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CAFE in the City – A Spatial Analysis of Fuel Economy Standards

Abstract

Climate policy instruments in the transportation sector like fuel economy standards (CAFE) and fuel taxes not only affect households' vehicle choice, but also the urban form in the long run. We introduce household level vehicle choice into the urban economic monocentric city model and run long-term climate policy scenarios to analyze the welfare effects of this urban adjustment in reaching emission goals. This goes beyond more short-term empirical analyses of the rebound effect in driving. We find that stricter CAFE standards lead to an urban expansion and considerable additional welfare costs for certain emission goals, unaccounted for in the previous literature on welfare costs of CAFE. These welfare costs can be reduced roughly by one half through the combination of CAFE with an urban growth boundary. Fuel taxes, in turn, lead to an urban contraction and additional welfare gains. We analyze the sensitivity of the results to changes in model parameters.

JEL code: H23, L9, Q48, R4
Keywords: Fuel economy standards, fuel tax, monocentric city, rebound effect

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1 Introduction[1]

Reducing carbon emissions in the transportation sector is crucial in combating climate change. Policy instruments like first-best gasoline taxes and second-best fuel economy standards are discussed in the academic literature and implemented in the political arena.[2] For the choice and design of the appropriate policy instrument it is important to understand the transmission channels and welfare implications of every measure (besides their effectiveness) relative to the first-best solution. Moreover, political economic and distributional concerns, which can constitute significant policy constraints, must be considered.[3]

The literature discusses important mechanisms like the (rather short-run) rebound effect[4] in the case of increasing fuel efficiency and fuel demand elasticities in the case of fuel taxes. But they do not analytically consider the complex long-run interplay between the spatial urban structure on the one hand and vehicle choice, environmental policies, and driving patterns on the other hand. The present paper integrates urban economic modelling and environmental economic analysis to yield two main contributions. First, it investigates the role of urban parameters (like land price, income level,

[1] We would like to sincerely thank Ken Gillingham, and Jan Brueckner for many extensive discussions and helpful comments on the study presented in this paper. We are also very grateful to the participants of the SURED, EAERE, NARSC, EEA conferences, the Yale Prospectus Environmental Economics Seminar, and the research seminar of the Mercator MCC group on Land Use, Infrastructure and Transport.

[2] In the United States transportation contributes to about 30 percent of all carbon emissions, and, worse, transportation carbon emissions are growing both in absolute numbers and also relative to the other sectors. To this end, besides reducing dependence on imported foreign oil, the Obama Administration issued in 2010 together with the National Highway and Transportation Safety Administration ("NHTSA", cf. National Highway Traffic Safety Administration (2010)) and the Environmental Protection Agency (EPA) stricter rules for the Corporate Average Fuel Economy (CAFE), the main environmental policy in the U.S. transportation sector. The goal is to almost double the vehicle fleet fuel efficiency standards for newly manufactured cars sold in the United States from 27.5 miles per gallon ("mpg") to more than 54 mpg in 2025. The EPA and the Department of Transportation proposed in 2018 to resort to less strict mileage which has not been enacted to date (cf. Davenport (2018)).

[3] Although taxes are the first-best way to internalize an externality, their generally low popularity in the electorate, for instance, can lead to the implementation of second-best measures. This was arguably the case with fuel economy standards for each new vehicle fleet since the 1970s in the U.S.

[4] Gains in technical efficiency, e.g. of fuel consumption, which aim at reducing total consumption or harmful emissions, can decrease the marginal costs of the good or fuel and lead to increased consumption. The term “rebound effect” refers to the share of reduced emissions that is offset by the according increase in consumption. For an extensive overview of microeconomic and macroeconomic rebound and according welfare effects see Gillingham et al. (2016).

population size, amenities and construction norms) for the welfare costs of partial equilibrium compliance with the environmental policies before an urban adjustment taking household level vehicle choice into account. Second, this is the first study to analytically integrate the long run effects of these environmental policies on driving behavior and vehicle choice based on fuel economy and the interdependent choice of location and commuting distances of households in general equilibrium. Again, urban economic factors play an important role for the magnitude and the spatial pattern of resulting urban expansion or contraction. Taking into account how the adjustment of the urban form feeds back into the individual choice of vehicle fuel efficiency, this paper presents a new channel through which fuel economy standards and fuel taxes affect aggregate welfare and emissions.

This paper incorporates two new mechanisms into the monocentric city model, a workhorse model in urban economics: first, household-level vehicle choice based on fuel economy and, second, an endogenous adjustment of the vehicle pricing scheme in the automobile sector for a change in fuel economy standards. This and recycling of land rents and fuel tax revenues as household income in turn affects all equilibrium values of the model variables. Therefore, the model has no closed-form solution and is solved numerically. This allows for a disentangling of welfare channels for both policies. A sensitivity analysis illustrates the role of the main model parameters.

In the analysis of welfare channels it is considered how the policies affect household utility from the consumption of housing and a composite good by inducing monetary costs and benefits for different emission reduction targets. There is no direct effect on utility from carbon emissions or climate damages. To better understand the welfare channels of both policies, the resulting effects are decomposed into a partial equilibrium and a general equilibrium welfare effect. The partial equilibrium effect ("step 1") considers additional compliance costs from the households' choice of cleaner vehicles while keeping household locations and real estate prices fixed ("compliance before urban adjustment"). The general equilibrium effects ("step 2") adjust for changes in household locations and housing prices ("urban adjustment"), which leads to two simultaneous, but counteracting, welfare channels: first, a change in vehicle and driving costs from the new choice of vehicle efficiency at the new locations and, second, the welfare effect from the change in housing prices and the according adjustment in consumption bundles.

The results show that the partial welfare cost of compliance before urban adjustment rises up until 1 to 6 percent of total welfare for an emission reduction of 75 percent, depending on the parameter setting. In all relevant parameter settings for the CAFE policy, the decrease in the marginal cost of driving leads to an expansion of the city area in the long run equilibrium. The corresponding commute-related rebound effect is between 2 percent and 16 percent for low emission reduction goals and falls significantly and monotonically to 0.5 to 3 percent for a high aggregate emission reduction of 75 percent. This expansion yields additional welfare costs from the choice of cleaner vehicles and additional welfare gains from an increase in housing supply and average consumption. The net welfare effect of urban adjustment, however, is negative, despite the additional degrees of freedom of location choice and adjusting housing prices. The reason is that the cross subsidy from dirty to clean vehicles via the CAFE mechanism creates a distortion of vehicle prices. This distortion is not accounted for by households in their vehicle choice and leads to a deadweight loss. The adjustment in spatial equilibrium imposes an additional net welfare cost of 10 to 65 percent over the partial equilibrium welfare cost for given emission reduction targets and decreases with more ambitious climate policy goals. The urban adjustment is, therefore, a major component in the overall welfare balance of the policies, but plays a smaller role in the decarbonization of the transportation sector.

In the case of the fuel tax policy urban adjustment implies a contraction of the city because of the increase in marginal driving costs. This leads to additional welfare gains from the choice of less costly and less fuel efficient vehicles and additional welfare costs from a decrease in housing consumption. The net welfare effect of urban adjustment ("step 2") for the fuel tax is positive and lies in the range of 5 to 40 percent of the welfare cost of compliance before urban adjustment. The positive net welfare effect of urban contraction due to the fuel tax policy even increases with progressive decarbonization.

The total resulting welfare gap between the fuel tax and fuel economy standards after urban adjustment lies in the range of 10 to 80 percent of the welfare cost of CAFE compliance without urban adjustment. Overall, the welfare cost of compliance before urban adjustment, the commute-related rebound effect and the welfare cost of urban adjustment are all higher for lower household income, for a larger city population and higher prices for vehicle efficiency technology and for gasoline. Taking the urban economic dimension of the problem into account, therefore, adds weight to the choice of the right climate policy instrument. This is even more the case for low income countries with large average city size.[5] If policy makers nevertheless must resort to second-best fuel economy standards, like in the U.S., a simultaneous introduction of urban growth boundaries is recommended. A combination of the two measures reduces the additional welfare cost of urban expansion by roughly one half and closes between 20 and 40 percent of the total welfare gap between the fuel tax and fuel economy standards. A discussion of distributional implications reveals that fuel economy standards can have regressive effects. In contrast, fuel taxes tend to be more progressive. But further research is needed in this direction.

This study contributes to the literature on welfare effects of fuel economy standards by bringing the urban economic dimension into the picture. The literature to date, on the one hand, considers direct effects of fuel economy standards on welfare over three channels connected to the vehicle market: first, the cost of compliance (cf. Austin and Dinan (2005), Anderson and Sallee (2011), Klier and Linn (2012), Jacobsen (2013)[6]), second, the opportunity cost from the car manufacturers' trading off of vehicle characteristics like horsepower against higher fuel efficiency (cf. Klier and Linn (2016) and West et al. (2017)), and, third, the effects on scrappage and values of used cars (cf. Jacobsen and van Benthem (2015)). On the other hand, indirect channels of fuel economy standards on welfare via their influence on externalities[7] from gasoline consumption (climate and local pollution) and from driving (congestion and traffic safety, cf. Jacobsen (2011)) are discussed. But none of the (mostly structural empirical) studies mentioned takes explicitly into account the welfare gains in housing consumption from urban expansion.[8] Nor do they consider that these direct and indirect welfare channels and the magnitude of the resulting effects are affected significantly by urban

[5] Newly industrializing countries like China and India exhibit relatively low income, at least compared to OECD countries, and rapid urbanization. But for a reasonable comparison with the U.S. or Europe, the role of public transit and mobility mode choice patterns, which are not modeled here, would have to be taken into account.

[6] While National Highway Traffic Safety Administration (2010) optimistically expects positive monetary net effects of compliance (with savings from reduced gasoline consumption exceeding additional vehicle costs), the other studies yield net costs of compliance. This view is supported by the evidence that Sallee et al. (2016) find for the households' full valuation of fuel efficiency and, therefore, against the notion that they might be myopic with respect to possible gains from increased fuel efficiency.

[7] A good overview over different automobile related externalities can be found in Parry et al. (2007)).

[8] National Highway Traffic Safety Administration (2010) considers an increase in consumer surplus from increased driving as "half of the product of the decline in vehicle operating costs per vehicle-mile and the resulting increase in the annual number of miles driven" (National Highway Traffic Safety Administration (2010)).

parameters and the adjustment of the urban form in the long run. The present paper fills that gap by identifying new channels of fuel economy standards on welfare 1) via the adjustment of the housing market and 2) via the role of urban parameters and the long-term adjustment of the urban form for the welfare channel of compliance. The theoretical urban economic perspective allows the present paper to go beyond empirical studies, whose time horizon is necessarily short due to data constraints, and simulate very long-term emission reduction scenarios. The influence of the urban form channel on the other welfare effects in the literature beyond compliance costs (opportunity costs of vehicle features, changes in used-car values, traffic safety, congestion, and local pollution) is left for future research.

The present study's analysis of fuel taxes in a spatial urban context also extends the literature on the effects of gasoline prices on gasoline consumption and fuel economy (cf. Burke and Nishitateno (2013); Klier and Linn (2013); Li et al. (2014)) and on the welfare costs of gasoline taxes (cf. Langer et al. (2017)). Like the studies on welfare effects of fuel economy standards, this empirical literature also has a short to medium time horizon and does not consider the long-term change of urban form and the new channels of gasoline taxes on welfare over vehicle choice and the real estate market which the urban adjustment creates. Again, the present theoretical framework enables the simulation of long-term scenarios for a fuel tax policy, just like for fuel economy standards.

This study also contributes to the literature on rebound effects in driving since Greene (1992) and to the according discussion about the right climate policy instrument in the transportation sector. Gillingham et al. (2013) point out the relatively small magnitude of rebound effects for the United States (referring to empirical studies like Small and van Dender (2007), Hughes et al. (2008), and Greene (2012)[9]). On the other hand, Frondel and Vance (2013) point to much higher rebound effects (around 60 percent) found in German data (cf. Frondel et al. (2008), Frondel et al. (2012))[10]. To tackle these questions and to assess the implications for different environmental policy mea-

[9] Small and van Dender (2007), estimate for the time period 2000 to 2004 a rebound effect of between 1.1 percent (short-run) and 5.7 percent after a few years. Hughes et al. (2008) observe for the time period 2001 to 2006 a price elasticity of -0.037 to -0.077, corresponding to a similar magnitude of the earlier obtained rebound effect. Greene (2012) does not find a significant effect of fuel efficiency on vehicle travel.

