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The optimal subsidy on electric vehicles in a metropolitan area - a SCGE study for Germany

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Abstract

We examine whether it is optimal to subsidize or tax electric vehicles and, how large, the corresponding optimal rate is. We, first, derive analytically the optimal subsidy in a spatial partial equilibrium model of a city with two zones where commuting, carbon emissions, endogenous labor supply, fuel and power taxes are considered and where we distinguish between fuel vehicles and electric vehicles. Second, we extend the model to a full spatial general equilibrium model and employ simulations to calculate sign and size of the optimal subsidy or tax rate. This model is calibrated to a typical German metropolitan area. The results show that electric vehicles should not be subsidized but taxed. The results are robust with respect to changes in the willingness to adopt electric vehicles (EVs), the elasticity of the energy mix in passenger travel, and even if emission of EVs are zero.

JEL classification: H21; R13; R14; R48; R51

Keywords: urban general equilibrium model; energy tax; urban passenger travel; hybrid cars; electric mobility, climate change

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1 Introduction

In Germany like in many other countries policy aims at raising the share of hybrid or fully electric vehicles (EV) in the automobile fleet. Germany's government, for instance, hopes that in 2020 about one million electric vehicles drive on German roads. To achieve those goals many governments subsidize research in, purchase of and the use of electric vehicles. For instance, in Germany, electric vehicles are not subject to a vehicle tax and tax rates on power are considerably lower than those on fuels. Furthermore, research in the use of power for mobility is subsidized too.

This is our point of departure. We ask whether such subsidies to the use of electric vehicles are socially optimal considering social benefits and costs of those policies. Given the hope and resources put into those policies this issue is important. Even if a higher share of electric vehicles (EV) in the car fleet might lower carbon emissions, social net-benefits are not straightforward. There might be negative side effect of this policy as well as interactions with other policy instruments. For instance, a subsidy on purchasing or using EV might increase travel demand and, thus, congestion. In addition, financing these subsidies might cause distortions and, hence, reduce efficiency and, in addition, lower tax revenue. These are some reasons why looking into interaction effects of subsidizing EV is important. The gains from a reduction in emissions have to be compared to the costs of the incentives set.only a full cost-benefit or welfare analysis of such policies will reveal whether the efficiency costs tied to those policies do not offset the social gains from the reduction of emissions. Further, even if this is the case a decision on the best policy requires to consider other policies and their welfare consequences.

Of course there is a bulk of literature on electric vehicles but the main focus is on the effectiveness of EV concerning the reduction of GHG emissions (e.g. Karplus et al. 2010, King et al. 2010, for environmental benefits see Kazimi 1997a, b) as well as on EV adoption (e.g. Graham-Rowe 2012, Lieven et al. 2011, Musti & Kockelman 2011, Gardner & Abraham 2007, Ewing & Sarigöllü 2000). Studies on private costs and benefits of EVs also fit into the latter literature (e.g. Delucchi & Lipman 2001, Axsen et al. 2009). There are also some studies on the cost-effectiveness of policies to foster the use of electric vehicles (e.g. Hahn 1995, Funk & Rabl 1999; a survey of older studies for the U.S. is provided by Wang, 1997, Baum 2010). These studies, however, do not account for general equilibrium effects mentioned above such as tax distortions, tax revenue effects, changes in relative prices or travel behavior. An exception is Carlsson & Johannson-Stenman (2003). They provide a full cost-benefit analysis of electric vehicles in Sweden. They derive the net benefit formula in a general equilibrium model showing that the net benefits is equal to the net gains in external costs minus the net costs of losses in tax revenue resulting from substituting high taxed cars by less taxed, i.e. subsidized EVs. As a consequence of this negative effect on the public budget, EVs are socially not profitable. Because this effect is weaker for hybrid cars, they might be socially profitable. Nonetheless, they assume weak separability between transport and labor supply and, thus, do not account

for repercussions on the labor market whose sign is a priori ambiguous. They also do not consider tax interaction effects nor provide an adjusted Pigou term (Parry & Small, 2005).

In this paper we focus on these interdependencies, interactions and synergies and ask whether it is optimal to subsidize or tax electric vehicles and, how large, the corresponding optimal rate is. We focus on cities because we expect that the use of EV will in particular be high in cities (see also the reasoning of Carlsson & Johannson-Stenman, 2003). They offer sufficiently short cruising ranges and enough density required for a battery loading systems. However, in cities congestion will be higher and, as taxes affect transport decisions they will also affect spatial decisions such as distances traveled, labor supply, and location decisions.

We proceed as follows. First, we derive analytically the optimal subsidy in a spatial partial equilibrium model of a city with two zones where commuting, carbon emissions, endogenous labor supply, fuel and power taxes are considered, and where we distinguish between fuel vehicles and electric vehicles. Second, we extend the model to a full spatial general equilibrium model and employ simulations to calculate sign and size of the optimal subsidy or tax rate. We add shopping trips, endogenous land in the fringe zones giving rise to the issue of sprawl, congestion and spatially differentiated firms. The model explicitly takes into account the interactions between spatially differentiated markets, households and firms. In this model all location decisions are endogenously determined (see Anas & Xu, 1999, Anas & Rhee, 2006, Tscharaktschiew & Hirte, 2010a, 2010b and 2012). This model is calibrated to a typical German metropolitan area. In the simulation we carry out sensitivity analyses to search for the interval of demand elasticities for electric vehicles for which a subsidy is optimal and the interval for which a tax is optimal. Eventually, we discuss the findings.

2 Optimal power tax rate in a spatial urban model

We derive the optimal fuel tax in a closed city model with absentee landlords which is, though more simple, structurally identical to the main part of the numerical simulation model used below. The model deviates from a standard monocentric city model because in the city implemented there are two zones and, there is no continuous change in distance. Given our intention to derive a general optimal tax formula, we do not consider shopping trips and some taxes for the time being. Looking at the optimal tax formula below it will be straightforward, how, such modifications will enter this equation.

2.1 The Model

In the city there are two zones $i \in \{1, 2\}$, one called 'Center' the other 'Suburbia' and there is a given number of households differing only with respect to their idiosyncratic

location preference. Both zones are of equal size and the homogenous and given land area is normalized so that average travel distance in a zone is set to unity. Traffic in this city occurs only due to commuting. Traveling generates two externalities: congestion and a climate change externality on account of carbon emissions. To simplify matters it is assumed that all good prices are set to unity and that wages might differ among zones. Further, we consider only automobile travel and there is no transport mode choice. Households housing demand is fixed at unity, too.

Energy use and transport Because we do not know which kind of EV will be used in the future we assume that the energy mix of vehicles can be chosen. We further assume that utility is additive separable with respect to the energy mix used for traveling and that a typical household drives a car with a share b of power energy and that changing b is free of costs. The household chooses this energy mix variable b. Energy consumption differs according to the energy type used. It is assumed that g units of gasoline are required to travel one unit of distance with a pure gasoline vehicle and g^e units of power are required to drive one unit of distance only with a pure EV. Given fixed fuel and power prices, a fixed fuel tax rate as well as a given amount of energy required per vehicle mile traveled (VMT), the decision on b depends only on the tax rate for power, τ^e. Monetary travel costs per unit of distance are, thus,

$$c\left(\tau^e\right) = \left(p^g + \tau^g\right)\left[1 - b\left(\tau^e\right)\right] g + \left(p^e + \tau^e\right) b\left(\tau^e\right) g^e, \quad b' < 0 \tag{1}$$

To simplify matters we assume that b' is negative and constant.

Daily traffic density is given by $f_i \equiv F_i/K_i$, where F_i are traffic flows and K_i is road capacity in zone i set to unity. The travel time per unit of distance in zone i depends on velocity, respectively, traffic density, so that

$$t_i \equiv t_i\left(f_i\right),\ t_i' > 0,\ t_i'' > 0, \qquad \forall i. \tag{2}$$

According to this there is a congestion time externality in zone i[1]

$$E_i^t \equiv \frac{\partial T_i}{\partial f_i} - t_i = f_i\, t_i' \qquad \forall i. \tag{3}$$

In addition carbon emissions per VMT are

$$em\left(\tau^e\right) = \phi_g\left[1 - b\left(\tau^e\right)\right] g + \phi_e b\left(\tau^e\right) g^e, \qquad em' = \left(\phi_e g^e - \phi_g g\right) b' \gtreqless 0, \qquad \forall i \tag{4}$$

causing social emission costs. Given $b' < 0$, a rise in the tax rate reduces emission per

[1]Note that the travel time of the additional driver has to be subtracted from the aggregate marginal change in travel time.

VMT if and only if $\phi_e g^e < \phi_g g^2$.

Households There is a two-tier utility decision process. Given a specific location choice set ij, i.e. residential location i and working location j which implies commuting from zone i to zone j, each resident decides on local consumption and leisure and, thus, how much labor to supply. While daily working time h is fixed, the number of workdays, D, is endogenous. The household then maximizes indirect utility to choose the most preferred location pair ij, taking into account idiosyncratic tastes associated with location choice set ij. Household decision is based on the random utility function

$$U_{ij} = u\left(z_{ij}, \ell_{ij}\right) + \epsilon_{ij}, \qquad \forall i, j, \tag{5}$$

where z_{ij} is consumption of the local good and ℓ_{ij} is endogenous leisure demand of household ij. The idiosyncratic taste constant ε_{ij} represents the stochastic part of the random utility function and varies among households. Concerning non-location decisions the household's ij indirect utility function is

$$\begin{aligned} V_{ij}\left(r_i, \theta_{ij}, \Omega_{ij}\right) \;=\; & \{\max u\left(z_{ij}, \ell_{ij}\right) \\ & \text{s.t.: } z_{ij} + r_i + \theta_{ij}\ell_{ij} = \theta_{ij}H - \tau^{ls}\} \qquad \forall i, j, \end{aligned} \tag{6}$$

where r_i is the endogenous land price in home zone i. $\theta_{ij}H - \tau^{ls}$ is full economic income with H as time endowment and τ^{ls} as lump sum tax rate. θ_{ij} is the value of time (VOT), where

$$\theta_{ij} = \frac{w_j h - c_{ij}}{h + t_{ij}} \qquad \forall i, j. \tag{7}$$

The VOT is the opportunity costs of one unit of leisure and is calculated as the daily wage income, i.e. daily wage w_j in working zone j times fixed daily hours of work h, minus monetary commuting costs per hour used for supplying one hour of working time. Because commuting time t_{ij} from home zone i to working zone j is required to supply a working day the average daily time spent for working and commuting is $h + t_{ij}$.

