.

Berg, Charlotte. 2007. Household transport demand in a CGE-framework. Environmental & Resource Economics, 37 (3): 573–597.

Bick, Alexander, Bettina Brüggemann, and Nicola Fuchs-Schündeln, 2016. Hours worked in Europe and the US: New Data, New Answers. IZA Discussion Paper no. 10179.

Blank, Rebecca M. 1988. Simultaneously modeling the supply of weeks and hours of work among female household heads. Journal of Labor Economics, 6: 177–204.

Blundell, Richard, Antoine Bozio, and Guy Laroque. 2011a. Extensive and intensive margins of labour supply: working hours in the US, UK and France. Institute for Fiscal Studies (IFS), Working Paper no. 11/01.

Blundell, Richard, Antoine Bozio, and Guy Laroque. 2011b. Labor supply and the extensive margin. American Economic Review Papers and Proceedings, 101(3): 482-86.

Blundell, Richard, Antoine Bozio, and Guy Laroque. 2013. Extensive and intensive margins of labour supply: Working hours in the US, UK and France. Fiscal Studies, 34(1): 1–39.

Blundell, Richard, and Thomas MaCurdy. 1999. Labor supply: A review of alternative approaches. In: Handbook of Labor Economics, vol. 3A, edited by Orley Ashenfelter and David Card. Elsevier, New York: 1559–1696.

Borck, Rainald, and Matthias Wrede. 2009. Subsidies for intracity and intercity commuting. Journal of Urban Economics, 66: 25–32.

Bovenberg, A. Lans, and Lawrence H. Goulder. 2002. Environmental taxation and regulation in a second-best setting. In: Handbook of Public Economics edited by Alan J. Auerbach, Vol.3: 1471-1545. Amsterdam: North-Holland.

Brueckner, Jan K. 2007. Urban growth boundaries: An effective second-best remedy for unpriced traffic congestion? Journal of Housing Economics, 16: 263–273.

Brueckner, Jan K. 2005. Transport subsidies, system choice, and urban sprawl. Regional Science and Urban Economics 35: 715–733.

Brueckner, Jan K., Jacques-François Thisse, and Yves Zenou. 2002. Local labor markets, job matching, and urban location. International Economic Review, 43: 155–171.

Bureau of Labor Statistics, 2015a. ASUS - Databases, Tables & Calculators by Subject
http://data.bls.gov/timeseries/TUU10101AA01002867, retrieved, 10.09.2015.

Bureau of Labor Statistics, 2015b. Economic New Release,
http://www.bls.gov/news.release/work.t01.htm, 9.6.2015.

Calthrop, Edward, "On subsidising auto-Commuting", CESifo Working Paper Series 566, 2001.

Calthrop, Edward, Stef Proost, and Kurt Van Dender, "Parking policies and road pricing," *Urban Studies*, 37 (2000), 63–76.

Chetty, Raj, "Bound on elasticities with optimization frictions: A synthesis of micro and macro evidence on labor supply," *Econometrica* 80 (2012), 969–1018.

Chetty, Raj, Adam Guren, Day Manoli, and Andrea Weber, "Does indivisible labor explain the difference between micro and macro elasticities? A meta-analysis of extensive margin elasticities", *NBER Macroeconomic Annual*, 27 (2012): 1–56.

Chetty, Raj, Adam Guren, Day Manoli, and Andrea Weber, "Are micro and macro labor supply elasticities consistent? A review of evidence on the intensive and extensive Margins", *American Economic Review: Papers & Proceedings*, 101 (2011), 471–76.

Cogan, John F., "Fixed costs and labor supply," *Econometrica*, 49 (1981), 945–963.

Corlett, W.J. and D.C. Hague, "Complementarity and the excess burden of taxation," *The Review of Economic Studies* 21 (1953), 21–30.

Cox, Wendell. 2013. US Suburbs Approaching Jobs-Housing Balance.
www.newgeography.com.

Davis, Steven J., Magnus Henrekson, "Tax effects on work activity, industry mix and shadow economy size: Evidence from rich country comparisons," in *Labour Supply and Incentives to Work in Europe*, Ramón Gómez-Salvador, Ana Lamo, Barbara Petrongolo, Melanie Ward, and Etienne Wasmer, ed. (Cheltenham, UK: Elgar, 2005).

Deaton, Angus, "Optimal taxes and the structure of preferences," Econometrica, 49 (1981), 1245–60.

Deaton, Angus, and Joseph Muellbauer, *Economics and Consumer Behavior.* (Cambridge: Cambridge. University Press, 1980).

De Borger, Bruno, and Kurt Van Dender. 2003. Transport tax reform, commuting, and endogenous values of time. Journal of Urban Economics, 53: 510–530.

De Borger, Bruno, and Sandra Wouters. 1998. Transport externalities and optimal pricing and supply decisions in urban transportation - a simulation analysis for Belgium. Regional Science and Urban Economics, 28: 163–197.

De Borger, Bruno, and Bart Wuyts. 2011a. The tax treatment of company cars, commuting and optimal congestion taxes. Transportation Research Part B, 45: 1527–1544.

De Borger, Bruno, and Bart Wuyts. 2011b. The structure of the labor market, telecommuting, and optimal peak period congestion tolls: A numerical optimization model. Regional Science and Urban Economics, 41: 426–438.

De Borger, Bruno, and Bart Wuyts. 2009. Commuting, transport tax reform and the labour market: Employer-paid parking and the relative efficiency of revenue recycling instruments. Urban Studies, 46: 213–233.

Dechter, Evgenia. 2013. Fixed costs, work schedules and the elasticity of labor supply. Univ of South Wales, unpublished.

De Lara, Michel, André De Palma, Moez Kilani, and Serge Piperno.2013. Congestion pricing and long term urban form: Application to Paris region. Regional Science and Urban Economics, 43: 282–295.

De Palma, André, and Robin Lindsey. 2004. Congestion pricing with heterogeneous travelers: A general-equilibrium welfare analysis. Networks and Spatial Economics, 4: 135–160.

Department of Transport, 2015. Table NTS0901 - Annual milagee of 4-wheeled cars by ownership and trip purpose: England, since 2002 (with chart). https://www.gov.uk /government/statistical-data-sets/nts09-vehicle-mileage-and-occupancy, 31.08.2015.

DeSerpa, Allan C. 1971. A theory of the economics of time. The Economic Journal, 81 (324): 828–846.

Diamond, Peter A. 1980. Income taxation with fixed hours of work. Journal of Public Economics, 13(1): 101–10.

Diamond, Rebecca. 2016. The determinants and welfare implications of US workers' diverging location choices by skill: 1980-2000. American Economic Review 106 (3): 479-524.

Dixit, Avinash.K., and Joseph E.Stiglitz. 1977. Monopolistic competition and optimum product diversity. American Economic Review, 67: 297–308.

Eissa, Nada, Hilary Williamson Hoynes. 2004. Taxes and the Labor Market Participation of married couples: The Earned Income Credit. Journal of Public Economics 88: 1931-1958.

Eissa, Nada, Henrik Jacobsen Kleven, and Claus Thustrup Kreiner. 2008. Evaluation of four tax reforms in the United States: Labor supply and welfare effects of single mothers. Journal of Public Economics 92: 795-816.

Federal Highwy Administration, 2015. NTHS National Household Travel Survey: Summary of Travel Trends 2011, Table 24. http://nhts.ornl.gov/publications.shtml, 08.12.2015.

Feldstein, Martin S. 1972. Equity and efficiency in public sector pricing: The optimal two-part tariff. Quarterly Journal of Economics, 86: 175–187.

Fetene, Gebeyehu M., Georg Hirte, Sigal Kaplan, Carlo G. Prato, and Stefan Tscharaktschiew. 2016. The economics of workplace charging. Transportation Research Part B: Methodological, 88: 93–118.

Fiorito, Riccardo, and Giulio Zanella. 2012. The anatomy of the aggregate labor supply elasticity. Review of Economic Dynamics 15(2):171–187.

Fujishima, Shota. 2011. The welfare effects of cordon pricing and area pricing. Journal of Transport Economics and Policy, 45: 481–504.

Gimenez-Nadal, J. Ignacio, José Molina, and Jorge Velilla. 2016. Commuting time and sex Ratios in the US. IZE Discussion paper 9933, Institute for the Study of Labor (IZA).

Gronau, Reuben, 1986. Home production – a survey. In: Orley Ashenfelter and Richard Layard (eds.) Handbook of Labor Economics, vol 1. Elsevier, 273–304.

Gutiérrez-i-Puigarnau, Eva, and Jos N. van Ommeren. 2010. Labour supply and commuting. Journal of Urban Economics, 68: 82–89.

Hamermesh, Daniel S. 1996. Workdays, Workhours and Work Schedules: Evidence for the United States and Germany. W.E. Upjohn Institute, Kalamazoo, MI.

Hamermesh, Daniel S. 1999. The timing of work over time. Economic Journal, 109: 37–66.

Hanoch, Giora. 1976. Hours and weeks in the theory of labor supply. Santa Monica, CA: RAND Corporation, 1976. http://www.rand.org/pubs/reports/R1787. Also available in print form.

Hanoch, Giora. 1980a. Hours and Weeks in the Theory of Labor Supply. In: Female Labor Supply, edited by James P. Smith. Princeton, N.J.: Princeton University Press, 1980.

Hanoch, Giora. 1980b. A multivariate model of labor supply: Methodology and estimation. In: Female Labor Supply, edited by James P. Smith. Princeton, N.J.: Princeton University Press, 1980.

Heckman, James J. 1993. What has been learned about labor supply in the past twenty years? American Economic Review, 83: 116–121.

Hirte, Georg and Hyok-Joo Rhee, 2016. Regulation versus taxation: efficiency of zoning and tax instruments as anti-congestion policies. CEPIE Working Paper 5/2016, TU Dresden.

Hirte, Georg, and Stefan Tscharaktschiew. 2013a. Income tax deduction of commuting expenses in an urban CGE study: The case of German cities. Transport Policy, 28: 11–27.

Hirte, Georg, and Stefan Tscharaktschiew. 2013b. The optimal subsidy on electric vehicles in German metropolitan areas: A spatial general equilibrium analysis. Energy Economics, 40: 515–528.