[10] Linn (2016) provides an intermediate rebound estimate of 20 to 40 percent taking additional aspects like multivehicle households and the correlation of fuel economy and vehicle and households attributes into account.

sures like fuel economy standards and fuel taxes it is of key importance to understand the endogenous interplay of distance driven (location choice), vehicle fuel economy, and gas price (as already Greene et al. (1999) pointed out) and to disentangle the resulting welfare effects.[11] The present paper incorporates these relations, especially the simultaneous choice of long-run housing location and vehicle fuel efficiency, and allows for a long-run perspective on rebound and on non-linear relationships which go beyond the available data base of empirical work. Given the prominent role of location choice, this paper focuses on commuting trips. Trips for recreation or shopping are abstracted from here, but they can be expected to be correlated to commuting trip lengths.

Moreover, this study establishes a connection of the urban economic literature in the tradition of monocentric city modelling (cf. Alonso (1977), Muth (1969), Mills (1967), Henderson (1985), Fujita (1990)) with the energy and environmental economic literature on fuel economy standards, fuel taxes, and rebound effects. Thus, I include urban economic and spatial considerations into the design of environmental policy in the transport sector. I extend the numerical simulation approach of a monocentric city model taken by Brueckner (2007) and Kim (2012) to incorporate household level vehicle choice based on fuel economy and a consistent implementation of fuel economy standards. Kim (2016) is, to my knowledge, the only other example of vehicle choice in a more stylized monocentric urban model. But there households base their vehicle choice on vehicle size and resulting inconvenience in congestion and not fuel economy, which is, in contrast, the focus of the present paper and of fuel economy policies in general. The present paper also goes beyond Kim (2016) in its modelling of endogenous adjustment of vehicle price policy after tightened fuel economy standards.

The remainder of the paper is organized as follows. After presenting the model in Section 2 and the way the policies are implemented in it in Section 3 I analyze the environmental and welfare effects of the policies in Section 4. An extension with urban growth boundaries is presented in Section 5. Section 6 concludes.

[11] Chan and Gillingham (2015) provide a systematic framework to analyze rebound related welfare effects like benefits from energy service use and costs from additional energy service provision, fuel externality, and energy service externality. But they do not consider the urban economic dimension of location choice and all the resulting effects that the present paper focuses on.

2 The Model

2.1 Households

The core of the model is the monocentric city model (in the tradition of Alonso (1977), Muth (1969), and Mills (1967)), as it is described in Brueckner (2007). The city is closed in the sense that population size L is exogenously given. All households receive income only from working in the central business district (CBD), to which they commute by car. There is no public transit. At each distance x from the CBD households maximize their Cobb-Douglas utility that they derive from the consumption of a composite good c and housing q by choosing their consumption bundle and – and this is an addition to the model of Brueckner (2007) – their car's mileage mpg, measured in miles per gallon.[12]

$$\max_{c,q,mpg} u(c,q) = c^{1-\alpha} q^{\alpha} \tag{1}$$

subject to the budget constraint

$$c + p(x)q = y - t(mpg)x - v(mpg) \tag{2}$$

with the price of the consumption good c being normalized to 1 and $p(x)$ being the price of a 'unit' of housing at every distance x. On the RHS of (2) there is the part of annual per capita income y which is available for consumption after the annual expenses for commuting $t(mpg)x$ and for the vehicle costs $v(mpg)$ have been made. Annual per capita income y is uniform across the city and consists of an exogenous part y_0, of lump-sum recycled land rent from the whole city y_{RPC}, and lump-sum recycled revenues from the fuel tax y_{Tax}, if there are any:

$$y = y_0 + y_{RPC} + y_{Tax} \tag{3}$$

Rent income y_{RPC} and tax income y_{Tax} both depend on the resulting general market equilibrium (cf. Equation (20) in Section 2.3 and Equation (27) in Section 3.2). The

[12] The maximization problem could be set up with the households maximizing over x as well. But since, in equilibrium, utility must be uniform over x to ensure non-arbitrage, this dimension is redundant.

annual travel costs per meter $t(mpg)$ read as follows

$$t(mpg) = \frac{p_G F}{mpg} + t_{main} \tag{4}$$

with the exogenous gasoline price per gallon p_G, the factor F for adjusting the units[13], and annual maintenance costs per meter of distance t_{main}. Annual vehicle cost $v(mpg)$ is a linear function[14] of the vehicle mileage mpg chosen and, in the initial state before any policy, equals the technological vehicle production costs $v_{tech}(mpg)$:

$$v(mpg) = v_{tech}(mpg) = v_{0,tech} + m_{tech} \cdot mpg \tag{5}$$

with the intercept $v_{0,tech}$ and m_{tech} being the technological cost of a marginal increase in vehicle mileage mpg. The vehicle price rises with increasing fuel efficiency because more fuel efficient technology (like hybrid engines or synthetic materials with certain features) is more expensive. Automakers are assumed to be perfectly competitive making zero profits. Without any binding policies they set the price of each vehicle equal to its production costs. The households' first-order condition for mpg reads

$$-\frac{p_G F}{mpg^2} x + m_{tech} = 0 \tag{6}$$

The benefit of a marginal efficiency increase in the form of a reduction in driving costs must equal its marginal technological cost. The resulting choice of vehicle mileage then reads

$$mpg^*(x) = \sqrt{\frac{p_G F}{m_{tech}} x} \tag{7}$$

changing (4) and (5) to

$$t(x) = \sqrt{\frac{p_G F m_{tech}}{x}} + t_{main} \tag{8}$$

[13] The factor $F = \frac{1}{1.6} \frac{miles}{km} \frac{1}{1000} \frac{km}{m} \cdot 2 \cdot 250 \frac{round-trips}{a} = 0.3125 \frac{miles}{m \cdot a}$ converts the costs of a singular trip into annual expenses and miles into meters.

[14] Following Austin and Dinan (2005), the vehicle cost curve implicitly incorporates future R&D related cost reductions, so that its shape is not convex, but linear.

and

$$v(x) = v_0 + \sqrt{p_G F m_{tech} x} \tag{9}$$

respectively. If fuel economy is the only factor determining vehicle choice, then households with a longer commute will buy more fuel efficient cars than those closer to the city center.[15]

Since the households' utility level in spatial equilibrium must be the same at every point x, higher commuting costs $t(x)x$ at higher distances x are counteracted by lower housing prices. This trade-off is incorporated in equations (1) and (2). Substituting the first-order conditions for c and q into (2) yields the expenses for the composite good

$$c(x) = (1 - \alpha)(y - t(x)x - v(x)) \tag{10}$$

and the rent expenses

$$p(x)q(x) = \alpha(y - t(x)x - v(x)) \tag{11}$$

which are equal to constant shares $(1 - \alpha)$ and α, respectively, of available income. By substituting (10) and (11) into (1) we obtain the housing price function in the city:

$$p(x, u) = \Psi(y - t(x)x - v(x))^{\frac{1}{\alpha}} u^{-\frac{1}{\alpha}} \tag{12}$$

[15] In principle, the household vehicle choice could be influenced by two factors: the economics of fuel consumption depending on distance driven and the convenience of the vehicle which is correlated with vehicle size and directly affects utility while driving and additionally with congestion. Vehicle choice in Kim (2016) only relies on vehicle size while abstracting from fuel economy as a choice criterion. Instead, I focus on fuel economy as the crucial choice criterion, which is more consistent with the micro foundation of households as rational agents and the empirical observation of Sallee et al. (2016) that consumers are not myopic and do value the gains in transportation costs correctly while choosing their car.

with $\Psi = \alpha(1-\alpha)^{\frac{1}{\alpha}-1}$ and a parametric utility level u.[16] Substituting (12) into (11) leads to the housing demand equation

$$q(x,u) = \Gamma(y - t(x)x - v(x))^{1-\frac{1}{\alpha}} u^{\frac{1}{\alpha}} \quad (13)$$

with $\Gamma = (1-\alpha)^{1-\frac{1}{\alpha}}$.

2.2 Housing Production

As in Brueckner (2007), housing is produced by developers with the inputs land and housing capital S. The housing output per unit of land is θS^{β} with the constant θ. The exponent β is smaller than one and, thus, implies decreasing returns to scale, that is, building higher.[17] Perfectly competitive developers maximize profits per unit of land at every distance x[18]

$$\max_S \Pi(S) = p(x)\theta S^{\beta} - S - r(x) \quad (14)$$

with the price of capital S being normalized to 1 and $r(x)$ being the rent per unit of land at distance x.[19] Substituting Equation (12) into the resulting first-order condition for S yields the housing capital demand function

$$S(x,u) = \Lambda(y - t(x)x - v(x))^{\kappa} \cdot u^{-\kappa} \quad (15)$$

[16] In the urban economic equilibrium, household utility u is uniform over all households and distances x to ensure non-arbitrage. Since the utility level u (as well as the city boundary $\bar{x}$) is endogenously and numerically determined only under usage of additional conditions in the urban economic equilibrium (cf. Section 2.3), it appears as a parameter from the perspective of a single household in the derivation here.

[17] The parameter β can be interpreted as capturing a technologically determined increase in effort for building higher, like more robust steel structures and a rising necessity for elevators. But it could also incorporate the degree of construction regulation: with low regulation (low β), one-story buildings can be built in a very simple way, so that the step toward a second and third floor involves a disproportionate increase in capital costs. In a highly regulated construction sector (high β), in contrast, already low buildings have to meet strict requirements. Adding more floors then raises capital costs more proportionally.

[18] Similarly to the utility maximization by households (cf. (1)), developers' profits in equilibrium are equal (and zero) at all distances x to exclude arbitrage. Therefore, profit maximization over x is redundant.

[19] Here the term "rent" is used because it is consistent with annual payments for the vehicle and driving costs and annual income in the household budget. In an efficient market the price for land must be equivalent to the present value of an infinite stream of rent payments.

with the constants $\Lambda = (\theta\beta\Psi)^{\frac{1}{1-\beta}}$ and $\kappa = \frac{1}{\alpha(1-\beta)}$. Setting (14) equal to zero and substituting (12) and (15) leads to the land rent function:

$$r(x,u) = \Omega(y - t(x)x - v(x))^{\kappa} \cdot u^{-\kappa} \tag{16}$$

with the constant $\Omega = \theta\Psi\Lambda^{\beta} - \Lambda$.