The two-way monetary travel costs per trip from i to j are given by

$$c_{ij}\left(\tau^e\right) \equiv cx_{ij} = \begin{cases} c & \text{if } i = j \\ 2c & \text{if } i \neq j \end{cases}, \qquad \forall i, k \tag{8}$$

where c are monetary travel costs per VMT specified below. Concerning traveling it is assumed that each worker traveling within a zone i travels the same distance. These

[2]The literature cited above suggests that this is true. However, a recent study for the German Federal Environment Agency says that this outcome depends on the kind of energy used in power generation. Only if renewable resources are used to produce a large share of the additionally required electric energy a reduction of emissions can be expected (Öko-Institut 2011)

workers are those living and working in the same zone i, those living in zone i and leaving the zone for working in zone j, and those living in the other zone j and entering zone i for working. Accordingly, a worker not traveling in both zones faces costs c otherwise $2c$. There are no additional costs for traveling from zone to zone.

The two-way travel time for a commuting trip from i to j is

$$t_{ij}\left(f_i, f_j\right) \equiv t_i\left(f_i\right) + |j-i| \cdot t_j\left(f_j\right) \qquad \forall i, j, \tag{9}$$

where f_i is the travel density in zone i. Travel time depends on traffic density and, thus, on congestion.

Utility maximization considering non-negative constraints yields the demand functions which at equilibrium can be written as

$$\begin{aligned} z_{ij}\left(r_i, \theta_{ij}, \theta_{ij}H - \tau^{ls}\right) &= z_{ij}^{+}\left(r_i, \tau^e, \tau^{ls}, f_1, f_2\right), & \forall i, j, & \quad (10)\\ q_{ij}\left(r_i, \theta_{ij}, \theta_{ij}H - \tau^{ls}\right) &= q_{ij}^{+}\left(r_i, \tau^e, \tau^{ls}, f_1, f_2\right), & \forall i, j, & \quad (11)\\ \ell_{ij}\left(r_i, \theta_{ij}, \theta_{ij}H - \tau^{ls}\right) &= \ell_{ij}^{+}\left(r_i, \tau^e, \tau^{ls}, f_1, f_2\right), & \forall i, j. & \quad (12) \end{aligned}$$

The supply of work days is

$$D_{ij}\left(r_i, \theta_{ij}, \theta_{ij}H - \tau^{ls}\right) = D_{ij}^{+}\left(r_i, \tau^e, \tau^{ls}, f_1, f_2\right) = \frac{H - \ell_{ij}^{+}\left(r_i, \tau^e, \tau^{ls}, f_1, f_2\right)}{h + t_{ij}}. \qquad \forall i, j. \tag{13}$$

The probability of a household to choose the specific location choice set ij is $\Psi_{ij} = \Pr\left[V_{ij} + \varepsilon_{ij} > V_{\tilde{i}\tilde{j}} + \varepsilon_{\tilde{i}\tilde{j}},\ \forall \tilde{i}\tilde{j} \neq ij\right]$, given by the multinomial logit model:

$$\Psi_{ij} = \frac{\exp\left(\Lambda V_{ij}\right)}{\sum_{a=1}^{I}\sum_{b=1}^{I}\exp\left(\Lambda V_{ab}\right)}, \qquad \forall i, j. \tag{14}$$

Closing the model Aggregating D_{ij} over all households traveling in zone i gives traffic density in this zone:

$$f_i = N\sum_j \Psi_{ij} D_{ij} + N\sum_{j\neq i} \Psi_{ji} D_{ji}, \qquad \forall i. \tag{15a}$$

The government levies a fuel and a power tax as well as a lump sum tax to finance fixed expenditure, $\bar{S}$. The tax bases are total gasoline consumption in zone i

$$G_i = f_i\left(1-b\right)g, \qquad \forall i\,, \tag{16}$$

total power consumption in zone i

$$G_i^e = f_i b g^e, \qquad \forall i. \tag{17}$$

and the number of households, N, in the city. The government budget constraint is then given by

$$\tau^{ls} N + \tau^e G^e + \tau^g G = \bar{S}.$$

We assume there is fully elastic demand of goods and demand for labor, so that spatially differentiated wages are constant and local good and labor markets are cleared. Further, energy supply is also fully elastic, and local land markets are cleared, too.

2.2 Welfare and Optimal Energy Subsidy / Tax Rate

Aggregate utility is calculated as the expected value of the maximized utilities (see e.g. Anas & Rhee 2006, based on Small & Rosen 1981). Under the assumption that idiosyncratic tastes ε_{ij} for a specific location choice set ij are i.i.d. Gumbel distributed, urban (non-environmental) aggregate welfare of the identical households, W_H, is

$$W_H = E\left[\max_{(ij)}\left(V_{ij} + \varepsilon_{ij}\right)\right] = \frac{1}{\Lambda} \ln \sum_{i=1}^{I} \sum_{j=1}^{I} \exp\left(\Lambda V_{ij}\right). \tag{18}$$

Marginal utility of income λ_H is assumed to be constant across alternatives and, thus, across identical individuals living at different locations (see Small & Rosen, 1981). In this case aggregate social welfare measured in terms of income is the weighted sum of the expected values of maximized utilities of the city households plus the weighted indirect utility of the landowners, also in terms of income, minus the climate change externality costs caused by carbon emissions. Accordingly

$$\begin{aligned} W &= \frac{N}{\lambda_H \Lambda} \ln \sum_{i=1}^{I} \sum_{j=1}^{I} \exp\left(\Lambda V_{ij}\right) + \frac{1}{\lambda_A} V_A - \omega \sum_{i=1}^{I} EM_i \qquad (19) \\ &= \frac{N}{\lambda_H} \sum_{i=1}^{I} \sum_{j=1}^{I} \Psi_{ij} V_{ij} + \frac{N}{\lambda_H} \frac{1}{\Lambda} \sum_{i=1}^{I} \sum_{j=1}^{I} \Psi_{ij} \left(-\ln \Psi_{ij}\right) + \frac{1}{\lambda_A} V_A - \omega \sum_{i=1}^{I} EM_i \end{aligned}$$

where λ_A is the marginal utility of income of absentee landlords, V_A is indirect utility of absentee landlords, ω are social costs per unit of carbon emission and EM_i are aggregate emissions.

Totally differentiating indirect utility (6) and applying Roy's theorem gives the marginal utility change induced by a change in the power tax

$$\begin{aligned} \frac{1}{\lambda_{ij}} \frac{dV_{ij}}{d\tau^e} &= \left(\frac{G^e}{N} - G^e_{ij}\right) + \tau^e \left(\frac{1}{N}\frac{dG^e}{d\tau^e} - \left.\frac{dG^e_{ij}}{d\tau^e}\right|_{\bar{b}}\right) + \tau^g \left(\frac{1}{N}\frac{dG}{d\tau^e} - \left.\frac{dG_{ij}}{d\tau^e}\right|_{\bar{b}}\right) \qquad (20) \\ &\quad - D_{ij} x_{ij} \left(p^e g^e - p^g g\right) b' - D_{ij} \theta_{ij} \frac{dt_{ij}}{d\tau^e} - \frac{dr_i}{d\tau^e}. \end{aligned}$$

The household of type ij is better off, the higher the following terms: first, if lump-sum

transfers due to the direct increase in tax revenue is larger than individual direct power tax payment. This is the term in the first bracket. Second, utility increases if changes in power and gasoline consumption imply a positive net lump-sum transfer accruing from changes in power and gasoline taxes. The second term describes the net change in the power tax base and the third term the change in the gasoline tax base implying changes in net lump sum transfers payments due to changes in commuting behavior. The remaining terms indicate changes in energy expenditure net of taxes, changes in congestion costs and changes in land rents induced by the change in the power tax rate.

Aggregating over all city inhabitants yields the *welfare change in the city*

$$\begin{aligned}\frac{dW^H/\lambda^H}{d\tau^e} = &\left(\bar{\theta}E^t - \eta\tau^e b g^e\right)\left(-\frac{dF}{d\tau^e}\right) \\ &+ \eta\tau^g\left(-G^e\frac{\partial G}{\partial \tau^{ls}} + N\frac{\partial G}{\partial \tau^e} + N\frac{dG_\Theta}{d\tau^e}\right) \\ &- F\left(p^e g^e - p^g g\right)b' - N\sum_i\sum_j \Psi_{ij}\frac{dr_i}{d\tau^e},\end{aligned} \tag{21}$$

where $\bar{\theta}$ is the weighted average value of time, F is aggregate miles traveled, and

$$\eta = \frac{N}{N + \tau^g \frac{\partial G}{\partial \tau^{ls}}}, \tag{22}$$

are the *marginal costs of public funds* (MCPF). Exactly speaking, this is the loss of all household per unit of tax revenue raised by a marginal change in the lump sum tax rate.

Totally differentiating (19), applying Roy's theorem, setting this to zero, and using the government budget constraint yields the *total welfare change*

$$\begin{aligned}\frac{dW}{d\tau^e} = &\left(\bar{\theta}E^t + \omega E^e - \eta\tau^e b g^e\right)\left(-\frac{dF}{d\tau^e}\right) \\ &+ \eta\tau^g\left(-G^e\frac{\partial G}{\partial \tau^{ls}} + N\frac{\partial G}{\partial \tau^e} + N\frac{dG_\Theta}{d\tau^e}\right) \\ &+ \frac{F\left(p^e g^e - p^g g\right)}{\eta g^e b\left(-dF/d\tau^e\right)}\left(-b'\right) \\ &+ N\sum_i\sum_j r_i\frac{d\Psi_{ij}}{d\tau^e},\end{aligned} \tag{23}$$

An increase in the power tax changes welfare through four channels: first, the social net costs of the externalities, second the change in the distortion in the gasoline market, and, third, changes in energy cost, and, fourth, changes in aggregate land rents due to relocation decisions.