Hirte, Georg, and Stefan Tscharaktschiew. 2015. Optimal fuel taxes and heterogeneity of cities. Review of Regional Research 35(2): 173–209.

Hotchkiss, David, and Michelle J. White. 1993. A simulation model of a decentralized metropolitan area with two-worker, traditional, and female-headed households. Journal of Urban Economics, 34: 159–185.

Immervoll, Herwig, Henrik Jacobsen Kleven, Claus Thustrup Kreiner, and Emmanual Saez. 2007. Welfare reform in European countries: A microsimulation analysis. Economic Journal 117: 1-44.

Jara-Díaz, Sergio R. 2007. Allocation and valuation of travel time savings. In Handbook of Transport Modelling, edited by David A. Hensher and Kenneth J. Button, second ed. Pergamon, Oxford: 363–379.

Jara-Díaz, Sergio R., Marcela A. Munizaga, Paulina Greeven, Reinaldo Guerra, and Kay Axhausen. 2008. Estimating the value of leisure from a time allocation model. Transportation Research Part B, 42: 946–957.

Johnson, M. Bruce. 1966. Travel time and the price of leisure. Western Economic Journal (Economic Inquiry), 4: 135-145. l

Keane, Michael P. 2011. Labor supply and taxes: A survey. Journal of Economic Literature 49 (4): 961-1075.

Keane, Michael P., and Richard Rogerson. 2012. Micro and macro labor supply elasticities: A reassessment of conventional wisdom. Journal of Economic Literature, 50(2): 464–476.

Keane, Michael. P., and Nada Wasi. 2016. Labour supply: The roles of human capital and the extensive margin. The Economic Journal 126: 578-617.

Kleven, Henrik J., and Claus T. Kreiner. 2006. The marginal cost of public funds: Hours of work versus labor force participation. Journal of Public Economics, 90: 1955–1973.

Kleven, Henrik J., Claus T. Kreiner, and Emmanuel Saez. 2009. The optimal income tax of couples. Econometrica, 77: 537-560.

Kono, Tatsuhito, Kirti K. Joshi, Takeaki Kato, and Takahisa Yokoi. 2012. Optimal regulation on building size and city boundary: An effective second-best remedy for traffic congestion externality. Regional Science and Urban Economics, 42: 619–630.

Kwon, Youngsun. 2005. Urban comparative statics when commuting cost depends on income. Journal of Housing Economics, 14: 48–56.

Laroque, Guy. 2005. Income maintenance and labor force participation. Econometrica, 73(2): 341–76.

Levine, Jonathan. 1998. Rethinking accessibility and jobs-housing balance. Journal of the American Planning Association, 64: 133–149.

Lin, C.-Y. Cynthia, and Lea Prince. 2009. The optimal gas tax for California. Energy Policy, 37: 5173–5183.

Lucas, Robert E., and Esteban Rossi-Hansberg. 2002. On the internal structure of cities. Econometrica, 70: 1445–1476.

Mackie, Peter J. Sergio Jara-Díaz, and Antony S. Fowkes. 2001. The value of travel time savings in evaluation. Transportation Research Part E 37: 91-106.

Martin, Richard W. 2001. Spatial mismatch and costly suburban commutes: Can commuting subsidies help? Urban Studies, 38: 1305–1318.

McDonald, John F. 2009. Calibration of a monocentric city model with mixed land use and congestion. Regional Science and Urban Economics, 39: 90–96.

McFadden, Daniel. 1973. Conditional logit analysis of qualitative choice behavior. In: Paul Zarembka (ed.). Frontiers in Econometrics. New York: Academic Press, 105–142.

Nickell, Stephen. 2003. Employment and Taxes. Center for Economic Studies Working Paper 1109.

Nitzsche, Eric, and Stefan Tscharaktschiew. 2013. Efficiency of speed limits in cities: A spatial computable general equilibrium assessment. Transportation Research Part A: Policy and Practice, 56: 23–48.

OECD, 2015. Average Annual Hours Actually Worked per Worker.
https://stats.oecd.org/Index.aspx?DataSetCode=ANHRS, 31.08.2015.

Oi, Walter. 1976. Residential location and labor supply. Journal of Political Economy, 84: 221–238.

Olwert, Craig, and Jean-Michel Guldmann. 2012. A computable general equilibrium model of the city: Impacts of technology, zoning, and trade. Environment and Planning A, 44: 237–253.

ONS (Office of National Statistics), 2015.
https://www.ons.gov.uk/ employmentandlabourmarket/peopleinwork
/earningsandworkinghours/timeseries/ybuy.

Oort, Conrad J. 1969. The evaluation of travelling time. Journal of Transport Economics and Policy, 3: 279–286.

Parry, Ian W.H. 1995. Pollution taxes and revenue recycling. Journal of Environmental Economics and Management, 29: 67–77.

Parry, Ian W.H.. 1997. Environmental taxes and quotas in the presence of resource and energy distorting taxes in factor markets. Resource and Energy Economics, 19: 203–220.

Parry, Ian W.H. 2011. How Much should highway fuels be taxed? In: Gilbert E: Metcalf (ed.). US Energy Tax Policy. Cambridge University Press

Parry, Ian W.H., and Antonio Bento. 2002. Estimating the welfare effect of congestion taxes: The critical importance of other distortions within the transport system. Journal of Urban Economics, 51: 339–365.

Parry, Ian W.H., and Antonio Bento. 2001. Revenue recycling and the welfare effects of road pricing. Scandinavian Journal of Economics, 103: 645–671.

Parry, Ian W.H., and Kenneth A. Small. 2009. Should urban transit subsidies Be reduced? American Economic Review, 99: 700–724.

Parry, Ian W.H., and Kenneth A. Small. 2005. Does Britain or the United States have the right gasoline tax? American Economic Review, 95: 1276–1289.

Parry, Ian W.H., and Govinda R. Timilsina. 2010. How should passenger travel in Mexico City be priced? Journal of Urban Economics, 68: 167–182.

Pencavel, John, 1986. Labor supply of men: A Survey. In: Orley Ashenfelter and Richard Layard (eds.). Handbook of Labor Economics, Vol. 1: 3-102. Amsterdam: Elsevier.

Piketty, Thomas, and Emmanuel Saez. 2014. Optimal labor income taxation. in: Handbook of Public Economics, edited by Alan J. Auerbach, Raj Chetty, Martin Feldstein, and Emmanuel Saez. Vol.5. 391–474. Amsterdam: Elsevier.

Pilegaard, Ninette, and Mogens Fosgerau. 2008. Cost-benefit analysis of a transport improvement in the case of search unemployment. Journal of Transport Economics and Policy, 42: 23-42.

Pines, David, and Efraim Sadka. 1985. Zoning, first-best, second-best and third-best criteria for allocating land to roads. Journal of Urban Economics 17, 167-183.

Prescott, Edward C. 2004. Why do Americans work so much more than Europeans? Federal Reserve Bank of Minneapolis Quarterly Review, 28(1): 2–13.

Rhee, Hyok-Joo, Sanggyun Yu, and Georg Hirte. 2014. Zoning in cities with traffic congestion and agglomeration economies. Regional Science and Urban Economics, 44: 82–93.

Rhee, Hyok-Joo. 2009. Telecommuting and urban sprawl. Transportation Research Part D, 14: 453–460.

Rhee, Hyok-Joo. 2008. Home-based telecommuting and commuting behavior. Journal of Urban Economics, 63: 198–216.

Ross, Stephen L., and Yves Zenou. 2008. Are shirking and leisure substitutable? An empirical test of efficiency wages based on urban economic theory. Regional Science and Urban Economics, 38: 498–517.

Rossi-Hansberg, Esteban. 2004. Optimal urban land use and zoning. Review of Economic Dynamics, 7: 69–106.

Saez, Emmanuel. 2002. Optimal income transfer programs: Intensive versus extensive labour supply responses. Quarterly Journal of Economics, 117: 1039–73.

Saez, Emmanuel, Joel Slemrod, and Seth H. Giertz. 2012. The elasticity of taxable income with respect to marginal tax rates: A critical review. Journal of Economic Literature 50 (1): 3-50.

Santos, Adella, Nancy McGuckin, Hikari Yukiko Nakamoto, Danielle Gray, and Susan Liss. 2011. Summary of Travel Trends: 2009 National Household Travel Survey. Report no. FHWA-PL-11-022, Washington, D.C.: Federal Highway Administration.

Schrank, David, Bill Eisele, and Tim Lomax. 2012. 2012 Urban Mobility Report. Texas A&M Transportation Institute.

Small, Kenneth A. 2012. Valuation of travel time. Economics of Transportation, 1: 2–14.

Small, Kenneth A., and Erik T. Verhoef. 2007. The Economics of Urban Transportation. Routledge.

Small, Kenneth A., Clifford Winston, and Jia Yan. 2005. Uncovering the distribution of motorists' preferences for travel time and reliability. Econometrica, 73 (4): 1367–1382.

Sullivan, Arthur M. 1983a. A general equilibrium model with external scale economies in production. Journal of Urban Economics, 13: 235–255.

Sullivan, Arthur M. 1983b. The general equilibrium effects of congestion externalities. Journal of Urban Economics, 14: 80–104.

Sullivan, Arthur M. 1983c. Second-best policies for congestion externalities. Journal of Urban Economics, 14: 105–123.

Sultana, Selima. 2002. Job/housing imbalance and commuting time in the Atlanta metropolitan area: Exploration of causes of longer commuting time. Urban Geography, 23: 728–749.

Triest, Robert K. 1990. The effect of income taxation on labor supply in the United States. The Journal of Human Resources, 25 (3), Special Issue on Taxation and Labor Supply in Industrial Countries: 491–516.

Tscharaktschiew, Stefan. 2014. Shedding light on the appropriateness of the (high) gasoline tax level in Germany. Economics of Transportation, 3: 189-210

Tscharaktschiew, Stefan. 2015. How much should gasoline be taxed when electric vehicles conquer the market? An analysis of the mismatch between efficient and existing gasoline taxes under emerging electric mobility. Transportation Research Part D: Transport and Environment, 39: 89-113.

