Fuel Economy Standards and Public Transport

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Abstract

We identify and examine a novel welfare channel of fuel economy standards in a monocentric city model. A stricter emission standard for cars decreases the marginal cost of driving and triggers a shift in modal choice from public to private transport and a rise in carbon emissions in the medium run. In the long run, the modal shift exacerbates the increase in the average commute length that results from lower driving costs. The resulting welfare cost for a 50 percent emission reduction goal turns out 36.5 percent higher than in a scenario without public transport. An alternative fuel tax policy, by contrast, induces a modal shift towards public transport and reduces the average commute and the welfare cost of emission reductions. The numerical model is calibrated with U.S. data.

JEL codes: H23, Q48, R13, R48

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1 Introduction

Greenhouse gas (GHG) emissions from the transport sector make up a large share of overall emissions in the U.S. and the E.U. and have still been rising in the years leading up to the Covid-19 pandemic.[1] Although Pigovian taxes on the carbon content of fuels are the first-best climate policy instrument from an economic perspective, corporate average fuel economy (CAFE) standards[2] have been the main environmental policy measure in the U.S. transport sector from the 1970s to the current Biden Administration.They also play a key role as CO_2 efficiency standards in the recent proposal of the E.U. Commission to tighten the emission reduction goal in the E.U. transport sector to 55 percent by 2030 relative to 1990 (EC, 2022).

To design effective and efficient climate policies for the transport sector, it is important to understand the relevant channels of fuel economy standards on welfare and emissions. The main focus in the conventional literature is on the welfare cost of compliance occurring in the automobile market from adjusting engine technology, car features and pricing schedules. However, we identify and examine a new channel of fuel economy standards on welfare and emissions through shifting mode choices from public transport to individual driving and through the interaction of this effect with the corresponding adjustment in the urban form. To this end, we incorporate public transport, mode choice and vehicle choice into a monocentric city model that we calibrate with empirically justified parameters and solve numerically.

On the one hand, fuel economy standards, on average, increase vehicle purchase costs. On the other hand, they reduce the marginal cost of driving and, thus, provide an incentive for households to switch their transport mode choice more often away from public transport to individual driving. This causes additional carbon emissions and

[1] Transport causes a large share of 29 percent of total GHG emissions in the U.S. and 23 percent in the E.U. (cf. EPA, 2022, and EEA, 2022).

[2] A fuel economy standard sets a certain level of fuel efficiency which the whole fleet sold by a car producer in the country in a certain year has to reach on average.

undermines the climate policy goals. Since the variable and fixed costs of the transit system must be covered by fewer passengers, ticket prices rise endogenously, making public transport use even less attractive. The resulting feedback loop additionally exacerbates the mode switching behavior towards individual driving and the corresponding increase in emissions. Our analysis proceeds in several steps yielding four main results.

First, we focus on the medium run and employ a partial-equilibrium perspective to account for adjustments in vehicle choice, mode choice, and ticket prices, but before an adjustment of location choices, the real estate market, and the urban form takes place. We find that our new mode choice channel induces an additional welfare cost of 24 percent relative to a scenario without public transport for achieving an aggregate emission reduction by 50 percent.

Second, the decrease in marginal driving costs with more fuel efficient vehicles shifts the households' location choice on average further away from the CBD. The resulting long-run expansion of the urban form in a general-equilibrium perspective induces additional welfare costs on top of the medium-run welfare cost of CAFE compliance for reaching certain emission goals, as examined by Marz and Goetzke (2019). The mode choice shift away from public transport and the urban expansion reinforce each other and additionally increase emissions. Therefore, the fuel economy standard must be tightened further to achieve an emission goal. As a result, the long-run welfare cost for reducing emissions by 50 percent is 36.5 percent higher with public transport than without.