Setting (23) to zero and solving for τ^e yields the *socially optimal power tax rate*[3]

$$\tau^{e,soc} = \underbrace{\frac{MC}{\eta}\frac{1}{bg^e}}_{\text{Adjusted Pigouvian Tax}} + \underbrace{\frac{1}{\eta\left(-dG^e/d\tau^e\right)}IE}_{\text{Tax Interaction (IE)}} + \underbrace{\frac{F\left(p^e g^e - p^g g\right)}{\eta\left(-dG^e/d\tau^e\right)}\left(-b'\right)}_{\text{Change in travel costs}} + \underbrace{\frac{N}{\eta\left(-dG^e/d\tau^e\right)}RE}_{\text{Redistribution Effect}} \tag{24}$$

It is the sum of the adjusted Pigouvian tax, the tax interaction effect, changes in travel costs and a redistribution effect[4].

The *Adjusted Pigouvian Tax component* is the aggregate marginal externality cost per unit of gasoline, EC (see (25a)), discounted by MCPF. Hence, the optimal tax rate depends on the trade-off between optimally internalizing externalities and raising revenues in the most efficient way. Externality costs, EC, is the sum of aggregate marginal external congestion costs and aggregate marginal emission costs. The discount factor, which also applies to the other tax components, reflect tax recycling costs which in the case of lump-sum tax recycling is equal to MCPF.

Externality costs, EC, are the sum of aggregate marginal external congestion costs, E^t, and aggregate marginal emission costs E^e:[5]

$$EC \equiv \bar{\theta}E^t + \omega E^e, \tag{25a}$$

$$E^t \equiv \frac{N\sum_i\sum_j \Psi_{ij}\theta_{ij}D_{ij}M^t_{ij}}{\bar{\theta}\left(-dF/d\tau^e\right)}, \tag{25b}$$

$$E^e \equiv \frac{\sum_i g_i \frac{df_i}{d\tau^e}}{\left(-dF/d\tau^e\right)} \tag{25c}$$

M^t_{ij} is the total change in marginal externalities occurring on account of changes in traffic flows, i.e.

$$M^t_{ij} = \frac{M^t_i}{f_i}\frac{df_i}{d\tau^e} + |j-i| \cdot \frac{M^t_j}{f_j}\frac{df_j}{d\tau^e} \tag{26a}$$

In a second-best world distortions generated by other taxes might change even with lump-sum tax recycling. This is indicated by the *Tax Interaction Effect*, IE, which is added to the Pigouvian component[6]. The change in the power tax affects location,

[3]Despite considering lump sum taxes η is not zero. The reason is that $dG/d\tau^e$ includes τ^e and, thus, solving for τ^e requires to decompose $dG/d\tau^e$ into different components one of which is $\partial G/\partial\tau^{ls}$.

[4]The additivity rule holds here, too (see Sandmo, 1976).

[5]Because total changes in traffic density cannot be eliminated from marginal externalities M^t_{ij}, total marginal externalities of a household include total changes in traffic density. Division by $df/d\tau^g$ gives the average change in total marginal externalities per unit of change of traffic flow. This approximates marginal externalities.

[6]Actually, the tax interaction effect is supposed to refer to changes in compensated demands. In (24) however, the tax interaction effect encompasses changes in compensated labor supply as well as income effects. Since in our case the fuel tax base depends not only on changes in individual labor supply but also in residence and commuting decisions and the change in suburbias land, we cannot analytically derive all effects included in the aggregate tax interactions effects.

housing demand, thus, also land rents in the city and the traffic pattern. Relocation indirectly affects aggregate labor supply, the spatial pattern of working location and so commuting behavior. These feedback effects change tax revenue and, thus, imply changes in the distortions implied by the pre-existing tax system. It can be decomposed into of three effects[7]

$$IE \equiv \underbrace{-\eta\tau^g G^e \frac{\partial G}{\partial \tau^{ls}}}_{TILS\ (-,d\tau^{ls}<0)} + \underbrace{\eta\tau^g N \frac{\partial G}{\partial \tau^e}}_{TIE\ (-)} + \underbrace{\eta\tau^g N \frac{dG_\Theta}{d\tau^e}}_{SIE\ (?)}. \tag{27}$$

1. The tax interaction effect between the lump-sum tax and the fuel tax. The efficiency costs of the lump sum tax are given by the change in fuel tax revenue and distortions caused by raising fuel taxes. This we call the *Tax Interaction Effect of the Lump-Sum Tax*, $TILS$. As $\frac{\partial G}{\partial \tau^{ls}} > 0$, given standard assumptions on leisure demand this effect is negative and, thus, the larger this effects the lower the power tax rate should be ($TILS < 0$).

2. The *Fuel Tax Interaction Effect*, TIE. Given the energy mix, a higher power tax causes a decline in the VOT and, thus, implies less commuting trips and, eventually, a smaller gasoline tax revenue. Accordingly, distortions due to the gasoline tax are getting smaller.

3. The *Spatial Tax Interaction Effect*, SIE. The change in the power tax affects location, housing demand, thus, also land rents in the city and the traffic pattern. Relocation indirectly affects aggregate labor supply, the spatial pattern of working location and so commuting behavior. These feedback effects change the distortions in in the fuel markets, too. The overall sign of the SIE is not clear.

$$\frac{dG_\Theta}{d\tau^e} = \underbrace{N \sum_i \sum_j G_{ij} \frac{d\Psi_{ij}}{d\tau^e}}_{(?)} + \underbrace{\sum_i \frac{\partial G_i}{\partial r_i} \frac{dr_i}{d\tau^e}}_{(?)} + \underbrace{(1-b)\, g \frac{dF}{d\tau^e}}_{(+)}$$

Since we are not able to derive a unique sign for the *Tax Interaction Effect* IE we, therefore, use numerical simulations to find the sign. As these calculations will show the overall sign of the IE is negative.

Another effect is the change in monetary travel costs accruing due to the change in the energy mix. In the model these payments go to the car producers outside of the city. Since in a fully closed model the current account of the city has to be considered, these costs only matter for overall welfare if the marginal utility of income created from these costs differ between city inhabitants and outside agents.

[7]Further, here we only consider fuel taxes. In the simulation model we add sales taxes and wage taxes. Then efficiency costs in consumption markets and labor markets are added.

Eventually, there is the redistribution effect, RE, between city inhabitants and absentee landlords

$$RE = N \sum_i \sum_j r_i \frac{d\Psi_{ij}}{d\tau^e}.$$

The influence of b on the optimal tax rate is ambiguous. It is not at all clear whether electric vehicles should be subsidized or taxed. This depends on the relative strength of different effects. For instance, subsidizing electric vehicles is expected to lower emissions because the composition of the car fleet changes. If the use of power including its production produces less emissions than the use of fuels raising b lowers emissions, c.p. (see (4)). In contrast, subsidizing power lowers average travel costs and, thus, the VOT. This might increase the number of commuting trips and, thus, congestion. Hence, the sign of the Pigouvian component is ambiguous. As a result, τ^e could be negative or positive. Therefore we do not know whether τ^e is a tax or a subsidy and whether it is larger or smaller than the fuel tax. This is the reason why we apply simulations in the second part of the paper.

Since the city inhabitants do neither consider the emission externality nor utility of absentee landlords their optimal tax rate differs from the socially optimal tax rate. If we drop redistribution and emissions costs, we get the optimal power tax rate of the city:

$$\tau^{e,city} = \underbrace{\frac{\bar{\theta} E^t}{\eta b g^e}}_{\text{Adjusted Pigouvian Tax}} + \underbrace{\frac{\tau^g (1-b)\, g}{b g^e \left(-dF/d\tau^e\right)} IE}_{\text{Tax Interaction (IE)}} + \frac{F\left(p^e g^e - p^g g\right)}{\eta b g^e \left(-dF/d\tau^e\right)} (-b') - \frac{N}{\eta b g^e \left(-dF/d\tau^e\right)} \sum_i \sum_j \Psi_{ij} \frac{dr_i}{d\tau^e} \tag{28}$$

which is the sum of the adjusted Pigouvian Tax, the Tax Interaction effect and additional net rent payments.

If a higher tax lowers the share of electric vehicles, b, and, thus, raises emissions the socially optimal tax rate faces a smaller Pigouvian component than the city. Provided the difference between the change in net rent payments and the redistribution effect is smaller, we can conclude: from the point of view of society the optimal power tax rate should be lower than that of the city. The reason is that the city does not consider the negative incentive for using EV the tax imposes.

3 Simulations of the Optimal Power Subsidy / Tax

3.1 Simulation Model

For the simulations we extend the model to consider some additional aspects which are important to determine sign and size of the tax rate (e.g. Parry & Bento 2002). We add other externalities: accidents and a fuel consumption externality (Tscharaktschiew & Hirte 2010a). These will enter the Pigouvian tax component. We also add sales taxes and a progressive income tax according to the German tax tariff. As long as additional

taxes are fixed and not used for tax recycling they constitute additional terms in the tax interaction effect. Further, land in the fringe suburbs is endogenous so that sprawl can be considered. Households additionally choose shopping trips and lot size. Despite home and working locations households now choose where and how much to shop, how much land to rent, and which travel mode to use. All theses interdependent decisions are endogenously determined in the simulation model and implicitly determine commuting and shopping distances, frequencies and, along with travel speeds, travel times.

The random utility function of household type ij becomes

$$U_{ij} = u\left(Z_{ij}, q_{ij}, \ell_{ij}\right) + \epsilon_{\iota} \tag{29}$$

where L_{ij} is the index for leisure not spent at home, Z_{ij} is the index for consumption goods, q_{ij} is the lot size and ℓ_{ij} denotes leisure time spent home. The subutility functions are

$$Z_{ij} = \left(\sum_{k=1}^{I} \left(z_{ijk}\right)^{\rho^z}\right)^{\frac{1}{\rho^z}}. \tag{30}$$

The shopping subutility for visiting different shopping locations over a certain period of time, Z_{ij}, is represented by a C.E.S. utility function. The household residing in i and working in j, travels from zone i to every zone k to purchase the composite commodity z_{ijk} produced and sold there.