Tscharaktschiew, Stefan, and Georg Hirte. 2010a. The drawbacks and opportunities of carbon Charges in metropolitan areas – A spatial general equilibrium approach. Ecological Economics, 70: 339–357.

Tscharaktschiew, Stefan, and Georg Hirte. 2010b. How does the household structure shape the urban economy? Regional Science and Urban Economics, 40: 498–516.

Tscharaktschiew, Stefan, and Georg Hirte. 2012. Should subsidies to urban passenger transport be increased? A spatial CGE analysis for a German metropolitan area. Transportation Research Part A, 46: 285–309.

U.S. Census Bureau. 2012. America's Families and Living Arrangements: 2012.

U.S. Census Bureau. 2011. American Community Survey Reports: Commuting in the United States 2009.

U.S. Department of Labor/Bureau of Labor Statistics. 2013a. American Time Use Survey 2013.

U.S. Department of Labor/Bureau of Labor Statistics. 2013b. Occupational Employment Statistics, May 2013.

Van Dender, Kurt. 2003. Transport taxes with multiple trip purposes. Scandinavian Journal of Economics, 105: 295–310.

Van Ommeren, Jos, and Mogens Fosgerau. 2009. The workers' marginal costs of commuting: A search and mobility approach. Journal of Urban Economics, 65: 38–47.

Van Ommeren, Jos and Eva Gutiérrez-i-Puigarnau. 2011. Are workers with a long commute less productive? An empirical analysis of absenteeism. Regional Science and Urban Economics, 41: 1-8.

Verhoef, Erik T., and Peter Nijkamp. 2002. Externalities in urban sustainability: Environmental versus localization-type agglomeration externalities in a general spatial equilibrium model of a single-sector monocentric industrial city. Ecological Economics, 40: 157–179.

West, Sarah E., and Roberton C. Williams III. 2007. Optimal Taxation and Cross-price effects on labor supply: estimates of the optimal gas tax. Journal of Public Economics, 91: 593–617.

Winston, Gordon C., 2008. The timing of economic activities. Firms, households and markets in time-specific analysis. New York: Cambridge University Press

White, Michelle J. 1988. Location choice and commuting behavior in cities with decentralized employment. Journal of Urban Economics, 24: 129–152

White, Michelle J. 1977. A model of residential location choice and commuting by men and women Workers. Journal of Regional Science, 17: 41–52

Wolff, Hendrik 2014. Value of time: speeding behavior and gasoline prices. Journal of Environmental Economics and Management, 67: 71–88.

Wrede, Matthias. 2001. Should commuting expenses be tax deductible? A welfare analysis. Journal of Urban Economics, 49 (1): 80–99.

Yamamoto, Toshiyuki and Ryuichi Kitamura, 1999. An analysis of time allocation in in-home and out-of-home discretionary activities across working days and non-working days. Transportation 26: 211-230.

Yu, Sanggyun, and Hyok-Joo Rhee. 2011. A study of the welfare function of a spatial equilibrium model and the implications. Journal of the Korea Planners Association, 46 (4): 199–208.

A FOCs and VOTs for approach: HY with homogeneous leisure

On account of the additional restriction $\ell \geq \bar{\ell}$, the Lagrangian is:

$$\begin{aligned}\mathcal{L} = u\left(z, q, \underbrace{\mathcal{L}_1 + \mathcal{L}_2}_{\ell D + lL}, t^z z, tD\right) + \lambda\left\{\left(w^n h - c\right)D + I - \left(p + c^z\right)z\right\} + \gamma\left\{E - L - D\right\} \\ + \mu\left\{eD - (h+t)D - \ell D - bt^z z\right\} + \rho\left\{eL - lL - (1-b)t^z z\right\} + \pi\left(\bar{\ell} - \ell\right)D\end{aligned}$$

FOCs (we do not display derivatives w.r.t. zq):

$$\frac{\partial \mathcal{L}}{\partial l}\colon\ u_{\mathcal{L}} L - \rho L = 0 \to\ u_{\mathcal{L}} = \rho \tag{A.1}$$

$$\frac{\partial \mathcal{L}}{\partial L}\colon\ u_{\mathcal{L}} l - \gamma + \rho\left(e - l\right) = 0 \to \gamma = e\rho \tag{A.2}$$

$$\frac{\partial \mathcal{L}}{\partial \ell}\colon u_{\mathcal{L}} D - \mu D - \pi D \leq 0 \perp \pi \geq 0 \to\ u_{\mathcal{L}}\begin{cases} = \mu & \text{if } \ell > \bar{\ell} \\ = \mu + \pi & \text{if } \ell = \bar{\ell}\end{cases} \tag{A.3}$$

$$\frac{\partial \mathcal{L}}{\partial D}\colon u_{\mathcal{L}}\ell + u_t t = -\lambda\left(w^n h - c\right) + \gamma - \mu\left(e - h - t - \ell\right) - \pi\left(\bar{\ell} - \ell\right) \tag{A.4}$$

$$\frac{\partial \mathcal{L}}{\partial h}\colon \lambda w^n D - \mu D = 0 \to \frac{\mu}{\lambda} = w^n \tag{A.5}$$

Case 1 *$\ell > \bar{\ell}$ (then $\pi = 0$). From FOCs*

$$\frac{\rho}{\lambda} = \frac{\mu}{\lambda} = w^n \tag{A.6}$$

However, from (A.4) when using $\mu e = \gamma$ and $u_{\mathcal{L}} = \mu$ (A.3)

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

Both equations are equal if $c = t = 0$, which is not the case.

Case 2 *If $\ell = \bar{\ell}$ then $\pi > 0$. Then from (A.3), (A.4), since $\gamma = (\mu + \pi)\,e$ and $w^n = \mu/\lambda$ from (A.5):*

$$\frac{\pi}{\lambda} = -\frac{\nu_t t + c}{e - \bar{\ell}} \tag{A.7}$$

where $\nu_t = w^n - \frac{u_t}{\lambda}$. Eventually, substitute (A.3) into (A.4), divide by λ and substitute (A.5). Further use (A.7) and (A.2) and solve for ρ/λ. This yields VOT_l for HY with homogeneous leisure in Table 1.

B Parry and Small, 2005 - Hybrid, inhomogeneous leisure

We assume, now, that non-commuting travel (which substitutes all travel in PS) depends only on fuel and monetary travel costs (linear homogenous function, see PS)[56]

$$M^o = M^o\left(F^o, C^o\right) \tag{B.1}$$

The superscript o denotes non-commuting trips. In addition, there are D commuting trips. Total VMT M, total fuel consumption F and total monetary travel costs C are:

$$M = M^o + mD, \quad F = F^o + fD, \quad C = C^o + cD, \tag{B.2}$$

where m is VMT per commuting trip. Costs and fuel consumption for commuting are defined per two-way trip. Fuel and monetary costs can be arbitrarily chosen (mode choice, car choice, fuel choice, fuel economy).

Total travel time per capita T is:

$$T = t\left(M\right)M, \qquad t' > 0 \tag{B.3}$$

where t is driving time per VMT that depends on total number of miles driven. To simplify notations we write $t \equiv t\left(M\right)$ in the following. Further, total travel time of non-commuting is

$$T^o = t\left(M\right)M^o \tag{B.4}$$

We assumpe that pollutants, P, and accidents, A, do not depend on day of traveling, such that they are defined exactly as in PS:

$$P = P_F\left(F\right) + P_M\left(M\right), \qquad P_F', P_M' > 0 \tag{B.5}$$

$$A = A\left(M\right) = a\left(M\right)M \tag{B.6}$$

where $a\left(M\right)$ is the accident rate per mile.

The monetary budget constraint is:

$$Z + \left(q_F + \tau_F\right)F + C = I = \left(1 - \tau_w\right)H. \tag{B.7}$$

There are two time constraints: the first for time on workdays, the second is the annual days constraint:

$$H + \mathcal{L}_1 + T = eD; \qquad D + L = E, \tag{B.8}$$

where $\mathcal{L}_1 = \ell D$ (leisure on workdays).

The governments finances expenditure G by fuel taxes at rate τ_F and wage taxes at rate τ_w on total labor:

$$\tau_w H + \tau_F F = G. \tag{B.9}$$

[56]PS assume that time costs do not matter for travel decisions.

B.1 Optimal gasoline tax formula

Some definitions

$$\alpha_{FM} = F/M; \qquad \alpha_{FM}^{o} = \frac{F^{0}}{M^{0}}; \qquad \alpha_{fm} = \frac{f}{m}; \qquad \alpha_{CM}^{o} = \frac{C^{o}}{M^{o}}; \qquad \alpha_{cm} = \frac{c}{m}; \quad \text{(B.10)}$$

$$\eta_{MI} \equiv (1-\sigma_m)\,\eta_{M^oI} + \sigma_m\left(\eta_{mI} + \frac{\eta_{HI}}{\varepsilon_{Hw}^{c}}\right);$$

$$\eta_{FF} = -\frac{\mathrm{d}F}{\mathrm{d}\tau_F}\frac{p_F}{F}; \qquad \eta_{MM} = -\frac{\mathrm{d}M}{\mathrm{d}\tau_F}\frac{p_F}{M}; \qquad \beta = \frac{\eta_{MM}}{\eta_{FF}};$$

$$I \equiv (1-\tau_w)\,H; \qquad \sigma_m = \frac{mD}{M}$$

$$\varepsilon_{Hw}^{c} = -\frac{\partial^c H}{\partial \tau_w}\frac{(1-\tau_w)}{H}; \qquad \eta_{HI} = \frac{\partial H}{\partial I}\frac{I}{H}; \qquad \varepsilon_{Dw}^{c} = -\frac{\partial^c D}{\partial \tau_w}\frac{(1-\tau_w)}{D}.$$

implying that all elasticities are positively defined.