2.3 General Market Equilibrium

A condition that is necessary to determine the city limit is that the land rent at the city boundary $\bar{x}$ has to equal the exogenous agricultural land rent r_A (using (16)).

$$r(\bar{x},u) = \Omega(y - t(\bar{x})\bar{x} - v(\bar{x}))^{\kappa} \cdot u^{-\kappa} = r_A \tag{17}$$

Dividing the amount of produced housing per unit of land (with $S(x,u)$ from (15)) by the amount of housing per person (13) yields the number of people per unit of land, which is the population density:

$$D(x,u) = \frac{\theta S(x,u)^{\beta}}{q(x,u)} = \Phi(y - t(x)x - v(x))^{\kappa-1} \cdot u^{-\kappa} \tag{18}$$

with $\Phi = \frac{\theta\Lambda^{\beta}}{\Gamma}$. To close the model, we need to add the condition that the whole population, that is, the integral over the whole inhabited city area of the population density $D(x,u)$ from (18), has to be equal to the exogenously given city population L

$$\iint_{city} D(x,u)\, dA = \int_0^{\bar{x}} D(x,u) 2\pi x \, dx = L \tag{19}$$

With conditions (17) and (19) the model can be solved and the city radius $\bar{x}$ and the utility level u can be calculated.[20] With the equilibrium solution also the aggregate land rent payments can be calculated. But only the excess rents, i.e., the difference between land rents r and the agricultural rent r_A, are redistributed to the households

[20] Because of the integral in (19) the model must be solved numerically. With the numerical value for u and Equations (13) and (12) the housing consumption function $q(x)$ and the housing price function $p(x)$ ("bid-rent curve") can be determined explicitly. In equilibrium, available income after expenses for mobility $(y - t(x)x - v(x))$ decreases over x. Therefore, $\frac{\partial c(x)}{\partial x} < 0$ holds as well. But at the same time we have $\frac{\partial p(x)}{\partial x} < 0$ and $\frac{\partial q(x)}{\partial x} > 0$. So, suburban residents are compensated for their high mobility expenses by larger dwellings and the resulting utility level is identical to central residents.

in a lump-sum fashion (cf. income components in Equation (3)) to be accounted for in the welfare balance.

$$y_{RPC} = \frac{1}{L} \iint_{city} r(x,u) - r_A \, dA = \frac{1}{L} \int_0^{\bar{x}} (r(x,u) - r_A) 2\pi x \, dx \tag{20}$$

A classical interpretation of excess rent recycling in the urban economic literature is that the city population owns the land that the city is built on collectively over a "city corporation". The "city corporation" receives the excess land rent payments and re-distributes them to the citizens as lump-sum payments to avoid further distributional distortions. The agricultural rent component, in contrast, is often seen as the opportunity cost of land and does not contribute to the relevant welfare balance from a policy maker perspective. Therefore, the agricultural rent here is paid to land owners outside the city.[21]

To calculate aggregate annual carbon emissions E_{CO2} in tons of CO_2, individual commuting distances divided by the individual car mileage and weighted with the population density $D(x,u)$ are integrated over the inhabited city area:

$$E_{CO2} = F_{CO2} \int_0^{\bar{x}} \frac{x}{mpg(x)} D(x,u) 2\pi x \, dx \tag{21}$$

The factor $F_{CO2} = 2.48027 \cdot 10^{-3} \frac{MPG}{m} \frac{t_{CO2}}{a}$ transforms gallons of E10 gasoline to tons of CO_2 emitted to the atmosphere and meters of geographical distance to the CBD to annual miles driven.[22]

[21] In the present case, the recipients of agricultural rent reside outside the city and the according payments leave the system. Alternatively, all the land inside and outside the city (up to a maximal radius which then would have to be chosen) could be seen as owned by all city households collectively. Then households would also receive the agricultural rent payments for the entire land inside and outside the city boundary. However, if different land owners inside and outside the city limits were assumed, then the owners of the land outside of the city would have to be modeled explicitly and included in the welfare balance from a neutral policy maker's perspective. This is avoided here.

[22] $F_{CO2} = 7.983226 \frac{kg_{CO2}}{gallon E10gas} \cdot \frac{500 \frac{one-way\,trips}{a}}{1000 \frac{kg_{CO2}}{t_{CO2}} 1000 \frac{m}{km} 1.609344 \frac{km}{mile}} = 2.48027 \cdot 10^{-3} \frac{mpg}{m} \frac{t_{CO2}}{a}$ with the CO_2 content of a gallon of E10 gasoline of $7.983226 \frac{kg_{CO2}}{gallon}$ (Energy Information Administration (2018))

3 Implementation of Policy Measures

3.1 CAFE Standards

Since the 1970s fuel economy standards have been the main environmental policy measure in the U.S. transportation sector. As its name "Corporate Average Fuel Economy" indicates, the policy puts a lower bound for the average fuel economy of the whole car fleet of every car producing corporation. Each company chooses how many vehicles of each type to produce and how to price them on the market as long as the company's average car fulfills the standard. As empirical evidence in Sallee et al. (2016) suggests, households optimally choose their car's fuel efficiency for the given vehicle prices, that is, they are not myopic.

If a binding fuel economy standard is tightened, it requires automakers to sell more fuel efficient vehicles, which people do not voluntarily choose in the first place. To incentivize the required purchasing behavior and achieve the goal, automakers will have to reduce the price of more fuel efficient vehicles relative to the price of less fuel efficient ones. At the same time their revenues must be high enough to cover the sum of all production costs. This mechanism is modelled as follows.

The slope of the vehicle cost curve m_{tech} is the only model parameter that drives vehicle choice for a given distance x and gas price p_G in the pre-policy equilibrium (cf. (7)). Now, with fuel economy regulation, the vehicle price curve is assumed to remain linear so that car producers can choose its slope and the according intercept.[23] This allows for a one-to-one mapping of each fuel economy standard onto the slope m_{CAFE} of the post-policy vehicle price curve for a given parameter setting: implicitly, car companies choose the slope m_{CAFE} which triggers the required household vehicle choice to fulfill the new fuel economy standard. Therefore, the policy shock of a tightening CAFE standard is implemented in the model as a shock directly on the slope of the vehicle price curve (5) ($m_{CAFE} < m_{tech}$). As a result, households at every distance x in the

[23] In reality automakers are free to choose their marketing and pricing policies according to many different strategic considerations. The present model abstracts from a number aspects which play a role in real automobile markets like taste, heterogeneity of consumer groups, particularly with respect to income, etc. A more elaborate pricing policy in the model than the choice of the slope and the intercept of a linear vehicle price curve would considerably increase model complexity and require additional assumptions without adding much to explanatory power.

model increase their vehicle mileage by the same factor due to the policy shock:

$$mpg_{CAFE}(x) = \sqrt{\frac{p_G F}{m_{CAFE}} x} > \sqrt{\frac{p_G F}{m_{tech}} x} \tag{22}$$

Aggregate production costs for these cleaner vehicles increase according to (5) and must be covered by aggregate revenues. Therefore, car companies endogenously increase the intercept of the vehicle price curve, so that $v_{0,CAFE} > v_{0,tech}$, until they exactly ensure full cost coverage and zero profits again, according to the following condition:

$$\begin{aligned} \sum v_{Revenues} &= \sum v_{Costs} \\ \int_0^{\bar{x}} D(x,u)(v_{0,CAFE} + \sqrt{m_{CAFE} p_G F x})\, 2\pi x\, dx &= \\ \int_0^{\bar{x}} D(x,u) \left(v_{0,tech} + m_{tech} \sqrt{\frac{p_G F x}{m_{CAFE}}} \right) 2\pi x\, dx & \end{aligned} \tag{23}$$

This means that automakers do not choose the intercept independently of the slope of the vehicle price curve. Also, household preferences, which play a role for location choice, affect vehicle choice and, thus, (indirectly) the intercept $v_{0,CAFE}$. The new vehicle price curve then is

$$v_{CAFE}(x) = v_{0,CAFE} + m_{CAFE} \cdot mpg_{CAFE}(x) = v_{0,CAFE} + \sqrt{m_{CAFE} p_G F x} \tag{24}$$

Figure 1 illustrates the decrease in slope and increase in intercept of the vehicle cost curve due to a CAFE policy shock.

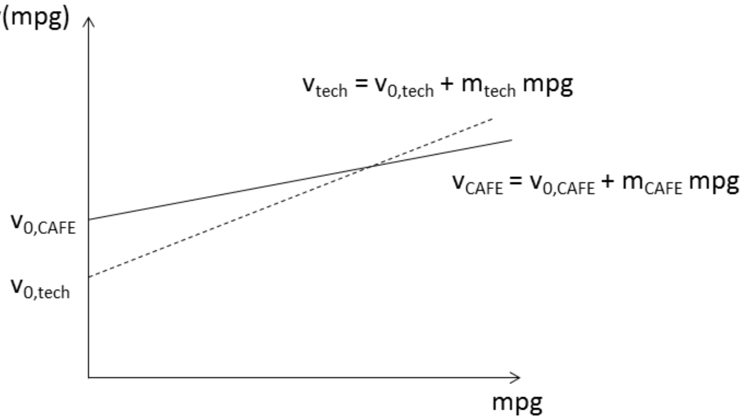

Figure 1: Change in the vehicle cost curve through CAFE policy

On average, vehicle expenses increase. But owners of less fuel efficient cars in the city center to a certain degree effectively subsidize cleaner cars in the suburbs. As long as we leave the adjustment in the urban form out of the picture, driving expenses $t(x)x$ for each household go down due to increased fuel efficiency. But since the marginal cost of driving decreases, distance to the CBD becomes cheaper and households at each distance x have an incentive to move further away from the center to benefit from lower housing prices in the suburbs compared to the center. The result is an overall expansion of the city with an increase of the average commuting trip length.

This can be seen as an urban economic long-term rebound effect. The energy economic literature on the rebound effect of driving typically deals with short term changes in driving distance after increases in efficiency. Reasons can be a higher frequency, as well as an increased length of all trips, that is, beyond commuting, also those for shopping and recreation. The agents' motives can be monetary as well as behavioral like a "greener feeling" when driving. I focus on this urban-form driven commute-related long-term rebound component. Even if we released the assumption that people only drive to commute to work in the present model and allowed for shopping and recreational trips, it would be plausible that an overall expansion of the city would also increase the average length of these trips. However, the increased commuting distances x in turn incentivize the choice of even more fuel efficient cars, reinforcing the effect of the flatter slope of the vehicle price curve on vehicle choice. The net effects of the adjustments of the real estate market and the car market on aggregate emissions and welfare are dealt with in more detail in the analysis in Section 4.

3.2 Fuel Tax

The alternative first-best environmental policy in the transportation sector is a fuel tax. The fuel tax τ is a unit tax. It is implemented as a markup on the price of gasoline and thus contributes to an increase in transportation costs and to a contraction of the city. Like CAFE standards, however, it also provides an incentive for households to buy more fuel efficient cars:[24]

$$mpg_{Tax}(x) = \sqrt{\frac{(p_G + \tau)F}{m_{tech}}x} > mpg_0^*(x), \quad for\ \tau > 0 \tag{25}$$

[24] Burke and Nishitateno (2013) and Klier and Linn (2013) empirically confirm that higher gasoline prices lead customers to the choice of more fuel efficient vehicles.

And the efficiency increase contributes to a decrease in driving costs. But, unlike the CAFE policy, a fuel tax does not require a different pricing policy from the car companies. They continue to set vehicle prices equal to technologically determined production costs. The vehicle cost curve over the distance x from (9) changes into

$$v_{Tax}(x) = v(x) = v_0 + \sqrt{m_{tech}\,(p_G + \tau)\,F\,x} \tag{26}$$

because vehicle efficiency changes with (25), even though the vehicle cost curve over mileage (5) does not. Tax revenues are recycled on a per-capita basis:

$$y_{Tax} = \frac{1}{L}\int_0^{\bar{x}} D(x,u)\frac{\tau\,F\,x}{mpg^*_{Tax}(x)}2\pi x\,dx \tag{27}$$

Since households at a higher distance bear a higher tax burden, the fuel tax redistributes income from suburban to central residents. With the tax, the marginal cost of driving from (8) turns into

$$t_{Tax}(x) = \sqrt{\frac{(p_G + \tau)Fm_{tech}}{x}} + t_{main} \tag{28}$$

As $\frac{\partial t_{Tax}(x)}{\partial \tau} > 0$, the marginal cost of driving overall increases with the tax despite the increase in fuel efficiency. This contributes to an overall contraction of the city, which in turn, according to (6), creates an incentive to invest less in fuel efficiency. These effects will also be discussed in more detail in the following Section 4.

4 Numerical Analysis

In the following, the effects of both policy instruments on the urban form, welfare, and emissions are analyzed. For tractability, I look at the effects in two steps, which actually take place simultaneously: first, in "step 1", I introduce a policy measure while keeping housing prices $p(x)$ and housing locations x unchanged. In this way I observe the costs and benefits of compliance of all households' vehicle choices with the policy measure before allowing for the urban economic adjustment. In this intermediate state utility levels vary over x (which they do not with endogenously adjusting housing prices $p(x)$ and household locations x). But the change in average utility indicates the per-capita welfare cost of compliance without urban adjustment with the new fuel economy standard. In "step 2", the urban form adjusts and triggers not just a change in location choice, but also an additional change in vehicle choice. The implications of urban adjustment for welfare and emissions are identified and the magnitude of the effects is compared to the case of compliance without urban adjustment in step 1. Step 1 is analyzed for fuel economy standards in Section 4.1, and step 2 in Section 4.2. Section 4.3 deals with both steps for a fuel tax policy.

For the entire analysis, a reference city is defined. Then the different model parameters are changed to illustrate their influence on the results. The (exogenous) parameter setting of the reference city is summarized in Table 1. It could be interpreted as a country's average metro area.