The time constraint of a type ij worker becomes

$$\underbrace{\underbrace{\underbrace{D_{ij}h}_{\text{Labor}} + \underbrace{\ell_{ij}}_{\text{Leisure}}}_{\text{Time spent not for traveling}} + \underbrace{\underbrace{t_{ij}D_{ij}}_{\text{Commuting}} + \underbrace{\sum_{k=1}^{I} t_{ik}z_{ijik}}_{\text{Shopping}}}_{\text{Time spent for traveling}}}_{} = H, \tag{31}$$

Individual automobile travel causes four kinds of externalities: congestion (travel time delays), additional gasoline consumption, and additional CO_2 emissions, caused by an additional driver on all other commuters, and accidents. Since all travel decisions are endogenous, the extent of the externalities is endogenous as well. Travel times, gasoline consumption and carbon emissions are endogenously determined and specified by empirically determined relationships (see appendix B).

The federal government levies a progressive income taxes with rate τ^L, sales taxes with rate τ^z. Revenues of taxes are shared with the local government following the German tax sharing rules. Further expenditure are transfers to households and purchases of locally produced commodities. The city government receives its shares of federal tax revenues and levies a local lump-sum tax with rate τ^{ls} to finance local goods such as roads. Infrastructure costs consist of opportunity costs due to land used for infrastructure.

The connection between the city and the outside world is implemented by financial outflows due to taxes, payments for monetary transport costs and rents paid to absentee

landlords. To close the model these flows have to be balanced by monetary flows into the city. These include transfers to city inhabitants, grants and tax sharing grants to the local government and exports to the external agents. In particular, it is assumed that absentee landowners use their rent income to buy urban commodities. The transport sector purchases intermediate urban commodities so that its zero profits condition holds and, the federal government buys local goods to in order to balance its budget. We assume that there are financial flows via the tax sharing system from the federal government to the city government, and exports of local goods to the federal government, absentee landlords and the transport sector. It is assumed that the composite commodity produced in a zone i can be exported at price p_i at zero transport costs and that city exports stem from different zones according to a Cobb Douglas like rule.

Other features are straightforward (see Tscharaktschiew & Hirte 2010a). We further add local production of goods where labor and land are inputs into production. The model is closed by considering a current account where all money flows to the outside world (rents, monetary transport costs, energy costs, taxes) are equalized by exports of the city to the outside world. Moreover, local goods, land and labor markets are cleared. Except for the numeraire price and the given energy prices all prices are endogenous.

3.2 Calibration

We calibrated the model to a German like city featuring important data of some of the large German areas (see also Tscharaktschiew & Hirte 2010a). Since we also know that different household types are important for the spatial pattern of the city, we also consider different household types within the city (see Tscharaktschiew & Hirte, 2010b). The calibration ensures that the benchmark city found as the result of the basic simulation exhibits figures such as rents, wages and incomes as well as automobile travel speeds, modal split, travel distances, travel times and, in particular, gasoline consumptions and CO_2 emissions which are representative for a German metropolitan area. In the following we assume that b equals zero in the benchmark, i. e. there are no electric vehicles in the benchmark. Further, we choose a household composition which approximates German conditions. Since adding endogenous land area in the outer suburbs and adding electric vehicles do not affect the calibration, the benchmark almost equals the benchmark used in Tscharaktschiew & Hirte (2010a). Thus, in the following we only present basic figures and the comparison between the calibration outcomes and real data. This aims at showing the accuracy of the calibration procedure.

The total number of households in the urban area is assumed to be 1.75 million where 1,163,750 are households with working members and 586,250 are non-working households. The percentage of high-skilled workers – reflecting university degree or higher – is assumed to be 20% compared to a percentage of 20.5 in Munich, 17.5 in Frankfurt/Main, 20.9 in Stuttgart, or 20.3 in Dresden (Stadt Frankfurt/Main 2009).

Table 1: Calibrated values of parameters

The parameters of the utility functions (see Table 1, see Tscharaktschiew & Hirte 2010a.) are chosen to fit several data such as the relative expenditure shares for consumption and housing (Federal Statistical Office, 2009). By fixing the parameter of shopping subutility at $\eta = 0.60$ we assume that there is some spatial taste variety in shopping (see Anas & Rhee 2006), implying that there is an elasticity of substitution among the spatially differentiated commodities equal to 2.5. Total time endowment H is fixed at 4500 h/year. According to Eurostat (2004) working time per day, h, is 8 hours. The dispersion parameter Λ equals 5 ensuring realistic population/employment densities. It is assumed that the residents own one third of the entire land in the urban area. According to the Federal Statistical Office (2007, 2009), retirement pensions for two retirees amount to about 1,600 € per month on average. Hence, transfer income Inc^t of non-working households is set at 19,200 € per year.

Cost shares in production approximate the distribution of national income among production factors. It is assumed that the cost share of land, ϕ, is higher in suburbs while the cost share of high-skilled labor is slightly higher in the inner city. This is chosen to reflect that firms with more land intensive technologies generally prefer to produce in the suburbs while more management-related jobs are located in the city (see e.g. Haas & Hamann 2008, Dewey & Montes-Rojas 2009). In addition, we assume a slightly increasing scale effect for suburban production to reflect, e.g., better interstate highways accesses or better parking opportunities at less central locations. These assumptions are made to achieve a more realistic spatial labor and wage distribution.

Urban travel speed is taken to be 4 km/hour for walking and 18 km/hour for public transport, respectively (Federal Ministry of Transport, Building and Urban Affairs 2004). Monetary travel costs for walking are fixed at zero. In public transport the ticket price for public transport is composed of a variable distance dependent component, $c^{1,public}$, and a fix distance independent component, $c^{3,public}$. The automobile travel cost rate, $c^{1,auto}$, is assumed to be 0.30 € per vkm which approximates average cost – except for gasoline cost, energy taxes and sales taxes – of owning and operating an automobile. (see e.g. ADAC 2009, Buehler & Kunert 2008). The consumer price for one liter super petrol is specified at 1.40 €. Since the energy tax amounts to $\tau^g = 0.65$ € per liter in Germany (April 2010) and the consumer price encompasses a sales tax of 0.22 € per liter, i.e. $\tau^{auto} = 0.19$, the pure gasoline cost (supply price) per liter amounts to $p^g = 0.53$ €. According to the maximum travel speed in German cities, free flow travel speed is set at 50 km/h ($f_{i0} = 1/50$) in zone 1(9) and decreases slightly when moving to the city center due to, e.g., more traffic lights (even without congestion). The mode-specific constants were

determined in order to obtain a representative modal split in a German urban area[8] and the travel mode choice dispersion parameters, $\bar{\Lambda}$, are chosen such as to produce reasonable mode choice elasticities being in line with the empirical literature (see Table 2).

According to tax sharing rules a percentage of 15 of income tax revenues collected from urban residents to the city government is transferred to the urban government, i.e. $\varpi^I = 0.15$ (see Artikel 106, Absatz 3 (5) GG, 2009, § 1 GemFinRefG 2009). Furthermore, the city receives a share of sales tax revenue amounting to $\varpi^S = 0.022$ and a share of the energy tax revenue which we set at $\varpi^E = 0.05$. In 2010, the sales tax rate τ^z is 0.19, whereas the reduced tax rate on the public transport ticket price is $\tau^{public} = 0.07$. According to the current policy, the tax deductibility rate δ to which commuting expenses are income tax deductible is set at 0.3 €/round-trip km. In order to reflect real observation, the share of land allocated to roads, $\Re_i$, decreases with distance from the city and one half of this share is owned by the public household.[9]

In addition, we paid attention to replicate realistic travel demand elasticities, travel patterns, gasoline consumptions and emissions comparable to patterns that can be observed in German urban areas. For example, the gasoline efficiency parameter is set at $e = 0.92$ such that the 'Benchmark' reflects realistic (average) consumptions of gasoline and emissions of CO_2 per driven vehicle kilometer.[10] Moreover, we computed, based on the 'Benchmark' calibration, general equilibrium long run travel demand elasticities to make sure that they are in line with the empirical literature. Travel demand is measured as the total distance traveled by all residents per year with the respective travel mode (see Table 2, see Tscharaktschiew & Hirte 2010a.)).

Table 2: Travel demand elasticities

Using these data and elasticities the main results of the benchmark equilibrium simulation are reported in Table 3 (see Tscharaktschiew & Hirte 2010a.))

[8] The the initial mode choice in the simulation is in accordance with the German modal split over three travel modes: Walking 30%; Public Transport 18%; Automobile 52% (Federal Ministry of Transport, Building and Urban Affairs 2009a).

[9] The total land area allocated to roads amounts to 15.3% in the model city (zones 3–7). For comparison, in Berlin, the share of land area allocated to roads amounted to 15.3 % and in Munich to 17.2% in 2007 (Berlin: Federal Statistical Office 2008a, Munich: Statistical Office Munich 2009). Considering the entire model urban area (zones 1–9), it is assumed that a share of 8.9% of the total land area is allocated to roads. For Germany as a whole, the share amounted to 5.0% in 2008 (Federal Statistical Office 2008a). Since we consider urban areas a higher share seem to be appropriate.

[10] According to the German Federal Motor Transport Authority, average gasoline consumption of (in 2007) new licensed passenger vehicles is 7.1 liters per 100 vkm. Considering the passenger vehicle stock in 2006, average CO_2 emissions amounted to 173 grams per vkm (Federal Motor Transport Authority 2007). However, under real traffic conditions, especially in cities, gasoline consumption and emissions are higher than those based on a theoretical test station driving cycle. As a consequence, we set the gasoline efficiency parameter such that average gasoline consumption as well as CO_2 emissions are slightly higher in the 'Benchmark'.