B.1.1 Utility maximization - HY inhomogeneous leisure

$$\begin{aligned}
&V(\tau_F, \tau_w; P, A, t) \qquad\qquad \text{(B.11)}\\
&= \Big\{ \max_{Z, M^o, C^o, F^o, m, \ell, L, D, h} u\left(\varphi(Z, M^o, tM^o, G), M^D, tM^D, \mathcal{L}_1, L\right) - \phi(P) - \delta(A)\\
&\quad + \mu_M\left[M^o(F^o, C^o) - M^o\right]\\
&\quad + \mu_{M^D}\left[m(f,c)\,D - M^D\right]\\
&\quad + \lambda\left[(1-\tau_w)\,H - Z - p_F(F^o + fD) - C^o - cD\right]\\
&\quad + \mu\left[eD - H - tM^D - \mathcal{L}_1 - tM^o\right]\\
&\quad + \gamma\left[E - L - D\right]\Big\}
\end{aligned}$$

Restrictions and utility are written in annual terms. Assume aggregate commuting miles depend on fuel consumption and monetary costs.

Maximizing w.r.t. Z, M^o, M^D, $\mathcal{L}_1$, L, D, H yields (after applying the Euler-Theorem $M^o = M^o_{F^o}F^o + M^o_{C^o}C^o$ (see PS) and $m = m_f f + m_c c$)

$$\begin{aligned}
&\frac{\mathrm{d}\pounds}{\mathrm{d}f}: \quad \frac{\mu_{M^D}}{\lambda} m_f = p_F \rightarrow \frac{\mu_{M^D}}{\lambda} = \frac{p_F}{m_f} = p_F\alpha_{fm} + \alpha_{cm}\\
&\frac{\mathrm{d}\pounds}{\mathrm{d}H}: \quad \frac{\mu}{\lambda} = 1-\tau_w\\
&\frac{\mathrm{d}\pounds}{\mathrm{d}\mathcal{L}_1}: \quad \frac{u_{\mathcal{L}_1}}{\lambda} = \frac{\mu}{\lambda} = 1-\tau_w\\
&\frac{\mathrm{d}\pounds}{\mathrm{d}M^D}: \quad \frac{u_{M^D}}{\lambda} = \frac{\mu_{M^D}}{\lambda} + \left(\frac{\mu}{\lambda} - \frac{u_t}{\lambda}\right)t = p_F\alpha_{fm} + \alpha_{cm} + \nu_t t = p_m,\\
&\qquad\qquad \text{where } \nu_t \equiv 1-\tau_w - \frac{u_t}{\lambda}\\
&\frac{\mathrm{d}\pounds}{\mathrm{d}D}: \quad \frac{\mu_{M^D}}{\lambda} m - \lambda(p_F f + c) + \mu e - \gamma = 0 \rightarrow \frac{\gamma}{\lambda} = (1-\tau_w)\,e\\
&\frac{\mathrm{d}\pounds}{\mathrm{d}L}: \quad \frac{u_L}{\lambda} = \frac{\gamma}{\lambda} = (1-\tau_w)\,e
\end{aligned}$$

where $\alpha_{fm} = f/m$ and $\alpha_{cm} = c/m$. The reason why VOT on a leisure day is $(1-\tau_w)\,e$ is that the commuting cost component is part of M^D. We assume that D has two components, one is fully substitutable with h and the other part is fully substitutable with m, which is the miles depending component.

$$\frac{u_Z}{\lambda} = 1; \quad \frac{u_{\mathcal{L}_1}}{\lambda} = 1 - \tau_w; \quad \frac{u_L}{\lambda} = \frac{1-\tau_w}{e}; \quad \frac{u_{M^o}}{\lambda} = p_M; \qquad \frac{u_{M^D}}{\lambda} = p_m$$

where the full consumer prices of a non-commuting VMT and a commuting VMT are

$$p_M \equiv p_F \alpha^o_{FM} + \alpha^o_{CM} + \nu^o t, \qquad p_m \equiv p_F \alpha_{fm} + \alpha_{cm} + \nu_t t$$

with VTTs for non-commuting and commuting travel

$$\nu^o \equiv (1-\tau_w) - \frac{u_{T^o}}{\lambda}, \quad \nu_t \equiv (1-\tau_w) - \frac{u_t}{\lambda}.$$

Further, $p_F \equiv q_F + \tau_F$ and the VOT of an hour is $1 - \tau_w$.

Partial derivatives are

$$\begin{aligned} \frac{\partial p_M}{\partial \tau_F} &= \alpha^o_{FM}; & \frac{\partial p_M}{\partial t} &= \nu^o \\ \frac{\partial p_m}{\partial \tau_F} &= \alpha_{fm}; & \frac{\partial p_m}{\partial t} &= \nu_t \end{aligned} \tag{B.12}$$

changes in travel time:

$$\frac{\mathrm{d}t}{\mathrm{d}\tau_F} = t' \left(\frac{\mathrm{d}M^o}{\mathrm{d}\tau_F} + \frac{\mathrm{d}M^D}{\mathrm{d}\tau_F} \right) = t' \frac{\mathrm{d}M}{\mathrm{d}\tau_F} \tag{B.13}$$

B.1.2 Differentiate government budget

Demands are

$$Z^o = Z^o(p_M, p_m, \tau_w); \qquad M^o = M^o(p_M, p_m, \tau_w); \qquad H = H(p_M, \tau_w, p_m); \tag{B.14}$$

$$\begin{aligned} & m = m(p_M, p_m, \tau_w); \qquad D = D(p_M, p_m, \tau_w); \\ & M^D = M^D(p_M, p_m, \tau_w) = m(p_M, p_m, \tau_w) D(p_M, p_m, \tau_w) \\ & F = \alpha_{FM^o}(\tau_F) M^0(p_M, p_m, \tau_w), \\ & F^D = f(\tau_F) M^D(p_M, p_m, \tau_w) \end{aligned} \tag{B.15}$$

Partial derivatives of $V(t_F, \tau_w, t; P, A)$ and applying the envelope theorem (B.11):

$$\begin{aligned} \frac{\partial V}{\partial \tau_F} &= -\lambda (F^o + fD); & \frac{\partial V}{\partial \tau_w} &= -\lambda H; \\ \frac{\partial V}{\partial P} &= -\varphi'(P); & \frac{\partial V}{\partial A} &= -\delta'(P); \\ \frac{\partial V}{\partial t} &= -\lambda (\nu^o M^o + \nu_t m D) \end{aligned} \tag{B.16}$$

Totally differentiating the government budget constraint (B.9) yields (at constant expenditure)

$$\frac{d\tau_w}{d\tau_F} = -\frac{F + \tau_F \frac{dF}{d\tau_F} + \tau_w \frac{dH}{d\tau_F}}{H} \tag{B.17}$$

B.1.3 Deriving the optimal fuel tax

Totally differentiating indirect utility $V(\tau_F, \tau_w, t; P, A)$ [note: $\theta = \theta(\tau_F, \tau_w, t)$] yields after using (B.16) and (B.17) and Roy's identity.

$$
\begin{aligned}
\frac{1}{\lambda}\frac{\mathrm{d}V}{\mathrm{d}\tau_F} &= \frac{1}{\lambda}\frac{\partial V}{\partial \tau_F} + \frac{1}{\lambda}\frac{\partial V}{\partial \tau_w}\frac{\mathrm{d}\tau_w}{\mathrm{d}\tau_F} + \frac{1}{\lambda}\frac{\partial V}{\partial P}\frac{\mathrm{d}P}{\mathrm{d}\tau_F} + \frac{1}{\lambda}\frac{\partial V}{\partial A}\frac{\mathrm{d}A}{\mathrm{d}t_F} + \frac{1}{\lambda}\frac{\partial V}{\partial t}\frac{\mathrm{d}t}{\mathrm{d}\tau_F} \\
&= -F - H\left(-\frac{F + \tau_F\frac{\mathrm{d}F}{\mathrm{d}\tau_F} + \tau_w\frac{\mathrm{d}H}{\mathrm{d}\tau_F}}{H}\right) - \underbrace{\frac{1}{\lambda}\phi' P_F'}_{E^{P_F}}\frac{\mathrm{d}F}{\mathrm{d}t_F} - \underbrace{\frac{1}{\lambda}\phi' M_F'}_{E^{P_M}}\frac{\mathrm{d}M}{\mathrm{d}t_F} \\
&\quad - \underbrace{\frac{1}{\lambda}\delta' A'}_{E^A}\frac{\mathrm{d}M}{\mathrm{d}t_F} - \underbrace{(\nu^o M^o + \nu_t m D)\, t'}_{E^c}\frac{\mathrm{d}M}{\mathrm{d}\tau_F}
\end{aligned}
$$

Consolidating yields:

$$
\frac{1}{\lambda}\frac{\mathrm{d}V}{\mathrm{d}\tau_F} = \left(E^{P_F} - \tau_F\right)\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_F}\right) + \left(E^c + E^{P_M} + E^A\right)\left(-\frac{\mathrm{d}M}{\mathrm{d}\tau_F}\right) + \tau_w\frac{\mathrm{d}H}{\mathrm{d}\tau_F} \tag{B.18}
$$

Look at $\tau_w\frac{\mathrm{d}H}{\mathrm{d}\tau_w}$ in (B.18). Since p_M, p_m and θ only depend on τ_w, τ_F and t we can rewrite $H = H(\tau_F, \tau_w, t)$ (see PS) implying

$$
\frac{\mathrm{d}H}{\mathrm{d}\tau_F} = \frac{\partial H}{\partial \tau_F} + \frac{\partial H}{\partial t}\frac{\mathrm{d}t}{\mathrm{d}\tau_F} + \frac{\partial H}{\partial \tau_w}\frac{\mathrm{d}\tau_w}{\mathrm{d}\tau_F} \tag{B.19}
$$

Substituting into (B.17) and solving for $\mathrm{d}t_w/\mathrm{d}t_F$ yields

$$
\frac{\mathrm{d}\tau_w}{\mathrm{d}\tau_F} = -\frac{F + \tau_F\frac{\mathrm{d}F}{\mathrm{d}\tau_F} + \tau_w\left(\frac{\partial H}{\partial \tau_F} + \frac{\partial H}{\partial t}\frac{\mathrm{d}t}{\mathrm{d}\tau_F}\right)}{H + \tau_w\frac{\partial H}{\partial \tau_w}} \tag{B.20}
$$