Population, L	1,000,000
Annual income p.c., y_0	50,000
Annual marginal cost of vehicle fuel efficiency, m_{tech} $[\frac{\$}{MPG\,a}]$[25]	15
Gas price p_G $[\frac{\$}{gal\,a}]$	2.5
Consumption share of housing, α	0.3
Scale exponent in housing production, β	0.85
Scaling constant in housing production, θ	0.025
Agricultural rent r_A $[\frac{\$}{m^2\,a}]$	0.5
Maintenance cost t_{main} $[\frac{\$}{m\,a}]$	0.05

Table 1: Parameter setting of the reference city

The initial equilibrium state before the introduction of any policies is summarized in Table 2.

[25] The long-term cost of technological improvements of fuel efficiency of course depend on uncertain factors like technological pathways and the pace of development. According to National Research Council (2015, p. 270), estimated additional technology costs per vehicle for each percent of reduction in fuel consumption roughly lie in the range between 25\$ and 100\$.
Starting at an average fuel economy of $25MPG$, or 0.04 gallons per mile, a reduction of fuel consumption by one percent from 0.04 to 0.0396 gallons per mile implies an increase of fuel economy by $0.253MPG$ to $25.253MPG$. Assuming a vehicle lifetime of 10 years, an annual marginal cost of fuel efficiency of $m_{tech} = 15\frac{\$}{MPG\,a}$ implies total (not annualized) marginal technology costs for a mileage increase by $0.253MPG$, that is, for a one-percent reduction in fuel consumption, of $15\frac{\$}{MPG\,a} \cdot 10a \cdot 0.253MPG = 37.95\$$. This is well in the range of 25 to 100\$ from National Research Council (2015, p. 270).
The figure for a three-times higher annual marginal technology cost of $m_{tech} = 45\frac{\$}{mpg\,a}$ that is used in the sensitivity analysis later on in this section, thus, is three times higher as well with 113.85\$ per percent of reduction in fuel consumption. This can be interpreted as an approximate upper bound of technology costs.

City radius $\bar{x}$[m]	30,509.06
Average commuting trip length [m]	18,441.96
Average car mileage [Miles per Gallon]	30.14
Average carbon emissions p.c. $[\frac{t}{a}]$	1.436
Utility [-]	7569.28

Table 2: Initial equilibrium values of reference city before any policy

4.1 Step 1 - Partial Equilibrium CAFE Compliance without Urban Adjustment

In step 1, CAFE standards are introduced while keeping real estate prices from the pre-policy state $p(x)$ and locations x of all households artificially constant. In this intermediate state, every household chooses a more fuel efficient vehicle so that its carbon emissions, and, thus, also average carbon emissions, decrease. While paying more for the more fuel efficient vehicles, households save money on driving their still unchanged commuting distances. As CAFE standards imply a cross-subsidy from central residents to suburban residents, the latter may actually have declining vehicle costs (despite the choice of higher efficiency) and a resulting monetary net benefit in some cases. But, nevertheless, the increased average fuel efficiency leads to higher aggregate vehicle production costs in the system and an according increase of the intercept of the vehicle price curve $v_{0,CAFE}$. This contributes to a decline in average utility, although some suburban households may be better off.[26] Starting from the pre-policy state without any CAFE standard ($v_{CAFE}(mpg) = v_{tech}(mpg)$), the fuel economy standard is continuously increased.

Vehicle choice adjusts to the CAFE regulation according to (22) and, thus, the household budget (2) is modified by the new vehicle cost curve (24) (that takes into account (23) with the pre-policy population density curve $D_0(x, u_0)$ and the pre-policy utility level u_0) and the change in driving costs (4) with new vehicle efficiency. The components of household income (3) remain unchanged. With the household budget modified in this way, individual household utility at distance x after step 1 is calculated according to (1), (10), and (11) with the pre-policy bid-rent curve $p_0(x, u_0)$ taken as exogenously

[26] Note, that utility is the same for all households in the full urban economic equilibrium. But in this intermediate state with $p(x)$ and x fixed utility differs over the distance x.

given:

$$u_{1,CAFE}(x) = \frac{\alpha^{\alpha}(1-\alpha)^{(1-\alpha)}}{p_0(x,u_0)}(y - t(mpg_{CAFE}(x))x - v_{CAFE}(x)) \tag{29}$$

To calculate average utility after step 1 $u_{\varnothing 1,CAFE}$, utility values at each distance x are weighted with the population density of the pre-policy state $D_0(x,u_0)$, integrated over the city area, and divided by the population L:

$$u_{\varnothing 1,CAFE} = \frac{1}{L}\int_0^{\bar{x}} u_{1,CAFE}(x) D_0(x,u_0) 2\pi x \, dx \tag{30}$$

Aggregate emissions are calculated according to (21), again with pre-policy population density $D_0(x,u_0)$, but with newly chosen fuel economy of vehicles.

Figure 2 shows average utility as a function of emission reduction in step 1 $u_{\varnothing 1,CAFE}$ relative to the initial utility level over the aggregate emission reduction in percent that results from a progressing increase in fuel economy standards. The blue curve in Figure 2 (and all subsequent figures) depicts the reference case. The other curves show parameter settings with one parameter deviating from the reference case. Figure 12 in the Appendix shows the same figure for absolute values of average utility and average per capita emissions. Since the pre-policy state is different for every parameter setting, the normalization enables comparability of the different cases.

For an aggregate emission reduction of up to approx. 40 percent, the welfare costs of compliance (which correspond to a relative income decrease of the same magnitude) are below one percent, that is, relatively small. They increase at different rising rates for more ambitious emission reduction goals.

Proposition 1. *Relative short-term welfare costs of compliance with fuel economy standards before an adjustment of the urban form are higher for a larger city population L, lower household income y_0, a higher gasoline price p_G, more expensive marginal annual technological costs of fuel efficiency m_{tech}, a higher elasticity of utility with respect to housing α, and a lower degree of decreasing returns to scale in housing production β.*

For a higher gas price, the city is smaller and denser in the first place with a shorter average commuting distance. Thus, the gains in driving costs are smaller, too. Also, higher gas prices lead to higher average fuel efficiency of the vehicles in the pre-policy state. But if fuel efficiency is already high, then a further increase in efficiency through

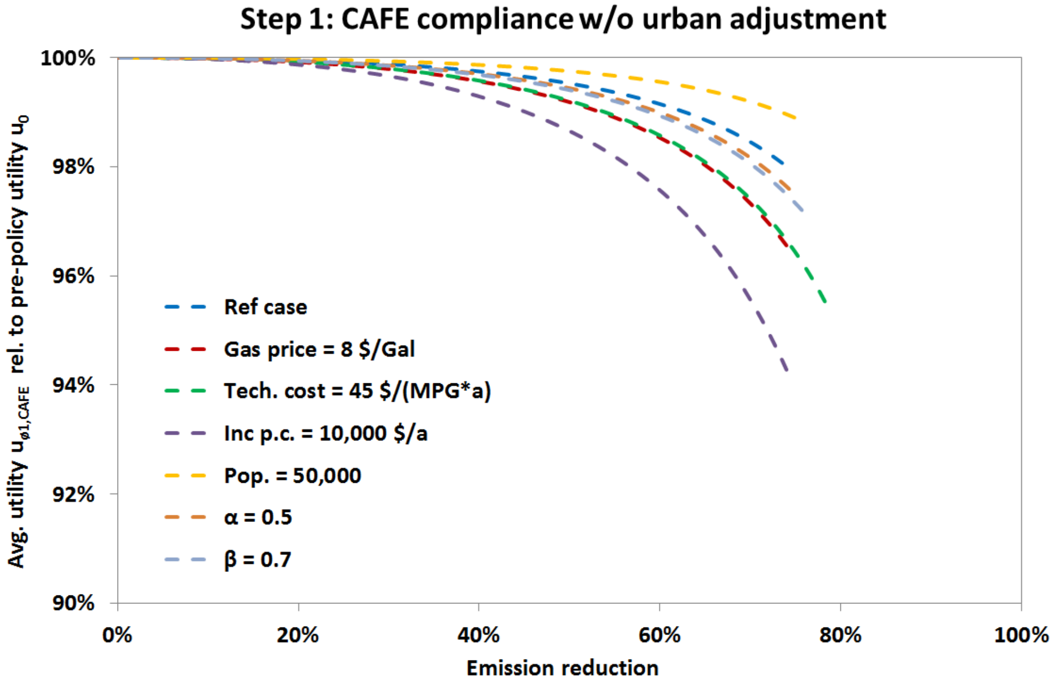

Figure 2: Average utility trajectories for CAFE compliance without urban adjustment ("step 1") relative to the pre-policy utility level.

a tightening CAFE standard leads to higher welfare costs due to a higher upward shift of the vehicle cost curve (because of a higher share of more expensive cleaner cars in the system compared to a "dirtier" car fleet in a case with cheap gasoline) .

Welfare costs are also higher for a higher slope of the technology cost curve of $m_{tech} = 45\frac{\$}{MPG\,a}$. With this parameter setting, households on average choose dirtier cars initially because of the marginal cost of efficiency. This (similarly to high gas prices) leads to a smaller and denser city with shorter commuting distances before the CAFE policy. The policy measure itself then comes with higher additional costs for vehicles and lower gains from saving gasoline. The same logic applies to a low elasticity of utility with respect to housing α and a high β which implies a low degree of decreasing returns to scale in housing production. Both lead to smaller and denser cities and the described consequences.[27]

[27] If the elasticity of utility with respect to housing α is low, then households' preference for housing is low compared to the composite good and households consume less housing on a smaller land area. If there is a low degree of decreasing returns to scale in housing production (high β), then it is cheaper to build high on a small land area than building low houses on a large area with high driving costs.

A city with a low household income (e.g., 10,000 $\frac{\$}{a}$) is also relatively small with short driving distances and small gains from lower marginal costs of driving. But the monetary costs of the CAFE policy lead to higher welfare losses because of higher marginal utility at lower income levels. A high-income city which is smaller than in the reference case because of smaller population, in contrast, suffers smaller welfare losses than in the reference case.

Overall the welfare costs without urban adjustment seem low, but not trivial: in the reference case, a reduction of carbon emissions in the transportation sector by roughly 75 percent induces a welfare loss of about 2 percent. For the average commuting distance in the reference case these 2 percent correspond to an average annual monetary loss of about 940$\frac{\$}{a}$. The adjustment of the urban form, which is left out of the picture here, takes place in the medium and long term. So, the resulting welfare effects may be interpreted as reflecting the short term.

4.2 Step 2 - General Equilibrium Urban Adjustment due to CAFE Policy

4.2.1 Rebound Effect

In the second step, household locations x and housing prices $p(x)$ become free to endogenously adjust to the CAFE policy shock and the city reaches its post-policy equilibrium according to (17) and (19). With higher fuel efficiency, the marginal cost of driving for all households is unambiguously lower than before the CAFE policy. So, every household moves further away from the CBD. The increase in the average commute contributes to higher carbon emissions and partly counteracts the emission reductions from the choice of more fuel efficient vehicles. This is the commute related part of the rebound effect in the long run. Figure 3 shows the average rebound effect from urban expansion over the degree of reduction in average carbon emissions for different parameter settings.