Table 2: Some results of the 'Benchmark' simulation

This benchmark city exhibits a quite realistic spatial pattern. The central location is relatively attractive for households and firms due to good accessibility. This is the reason why rents decline steeply with distance from the center. Because commodity prices depend on both, rents and wages, the price gradient is steeper than the wage gradient but flatter than the rent gradient. High-skilled workers commute more than their lower skilled counterparts, but spend, on average, less time on leisure and travel activities. The reason for the former finding is their higher opportunity cost of leisure, while the latter finding results from the fact that high-skilled workers use more often faster travel modes such as automobile.

Table 2: Some results of the 'Benchmark' compared with empirical evidence

Table 4 compares some spatial and economic results of the benchmark city with empirical evidence. For example, it contains the results of the so-called job-housing balance which is the ratio of the number of jobs at a certain location in the urban area to the number of employees residing at that location (see , Tscharaktschiew & Hirte 2010a.). According to evidence cited by Siedentop (2007) this ratio is usually smaller than unity for decentralized locations (suburbs) and bigger than unity for centralized locations (city) in German urban areas. In other words, the number of jobs in the city exceeds the number of employees residing in the city which is exactly the pattern we reproduce in the 'Benchmark' city.

Finally, we have to add central data on electric vehicles and the use of power. We choose the following basic figures : traveling by electric vehicles requires 13.15 kWh per 100 km (see ADAC 2012). Carbon emissions are 563 gram per kWh (Umweltbundesamt 2011). The current price of an kWh is 0.182€ and the current German tax is 0.021 € per kWh (Mühlenhoff 2011). Average costs per EV are 0.45 €/km (ADAC 2012).

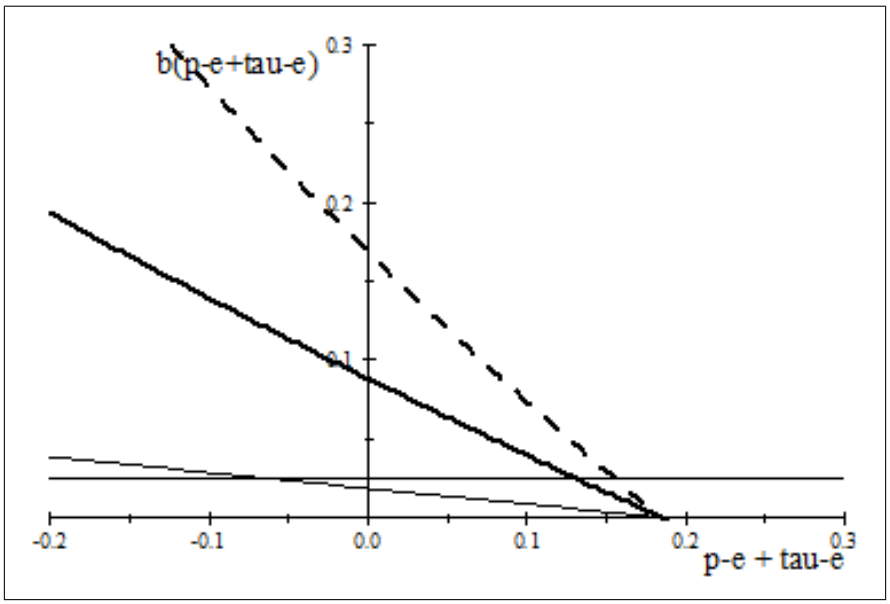
4 Results and Discussion

In the simulations we calculate emissions and welfare for different power subsidy rates to derive the optimal subsidy or tax level. First, we present some hypotheses on the expected changes in the optimal tax rate in the full SCGE model. Thereafter we present simulations and sensitivity analyses.

Optimal power tax in the polycentric SCGE model Since the full polycentric model extend the basic theoretical model, the optimal tax formula changes. Though it is not possible to derive it in the extended model, it is possible to describe some easy to see changes in comparison to the optimal subsidy formula (24). First, the consumption fuel externality enters the adjusted Pigouvian tax. This term is likely to lower the optimal

fuel tax rate because a lower tax implies a smaller share of fuel use. Second, sales tax and progressive income tax interactions have to be added to the tax interaction term (IE). The sign of the income tax interaction might be the same than the sign of the fuel tax interaction term because travelling and labor supply are complements in this model. Third, the change in travel costs should be lower because in the general equilibrium approach additional energy costs for driving are not only sunk costs. Nonetheless, the cost term reflects the change in travel costs if the share of power used for transport increases. Since power is currently more expensive this terms implies a higher power tax rate. Hence, traveling by EVs wastes resources. Fourth, redistribution changes because a share of landowners are living in the city. This weakens the redistribution effect. However, since we consider different household groups, other redistribution components add this formula. Exactly, speaking considering different household groups facing different marginal utility of income will change much more. Eventually, there are changes in traffic flows, gasoline consumption, power consumption which we cannot derive explicitly but which affect the optimal tax rate in all components in an a priori ambiguous way.

Baseline simulation We, first, present the results of the baseline simulation. In this simulation we assume that the response of the energy mix with respect to the power tax is small. For the time being we use a energy mix function $b\left(\tau^{e}\right) = e^{-a(p^{e}+\tau^{e})} - e^{-a(p^{e}+0.021)}$. This is possible because we do not consider changes in fuel taxes or prices, assume given power prices and the only variable we change is the power tax rate. Starting from a power tax rate of 0.021 €/kWh and a power price of 0.182 €/kWh Figure 4 shows the plot of $b\left(\tau^{e}\right)$ for $a = 1$(dashed curve), $a = 0.5$ (thick curve), $a = 0.1$(thin curve). The straight line gives a share of 2.5% of all cars which is the aim of German policy. Accordingly, the baseline response parameter $a = 0.1$ implies that a subsidy of about 0.24 €/kWh is required to achieve this goal given current parameters. With $a = 0.5$ a subsidy of 0.05 €/kWh is sufficient to achieve this policy goal.



$$b = e^{-a(p^e+\tau^e)} - e^{-a\cdot(p^e+\tau_0^e)}$$

We use $a = 0.01$ to calculate the baseline case. Figure 1 displays the welfare effects and the welfare gain on account of changes in CO_2 emission costs for different levels of the subsidy. Welfare is given as Equivalent Variation (W) and presented in Mill. €/Year (see vertical axis). Emissions are also given in Mill €/Year. The subsidy level is printed on the horizontal axis.

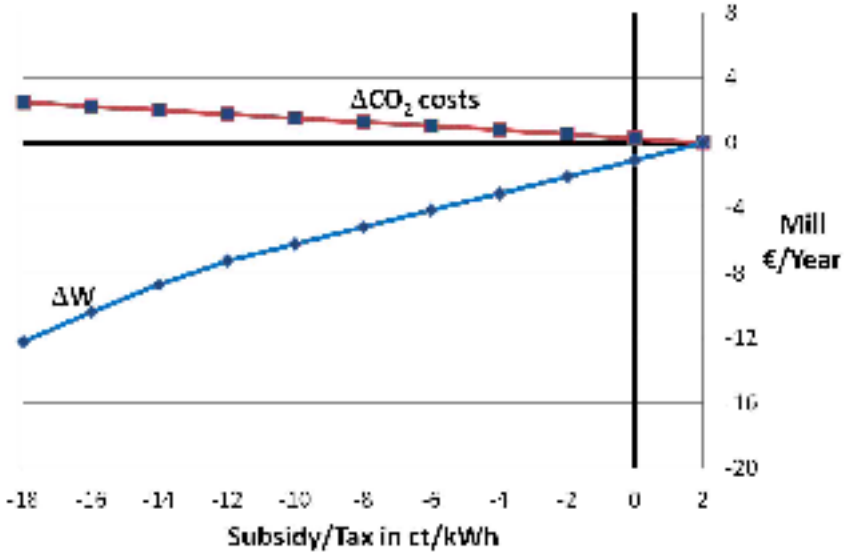


Figure 1: Basline simulation: welfare effects and changes in emission costs

The lower the subsidy rate on power the higher welfare costs. In contrast emission costs are reduced. The reason for this outcome is the strong interaction term. The subsidy implies a switch from traditional cars to EVs. Since this raises transport costs, the value of time of households increase and labor supply declines. It is critical to note that travel costs per km increase even though EVs are subsidized. Individuals switch on account of other reasons. For instance, the subsidy raises the reputation of the government concerning its determination to raise the share of EVs is. This might imply positive adjustments of households to this revealed policy.[11] This results suggest that there is no optimal subsidy. Instead there is a border solution at the current power tax level of 2.1 ct./kWh. Since there is no demand for EVs beyond this level, we cannot explicitly demonstrate what happens beyond τ_0^e. In any case is becomes clear, that taxing power is the optimal policy.

Willingness to adopt EVs Since we actually have not enough information on different variables and since we want to examine robustness of this results, we vary different

[11] Of course, such motives should enter the utility and, thus, constitute a positive term for welfare. However, we cannot say anything on the size of this effect and its link to utility. Instead we could assume that individuals are ordered according to their preference for EVs. A small subsidy, then, shifts the border between households using EVs and the others a little in favor of EVs.

important variables. Concerning the responsiveness of households to the subsidy we raise the parameter a to 0.5. This level implies that a subsidy of 6 ct./kWh generates a demand of one million EVs. This response is very strong and we take it to be the upper ceiling of responsiveness. Figure 2 displays the results, where the dashed line represent the baseline case with a low responsiveness and the solid lines the case with a high responsiveness.