Insert into (B.19) and multiply by τ_w to get (see PS)

$$
\tau_w\frac{\mathrm{d}H}{\mathrm{d}\tau_F} = MEB\cdot\tau_F\frac{\mathrm{d}F}{\mathrm{d}\tau_F} - \frac{MEB}{\partial H/\partial \tau_w}\left(\frac{\partial H}{\partial \tau_F}H - \frac{\partial H}{\partial \tau_w}F + H\frac{\partial H}{\partial t}\frac{\mathrm{d}t}{\mathrm{d}\tau_F}\right) \tag{B.21}
$$

where

$$
MEB_H = \frac{-\tau_w\frac{\partial H}{\partial \tau_w}}{H + \tau_w\frac{\partial H}{\partial \tau_w}} = \frac{\tau_w\varepsilon_{Hw}}{1 - \tau_w(1 + \varepsilon_{Hw})} \tag{B.22}
$$

Further, terms in brackets in (B.21) are due to (B.12):

$$
\begin{aligned}
\frac{\partial H}{\partial \tau_F} &= \frac{\partial H}{\partial p_M}\frac{\partial p_M}{\partial \tau_F} + \frac{\partial H}{\partial p_m}\frac{\partial p_m}{\partial \tau_F} \\
&= \alpha_{FM}^o\frac{\partial H}{\partial p_M} + \alpha_{fm}\frac{\partial H}{\partial p_m}
\end{aligned} \tag{B.23}
$$

$$
\begin{aligned}
\frac{\partial H}{\partial t} &= \frac{\partial H}{\partial p_M}\frac{\partial p_M}{\partial t} + \frac{\partial H}{\partial p_m}\frac{\partial p_m}{\partial t} \\
&= \nu^o\frac{\partial H}{\partial p_M} + \nu_t\frac{\partial H}{\partial p_m}.
\end{aligned} \tag{B.24}
$$

To perform simulations we apply the following manipulations. From Slutsky

$$\begin{aligned}
\frac{\partial H}{\partial p_M} &= \frac{\partial^c H}{\partial p_M} - \frac{\partial H}{\partial I} M^o; \qquad \frac{\partial H}{\partial \tau_w} = \frac{\partial^c H}{\partial \tau_w} - \frac{\partial H}{\partial I} H; \\
\frac{\partial H}{\partial p_m} &= \frac{\partial^c H}{\partial p_m} - \frac{\partial H}{\partial I} M^D; \\
\frac{\partial D}{\partial \tau^w} &= \frac{\partial^c D}{\partial \tau^w} - \frac{\partial D}{\partial I} H
\end{aligned} \tag{B.25}$$

it follows that (B.23) and (B.24) change into (assume $fD/F = mD/M = \sigma_m$

$$\begin{aligned}
\frac{\partial H}{\partial \tau_F} &= \alpha^o_{FM} \frac{\partial^c H}{\partial p_M} + \alpha_{fm} \frac{\partial^c H}{\partial p_m} - F \frac{\partial H}{\partial I} \\
\frac{\partial H}{\partial t} &= \nu^o \frac{\partial^c H}{\partial p_M} + \nu_t \frac{\partial^c H}{\partial p_m} - \nu M \frac{\partial H}{\partial I}.
\end{aligned} \tag{B.26}$$

where $\sigma_f \equiv fD/F$ and $\sigma_m \equiv M^D/M$ and $\nu M = \nu^o M^o + \nu_t mD$. Further due to symmetry of the Slutsky substitution matrix:

$$\frac{\partial^c H}{\partial p_M} = \frac{\partial^c M^o}{\partial \tau_w}, \qquad \frac{\partial^c H}{\partial p_m} = D \frac{\partial^c m}{\partial \tau_w} + m \frac{\partial^c D}{\partial \tau^w} \tag{B.27}$$

On account of the weak separability assumption all effects of τ_w on M occur via "a change in disposable income (Layard and Walters 1978, p.166)" [see PS]:

$$\frac{\partial^c M^o}{\partial \tau_w} = \frac{\partial M^o}{\partial I} (1 - \tau_w) \frac{\partial^c H}{\partial \tau_w}, \qquad \frac{\partial^c m}{\partial \tau_w} = \frac{\partial m}{\partial I} (1 - \tau_w) \frac{\partial^c H}{\partial \tau_w} \tag{B.28}$$

Then, from Slutsky we get

$$\frac{\partial^c H}{\partial p_m} = \frac{\partial^c M^D}{\partial \tau_w} = D \frac{\partial m}{\partial I} (1 - \tau_w) \frac{\partial^c H}{\partial \tau_w} + m \frac{\partial^c D}{\partial \tau_w} \tag{B.29}$$

Using (B.28) and (B.29) we can rewrite (B.26) as

$$\begin{aligned}
\frac{\partial H}{\partial \tau_F} H = &- \alpha^o_{FM} \frac{\partial M^o}{\partial I} (1 - \tau_w) \left(- \frac{\partial^c H}{\partial \tau_w} \right) H - \alpha_{fm} D \frac{\partial m}{\partial I} (1 - \tau_w) \left(- \frac{\partial^c H}{\partial \tau_w} \right) H \\
&- f \left(- \frac{\partial^c D}{\partial \tau_w} \right) H - F \frac{\partial H}{\partial I} H
\end{aligned}$$

respectively

$$\begin{aligned}
\frac{\partial H}{\partial t} = &- \nu^o \frac{\partial M^o}{\partial I} (1 - \tau_w) \left(- \frac{\partial^c H}{\partial \tau_w} \right) - \nu_t D \frac{\partial m}{\partial I} (1 - \tau_w) \left(- \frac{\partial^c H}{\partial \tau_w} \right) \\
&- \nu_t m \left(- \frac{\partial^c D}{\partial \tau_w} \right) - \nu M \frac{\partial H}{\partial I}.
\end{aligned}$$

Expanding and substituting elasticities implies

$$\begin{aligned}
\frac{\partial H}{\partial \tau_F} H = &- \left[(1 - \sigma_f) \eta_{M^o I} + \sigma_f \eta_{mI} \right] \varepsilon^c_{Hw} F \frac{H}{1 - \tau^w} \\
&- \sigma_f \varepsilon^c_{Dw} \frac{H}{1 - \tau^w} - F \eta_{HI} \frac{H}{1 - \tau_w},
\end{aligned}$$

respectively

$$\frac{\partial H}{\partial t}H = -\left[\left(1-\sigma_m\right)\eta_{M^oI} + \sigma_m \eta_{mI}\right]\nu M \varepsilon^c_{HW}\frac{H}{1-\tau^w} - \frac{\nu_t}{\nu}\sigma_m \varepsilon^c_{Dw} M \frac{H}{1-\tau_w} - \eta_{HI}\nu M \frac{H}{1-\tau_w}$$

To simplify, we assume $\nu^o = \nu_t = \nu$ and define the aggregate income elasticity of miles as[57]

$$\eta_{MI} \equiv \left(1-\sigma_m\right)\eta_{M^oI} + \sigma_m \eta_{mI} \tag{B.30}$$

From Slutsky equation: $\eta_{HI} = \varepsilon_{Hw} - \varepsilon^c_{Hw}$, thus:

$$\frac{\partial H}{\partial \tau_F}H - \frac{\partial H}{\partial \tau_w}F = \left(1-\eta_{MI}\right)\varepsilon^c_{Hw} F \frac{H}{1-\tau_w} - \sigma_m \varepsilon^c_{Dw} F \frac{H}{1-\tau_w}, \tag{B.31}$$

respectively

$$\frac{\partial H}{\partial t}H = -\left[\varepsilon_{Hw} - \left(1-\eta_{MI}\right)\varepsilon^c_{Hw}\right]\nu M \frac{H}{1-\tau_w} - \sigma_m \varepsilon^c_{Dw}\nu M \frac{H}{1-\tau_w}. \tag{B.32}$$

Substitute (B.31) and (B.32) into (B.21) (note that $\varepsilon_{Hw} = -\frac{\partial H}{\partial \tau_w}\frac{1-\tau_w}{H}$):

$$\begin{aligned}\tau_w \frac{\mathrm{d}H}{\mathrm{d}\tau_F} = & -MEB \cdot \tau_F \left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_F}\right) \\ & + \frac{MEB}{\varepsilon_{Hw}}\left(1-\eta_{MI}\right)\varepsilon^c_{Hw} F - \sigma_m \frac{MEB}{\varepsilon_{Hw}}\varepsilon^c_{Dw} F \\ & - \frac{MEB}{\varepsilon_{Hw}}\left[\varepsilon_{Hw} - \left(1-\eta_{MI}\right)\varepsilon^c_{Hw}\right]\nu M t' \frac{\mathrm{d}M}{\mathrm{d}\tau_F} \\ & - \frac{MEB}{\varepsilon_{Hw}}\sigma_m \varepsilon^c_{Dw}\nu M t' \frac{\mathrm{d}M}{\mathrm{d}\tau_F}\end{aligned} \tag{B.33}$$

Next, equate (B.18) to zero and substitute (B.33). Solving for τ_F yields

$$\begin{aligned}\tau_F = & \frac{MEC}{1+MEB} \\ & + \frac{MEB}{\left(1+MEB\right)\varepsilon_{Hw}}\frac{\left(1-\eta_{MI}\right)\varepsilon^c_{Hw}}{\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_F}\frac{1}{F}\right)} - \sigma_m \frac{MEB}{\left(1+MEB\right)\varepsilon_{Hw}}\frac{\varepsilon^c_{Dw}}{\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_F}\frac{1}{F}\right)} \\ & - \frac{MEB}{\left(1+MEB\right)\varepsilon_{Hw}}\frac{\left[\varepsilon_{Hw} - \left(1-\eta_{MI}\right)\varepsilon^c_{Hw}\right]E^c \frac{\mathrm{d}M}{\mathrm{d}\tau_F}}{\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_F}\frac{1}{F}\right)} - \sigma_m \frac{MEB}{\left(1+MEB\right)\varepsilon_{Hw}}\frac{\varepsilon^c_{Dw}E^c \frac{\mathrm{d}M}{\mathrm{d}\tau_F}}{\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau_F}\frac{1}{F}\right)}\end{aligned}$$

Since

$$\frac{MEB_H}{\left(1+MEB_H\right)\varepsilon_{Hw}} = \frac{\tau_w}{1-\tau_w}, \quad \eta_{FF} = -\frac{\frac{\mathrm{d}F}{\mathrm{d}\tau_F}}{F}p_F$$

we get

$$\begin{aligned}\tau_F = & \frac{MEC}{1+MEB} \\ & + \left[\frac{\left(1-\eta_{MI}\right)\varepsilon^c_{Hw}}{\eta_{FF}} - \sigma_m \frac{\varepsilon^c_{Dw}}{\eta_{FF}}\right]\frac{p_F \tau_w}{1-\tau_w} \\ & - \frac{\frac{\mathrm{d}M}{\mathrm{d}\tau_F}p_F}{\eta_{FF}}\left[\left[\varepsilon_{Hw} - \left(1-\eta_{MI}\right)\varepsilon^c_{Hw}\right] + \sigma_m \frac{\varepsilon^c_{Dw}}{\eta_{FF}}\right]E^c \frac{\tau_w}{1-\tau_w}\end{aligned}$$

[57]We further assume that $\sigma_f = \sigma_m$ implying that $fD/F = M^D/M$ so that fuel consumption per VMT is the same for commuting and non-commuting travel.