The rebound effect here is the share of the emission reduction in step 1 that is offset by the urban expansion of step 2. In the reference case it lies between 1 percent and 5 percent. This magnitude is well in the range of empirical estimates for the rebound

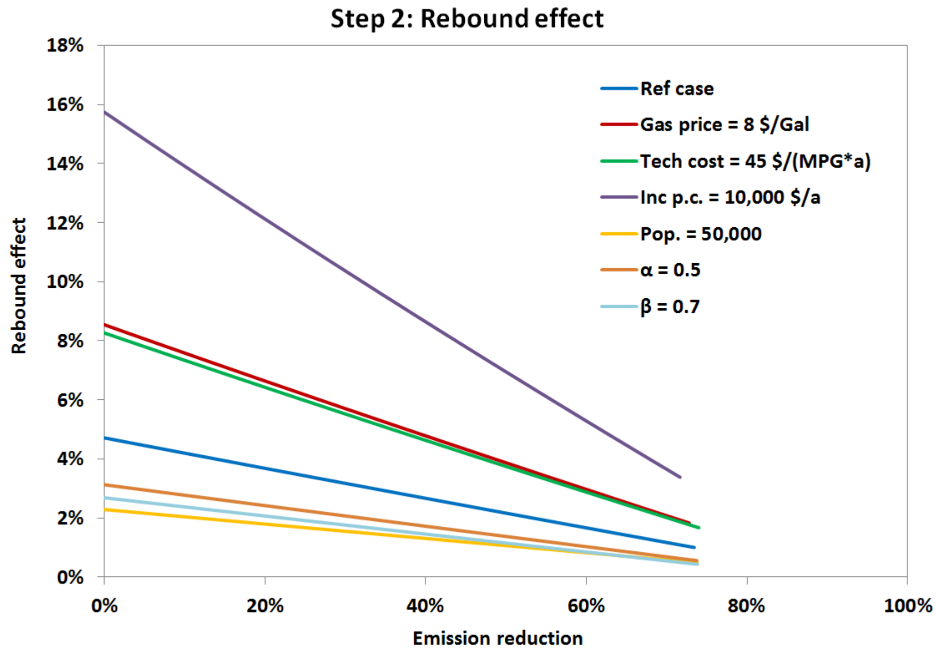

Figure 3: Commute related long-term rebound effect for the reference case and deviating parameter settings

effect in the U.S. (cf. Small and van Dender (2007), Hughes et al. (2008)) where public transit does not play as big a role as in Europe.[28]

The rebound effect for the same relative emission reduction, however, is much larger for lower exogenous household income y_0. It is also larger in the scenarios with higher gas prices p_G and with higher marginal technological costs of fuel efficiency m_{tech}.[29] This is in line with the empirical rebound literature. The new urban related effects on the rebound are summed up in the following proposition:

Proposition 2. *The rebound effect is large for relatively small, dense cities. It is larger than in the reference case for higher city population L, for a lower elasticity of utility with respect to housing α, this is, lower consumer preference for housing*[30]*, and for more strongly decreasing returns to scale in construction β.*

[28] Non-commuting trips also constitute a component of the rebound effect, but as long as we do not assume different magnitudes of rebound for different types of trips, the observed magnitude of the commute rebound effect should be the same as the size of the total effect.

[29] This is at least consistent with the empirical finding of Frondel et al. (2012) that the rebound effect is greater in Germany with its higher gasoline prices – but also many other different features like the public transit system – than the U.S.

[30] The elasticity of utility with respect to housing α can also be interpreted as the level of amenities in the city, which leads to a higher preference for housing compared to the composite good.

The relative differences in the rebound effect for different parameter settings can in large part be explained by the parameters' effect on population density and the resulting urban form: for instance, high gasoline prices lead to high marginal travel costs (despite the choice of more fuel efficient vehicles by households). This, in turn, leads to a much denser city in the first place because people consume less housing. The same is true for high marginal technological costs of fuel efficiency: households choose less fuel efficient cars and face higher marginal costs of travel. The two numerical scenarios with a high gasoline price p_G (red) and high marginal technological costs of fuel efficiency m_{tech} shown in Figure 3 happen to yield very close results in terms of marginal driving costs, city size and rebound effect. A lower household income of $10,000\frac{\$}{a}$ (instead of $50,000\frac{\$}{a}$) leads to an even more compact, dense city with small dwellings for relatively poor households.

But in a relatively dense city the average commute must increase more strongly to reach a new equilibrium after a decrease in marginal driving costs. In the urban economic equilibrium the housing price gradient over the distance x must correspond to the marginal costs of an increase in commuting distance. If travel costs decrease because of the fuel economy policy, then households must move away from the CBD to cause a sufficient decrease in the housing price gradient and to reach the new equilibrium. With high population density on a geographically small city area, a one-percent increase in the average commute only yields a small relative increase in additional area for new developments, causing only a small adjustment in the housing price gradient. But if the same population in the beginning is distributed over a larger area, a one-percent increase in the (also longer) average commute yields a significantly larger increase in city area and housing supply. This is because, on the one hand, one percent of a longer distance is longer in absolute terms and, on the other hand, the circular area increases quadratically with radius, but the average commute only increases approximately linearly. Therefore, in a denser city a larger relative increase in the average commute is needed to achieve the required adjustment of the housing price gradient after a CAFE-driven increase in driving costs. Coming back to Figure 3, for expensive gasoline and marginal technology improvements, the city is dense and the resulting rebound is high, even more so for low income. In contrast, for cities with low, but wealthy, population, high preference for housing α and low degree of decreasing returns to scale in construction β (possibly due to low regulation in construction), density is low, as is the magnitude of the rebound effect.

It is also interesting that the commute related long-term rebound effect decreases with tightening CAFE policy in all parameter settings. The reason for that is that for more ambitious emission reduction goals the rising aggregate vehicle costs in the system contribute to a contraction of the city due to lower available income, counteracting the rebound effect.[31]

While rents in the city center decrease, rents in the suburbs increase and a ring of additional land is developed around the city. The dwelling size in the center increases, while it decreases in the outskirts due to the rise in population density. On average, however, dwelling size rises. But since the choice of fuel efficiency is also a function of distance to the CBD (cf. Equation (22)), households at the new location choose even more efficient vehicles, decreasing the marginal costs of driving even further. Increasing distance and rising fuel efficiency, thus, reinforce each other until a new equilibrium is reached. Table 3 shows how the city size, the average commuting trip length, and carbon emissions are affected by the CAFE policy in the two analytic steps.

	Pre- policy	Step 1 CAFE compliance w/o urban adjustment	Step 2 CAFE w/ urban adjustment
m_{CAFE} $[\frac{\$}{MPG\,a}]$	15	3	3
City boundary $\bar{x}$ [m]	30,509.06	30,509.06	31,330.07 (+2.69%)
Avg. commute [m]	18,441.96	18,441.96	19,285.76 (+4.6%)
Avg. CO_2 emissions $[\frac{tons\,p.c.}{a}]$	1.436	0.642	0.658 (+2%)
Avg. mileage $[\frac{Miles}{Gal}]$	30.145	67.405	69.035 (+2.4%)

Table 3: Change of city characteristics for CAFE compliance without and with urban adjustment. Change of step 2 rel. to step 1 in brackets.

4.2.2 Welfare Analysis

After the urban adjustment in step 2, the city reaches its uniform post-policy utility level $u_{2,CAFE}$. The urban adjustment leads to two new channels of fuel economy standards on welfare summed up in the following proposition.

[31] Additionally, the more fuel efficiency rises on average, the lower is the share of actual gasoline expenses in the marginal cost of driving and the higher is the share of marginal costs of maintenance. Therefore, tightening the fuel economy standard even further only triggers a smaller decrease of marginal driving costs in percentage terms and, thus, a smaller rebound effect. But the magnitude of this effect is clearly subordinate to the first effect.

Proposition 3. *The long-term expansion of the urban form leads to two counteracting effects on welfare on top of the welfare costs of compliance of step 1: additional welfare costs from an additional increase in fuel efficiency and welfare gains from an increase in housing supply. The net welfare effect is negative and large for a strong rebound effect.*

First, the additional increase in every household's chosen fuel efficiency and simultaneous change in travel costs lead to additional monetary costs. The decrease in available income translates into additional welfare costs. Here, the increase in average commuting distance and vehicle costs outweighs the gains from the reduction in marginal driving costs. On top of that, a distortion in the vehicle market that the CAFE policy creates amplifies this negative welfare channel: the adjustment in vehicle choice causes additional production costs of m_{tech} for each additional mile per gallon, but households only account for m_{CAFE} for each additional mile per gallon in their vehicle choice decision (22). The difference of $(m_{tech} - m_{CAFE})$ is shifted equally to all households through the increase of the intercept $v_{0,CAFE}$ in the CAFE mechanism. This distortion in the vehicle market creates a cross-subsidy from central owners of less efficient cars to suburban owners of more efficient cars. The result is an according deadweight loss.

The second effect is the welfare effect from the increase in average dwelling size. It is always positive in the case of urban expansion. Since the city population distributes over a larger area housing supply rises. Also, the decreasing returns to building higher imply that a flatter city leads to lower housing production costs. These factors contribute to a decrease in average housing prices and, therefore, an increase in average consumption of housing and of the composite good.

It is difficult to quantitatively disentangle the two components of the welfare effect of urban expansion in an analytically consistent way because both effects necessarily happen simultaneously. Also, the increase in housing supply is the incentive for households to increase their distance to the CBD in the first place. The housing supply component works through housing prices and the vehicle choice component works through an effect on available household income. Thus, it would be interesting, despite the logical simultaneity, to calculate the effect of this change in available income (due to the change expenses for the vehicle and for driving the new increased distance) on household utility while assuming the housing price curve $p_0(x)$ from before the urban expansion. However, there is no clear way of matching new distances x_2 and vehicles $mpg(x_2)$ of every household after the expansion with the same household's location x_1 before the expansion because the model does not contain discrete households, but instead a continuous population density function. But a way to at least gain some insight from a rough approximation is to compare utility of a household at the average distance with the average vehicle before the expansion to that of its counterpart after the expansion. In this exercise for the parameter setting of the reference case (cf. Appendix 8.2) the (negative) vehicle related component and the (positive) housing related component of the total welfare effect of step 2 have a magnitude between 10 percent and 120 percent of the welfare costs of compliance in step 1.

The resulting net welfare effect of long-run urban expansion is negative because of the distortion in the vehicle market and the resulting deadweight loss. Despite the additional degree of freedom in the system via urban adjustment, utility decreases because the deadweight loss due to the distortion of the vehicle market is not accounted for by households in their vehicle choice. Figure 4 shows the size of this net welfare cost of long-term expansion in step 2 ($\Delta u_{2,CAFE} = u_{\varnothing 1,CAFE} - u_{2,CAFE}$) relative to the welfare cost of short-term CAFE compliance without urban adjustment in step 1 ($\Delta u_{1,CAFE} = u_0 - u_{\varnothing 1,CAFE}$) for the reference case, but also for the same deviating parameter settings as in Figures 2 and 3.

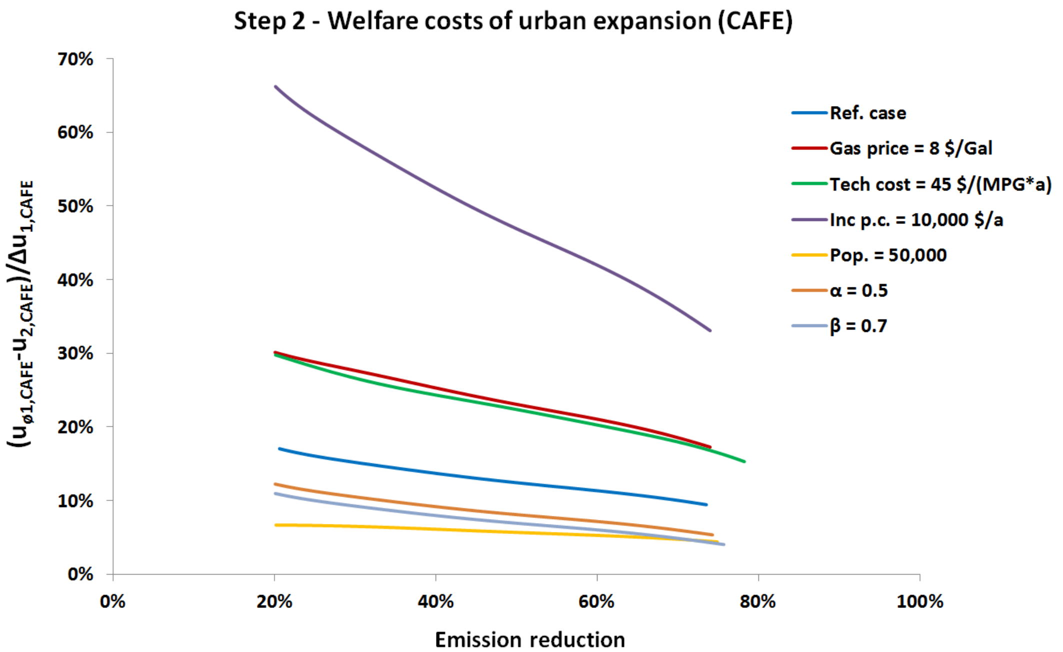

Figure 4: Net welfare costs of urban expansion (step 2) relative to the welfare cost of CAFE compliance without urban expansion (step 1) for different emission reduction targets

Figure 4, as well as the following figures, starts at a reduction of aggregate emissions by 20 percent. Since long-term decarbonization paths are in the focus, smaller emission reduction targets are not as politically relevant. Another technical reason to leave the area below 20 percent out of the picture is that limits in numerical accuracy can lead to a non-negligible bias of the results for very small emission reduction targets.