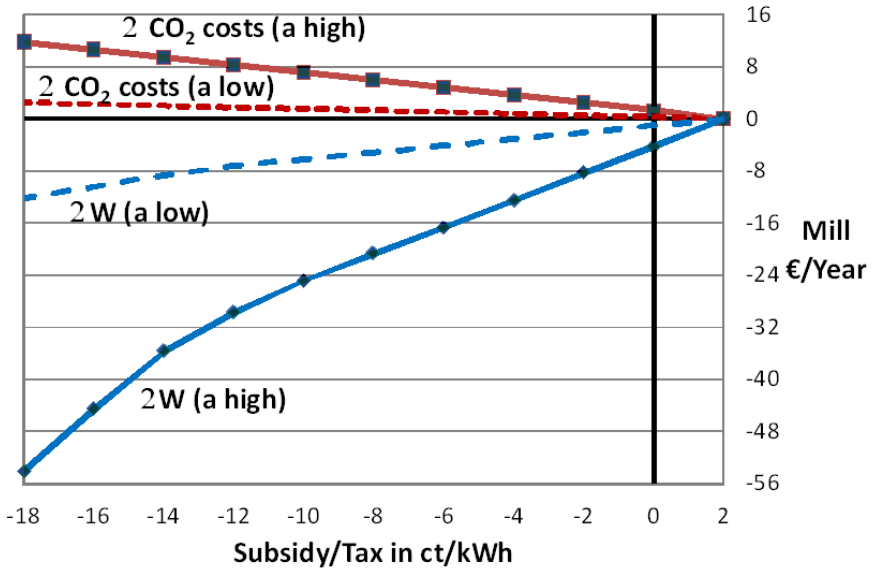


Figure 2: Welfare effects and change in emission costs for low and high responsiveness

If households are more willing to switch to EVs and if they get a subsidy the aggregate welfare loss (W a high) is much higher than in the case of a lower willingness to switch (W a low). This is the case even though emission costs decrease more. And, this outcome is the stronger the larger the subsidy is. This results are surprising. It makes clear that the gain in emission costs is a minor point in comparison to interaction effects, congestion costs, changes in transport costs and redistribution issues. Since EVs raise gross costs of transport, given current energy prices, providing transport implies a waste of resources. In addition, the switching implies an increase in the VOT and a loss in income. This is even true for high subsidy levels. As a consequence labor supply declines. From this we conclude that the raising the willingness to switch to EVs might help to achieve emission goals but goes along with considerable costs.

Fix costs of EVs While the responsiveness seems not to be so important concerning welfare - but of course it is important concerning other goals (emissions, number of EVs), costs should be crucial. How do they influence the results? Our assumption of average fix costs of 45 ct./km in the baseline is already quite low but higher than average costs for traditional cars (30 ct./km). However, raising the share of EV might allow to exploit economies of scale in production, provision and using EVs we assume that average costs decline to 35 ct./km and, thus, almost achieve the level of the traditional cars. Figure 3

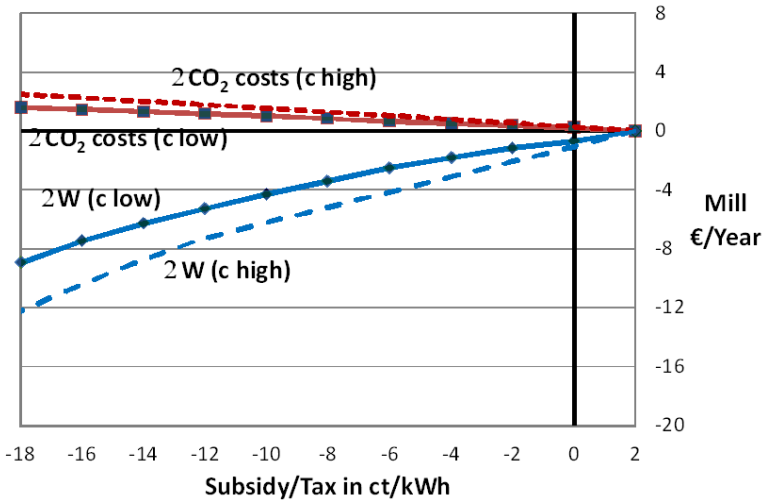


Figure 3: Welfare changes and changes in emission costs if EV's average costs per km decline.

Comparing the dashed curve of the baseline case with the solid curves in the case of lower fix costs show that even a reduction of costs of 1/3 does hardly change the findings. There is only a small improvement in emission costs and a slightly higher mitigation of welfare losses. Nonetheless, taxing EVs stays optimal even if producing these cars requires less resources and fix costs decline. Furthermore, we do yet not consider time costs for loading, inconveniences for loading nor investments required in the loading infrastructure and, thus, there is an upward bias of our calculations. One can hardly imagine that costs of EVs will decline much more. If one considers also improvements in fuel efficiency it becomes even less likely that relative costs improve in favor of EVs in a sufficient way. But in any case, the findings show that lowering costs reduces welfare costs.

Emissions of EVs and emission trading Until now we have not discussed emissions. These can also be changed by technological progress or by changes in upstream emissions. In addition emissions from fuel use can also change in the future. Since we do not know what will happen we construct the extreme event that EVs do not at all cause additional emission costs. This case is not as unrealistic than it sounds. Since power production is subject to emission trading in the EU increasing power use for passenger travel cannot raise emissions if trading permits are restricted. Figure 4 shows the results.

The solid curve represent the emission trading case. There is a decline in emissions costs (curve: CO_2 costs $CO_2 = 0$). In the baseline case emissions costs decline by 70 per cent per km if an EV is used this now increases to 100 percent, this is only a quarter more. Because emission costs contribute additively to welfare other decisions are not affected. Hence, adverse effects of subsidies to power used do not change.

[Further discussion not yet finished: congestion, labor supply, tax interaction effect, redistribution effects..]

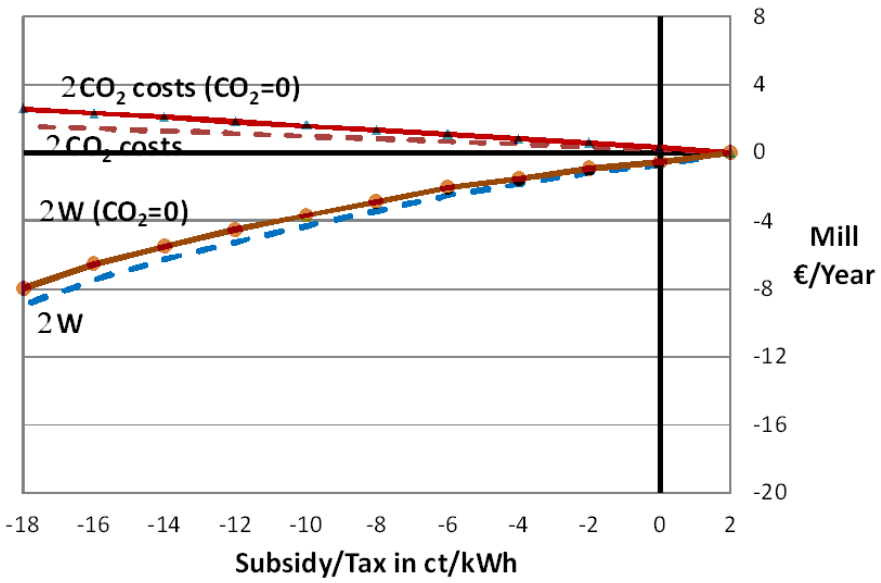


Figure 4: Change in welfare and emission costs in the case of emission trading

5 Conclusions

The theoretical model shows the components of the optimal power tax rate. Despite externality costs, tax interaction effects, changes in producer travel prices and redistribution effects determine the optimal power tax rate. The simulations show that these components add up so that there is no optimal subsidy. This implies that power should be taxed despite the potential of EVs to lower emissions. Different sensitivity analyses show that these results are surprisingly robust with respect to changes in the willingness to adopt EVs, fix costs of EVs and the change in emissions implied by switching from traditional cars to EVs. Neither an extremely high willingness to adopt EVs, nor a strong reduction in fix costs of EVs, nor a zero CO_2 emission of EVs do change these findings. Given that we do not consider other costs (loading system) our findings constitute a preliminary case against subsidizing E-mobility. Moreover, they also suggest that investing in E-mobility is not a good policy: the effects on emissions are small and it lowers welfare considerably. Since there are instruments which allow to improve welfare and lower emissions (e.g. Tscharaktschiew & Hirte 2010b for German cities) the focus shall be on those policies not on EVs.

Our simulations are very conservative: we do not consider tax recycling but finance subsidies only by lump-sum taxes, we look at very low fix costs, very high responsiveness of households and zero emissions of EVs. Hence, the results are very optimistic were it not for noise and local pollution. We do not account for reductions in noise and local pollution which might be one of the major advantages of EVs. Hence, future research shall also consider noise and local pollution. Then, external accident cost are important too. Considering these externalities in addition to those already modelled and simultaneously

lowering fix costs, reducing emissions per km and raising the responsiveness of households might in the end change this outcome.

Furthermore, further research concerning policies shall focus on policy packages. If there is a case for E-mobility it can come from combining this policy with other policies. For instance, levying an optimal congestion charge to internalize congestion, and or raise the fuel tax to lower fuel related externalities and subsidizing EVs to exploit additional gains from reducing synergy effects concerning emissions might improve welfare and lower emissions (see Tscharaktschiew & Hirte 2010b for a policy package without EVs).

Our simulations make clear that we really have to now more on advantages and disadvantages of a policy aiming at raising the number of EVs, in particular how they can be quantified. But, they also make clear, that even then E-mobility might not pay off if implemented as single instrument. Rather it is necessary to consider policy packages where E-mobility is one of the instruments implemented. E-mobility might be a supplement to other policies but quite certainly not the one and only policy to fight GHG emissions.