Further, substituting $\beta = \frac{\eta_{MF}}{\eta_{FF}}$ and $\eta_{MF} = -\frac{\partial M}{\partial \tau_F}\frac{p_F}{M}$

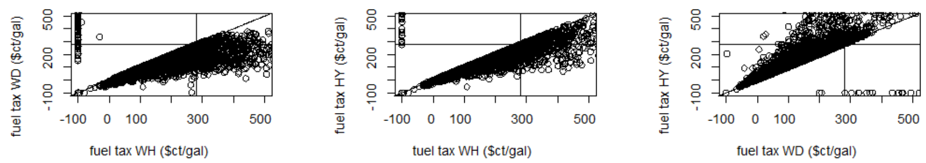
$$\begin{aligned}
\tau_F = &\frac{MEC}{1+MEB} \\
&+ \left[\frac{(1-\eta_{MI})\,\varepsilon^c_{Hw}}{\eta_{FF}} - \sigma_m \frac{\varepsilon^c_{Dw}}{\eta_{FF}}\right]\frac{p_F \tau_w}{1-\tau_w} \\
&+ \beta \frac{M}{F} E^c \left[\left[\varepsilon_{Hw} - (1-\eta_{MI})\,\varepsilon^c_{Hw}\right] + \sigma_m \frac{\varepsilon^c_{Dw}}{\eta_{FF}}\right]\frac{\tau_w}{1-\tau_w}
\end{aligned}$$

C Data and Monte Carlo Simulation

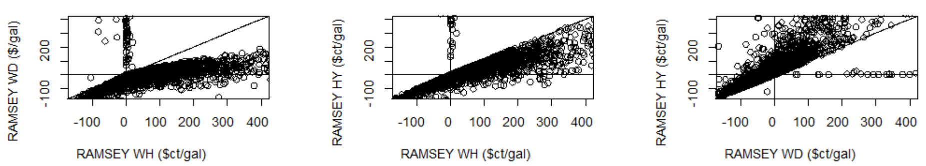
Table C.1: Parameters in the Monte Carlo Simulation

Parameter	US central value	US range	UK central value	UK range
Compensated workdays elasticity ε^c_{Dw}	0.2	0.0-ε^c_{Hw}	0.2	0.0-ε^c_{Hw}
Compensated labor supply elasticity ε^c_{Hw}	0.35		0.35	
Uncompensated labor supply elasticity ε^u_{Hw}	0.2		0.2	
Uncompensated labor supply elasticity ε^u_{Hw}	0.2		0.2	
VMT income elasticity η_{M^0I}	0.6	0.3-0.9	0.9	0.4-1.2
VMT expenditure elasticity η_{FF}	0.6	0.3-0.9	0.9	0.4-1.2
VMT portion of gas price elasticity β	0.4	0.2-0.6	0.4	0.2-0.6
Workdays per year (days)	236.8		223.2	
Share of non-commuting miles	0.72		0.725	

Figure C.1: Comparison of LSMs in case of UK



A) fuel tax UK WD/WH B) fuel tax UK HY/WH C) fuel tax UK HY/WD



D) Ramsey UK WD/WH E) Ramsey UK HY/WH F) Ramsey UK HY/WD

Pairwise plots of optimal fuel taxes (upper panels; vertical and horizontal lines represent the UK fuel tax in 2005: 2.80 BRP ¢/gallon) and Ramsey tax terms (lower panels) for the UK for the LSMs. Each dot represents the results for the identical parameter constellation. Panels A) and D): WD vs. WH, WH is the upper limit for WD. Panels B) and E): HY vs. WH, WH is the upper limit for HY. Panel C) and F): HY vs. WD, WD is the lower limit for HY. A few parameter combinations produce irregularities (division by zero etc.) Source: own calculations.

D General hybrid model: HY with inhomogeneous leisure

D.1 Congestion tolls with head tax recycling

Definitions and derivatives

Consolidate (10)-(13) to get the consolidated budget constraint

$$\theta_{ij}^{l} E + I = \sum_{k} P_{ijk} z_{ijk} + r_i q_{ij} + w_j^n \left(E - L_{ij}\right) \ell_{ij} + \theta_{ij}^{l} l_{ij} L_{ij}, \tag{D.1}$$

where $\theta_{ij}^{l} \equiv VOTl^{Yi}$ (2). The full consumer price of shopping in zone k is

$$P_{ijk} \equiv p_k + c_{ik}^{z} + \left[b w_j^n + (1-b)\,\theta_{ij}^{l}\right] t_{ik}^{z}$$

For later reference we have

$$\mathrm{d}\theta_{ij}^{l} = \left(\frac{e - t_{ij}}{e}\right) \mathrm{d}w_j^n - \frac{w_j^n}{e} \mathrm{d}t_{ij} - \frac{1}{e} \mathrm{d}c_{ij} \tag{D.2}$$

$$\mathrm{d}P_{ijk} = \mathrm{d}p_k + \mathrm{d}c_{ik}^{z} - (1-b)\,\frac{t_{ik}^{z}}{e} \mathrm{d}c_{ij} - (1-b)\,\frac{w_j^n t_{ik}^{z}}{e} \mathrm{d}t_{ij}$$
$$+ \left[1 - (1-b)\,\frac{t_{ij}}{e}\right] t_{ik}^{z} \mathrm{d}w_j^n \tag{D.3}$$

Using (8)-(13) gives indirect utility. Since all prices depend on the policy parameters τ_{hk}^{t} and the recycling tax τ^{ls} we write

$$V_{ij}\left(\tau_{hk}^{t} | \forall hk, \tau^{ls}\right) = \{\max u\left(z_{ijk}, q_{ij}, \mathcal{L}_{1ij}, \mathcal{L}_{2ij}\right) \tag{D.4}$$
$$+\lambda\left(\theta_{ij}^{l} e E_{ij} + I - w_j^n \ell_{ij} D_{ij} - \theta_{ij}^{l} l_{ij} L_{ij} - \textstyle\sum_{k} P_{ijk} z_{ijk} - r_i q_{ij}\right)\right\},$$

For later use we totally differentiate V w. r. t. policy parameters and apply the envelope theorem (Yu and Rhee, 2011; Rhee et al., 2014) to (D.4)[58], yielding

$$\frac{1}{\lambda_{ij}} \frac{\mathrm{d}V_{ij}}{\mathrm{d}\tau_{hk}^{t}} = \left(e E_{ij} - l_{ij} L_{ij}\right) \frac{\mathrm{d}\theta_{ij}^{l}}{\mathrm{d}\tau_{hk}^{t}} - \ell_{ij} D_{ij} \frac{\mathrm{d}w_j^n}{\mathrm{d}\tau_{hk}^{t}} + \frac{\mathrm{d}ARL}{\mathrm{d}\tau_{hk}^{t}} - \frac{\mathrm{d}\tau^{ls}}{\mathrm{d}\tau_{hk}^{t}} - \sum_{l} z_{ijl} \frac{\mathrm{d}P_{ijl}}{\mathrm{d}\tau_{hk}^{t}} - q_{ij} \frac{\mathrm{d}r_i}{\mathrm{d}\tau_{hk}^{t}}.$$

Substituting (D.2), (D.3), the time budget constraints (11)-(13) and defining $H_{ij} \equiv h_{ij} D_{ij}$ yields:

$$\frac{1}{\lambda_{ij}} \frac{\mathrm{d}V_{ij}}{\mathrm{d}\tau_{hk}^{t}} = H_{ij} \frac{\mathrm{d}w_j^n}{\mathrm{d}\tau_{hk}^{t}} - w_{ij}^n D_{ij} \frac{\mathrm{d}t_{ij}}{\mathrm{d}\tau_{hk}^{t}} - \delta_{ij} D_{ij} \tag{D.5}$$
$$+ \frac{\mathrm{d}ARL}{\mathrm{d}\tau_{hk}^{t}} - \frac{\mathrm{d}\tau^{ls}}{\mathrm{d}\tau_{hk}^{t}} - q_{ij} \frac{\mathrm{d}r_i}{\mathrm{d}\tau_{hk}^{t}} - \sum_{l} z_{ijl} \frac{\mathrm{d}p_l}{\mathrm{d}\tau_{hk}^{t}}.$$

where we assume that monetary transport costs other than tolls are constant. δ_{ij} is an indicator set to unity if $ij = hk$ and zero otherwise.

From $X_i = f\left(Q_i, M_i\right)$ Euler's theorem implies $\mathrm{d}X_i = f_Q \mathrm{d}Q_i + f_M \mathrm{d}M_i$. Multiplied by p_i and due to profit maximization:

$$p_i \mathrm{d}X_i = r_i \mathrm{d}Q_i + w_i \mathrm{d}M_i. \tag{D.6}$$

[58] This is equivalent to applying Roy's identity to $V\left(P_{ijk} | \forall ijk, r_i, w_j^n, \theta_{ij}^{l}, \theta_{ij}^{l} e E_{ij} + I\right)$.