A common pattern of all cases is that for small emission reductions the additional welfare loss of urban adjustment is large relative to the welfare effect of compliance without urban adjustment. However, absolute welfare costs are rather small (cf. Figure 2). For more ambitious climate goals the magnitude of the additional welfare loss of urban expansion decreases relative to compliance without urban adjustment, but the total welfare loss is larger, so that in absolute terms the welfare cost of urban adjustment is still larger than for small emission reductions. The order of cases is the same as for the size of the rebound effect. Urban expansion (and the according increase in emissions and chosen fuel efficiency of vehicles) induces between 10 percent and 20 percent additional welfare costs on top of CAFE compliance in step 1 for the reference city. These values rise to 20 percent to 35 percent for the scenarios with significantly more expensive gasoline and vehicle technology. For lower household income (from $50,000\frac{\$}{a}$ to $10,000\frac{\$}{a}$) near the level of emerging economies the additional welfare cost of urban adjustment is in the range of 40 percent to 70 percent of the welfare cost of compliance without urban adjustment. The cases with a stronger urban expansion (and higher rebound effect) also exhibit higher additional welfare costs due to this expansion.

4.3 Fuel Tax Policy

The urban parameters of a city obviously play a role for the magnitude of welfare costs of the "command-and-control" CAFE policy in the compliance case without urban adjustment, and of the welfare costs of urban adjustment itself. But the welfare costs of a fuel tax, which is the first-best policy instrument here, are also affected by the very same urban parameters. On the one hand, households' vehicle choice is influenced differently by the tax at different distances x, depending on the city's parameters. On the other hand, there is also an adjustment of the urban form with a fuel tax, but in the opposite direction than with CAFE: the increase of the consumer fuel price leads to a contraction of the city and to the choice of less efficient vehicles than without a contraction. Again, the welfare effects of the policy measure are analyzed in two steps: in step 1, real estate prices $p_0(x, u_0)$ and distances x are frozen and households only react to the tax increase by choosing more efficient vehicles by (25), leading to short-term welfare costs of compliance. But despite the improvement in fuel efficiency, the marginal cost of driving increases. In step 2 the real estate market reaches its new equilibrium and the city exhibits a contraction.

4.3.1 Step 1 - Fuel Tax Compliance before Urban Adjustment

In analogy to the CAFE policy (cf. (29)), the household budget ((2) and (3)) is modified by using (26) and (28), while $p_0(x, u_0)$ and $D_0(x, u_0)$ remain unchanged in step 1. Also, the utility level after step 1 of the fuel tax policy is calculated using (1), (12), and (13):

$$u_{1,Tax}(x) = \frac{\alpha^{\alpha}(1-\alpha)^{(1-\alpha)}}{p_0(x, u_0)}(y - t_{Tax}(x)x - v_{Tax}(x))$$

Average utility after step 1 $u_{\varnothing\,1,Tax}$ is calculated like in (30):

$$u_{\varnothing\,1,Tax} = \frac{1}{L}\int_0^{\bar{x}} u_{1,Tax}(x) D_0(x, u_0) 2\pi x\, dx$$

For step 1, (short-term tax compliance without urban adjustment) the trajectory of welfare over reduction of carbon emissions in all observed cases is relatively close to the CAFE policy: for the reference city the difference between the welfare costs of CAFE and the fuel tax is below 5 percent of compliance costs for CAFE (cf. Figure 5). Again, for low income, the deviation between CAFE and the fuel tax policy of welfare costs in step 1 is the largest with up to 15 percent of $\Delta\, u_{\varnothing\,1,CAFE}$.

All commuting distances remain unchanged at this stage. The only variable that can adjust is the vehicle choice. Therefore it is not surprising that an emission reduction over the same variable (vehicle mileage) leads to similar welfare costs. What accounts for the difference are the different market distortions and according welfare costs of the two policies: with the CAFE policy households do not internalize the correct cost of fuel technology due to the cross subsidy from owners of dirty cars to owners of cleaner ones. But the fuel tax distorts the gas price and, despite the lump-sum recycling of revenues, causes a deadweight loss different to the CAFE distortion on the vehicle market.

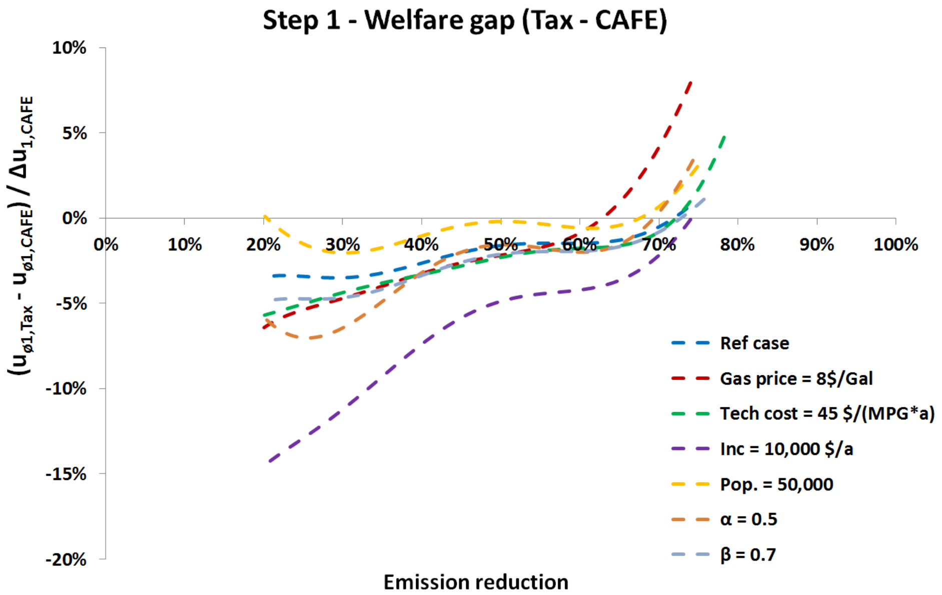

Figure 5: Difference in the welfare cost of compliance without urban adjustment (Step 1) between the fuel tax policy and the CAFE policy

4.3.2 Welfare analysis of urban contraction

The urban adjustment induced by the fuel tax policy yields, similarly to the CAFE policy (cf. Proposition 3), two new welfare channels, summarized in the following proposition.

Proposition 4. *The long-term urban contraction leads to two counteracting effects of fuel taxes on welfare: welfare gains from reduced expenses due to less fuel efficient vehicles and welfare costs from a reduction in average housing consumption. The net welfare effect is positive and large for the parameter settings which cause a large rebound effect in the case of the CAFE policy.*

Figure 6 illustrates the trajectories of utility after the steps 1 and 2 for different aggregate emission reduction targets for the fuel tax policy (green) and, for comparison, for the CAFE policy (blue).

The trajectory of short-term compliance without urban adjustment (step 1, dashed line) is almost identical for both policies here. While the CAFE curve with urban adjustment (solid, blue) lies below the short-term CAFE compliance curve (cf. Section 4.2), the fuel tax curve with urban adjustment (solid, green) lies above the short-term pure tax compliance curve. The reason is exactly opposite to the CAFE case: the urban contraction reduces the average commuting trip length and emissions, while it

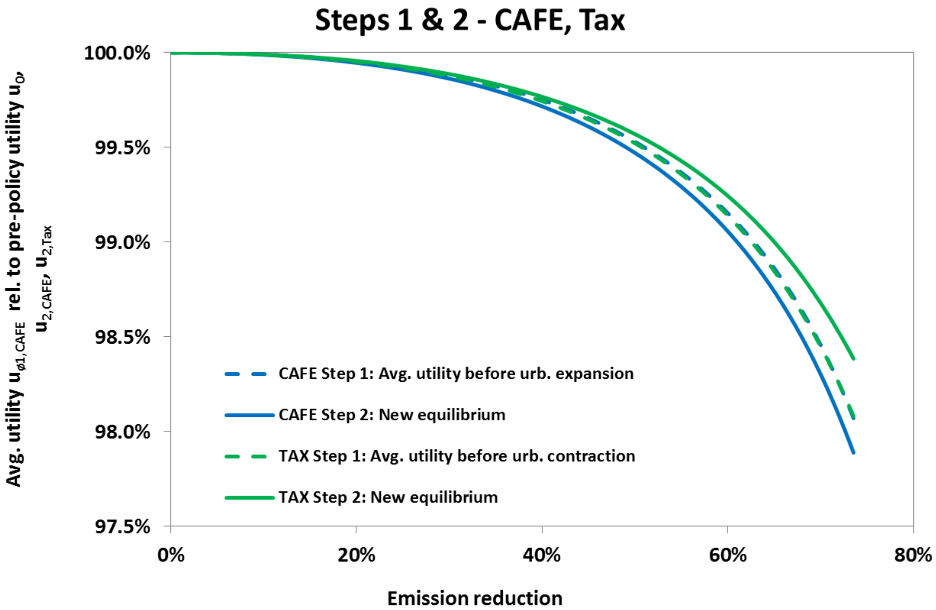

Figure 6: Welfare effects of CAFE and the fuel tax policy over emission reduction goals for the reference case

also yields an increase in available income and resulting utility due to vehicle cost reductions because of the choice of less fuel efficient vehicles at shorter commuting distances x. The positive net welfare effect of urban contraction in the tax policy case ($\Delta u_{2,Tax} = u_{2,Tax} - u_{\varnothing 1,Tax}$) relative to the welfare costs of compliance in step 1 is depicted for different parameter values in Figure 7.

Of course, it is clear from the outset that the fuel tax policy, which is the first-best instrument, leads to higher welfare than a command-and-control CAFE policy for a given emission reduction target. But the final (post step 2) welfare gap between the two policies in this model is largely driven by the welfare effects of urban adjustment. The size of the total welfare gap between CAFE and the fuel tax policy, therefore, depends on the model parameters which determine the magnitude of urban expansion (CAFE) and contraction (fuel tax), as is summarized in the next proposition, and as we see in Figure 8.

Proposition 5. *The total welfare gap between the fuel tax and fuel economy standard policy is large for the parameter settings which also put a large weight on the welfare costs of urban adjustment under both policies.*

The order of cases is the same for the different parameter settings as in Sections 4.1 and 4.2. This is plausible since the magnitude of urban expansion or contraction, that

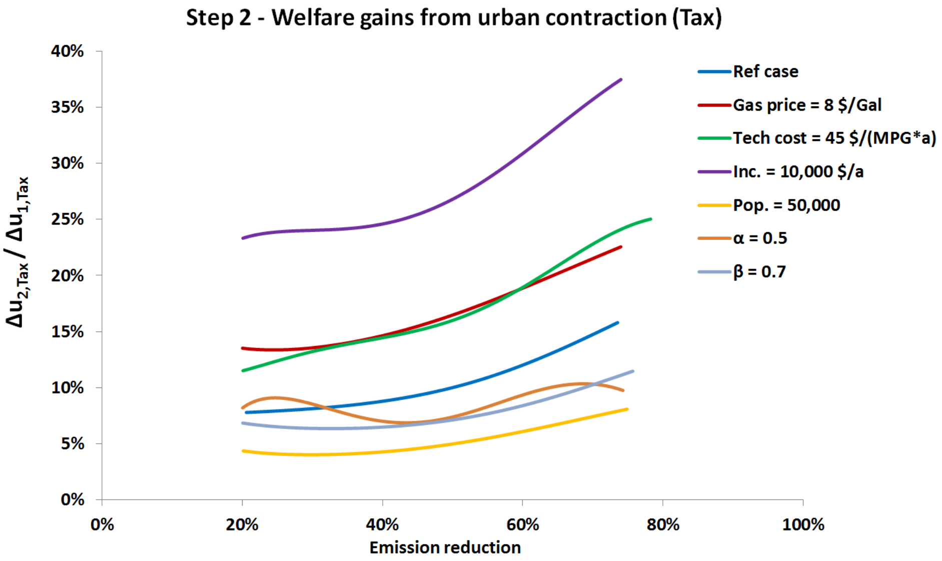

Figure 7: Welfare gains from urban contraction for the fuel tax policy rel. to the welfare costs of tax compliance without urban adjustment $\Delta\, u_{1,Tax}$

drives the size of the commute related rebound effect in Section 4.2, also drives the magnitude of the welfare effect of expansion or contraction.[32]

For the reference city the welfare gap is in the range of 20 percent to 30 percent. For a smaller rebound effect (cf. Figure 3) the welfare gap is smaller, and vice versa. Again, a low income level of $10,000\frac{\$}{a}$ yields the largest effect: the welfare gap between CAFE and a fuel tax policy has a considerable magnitude of 70 percent to 80 percent of $\Delta\, u_{1,CAFE}$. Not only are the (step 1) welfare costs of any of the two policies without urban adjustment significantly higher for low household income (cf. Section 4.1). But in poor cities the additional welfare costs of (step 2) urban adjustment – expansion in the case of CAFE, as well as contraction in the case of a fuel tax – are much greater too. The big welfare gap between the two policies leads to the conclusion that the importance of the instrument choice decreases with the income level. While in high income countries the welfare gap does not seem to be crucial for the policy choice, its importance is higher for low income countries. But for a reasonable policy advice, e.g., for newly industrializing countries additional aspects like mobility patterns and development of public transit e taken into account.