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A Simulation Model

B Transportation Part of the Simulation

Travel Mode Choice

Individual expected travel costs $c_{i\zeta}$ and travel times $t_{i\zeta}$ for all residents in the urban area depend on the travel mode tm used to travel $d_{i\zeta}$ miles from zone i to zone $\zeta \in [j, k, l]$. Let $c^{1,tm}$ be the travel mode specific travel cost rate per mile (excluding gasoline costs and taxes); $c^{2,au}$ be the automobile gasoline cost per gallon; and let $c^{3,tm}$ be other travel mode specific fixed costs, i.e. costs not depending on the distance traveled. Then, aggregate monetary one-way travel costs from zone i to zone ζ with travel mode tm are[12]

$$c_{i\zeta}^{tm} = c^{1,tm} d_{i\zeta} + (1-b)\, c^{2g,au} \hat{g}_{i\zeta}^{au} + b c^{2e,au} g_{i\zeta}^{e,au} + c^{3,tm}, \tag{32}$$

where the retail price per gallon of gasoline is $c^{2g,au} = (1+\tau^s)(p^g + \tau^g)$ and that of one unit of power is $c^{2e,au} = (1+\tau^s)(p^e + \tau^e)$. The pure gasoline (supply) price is denoted by p^g and the fuel tax imposed by the federal government by τ^g. The retail price includes sales taxes at rate τ^s. Gasoline consumption [gallon] for an automobile trip from zone i to zone ζ is denoted by $\hat{g}_{i\zeta}^{au}$. Note that gasoline consumption $g_{i\zeta}^{au}$ is endogenously determined, depending on traffic speed which is endogenous as well. $g^{e,au}$ is power consumption for a trip by car from zone i to zone ζ is, while p^e and τ^e are the price and the tax on power. Travel times from zone i to zone ζ are assumed to be exogenous in the case of travel mode *walking* and *publictransport*. Hence, it is assumed that there is no congestion in public transport.[13] In contrast, automobile travel times $t_{i\zeta}^{au}$ are endogenously determined, depending on, e.g., traffic volume, F_i, and road infrastructure capacity, K_i (see below). By assuming that an exogenously given specific average walking and public transport travel speed is given by $\bar{v}^{wa}$ and $\bar{v}^{pu}$, one-way travel times $t_{i\zeta}^{tm}$ from zone i to zone ζ using

[12] Note that when the specific superscript *auto*, denoting travel mode $tm = automobile$, is used in Eq. (32), then the respective travel cost component applies exclusively to the travel mode *automobile*. Travel mode *public transport* is abbreviated by '*public*' hereafter.

[13] This is a reasonable assumption particularly for U.S. Transit Authorities located in cities/city districts/metropolitan areas dominated by rail such as 'MTA New York City Transit, Brooklyn, NY'; 'Washington Metropolitan Area Transportation Authority'; or 'Massachusetts Bay Transportation Authority, Boston, MA' (see Parry and Small, 2005). As opposed to that, this treatment is, however, a simplification for cases where public transport is dominated by bus, e.g. 'Los Angeles County Metropolitan Transportation Authority, Los Angeles, CA'. Parry and Small (2005) cite evidence that for the 20 largest U.S. Transit Authorities most passenger miles driven can be attributed to rail (72% vs. 28% in 2003). In addition, in the long-run increased passenger demand could be satisfied by replacing smaller buses by larger vehicles implying that there would not necessarily be an increase in traffic. We therefore think that this assumption affects the quantitative results derived here only to a moderate degree. Another argument is that holding characteristics of the public transport system fixed in the different scenarios allows focusing on the relationship between fuel taxes and urban spatial structure.

travel mode tm are then

$$t_{i\zeta}^{tm} = \begin{cases} d_{i\zeta}/\bar{v}^{wa} & \text{if } tm = walking \\ d_{i\zeta}/\bar{v}^{pu} & \text{if } tm = public\ transport \\ t_{ij}^{au}\left(F_i, K_i\right) & \text{if } tm = automobile \end{cases}. \tag{33}$$

These travel mode specific one-way travel costs $c_{i\zeta}^{tm}$ and travel times $t_{i\zeta}^{tm}$ can be transformed into traveler specific expected two-way travel costs and travel times which enter the budget and time constraint of urban residents

$$c_{i\zeta} = 2\sum_{tm} \pi_{i\zeta}^{tm} c_{i\zeta}^{tm} \qquad\qquad t_{i\zeta} = 2\sum_{tm} \pi_{i\zeta}^{tm} t_{i\zeta}^{tm}, \tag{34}$$

where $\pi_{i\zeta}^{tm}$ is the probability that a traveler chooses travel mode tm for a trip from zone i to zone ζ. That means, it is assumed that over a certain period of time, a traveler will choose the available travel modes tm with some probability, depending on utility (derived from full economic travel cost) associated with travel mode tm on relation $i-\zeta$. These mode choice probabilities are computed by using a mode choice model in multinomial logit form.

Automobile Congestion, Gasoline Consumption and CO_2 Emission

Each commuting and shopping trip in the urban area is associated with travel time and monetary travel costs. Concerning the latter gasoline is only required for traveling by automobile. In addition, emissions of CO_2 accrue by using travel mode *public transport* as well as *automobile*. Automobile travel time, gasoline consumption as well as CO_2 emissions are all endogenously determined, depending on traffic speed. In order to determine automobile travel times, gasoline consumptions and CO_2 emissions, empirical functional relationships are employed.

The individual automobile travel time per VMT in zone i is given by the Bureau of Public Roads type congestion function (see e.g. Small & Verhoef, 2007):

$$t_i^{au}\left(F_i, K_i\right)\frac{1}{v_i\left(F_i, K_i\right)} = f_0\left[1 + f_1\left(\frac{F_i}{K_i}\right)^{f_2}\right], \tag{35}$$

where $f_1,\ f_2 > 0$; f_0 is the inverse of the free of congestion traffic speed; and F_i denotes total automobile traffic flow, i.e. traffic demand, traversing zone i. Road capacity K_i in zone i is proportional to $\Re_i$, the land allocated to roads in zone i, where $K_i = \chi\Re_i\,(\chi > 0)$.[14] The individual consumption of gasoline per VMT in zone i is given by the function (see

[14] In order to avoid the distraction from the main focus of the paper (the relationship between fuel taxes and urban spatial structure in terms of the decentralization of employment) road infrastructure capacity is assumed to be exogenously given in all cities (city structures) considered. We therefore abstract from a first-best allocation of land to roads (as examined by, e.g., Anas and Xu, 1999).

Anas and Timilsina, 2009)

$$g_i^{au}(F_i, K_i) = e\left[e_0 - e_1(v_i) + e_2(v_i)^2 - e_3(v_i)^3 + e_4(v_i)^4 - e_5(v_i)^5 + e_6(v_i)^6\right], \quad (36)$$

where $e_0 = 0.122619$, $e_1 = 0.011721$, $e_2 = 6.413 \times 10^{-4}$, $e_3 = 1.8732 \times 10^{-5}$, $e_4 = 3.0 \times 10^{-7}$, $e_5 = 2.4718 \times 10^{-9}$, $e_6 = 8.233 \times 10^{-12}$ are exogenously given constant parameters and e is an exogenously given efficiency parameter used to obtain a reasonable benchmark consumption of gasoline.

In addition we assume that fuel economy – measured as miles driven per gallon of gasoline $(1/g_i^{au}(F_i, K_i))$ – will rise with higher gasoline prices.[15] By assuming that long-run gasoline demand exhibits a constant elasticity with respect to own gasoline consumer price[16] (producer price plus taxes), effective gasoline consumption per VMT in zone i is

$$\hat{g}_i^{au}(F_i, K_i) = \underbrace{\left[\frac{(1+\tau^s)(p^g+\tau^g)}{(1+\tau^s)(p^g+\tau_0^g)}\right]^{\epsilon^g}}_{\Gamma} g_i^{au}(F_i, K_i), \quad (37)$$

where τ_0^g is the initial fuel tax and ϵ^g is the elasticity of per mile gasoline demand (the inverse of fuel economy) with respect to the gasoline price.[17] This allows for a non-proportional relationship from two directions: first, in response to higher fuel taxes residents are likely to drive less. This reduces congestion and, thus, gasoline consumption per VMT $g_i^{au}(F_i, K_i)$ and second, travelers will buy more fuel-efficient cars, thus, further decrease $g_i^{au}(F_i, K_i)$.

Since the amount of CO_2 emissions corresponds with gasoline consumption in a direct way and is strictly proportional to gasoline consumption individual emissions in grams discharged per VMT in zone i are implemented by the function

$$em_i^{au}(F_i, K_i) = e_f\left[\hat{g}_i^{au}(F_i, K_i)\right]. \quad (38)$$

The emission factor $e_f = 8788$ grams/gallon converts gasoline consumption in gallons into CO_2 emissions accruing from the combustion of gasoline on the road (direct emissions) in grams. Note that gasoline consumption per VMT as well as emissions in zone i depend directly on automobile travel speed $v_i(F_i, K_i) = 1/t_i^{au}(F_i, K_i)$ and thus indirectly on traffic flow, F_i, and road capacity K_i.

The functional relationship between gasoline consumption and speed is U-shaped, that is at low travel speeds gasoline consumption per VMT is high and becomes higher the lower the speed. As speed increases, gasoline consumption and emissions fall until a certain

[15] There is empirical evidence that about half of the long-run price responsiveness of gasoline consumption is due to changes in VMT while the other half comes from changes in average fuel economy (see Parry & Small, 2005).

[16] See Parry& Small (2005) and Parry (2011) who also apply a constant elasticity relationship.

[17] In the benchmark simulation $\tau_0^g = \tau^g$, implying that $g_i^{au}(F_i^{au}, K_i) = \hat{g}_i^{au}(F_i^{au}, K_i)$.

threshold of speed, then raising again when speed increases further.