Totally differentiate zero profits $p_i X_i = w_i M_i + r_i Q_i$:

$$p_i \mathrm{d}X_i + X_i \mathrm{d}p_i = w_i \mathrm{d}M_i + M_i \mathrm{d}w_i + r_i \mathrm{d}Q_i + Q_i \mathrm{d}r_i.$$

Plug in (D.6) yields

$$X_i \mathrm{d}p_i = M_i \mathrm{d}w_i + Q_i \mathrm{d}r_i. \tag{D.7}$$

Differentiating the government budget constraint (14) w.r.t. to τ^t_{hk}:

$$\frac{\mathrm{d}\tau^{ls}}{\mathrm{d}\tau^t_{hk}} = \frac{1}{N} \sum s_i A_i \frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}} - \frac{1}{N} T_{hk} - \frac{1}{N} \sum_{i,j} \tau^t_{ij} \frac{\mathrm{d}T^t_{ij}}{\mathrm{d}\tau^t_{hk}} - \frac{\tau^w}{N} \frac{\mathrm{d}T^w}{\mathrm{d}\tau^t_{hk}} \tag{D.8}$$

Eventually, the population has to be fully distributed across the city. This is achieved because $\sum_{i,j} \psi_{ij} = 1$. 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 (16)–(D.10):

$$\mathrm{d}X_i = N \sum_{j,k} (\psi_{ij} \mathrm{d}z_{ijk} + z_{ijk} \mathrm{d}\psi_{ij}) \tag{D.9}$$

$$\mathrm{d}M_j = N \sum_{i} (\psi_{ij} \mathrm{d}H_{ij} + h_{ij} D_{ij} \mathrm{d}\psi_{ij}) \tag{D.10}$$

$$0 = \mathrm{d}Q_i + N \sum_{j} (\psi_{ij} \mathrm{d}q_{ij} + q_{ij} \mathrm{d}\psi_{ij}) \tag{D.11}$$

Eventually, differentiating $ALR \equiv \frac{1}{N} \sum_i r_i A_i$ w. r. t. the policy variable:

$$\begin{aligned} \frac{\mathrm{d}ALR}{\mathrm{d}\tau^t_{lh}} = N \sum_{i,j} & \left(\psi_{ij} r^q_i \frac{\mathrm{d}q_i}{\mathrm{d}\tau^t_{lh}} + \psi_{ij} q_i \frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{lh}} + r^q_i q_i \frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau^t_{lh}} \right) \\ & + \sum_i \left(r_i \frac{\mathrm{d}Q_i}{\mathrm{d}\tau^t_{lh}} + Q_i \frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{lh}} \right) + \sum_i s_i A_i \frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{lh}}. \end{aligned} \tag{D.12}$$

Marginal welfare changes with lump sum recycling

Plugging (D.5) into (19) yields for the congestion toll

$$\begin{aligned} \frac{\mathrm{d}W}{\mathrm{d}\tau^t_{hk}} = & -N \sum_i \sum_j \psi_{ij} \lambda_{ij} w^n_j D_{ij} \frac{\mathrm{d}t_{ij}}{\mathrm{d}\tau^t_{hk}} - N \psi_{hk} \lambda_{hk} D_{hk} \\ & + N (1 - \tau^w) \sum_{i,j} \psi_{ij} \lambda_{ij} H_{ij} \frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}} - N \sum_{i,j,l} \psi_{ij} \lambda_{ij} z_{ijl} \frac{\mathrm{d}p_l}{\mathrm{d}\tau^t_{hk}} \\ & - N \sum_{i,j} \psi_{ij} \lambda_{ij} q_{ij} \frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}} + N \lambda \left(\frac{\mathrm{d}ALR}{\mathrm{d}\tau^t_{hk}} - \frac{\mathrm{d}\tau^{ls}}{\mathrm{d}\tau^t_{hk}} \right) \end{aligned} \tag{D.13}$$

Using (D.12) to substitute $\frac{\mathrm{d}ALR}{\mathrm{d}\tau^t_{hk}}$ and (D.8), the derivatives of (15) w. r. t. τ^t_{hk} to substitute $\frac{\mathrm{d}\tau^{ls}}{\mathrm{d}\tau^t_{hk}}$ expands (D.13)

$$
\begin{aligned}
\frac{1}{\lambda}\frac{\mathrm{d}W}{\mathrm{d}\tau^t_{hk}} = &- \frac{N}{\lambda}\sum_{i,j}\psi_{ij}\lambda_{ij}D_{ij}w^n_j\frac{\mathrm{d}t_{ij}}{\mathrm{d}\tau^t_{hk}} \\
&+ \frac{N}{\lambda}\left(1-\tau^w\right)\sum_{i,j}\psi_{ij}\lambda_{ij}H_{ij}\frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}} \\
&- \frac{N}{\lambda}\sum_{i,j,l}\psi_{ij}\lambda_{ij}z_{ijl}\frac{\mathrm{d}p_l}{\mathrm{d}\tau^t_{hk}} - \frac{N}{\lambda}\sum_{i,j}\psi_{ij}\lambda_{ij}q_i\frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}} \\
&+ N\sum_i\left(\psi_{ij}r_i\frac{\mathrm{d}q_i}{\mathrm{d}\tau^t_{hk}} + \psi_{ij}q_i\frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}} + r_iq_i\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau^t_{hk}}\right) + \sum_i\left(r_i\frac{\mathrm{d}Q_i}{\mathrm{d}\tau^t_{hk}} + Q_i\frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}}\right) \\
&+ \sum_i s_iA_i\frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}} - \sum s_iA_i\frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}} + \underbrace{\left(N\sum_j\psi_{kj}D_{kj} + N\sum_{j,j\neq k}\psi_{jk}D_{jk}\right)}_{\sum_{i,j}\psi_{ij}\delta^kD_{ij}} \\
&+ N\psi_{hk}D_{hk} - \frac{N}{\lambda}\lambda_{hk}\psi_{hk}D_{hk} + N\sum_{i,j}\tau^t_{ij}\left(\psi_{ij}\frac{\mathrm{d}D_{ij}}{\mathrm{d}\tau^t_{hk}} + D_{ij}\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}tau^t_{hk}}\right) \\
&+ \tau^wN\sum_{i,j}\left(\psi_{ij}w_j\frac{\mathrm{d}H_{ij}}{\mathrm{d}\tau^t_{hk}} + w_jh_{ij}D_{ij}\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau^t_{hk}} + \psi_{ij}h_{ij}D_{ij}\frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}}\right).
\end{aligned}
\tag{D.14}
$$

After expanding (D.14) by λ times different terms, we have

$$
\begin{aligned}
\frac{1}{\lambda}\frac{\mathrm{d}W}{\mathrm{d}\tau^t_{hk}} = &MEC^t_{hk}\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau^t_{hk}}\right) \\
&+ N\sum_{i,j}\underbrace{\psi_{ij}H_{ij}}_{L_j}\frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}} - N\sum_{i,j,l}\underbrace{\psi_{ij}z_{ijl}}_{X_l}\frac{\mathrm{d}p_l}{\mathrm{d}\tau^t_{hk}} + \sum_i Q_i\frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}} \\
&+ \sum_i\left[\sum_j N\left(\psi_{ij}r_i\frac{\mathrm{d}q_i}{\mathrm{d}\tau^t_{hk}} + r_iq_i\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau^t_{hk}}\right) + r_i\frac{\mathrm{d}Q_i}{\mathrm{d}\tau^t_{hk}}\right] \\
&+ N\left[\psi_{hk}D_{hk} + \sum_{i,j}\tau^t_{ij}\left(\psi_{ij}\frac{\mathrm{d}D_{ij}}{\mathrm{d}\tau^t_{hk}} + D_{ij}\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau^t_{hk}}\right)\right] \\
&+ \tau^wN\sum_{i,j}\left(\psi_{ij}w_j\frac{\mathrm{d}H_{ij}}{\mathrm{d}\tau^t_{hk}} + w_jh_{ij}D_{ij}\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\tau^t_{hk}}\right) \\
&+ MEC^t_{hk}\left(-\frac{\mathrm{d}F}{\mathrm{d}\tau^t_{hk}}\right)\left(\phi^{mec}_{hk}-1\right) + Y^t_{hk}\left(\phi^y_{hk}-1\right) - N\psi_{hk}D_{hk}\left(\phi^{toll}_{hk}-1\right) \\
&- \tau^wN\left(\sum_{i,j}\psi_{ij}H_{ij}\frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}}\right)\left(\phi^{wtax}_{hk}-1\right).
\end{aligned}
\tag{D.15}
$$

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 MECs

$$Y^t_{hk} \equiv N \sum_{i,j} \psi_{ij} h_{ij} D_{ij} \frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}} - N \sum_{i,j,l} \psi_{ij} z_{ijl} \frac{\mathrm{d}p_l}{\mathrm{d}\tau^t_{hk}} - N \sum_{i,j} \psi_{ij} q_i \frac{\mathrm{d}r_i}{\mathrm{d}\tau^t_{hk}} \tag{D.16}$$

$$y^t_{hk} \equiv N \sum_{i,j} \psi_{ij} \lambda_{ij} h_{ij} D_{ij} \frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}} - N \sum_{i,j,l} \psi_{ij} \lambda_{ij} z_{ijl} \frac{\mathrm{d}p_l}{\mathrm{d}\tau^t_{hk}} - N \sum_{i,j} \psi_{ij} \lambda_{ij} q_i \frac{\mathrm{d}r^q_i}{\mathrm{d}\tau^t_{hk}} \tag{D.17}$$

$$mecc^t_{hk} \equiv N \sum_{i,j} \psi_{ij} \lambda_{ij} D_{ij} w^n_j \frac{\mathrm{d}t_{ij}/\mathrm{d}\tau^t_{hk}}{\mathrm{d}F/\mathrm{d}\tau^t_{hk}}. \tag{D.18}$$

$$T^{wtax}_{hk} \equiv N\tau^w \sum_{i,j} \psi_{ij} H_{ij} \frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}} \left(1 - \phi^{T^{wtax}}\right).$$