[32] Note, that the total size of the welfare gap between CAFE and a fuel tax policy does not exactly equal the sum of the absolute values of the CAFE policy's expansion related welfare costs and the contraction related welfare gains of the tax. The average utility levels after step 1, which are used for the calculation of the respective welfare effect of urban adjustment, slightly differ for the two policies (cf. Figure 5).

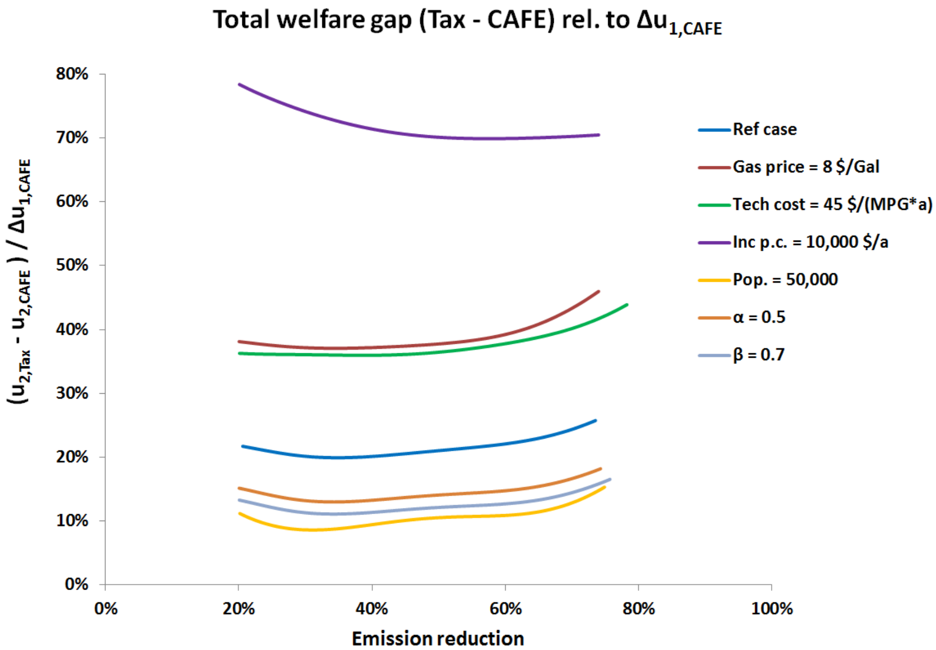

Figure 8: Total welfare gap between the fuel tax and CAFE rel. to $\Delta u_{1,CAFE}$

5 CAFE with Urban Growth Boundaries

The reaction of the urban form is an important factor for the overall welfare implications of different environmental policies in the transportation sector. An expansion leads to additional welfare costs in the form of higher spending on fuel efficiency technology for cars to reach a certain emission goal. An additional spatial constraint like a policy-driven urban growth boundary (UGB) should be expected to affect the results. In this section, this influence on the results of the welfare analysis from above is analyzed.

Urban growth boundaries are discussed in urban economics as a measure to reduce urban sprawl (see, e.g., Turnbull (2004), Dempsey and Plantinga (2013)) and traffic congestion (cf. Brueckner (2007), Anas and Rhee (2007)). The outer boundary of the city becomes fixed at the preexisting magnitude ($\bar{x} = \bar{x_0}$), so that the city cannot expand into the surrounding area. Households can still move within the boundary. But the density profile, the housing market, and – in the present case – vehicle choice at every point of the city are affected by the presence of an urban growth boundary. If the UGB is binding, then at the edge of the city the land rent lies above the agricultural rent ($r(\bar{x}) > r_A$), so that (17) does not hold anymore. In the case of a fuel tax policy, an urban growth boundary has no effect since it does not stop the city's contraction. But in the case of fuel economy standards a growth boundary can be, and mostly is, binding.[33] Households still move away from the center, but within the spatial limit. They also choose more fuel efficient vehicles, but only according to their smaller increase of distance to the CBD. Overall, the CAFE-driven increase in average commuting distance and decrease in emissions still takes place, but in a dampened fashion. Figure 9 depicts the influence of an urban growth boundary on the welfare effect of urban expansion for the reference case (zooming in on a section of the trajectory).

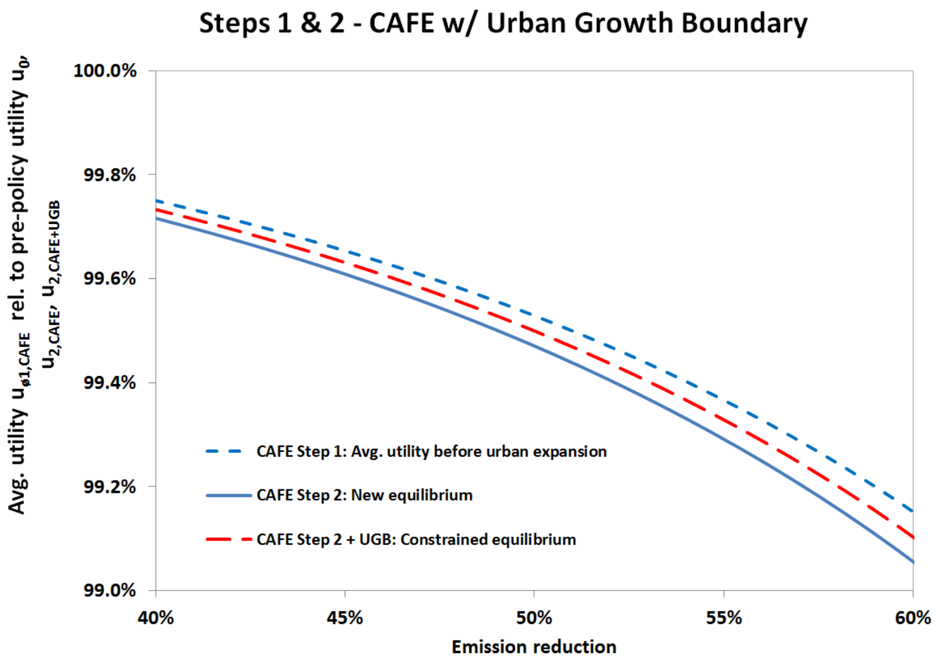

Figure 9: Influence of an urban growth boundary (UGB) on the welfare effect of urban adjustment for CAFE

The dashed blue curve is the compliance case without urban adjustment known from Section 4.1. And the solid blue curve is the outcome unrestricted by an urban growth boundary from Section 4.2. The red dashed curve is the final equilibrium outcome of CAFE combined with an UGB.

Proposition 6. *A combination of fuel economy standards with an urban growth boundary reduces urban expansion to the increase of commuting distances x within the initial city boundary $\bar{x}_0$. It decreases the according welfare costs of urban expansion for a given emission reduction goal by roughly one half.*

[33] There might be cases in which CAFE standards also lead to contraction. The monetary loss through rising vehicle cost, which is contributing to contraction, might outweigh the expanding effect of decreasing marginal costs of driving. There are parameter settings where the CAFE-induced expansion stopped and the city started to shrink if the fuel economy standard was raised further.

Figure 10 gives an overview over how strongly the combination of fuel economy standards with an UGB reduces the welfare costs of urban expansion for the reference city and again for deviating parameter settings.

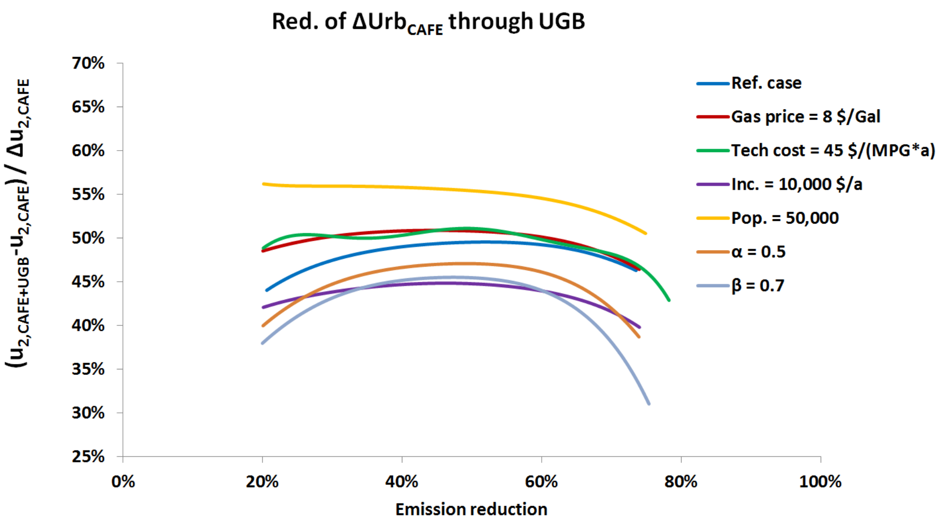

Figure 10: Reduction of the welfare costs of CAFE-driven urban expansion relative to $\Delta u_{1,CAFE}$ due to the combination of CAFE with an UGB for different parameter settings

For all analyzed parameter settings between 40 percent and 60 percent, so roughly half, of the detrimental welfare effect of urban expansion is avoided by the combination of CAFE with an UGB. Differences in model parameters and the strictness of the climate goal do not seem to play a big role for this effect of UGB. Figure 11 shows the reduction of the total welfare gap between the case of a fuel tax, as the first-best policy, and a second-best fuel economy standard which results from the combination of CAFE standards with UGB.

Between 20 percent and 40 percent of the welfare gap can be closed, mostly uniformly over the different parameter settings. For more ambitious climate goals the advantage in percentage terms decreases below 20 percent. But the absolute gains from the use of UGB are still higher since absolute welfare costs of compliance are higher for stronger emission reductions too.

This shows that UGBs should be seriously considered as a complementary policy together with fuel economy standards, and the more so in countries with a lower income level. The fact that in many European countries metro areas have de-facto UGB is favorable to the use of fuel economy standards as climate policy in the transportation sector.