Third, if the negative feedback loop of fewer passengers, rising ticket prices and decreasing marginal driving costs is sufficiently strong, it can lead to a collapse of the public transport system. A lump-sum-funded subsidy to public transport can prevent the collapse and attract more passengers by reducing the ticket price. We examine the second-best combination of fuel economy standards and public-transport subsidy that minimizes the welfare cost for emission reductions.

Fourth, we find that a fuel tax has the opposite effect on commuting distances and welfare costs: marginal driving cost increases. Households shift their mode choice toward public transport and emission reduction targets are reached at a lower welfare cost.

We contribute to the literature on the welfare costs and channels of fuel economy standards. Direct effects of fuel economy standards appear in the vehicle prices and encompass the cost of fuel regulation compliance (Austin and Dinan, 2005; NHTSA (2010); Anderson and Sallee, 2011; Klier and Linn, 2012; Jacobsen, 2013; Sallee et al. (2016)), the opportunity cost of trading off car features against fuel efficiency (Klier and Linn, 2016; West et al., 2017), and the effects on used car values (Jacobsen and van Benthem, 2015). Fuel economy standards also indirectly affect welfare through their impact on externalities, such as local pollution, carbon emissions, traffic fatalities, and congestion (Parry et al. (2007) gives an overview of traffic externalities). Finally, Marz and Goetzke (2019) examine the role of long-run urban-form adjustments and a CAFE-induced distortion of the vehicle market for the welfare consequences of fuel economy standards. However, none of these studies considers the role of public transport and adjustments in mode choice for the welfare balance of fuel economy standards or the interaction of these effects with the urban form. We fill this gap by identifying and examining our novel welfare channel of CAFE standards and its role for a long-run decarbonization of the transport sector.

Our analysis also contributes to the literature that links urban economic modelling with environmental-economic analysis of transport (Brueckner, 2007; Kim, 2012; Borck and Brueckner, 2018; Marz and Sen, 2021). But again, none of these studies accounts for public transport and the mechanisms we examine.

We, finally, contribute to the literature on the economics of public transport in the context of the monocentric city model (e.g., Brown, 1986; Liu et al., 2009; Creutzig, 2014; Tikoudis et al., 2015; Wang and Connors, 2018, among others). Our research is the first in this area that examines the interaction of public transport systems with fuel economy standards, vehicle choice and location choice and a long-run adjustment of the urban form in an urban economic framework.

The rest of the paper is organized as follows. Section 2 presents the model. We examine the effects of fuel economy standards in Section 3 and the implications of a fuel tax in Section 4. In Section 5, we discuss how subsidies can prevent a collapse of the public transport system. Section 6 concludes.

2 Model

2.1 Households

The basis for our framework is the monocentric city model in the tradition of Alonso (1977), Mills (1967), and Muth (1969). We interpret the model as a representative metropolitan area and, thus, abstract from households moving in or out. Commuters travel daily to the central business district (CBD) with their respective commuting distance x. In addition, we introduce a public transport sector and mode choice between car travel and public transport. Households affect their respective budget constraint by choosing the share $\mu < 1$ of working days on which they commute by car and the corresponding share $1 - \mu$ of public transport use. Overall, households maximize Cobb-Douglas utility by choosing their consumption of housing q and a numeraire composite good c and their car's fuel economy mpg in Miles per Gallon (following Marz and Goetzke, 2019).

$$\begin{aligned} \max_{c,q,mpg} \quad & u(c,q) = c^{1-\alpha} q^{\alpha} \qquad s.t. \\ & c + p(x)q = y - v(mpg) - (\mu \cdot t_C(mpg) + (1-\mu) \cdot t_P + \epsilon) \cdot x \end{aligned} \tag{1}$$

Housing price per unit of floor space is $p(x)$. On the budget constraint's RHS, the annual mobility expenditures consist of the vehicle cost $v(mpg)$ and the travel cost by car $t_C(mpg)$ and public transport t_P and the cost of travel time ϵ in Dollars per Meter of CBD distance and year (equal for both modes). The remainder of the uniform annual per capita income y is available for consumption. Total income, $y = y_0 + y_{rent} + y_{tax}$ consists of an exogenous wage income y_0 and a lump-sum of recycled excess land rent y_{rent} above the agricultural rent and of fuel tax revenues y_{tax} if they occur. Both latter components are determined in the general market equilibrium (s. Sections 2.3 and 4 below).