Further, distributional characteristics are:

$$\phi^y_{hk} \equiv \frac{y^t_{hk}}{\lambda Y^t_{hk}}, \qquad \phi^{mec}_{hk} \equiv \frac{mec^t_{hk}}{\lambda MEC^t_{hk}}, \qquad \phi^{toll}_{hk} \equiv \frac{\lambda_{hk}}{\lambda} \tag{D.19}$$

$$\phi^{wtax} = \frac{\tau^w \sum_{i,j} \psi_{ij} \lambda_{ij} H_{ij} \frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}}}{\lambda \tau^w \sum_{i,j} \psi_{ij} H_{ij} \frac{\mathrm{d}w_j}{\mathrm{d}\tau^t_{hk}}}$$

The second row in (D.15) 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 rows represent redistribution effects due to differences in the MUI between worker types. By inserting (D.7) (D.15) simplifies to (20)

D.2 Land use type regulation: general case (HY) with homogeneous leisure and no restriction

With zoning we have $\left(\zeta\left(1-s_i\right)A_i=\sum\psi_{ij}q_{ij},\ \left(1-\zeta\right)\left(1-s_i\right)A_i=Q_i\right)$. Then totally differentiating land market clearing conditions leads to:

$$\frac{\mathrm{d}Q_i}{\mathrm{d}\zeta}=-N\sum_j\left(\psi_{ij}\frac{\mathrm{d}q_{ij}}{\mathrm{d}\zeta}+q_{ij}\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\zeta}\right) \tag{D.20}$$

For land-use regulation ζ_i we get an expression similar to (D.13)

$$\begin{aligned}\frac{\mathrm{d}W}{\mathrm{d}\zeta_k}=&-N\sum_{i,j}\psi_{ij}\lambda_{ij}w_j^nD_{ij}\frac{\mathrm{d}t_{ij}}{\mathrm{d}\zeta_k}+N\left(1-\tau^w\right)\sum_{i,j}\psi_{ij}\lambda_{ij}H_{ij}\frac{\mathrm{d}w_j}{\mathrm{d}\zeta_k}\\&-N\sum_{i,j,l}\psi_{ij}\lambda_{ij}z_{ijl}\frac{\mathrm{d}p_l}{\mathrm{d}\zeta_k}-N\sum_{i,j}\psi_{ij}\lambda_{ij}q_{ij}\frac{\mathrm{d}r_i^q}{\mathrm{d}\zeta_k}+N\lambda\frac{\mathrm{d}ALR}{\mathrm{d}\zeta_k}-N\lambda\frac{\mathrm{d}\tau^{ls}}{\mathrm{d}\zeta_k}.\end{aligned}$$

Using (D.12) and (D.8) expands (D.13)

$$\begin{aligned}\frac{\mathrm{d}W}{\mathrm{d}\zeta_k}=&-N\sum_{i,j}\psi_{ij}\lambda_{ij}w_j^nD_{ij}\frac{\mathrm{d}t_{ij}}{\mathrm{d}\zeta_k}\\&+N\left(1-\tau^w\right)\sum_{i,j}\psi_{ij}\lambda_{ij}h_{ij}D_{ij}\frac{\mathrm{d}w_j}{\mathrm{d}\zeta_k}-N\sum_{i,j,l}\psi_{ij}\lambda_{ij}z_{ijl}\frac{\mathrm{d}p_l}{\mathrm{d}\zeta_k}-N\sum_{i,j}\psi_{ij}\lambda_{ij}q_{ij}\frac{\mathrm{d}r_i^q}{\mathrm{d}\zeta_k}\\&+\lambda N\sum_i\left(\psi_{ij}r_i^q\frac{\mathrm{d}q_i}{\mathrm{d}\zeta_k}+\psi_{ij}q_i\frac{\mathrm{d}r_i^q}{\mathrm{d}\zeta_k}+r_i^qq_i\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\zeta_k}\right)+\lambda\sum_i\left(r_i^Q\frac{\mathrm{d}Q_i}{\mathrm{d}\zeta_k}+Q_i\frac{\mathrm{d}r_i^Q}{\mathrm{d}\zeta_k}\right)\\&+\tau^wN\sum_{i,j}\left(\psi_{ij}w_j\frac{\mathrm{d}H_{ij}}{\mathrm{d}\zeta_k}+w_jh_{ij}D_{ij}\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\zeta_k}+\psi_{ij}h_{ij}D_{ij}\frac{\mathrm{d}w_j}{\mathrm{d}\zeta_k}\right).\end{aligned} \tag{D.21}$$

We expand this by λ times different terms and using several definitions equivalent to (21), (D.16)–(D.18) and (D.19) ($\phi_{\zeta k}^{toll}=0$, $\mathrm{d}\zeta_k$ instead of $\mathrm{d}\tau_{hk}^t$ and r^q instead of r) yielding

$$\begin{aligned}\frac{1}{\lambda}\frac{\mathrm{d}W}{\mathrm{d}\zeta_k}=&MEC_{\zeta k}\left(-\frac{\mathrm{d}F}{\mathrm{d}\zeta_k}\right)+\sum_i\left[\left(r_i^Q-r_i^q\right)\frac{\mathrm{d}Q_i}{\mathrm{d}\zeta_k}\right]+\\&\underbrace{+N\sum_{i,j}\underbrace{\psi_{ij}h_{ij}D_{ij}}_{L_j}\frac{\mathrm{d}w_j}{\mathrm{d}\zeta_k}-N\sum_{i,j,l}\underbrace{\psi_{ij}z_{ijl}}_{X_l}\frac{\mathrm{d}p_l}{\mathrm{d}\zeta_k}+\sum_iQ_i\frac{\mathrm{d}r_i^Q}{\mathrm{d}\zeta_k}}_{=0\text{ from production and zero profits }(D.7)}\end{aligned} \tag{D.22}$$

$$\begin{aligned}&\tau^wN\sum_{i,j}\left(\psi_{ij}w_j\frac{\mathrm{d}H_{ij}}{\mathrm{d}\zeta_k}+w_jh_{ij}D_{ij}\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\zeta_k}\right)\\&+MEC_{\zeta k}\left(-\frac{\mathrm{d}F}{\mathrm{d}\zeta_k}\right)\left(\phi_{\zeta k}^{mec}-1\right)+Y_{\zeta k}\left(\phi_{\zeta k}^{y}-1\right)\\&-\tau^wN\left(\sum_{i,j}\psi_{ij}H_{ij}\frac{\mathrm{d}w_j}{\mathrm{d}\zeta_k}\right)\left(\phi_{\zeta k}^{wtax}-1\right).\end{aligned} \tag{D.23}$$

where we used $\left(N\sum_j\left(\psi_{ij}\frac{\mathrm{d}q_{ij}}{\mathrm{d}\zeta}+q_{ij}\frac{\mathrm{d}\psi_{ij}}{\mathrm{d}\zeta}\right)-\frac{\mathrm{d}Q_i}{\mathrm{d}\zeta}\right.$ from (D.11)) Defining the third row as the tax interaction term and the fourth row as the redistribution term yields

$$\frac{1}{\lambda}\frac{\mathrm{d}W}{\mathrm{d}\zeta_k}=MEC_{\zeta k}\left(-\frac{\mathrm{d}F}{\mathrm{d}\zeta_k}\right)+TI_{\zeta k}+N\sum_i\left(r_i^q-r_i^Q\right)\left(1-s_i\right)A_i+RE_{\zeta k}. \tag{D.24}$$

Concerning land-use policy, ζ, or capacity enhancement all LSMs provide similar findings. The welfare change of zoning shows that labor supply affects only TI, while the land market distortion, i.e. the third term on the RHS, does not depend on labor supply.

E Detailed Tables for other policies

Table E.1: Policy effects of road capacity expansion with inhomogeneous leisure

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

[a] million per year, [b] million $ per year

Table E.2: Policy effects of a miles tax with inhomogeneous leisure

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

[a] million per year, [b] million $ per year

Table E.3: Policy effects of a cordon toll with inhomogeneous leisure

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

[a] million per year, [b] million $ per year

Table E.4: Policy effects of Zoning with inhomogeneous leisure

Zoning - Case 5a	Benchmark	WH	HY	WD
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 [h/year]	2187	+22	+24	−19
Total leisure demand [h/year]	2164	−12	−15	+30
Total commuting time on workdays [h/year]	272	−4	−4	−4
Total shopping time [h/year]	417	−5	−5	−7
Travel/Transport/Traffic				
Travel time delay [h/year]	31	−4	−3	−3
MEC [$-cents/mile]	22	−3	−3	−3
Total travel time [hours/year]	689	−10	−9	−11
One-way commuting time [minutes]	31	0	0	0
VOT of one hour on a workday [$/h]	13.87	−0.34	−0.35	−0.63
Commuting trips [m./y.][a] City–City	25.4	+1.2	+1.2	+1.1
Commuting trips [m./y.][a] City–Suburb	19.3	+1.1	+1.1	+1.1
Commuting trips [m./y.][a] Suburb–City	45.0	−1.3	−1.2	−1.2
Commuting trips [m./y.][a] 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 [m. $/year][b]	8171	−65	−87	−155
Lump-sum tax revenue [m. $/year][b]	–974	−817	−804	−791
Infrastructure costs [m. $/year][b]	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

[a]) million per year, [b]) million $ per year

Table E.5: Congestion tolls and labor supply elasticities

		Inhomog. leisure			Homog. leisure		
		WH	HY	WD	WH	HY	WD
1	Uncomp. elast. of labor supply	+0.20	+0.22	+0.03	+0.21	+0.20	+0.21
2	Uncomp. elast. of days supply	+0.00	+0.02	+0.03	+0.00	+0.26	+0.21
3	Uncomp. elast. of daily hours	+0.20	+0.20	+0.00	+0.21	−0.06	+0.00
4	Comp. elast. of labor supply	+0.58	+0.66	+0.11	+0.66	+0.64	+0.64
5	Comp. elast. of annual days	+0.00	+0.10	+0.11	+0.00	+0.64	+0.64
6	Comp. elast. of daily hours	+0.58	+0.56	+0.00	+0.66	+0.00	+0.00

Average benchmark elasticities. HY hybrid approach, WH workhours approach, WD workdays approach.