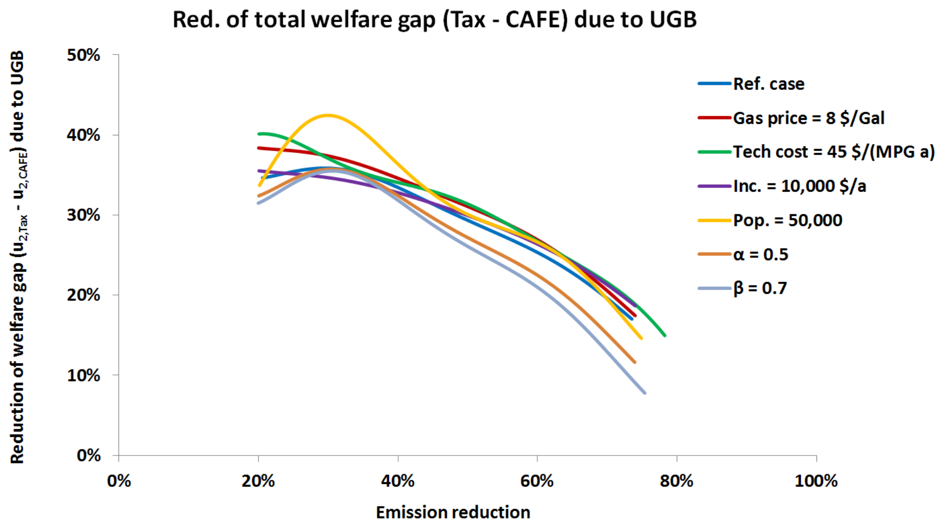

Figure 11: Reduction of the total welfare gap between a fuel tax and CAFE standards through the addition of UGB

6 Conclusion

This paper shows the important role of urban economic factors and mechanisms for the welfare costs of fuel economy standards and fuel taxes as environmental policies in the transportation sector. Even in the short term, before an adjustment of the urban form and of the simultaneous vehicle choice takes place, urban parameters affect the welfare costs of compliance. But the long-term urban adjustment opens up two new welfare channels for each policy: in the case of fuel economy standards, the increase in fuel efficiency implies an urban expansion with longer commuting distances and a self-reinforcing feedback loop on vehicle efficiency with welfare gains from additional housing and welfare losses from additional compliance costs. This commute related long-run rebound effect is large for all parameter setting which make the city small and dense: for low household income, high city population, a low preference for housing, and strongly decreasing returns to scale in building high. Similarly, a fuel tax policy leads to urban contraction with shorter commuting trips and less fuel efficient vehicles, again reinforcing each other. The welfare losses from the reduction in housing consumption are outweighed by welfare gains from lower expenses for fuel efficiency. The magnitude of these new welfare channels is significant: especially for low household income, high gasoline prices, and/or high marginal costs of fuel efficiency technology the welfare effects of housing adjustment and additional compliance can have similar or even a greater magnitude than the short-term welfare costs of compliance before any urban adjustment.

The total resulting welfare gap between the fuel tax policy and fuel economy standards is strongly affected by the magnitude of induced urban adjustments. In countries with small average city size, high household income, a high amenity value (that is, high preference for housing in the consumption bundle), and strongly decreasing returns to scale in housing production, which might often well describe U.S. cities, the disadvantage of fuel economy standards is actually not very high. In contrast, for emerging economies like China, India or Brazil, where most traffic takes place in (on average) large metro areas with a relatively low income, and often low amenities, applying fuel economy standards instead of fuel taxes might incur a much greater additional welfare cost with a magnitude of some 80 percent of short-run welfare costs of compliance. Measures which reduce urban expansion, like urban growth boundaries, therefore, can significantly improve the welfare balance of fuel economy standards by cutting the additional welfare costs of urban expansion roughly in half.

Both, fuel economy standards and fuel taxes, involve distributional effects which can play an important role for the political economy of these measures. In a short discussion, I provide an overview over different spatial distributional effects in this context. While fuel economy standards constitute a cross subsidy from central to suburban residents, a fuel tax policy has exactly the opposite effect. Depending on the location of different income groups (which have not been modelled here) this can overall imply progressive or regressive effects. But since the policies are typically introduced on a national (or, in the case of the E.U., even supranational) level, they might lead to significant distributional effects between cities with different characteristics. This complex of questions and effects will be analyzed in a subsequent study.

A crucial next step for future research is the incorporation of public transit and a plausible mobility mode choice mechanism into the model. It can be expected that the changes in marginal costs of driving and the according cross-subsidies due to the environmental policies affect mode choice to a significant extent, depending on the household location. The switching of a considerable share of households into or out of public transit might constitute an important determinant of the degree of transit capacity utilization and the according pricing schemes. A subsequent increase in transit prices might reinforce the choice of individual vehicles even more, or vice versa. This issue deserves further examination.

Another energy economic issue which is not addressed here is the transition to electric vehicles and their economic and environmental implications in an urban framework.

Electric vehicles could be included in the model as having a high "fuel efficiency" in terms of miles per kg of carbon emissions, but a limited driving range. For now, combustion engines constitute the lion's share of the vehicle fleet and the vehicle markets. But especially in the long run, the role of a higher share of electric cars and transition pathways towards it should be taken into account. The present study provides an advance relative to the scarce previous literature in the modelling of household vehicle choice based on fuel economy and the according implications of fuel economy standards for automakers' pricing and R&D policies, but abstracts from the role of vehicle convenience (for also which driving range issues might play a role). An enhanced view on vehicle choice based not only on fuel economy, but also on vehicle convenience, would certainly contribute to a more realistic analysis and a more informed perspective on the importance of this vehicle choice dimension. Moreover, the assumption of linear pricing schedule could be relaxed in favor of a more elaborate vehicle pricing policy.

Of course, the underlying monocentric urban model is stylized, but it allows for this type of energy economic extensions in a relatively tractable way. Real cities are often polycentric in varying degrees. Also, I use a static model without any forward-looking behavior on the side of households, although it is quite plausible that some long-term developments like demographics play a role for household decisions like buying a house. The significance of these factors for environmental economic questions like in the present paper should be taken care of in future work.

7 Appendix

8 Numerical Analysis

8.1 CAFE Compliance without Urban Adjustment (Step 1)

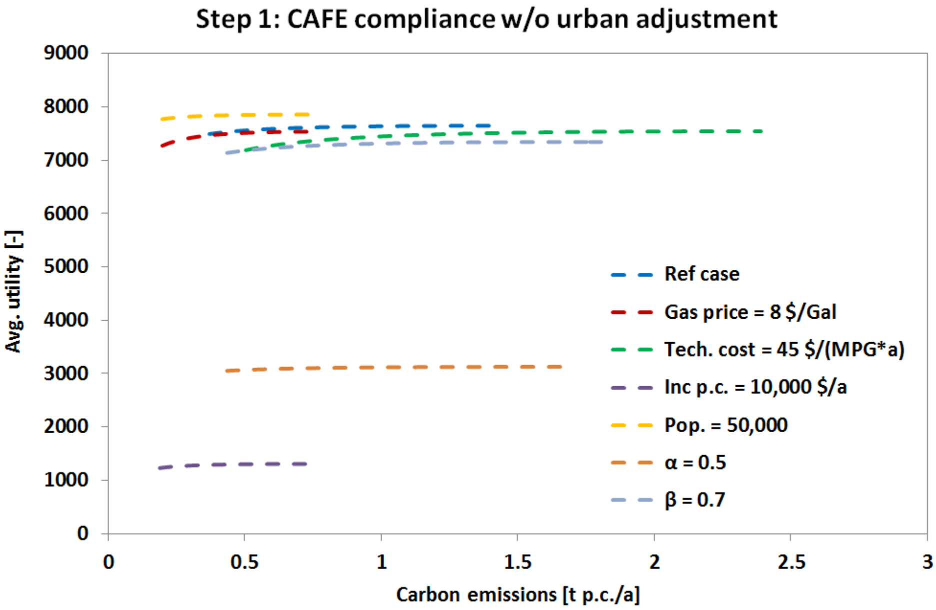

Figure 12: Reduction of average utility with emission reductions for CAFE compliance case without urban adjustment for the reference case and some deviating parameters

The blue curve represents the reference case, while the others represent cases where one parameter is changed relative to the reference case. All the curves start at the right end, but in different points, because the different parameter settings lead to different initial states. With tightening CAFE standards the city moves to the left along the respective curve towards lower average emissions per capita, but also towards lower average utility levels. The purple curve of the case with a lowered household income of $10,000\frac{\$}{a}$ is way below the other graphs and not visible in the figure. The shape of the curves seems to vary considerably. But looking at Figure 2, where we have normalized average utility and per-capita emission reductions, we see that the overall pattern is fairly similar.

8.2 Welfare Effects of Urban Adjustment (Step 2)

With a Cobb-Douglas utility function and constant prices utility scales linearly with available income. Here, a constant housing price curve $p_0(x)$ from before the policy intervention is assumed (the price of the numeraire composite good is 1). To approximate the average change in available household income due to the effect of the change in distances x and vehicle efficiency $mpg(x)$ in the expansion of step 2, the average commuting distance before ($x_{\varnothing\, comm,1}$) and after the expansion ($x_{\varnothing\, comm,2}$) and the average vehicle efficiency before ($mpg_{\varnothing\, comm,1}$) and after the expansion ($mpg_{\varnothing\, comm,2}$) are considered. Starting with average utility after step 1 ($u_{\varnothing\, 1,CAFE}$) and substituting available income after the mentioned income shock for available income before yields an approximated utility level $u_{\varnothing,comm,2}$ of a hypothetical average household.

$$u_{\varnothing,comm,2} = u_{\varnothing\, 1,CAFE} \frac{(y - t(mpg_{\varnothing\, comm,1})x_{\varnothing\, comm,2} - v(mpg_{\varnothing\, comm,2}))}{(y - t(mpg_{\varnothing\, comm,1})x_{\varnothing\, comm,1} - v(mpg_{\varnothing\, comm,1}))} \tag{31}$$

The fact that the housing price adjustment which is not considered in this exercise is the logical reason for the increase in commute x and in vehicle mileage mpg is ignored here. The resulting difference between the states before and after the income shock are a proxy for the average vehicle related component of the total (negative) welfare effect of urban expansion:

$$\Delta u_{2,veh} = u_{\varnothing\, 1,CAFE} - u_{\varnothing,comm,2}$$

To capture the according proxy for the average housing related component of the welfare effect of urban expansion we take the difference between the final utility level in equilibrium after the full housing price adjustment $u_{2,CAFE}$ and the approximated average utility level calculated in (31) $u_{\varnothing,comm,2}$:

$$\Delta u_{2,hou} = u_{2,CAFE} - u_{\varnothing,comm,2}$$

Figure 13 visualizes $\Delta u_{2,veh}$ and $\Delta u_{2,hou}$ relative to the welfare cost of compliance of step 1 ($\Delta u_{1,CAFE}$). The difference of the two welfare effect components is the magnitude of the negative net effect of the urban expansion of welfare that is shown in Figure 4.

Both, the housing related component and the vehicle related component have a significant magnitude between 10 percent and 120 percent of $\Delta u_{1,CAFE}$. Although this is just a rough exercise, the order of magnitude of the components is visualized. If one of

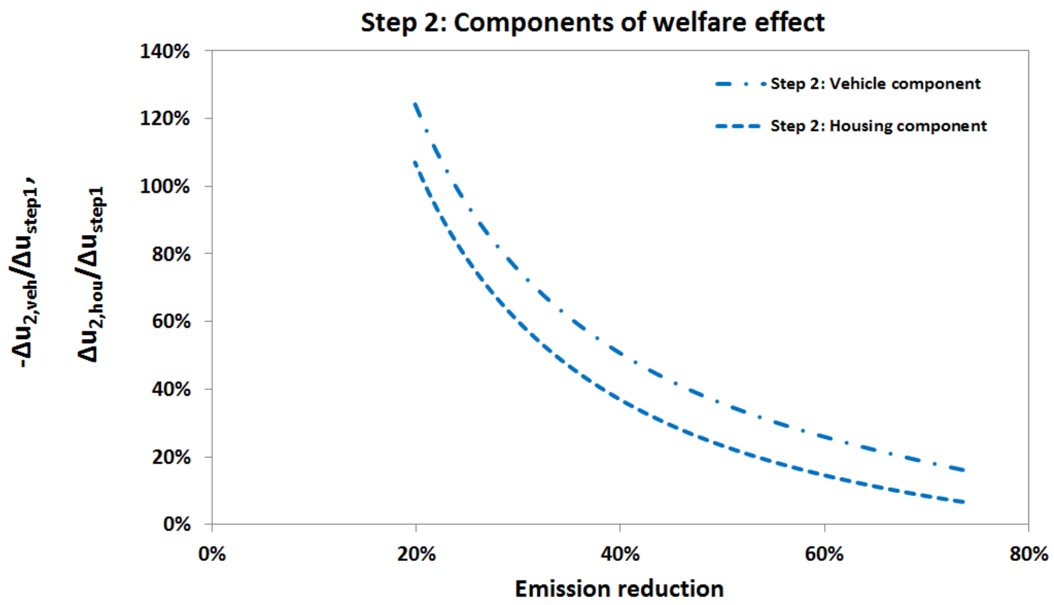

Figure 13: Components of the welfare effect of urban adjustment (step 2) for CAFE policy

the components in a possible future empirical study is left out of the picture resulting estimates for the welfare effect of urban adjustment due to CAFE standards could be highly biased.

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