2.1.1 Commuting by Car

Each household owns a car differentiated by fuel efficiency mpg in Miles per Gallon with annual vehicle cost $v(mpg)$, a linear function of mpg. Vehicle production is perfectly competitive with zero profits. Thus, before the introduction of CAFE standards, the vehicle cost equals the exogenous technological cost of vehicle production $v_{tech}(mpg)$ with intercept $v_{0,tech}$ and slope m_{tech}. Thinking of Miles per Gallon of gasoline on a CO_2-equivalent basis, we, therefore, also implicitly account for electric vehicles as 'relatively carbon efficient vehicles' with high mpg.

$$v(mpg) = v_{tech}(mpg) = v_{0,tech} + m_{tech} \cdot mpg \tag{2}$$

For the days of car commuting (share μ), annual driving costs per meter are $t_C(mpg) = \frac{p_G F}{mpg} + t_{main}$ with the gasoline price p_G, maintenance cost per Meter and year t_{main}, and the unit adjustment factor[3] F. In their choice of mpg Households therefore face a trade-off between a higher vehicle price and lower driving costs with a cleaner vehicle accounting for their use of public transport. The first-order condition for mpg from (1), $m_{tech} - \mu \cdot \frac{p_G F}{mpg^2} x = 0$, yields the optimal choice of fuel efficiency

$$mpg^*(x) = \sqrt{\frac{p_G F}{m_{tech}} \mu \, x} \tag{3}$$

[3] $F = \frac{1}{1.6} \frac{miles}{km} \frac{1}{1000} \frac{km}{m} \cdot 2 \cdot 250 \frac{roundtrips}{year} = 0.3125 \frac{miles}{m \cdot year}$ converts the cost of a single trip in miles into annual expenses in meters.

Accordingly, $t_C(mpg)$ changes to $t_C(x) = \sqrt{\frac{p_G F m_{tech}}{\mu x}} + t_{main}$ and $v(mpg)$ to $v(x) = v_0 + \sqrt{\mu p_G F m_{tech} x}$.

2.1.2 Commuting by Public Transport

For the remaining days of commuting by public transport (share $(1-\mu)$), travel costs per Meter of distance to the CBD and year are t_P. In equilibrium, the public transport company's marginal revenue from ticket sales at price t_P must cover the constant marginal cost of each ride and the fixed costs of the public transport (PT) system. If the number of passengers and/or commuting distances change, then the fixed cost of the system remains unchanged, while variable costs change. Consequently, ticket prices must adjust to achieve cost-coverage.

We model the mode choice in commuting as a logit choice probability following Tikoudis et al. (2015). Households at each x evaluate their utility from exclusively commuting by car (i.e., $\mu_C = 1$)

$$u_C(x) = \frac{\alpha^\alpha (1-\alpha)^{(1-\alpha)}}{p(x,u)^\alpha} (y - v(x) - (t_C(x) + \epsilon)x) \tag{4}$$

or exclusively commuting by public transport (i.e., $\mu_P = 0$)

$$u_P(x) = \frac{\alpha^\alpha (1-\alpha)^{(1-\alpha)}}{p(x,u)^\alpha} (y - v(x) - (t_P + \epsilon)x) \tag{5}$$