Externalities related to Congestion

In the following we describe externalities related to travel speed, i.e. to congestion. Given the congestion function (35), total travel time T_i per VMT accruing from automobile travel in zone i is $T_i^{au}(F_i, K_i) = t_i^{auto}(F_i, K_i) F_i$. The congestion time externality (see (3) in *units of hours* becomes:

$$E_i^t = f_0 f_1 f_2 \left(\frac{F_i}{K_i}\right)^{f_2}. \tag{39}$$

Equivalently, total gasoline consumption G_i per vehicle mile accruing from automobile passenger travel in zone i is $G_i^{au}(F_i, K_i) = g_i^{au}(F_i, K_i) F_i$. Since the marginal driver does not take into account his impact on gasoline consumption of all other drivers by affecting their travel speed, the marginal gasoline consumption externality, E_i^g, in *units of gallons*, is given by the difference between the total marginal social gasoline consumption that the driver is imposing on all drivers, $\partial G_i^{au}(F_i, K_i)/\partial F_i$, and his average private consumption of gasoline at optimum, $g_i^{au}(F_i, K_i)$:

$$\begin{aligned} E_i^g &= \Gamma e \left[e_1 (t_i^{au})^{-2} - 2e_2 (t_i^{au})^{-3} + 3e_3 (t_i^{au})^{-4}\right. \\ &\quad \left. -4e_4 (t_i^{au})^{-5} + 5e_5 (t_i^{au})^{-6} - 6e_6 (t_i^{au})^{-7}\right] E_i^t \end{aligned} \tag{40}$$

As a consequence, the CO_2 emission externality, E_i^{em}, in *units of grams*, is

$$E_i^{CO} = e_f E_i^{CO} + em_i^{au}(F_i, K_i). \tag{41}$$

Traffic Flows

The private trip purposes commuting, shopping and leisure cause traffic flows from any residence in zone i to any destination ζ with travel mode tm per period.[18] Automobile traffic flow with respect to commuting or shopping per period from zone i to zone j is $F_{ij/c} = \Psi_{ij} N \tilde{D}_{ij} \pi_{ij}^{au}$ or $F_{ij/s} = \sum_{a=1}^{I} \Psi_{ia} N \tilde{z}_{iaj} \pi_{ij}^{au}$. In total, aggregate automobile traffic flow from zone i to zone j is then $F_{ij} = \left(F_{ij/c} + F_{ij/s}\right)$. Hence, we assume that traffic is uniform across the day and so do not focus on trip scheduling issues in regard to the different trip purposes. Based on the relation (zone-to-zone) specific aggregate traffic flows, aggregate zonal traffic flow – entering the congestion function (35) as well as the empirical relationships determining gasoline consumption (36) and CO_2 emissions (38) –

[18] Here we use j to denote any destination zone regardless of whether the destination zone is meant as work, shopping or leisure location.

traversing zone i is then:

$$F_i = \underbrace{\underbrace{F_{ii} + \sum_{i \neq j} (F_{ij} + F_{ji})}_{\text{if } i=1 \text{ and } i=I} + 2 \sum_{a=1}^{i-1} \sum_{b=i+1}^{I} (F_{ab} + F_{ba})}_{\text{if } 1<i<I-1} .. \tag{42}$$

The first term on the right-hand-side is intrazonal traffic (origin and destination is zone i) and the second term is traffic originating and ending in zone i. These two terms are equal to aggregate local traffic flow in zone i if that zone i is an edge zone. The determination of internal traffic flows (if zone i is not an edge zone) requires to take into account the third term on the right-hand-side. It reflects all the traffic traversing an entire zone. Hence, when zone i is an edge zone there is no traffic traversing an entire zone such that the third term on the right-hand-side can be neglected. Note that internal traffic flows are multiplied by 2 because they traverse the entire zone.

Table 1: Calibrated values of parameters

Households HH (Consumers)					
Utility function	Non-working		Low-skilled		High-skilled
α (consumption)	0.41		0.38		0.41
β (housing)	0.22		0.22		0.19
γ (leisure)	0.37		0.40		0.40
η (shopping)	0.60		0.60		0.60
$E = 4500$ hours/year (250 operating days per year $\times$ 18 hours per day)					
$L = 8$ hours/day		$\Lambda = 5$ (all HH)		$Inc^t = 19.200$ €	
Production (Urban Firms)					
Production function	Zone 1 (9)	Zone 2 (8)	Zone 3 (7)	Zone 4 (6)	Zone 5
ϕ_i (land)	0.400	0.350	0.300	0.250	0.200
$\delta_i^{low-skilled}$(labor)	0.400	0.400	0.400	0.400	0.400
$\delta_i^{high-skilled}$ (labor)	0.200	0.250	0.300	0.350	0.400
Scale parameter B_i	1.020	1.015	1.010	1.005	1.000
Travel					
Travel mode tm		$\bar{v}^{tm}$	b^{tm}	$c^{1,tm}$	$c^{3,tm}$ τ^{tm}
		[km/h]		[€/km]	[€]
Walking		4	17.70	0.00	0.00 0.00
Public Transport		18	01.60	0.15	1.50 0.07
Automobile		–	05.20	0.30	0.00 0.19
$p^g = 0.53$ €/liter			$\tau^g = 0.65$ €/liter		
$\bar{\Lambda}$: 0.25 (Non-working)		0.30 (low-skilled working)		0.80 (high-skilled working)	
Transport					
	Zone 1 (9)	Zone 2 (8)	Zone 3 (7)	Zone 4 (6)	Zone 5
Share of roads $\Re_i$	0.050	0.075	0.125	0.175	0.425
BPR-Function: f_{i0}	1/50	1/48	1/46	1/44	1/42
BPR-Function: $f_1 = 6$		$f_2 = 4$	$\chi = 44$		
$e = 0.92$		$ASCE = 72$ gCO_2/pkm			
Public Sectors					
Community shares		$\varpi^I = 0.15$	$\varpi^S = 0.022$	$\varpi^E = 0.05$	
Tax/Subsidies	$\tau^z = 0.19$	$\Pi = 920$ €	$\Upsilon = 500$ €	$\delta = 0.3$ €/round-trip km	
Public land ownership	$0.5\Re_i$				
Others					
Numeraire $p_5 = 100$ €					

Table 2: Travel demand elasticities

Elasticity	Urban Model	Empirical Literature
Own-price elasticity of travel demand for private automobile with respect to gasoline price	−0.2	[1] (−0.1) – (−0.3) [2]/[4]/[5] −0.3 [6]/[7] −0.2 [3] (−0.1) – (−0.5)
Own-price elasticity of travel demand for public transport with respect to transit fare	−0.7	[1] −0.4 (on average) [2] (−0.5) – (−0.6) (Bus) [2] (−0.4) – (−1.0) (Metro) [2] (−0.1) – (−1.1) (Rail) [3] (−0.0) – (−0.8)
Cross-price elasticity of travel demand for public transport (tram) with respect to gasoline price	+0.3	[2] +0.3 (on average) [2] (+0.1) – (+0.8) (Range)

[1] Small & Verhoef (2007) [2] Goodwin (1992) [3] Oum et al. (1992)
[4] Goodwin et al. (2004) [5] Graham & Glaister (2004) [6] Hymel et al. (2010)
[7] Steiner & Cludius (2010)

Table 3: Some results of the 'Benchmark' simulation

Rents / Wages / Prices / Output / Shopping / Jobs						
Zone		Zone 1(9)	Zone 2(8)	Zone 3(7)	Zone 4(6)	Zone 5
Rent [€/m^2/year]		23.19	27.99	36.46	55.94	171.54
Gross-Wage	low-skilled	15.64	15.29	14.79	14.42	14.13
[€/h]	high-skilled	33.71	35.14	36.50	37.70	38.67
Price [€/unit]		60.12	67.53	74.79	83.11	100.00
Output [million units/year]		115.477	100.294	87.528	75.332	57.926
Shopping		49.889	41.907	34.806	27.887	18.497
Jobs	low-skilled	106,377	106,328	104,136	100,828	95,662
	high-skilled	20,961	24,201	26,925	29,125	30,326
Private Households						
Income / Taxes [€/year]		Disposable Income		Income Tax		
Working	low-skilled	26,590–27,427		6,136–6,624		
	high-skilled	54,128–55,684		24,190–25,499		
Non-working		22,308		4,807		
Time Allocation		Work days (Commutes)		Travel [h/year]	Leisure [h/year]	
Working	low-skilled	207–219		460–536	2,289–2,307	
	high-skilled	243–252		403–467	2,081–2,105	
Non-working		—		215–303	4,197–4,285	
Public Household (Total federal tax revenues)						
Tax		Income tax	Sales tax	Energy tax	Sum	
[1,000 million €/year]		14.514	11.862	0.432	26.808	
Share		0.541	0.442	0.017	1.000	
Zone		Zone 1(9)	Zone 2(8)	Zone 3(7)	Zone 4(6)	Zone 5
Gasoline Consumption (Automobile)						
Zone specific [liters/100 vkm]		6.6	6.8	7.0	8.1	15.6
Urban Area Average		8.3 liters/100 vkm				
Total Urban Area		664.817 million liters/year				
CO_2 emissions (Automobile)						
Zone specific [grams/vkm]		154 (39)	160 (40)	165 (41)	189 (47)	365 (91)
Urban Area Average		195 (49) gCO_2/vkm				
Total Urban Area		1,555,673 (388,918) tCO_2/year				
CO_2 emissions (Public Transport)						
Urban Area Average		72 gCO_2/pkm				
Total Urban Area		362,825 tCO_2/year				
CO_2 emissions (Total)						
Total Urban Area		1,555,673 + 388,918 + 362,825 = 2,307,416 tCO_2/year				

Table 4: Some results of the 'Benchmark' compared with empirical evidence

Average (over all locations and persons)		Urban Model	Empirical Evidence	Source
Gross Wage [€/h]	Urban Area	19.23	20.04 (Germany 2007)	[1]
	City	19.56	19.26 (Berlin 2007)	
Average - average income tax rate[1] [%]		20.6	20.3 (2004)	[2]
Work days [days/year]		219	215–223 (2004)	[3]
Percentage Commuters (commuting distance < 10 one-way km)		55	52 (2004)	[4]
Average one-way commuting distance [km]		12	12–13	[5]
Ratio Shopping Trips/Commuting Trips		1.29	1.32 (2002)	[6]
Share travel costs on disposable income		0.09	0.10	[7]
Job–Housing–Balance $\frac{\text{Number of jobs in } i}{\text{Number of workers residing in } i}$	Suburb/City	0.75/1.37	0.87/1.54 (Hannover) 0.79/1.33 (Hamburg) 0.86/1.39 (Munich) 0.89/1.56 (Stuttgart)	[8]

[1] Arbeitskreis Volkswirtschaftliche Gesamtrechnungen der Länder (2009)
[2] Federal Statistical Office (2008b) [3] IAB (2005) [4] Federal Statistical Office (2005)
[5] Federal Ministry of Transport, Building and Urban Affairs, 2009
[6] Federal Ministry of Transport, Building and Urban Affairs, 2004
[7] Federal Statistical Office (2009) [8] Siedentop (2007)