In doing so, they continue to act as price takers and do not consider any changes in the vehicle market $v(x)$ or the real estate market $p(x,u)$ that might result from their decision. In the mode consideration they also assume that the continue to use their currently optimal vehicle according to Equation (3) (affecting $t_C(x)$, cf. Section 2.1.1). This approach avoids unimodal choice of transport mode and allows for a plausible degree of behavioral "fuzziness" when both transport modes are similarly attractive. This yields the probability to commute by car with Equations 4 and 5 (cf. Tikoudis et al., 2015)

$$\mu = \mu(x) = \frac{exp(u_C(x))}{exp(u_C(x)) + exp(u_P(x))} \tag{6}$$

2.2 Housing Market

Given homogeneous utility at any commuting distance x in equilibrium to prevent arbitrage, higher commuting costs are compensated by a lower price for housing $p(x)$. From the first-order conditions for c and q and the budget constraint in (1), we obtain constant expenditure shares $(1-\alpha)$ for $c(x)$[4] and α for $p(x)q(x)$[5], respectively. The housing price function is obtained by substituting both $c(x)$ and $p(x)q(x)$ into the objective function (1) leading to $p(x,u) = \Psi[y - v(x) - (\mu \cdot t_C(x) + (1-\mu) \cdot t_P + \epsilon)x]^{\frac{1}{\alpha}} u^{-\frac{1}{\alpha}}$ with $\Psi = \alpha(1-\alpha)^{1-\frac{1}{\alpha}}$ and u as a parametric utility level. Housing demand is given by $q(x,u) = \Gamma[y - v(x) - (\mu \cdot t_C(x) + (1-\mu) \cdot t_P + \epsilon)x]^{1-\frac{1}{\alpha}} u^{\frac{1}{\alpha}}$ with $\Gamma = (1-\alpha)^{1-\frac{1}{\alpha}}$.

As in Brueckner (2007), land priced at land rent $r = r(x)$ and housing capital per unit of land S, priced at 1, are inputs for housing production per unit of land, which is given by θS^{β} with the constant θ. The exponent $\beta < 1$ expresses the decreasing returns to scale in building higher. In a perfectly competitive housing market, developers maximize their (zero) profits at every distance x according to

$$\max_{S} \Pi(S) = p(x)\theta S^{\beta} - S - r(x) \tag{7}$$

Using the housing price $p(x,u)$ from above yields housing capital demand $S(x,u) = \Lambda[y - v(x) - (\mu \cdot t_C(x) + (1-\mu) \cdot t_P + \epsilon)x]^{\kappa} \cdot u^{-\kappa}$ with $\Lambda = (\theta\beta\Psi)^{\frac{1}{1-\beta}}$ and $\kappa = \frac{1}{\alpha(1-\beta)}$. Substituting $S(x,u)$ and $p(x,u)$ with profits $\Pi(S)$ equal to zero, this leads to the land rent function

$$r(x,u) = \Omega[y - v(x) - (\mu \cdot t_C(x) + (1-\mu) \cdot t_P + \epsilon)x]^{\kappa} \cdot u^{-\kappa} \tag{8}$$

[4] $c(x) = (1-\alpha)[y - v(x) - (\mu \cdot t_C(x) + (1-\mu) \cdot t_P + \epsilon)x]$ for the composite good.

[5] $p(x)q(x) = \alpha[y - v(x) - (\mu \cdot t_C(x) + (1-\mu) \cdot t_P + \epsilon)x]$ for rent expenses.

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

2.3 General Market Equilibrium

At the city boundary at distance $\bar{x}$ from the CBD, the land rent $r(x, u)$ in (8) equals the exogenous agricultural land rent r_A:

$$r(\bar{x}, u) = \Omega[y - v(\bar{x}) - (\mu \cdot t_c(\bar{x})\bar{x} + (1-\mu) \cdot t_P + \epsilon)\bar{x}]^{\kappa} \cdot u^{-\kappa} = r_A \tag{9}$$

To close the model, we determine the population density, i.e. the number of people per unit of land, $D(x, u) = \frac{\theta S(x,u)^{\beta}}{q(x,u)} = \Phi[y - v(x) - (\mu \cdot t_C(x) + (1-\mu) \cdot t_P + \epsilon)x]^{\kappa} \cdot u^{-\kappa}$ with $\Phi = \frac{\theta\Lambda^{\beta}}{\Gamma}$ and integrate over the whole city area. L is the exogenous total population.

$$\iint_{city} D(x, u) dA = \int_0^{\bar{x}} D(x, u) 2\pi x \; dx = L \tag{10}$$

Aggregate excess rent payments (part of land rent $r(x)$ above the agricultural rent r_A) are given back as rent income y_{rent} to the households in a lump-sum fashion (cf. above).

$$y_{rent} = \frac{1}{L} \iint_{city} r(x, u) - r_A \; dA = \frac{1}{L} \int_0^{\bar{x}} [r(x, u) - r_A] 2\pi x \; dx \tag{11}$$

The agricultural rent can be seen as the opportunity cost of land while the land within the city is owned collectively by a "city corporation" avoiding further distortions. Bringing (9), (10), and (11)together, we can solve the model and determine the city size $\bar{x}$ and the utility level u. The equilibrium also yields aggregate annual carbon emissions E_{CO2} (cf. Appendix 1).

2.4 Raising Fuel Economy Standards

Sallee et al. (2016) show that households do account for fuel economy to a pretty large degree in their vehicle choice. Therefore, when the government makes a binding fuel economy standard stricter, then car producers adjust car features and their pricing schedule to provide sufficient incentives for customers to buy cleaner cars then they do in the first place. Since total vehicle revenues must cover total costs, this implies a cross-subsidy from less fuel-efficient to cars to more fuel-efficient ones. We implement this mechanism as a reduction in the slope of the vehicle cost curve (2) from m_{tech} to m_{CAFE}. As a result, households at all locations x choose cleaner cars according to (3):

$$mpg_{CAFE}(x) = \sqrt{\frac{p_G F}{m_{CAFE}} \mu(x)\, x} > \sqrt{\frac{p_G F}{m_{tech}} \mu(x)\, x} \tag{12}$$

An endogenous increase in the intercept of the vehicle cost curve ($v_{0,CAFE} > v_{0,tech}$) ensures full cost coverage and zero profits under perfect competition.

$$\iint_{city} v_{revenues}(m_{CAFE})\, dA = \iint_{city} v_{costs}(m_{CAFE})\, dA \tag{13}$$

The increase in the intercept of the vehicle cost curve $v_{0,CAFE}$ illustrates the increase in total car production costs for, on average, more fuel efficient vehicles.

3 Analysis of Fuel Economy Standards

In the following, we examine the effects of stricter fuel economy standards. In a first step, the medium run, households adjust their vehicle and mode choices, but their location choice, the real estate market and the urban form remain unchanged. In this partial equilibrium (PE), individual utility levels vary. In the second step, we are looking at the long run from a general-equilibrium (GE) perspective with an additional adjustment of location choice and urban form. The results highlight the implications of the urban adjustment for welfare, emissions and the role of public transport.

The model is calibrated to the metropolitan statistical area of the median US citizen (Table 1). Appendix A.3 elaborates on the details of the calibration, while Appendix B presents a sensitivity analysis of the model parameters.

Population	L	845,000
Income p.c.	[\$ p.a.] y_0	46,380
Consumption share of housing	α	0.24
Scaling constant in housing production	θ	0.0283
Decrease of production productivity	β	0.825
Value of time travelled	ϵ	0.0257
Gas price	$[\frac{\$}{gal\ a}]\ p_G$	2.5
Agricultural rent	r_A	0.03123
Maintenance cost per km travelled	t_{main}	0.03
Conversion factor m/mpg in tCO2	F_{CO2}	0.00248
Annual marginal cost of vehicle fuel efficiency	$[\frac{\$}{mpg\ a}]\ m_{tech}$	15
Baseline vehicle cost	$v_{0,tech}$	1480

Table 1: Reference parameter setting

3.1 Partial Equilibrium: Medium Run

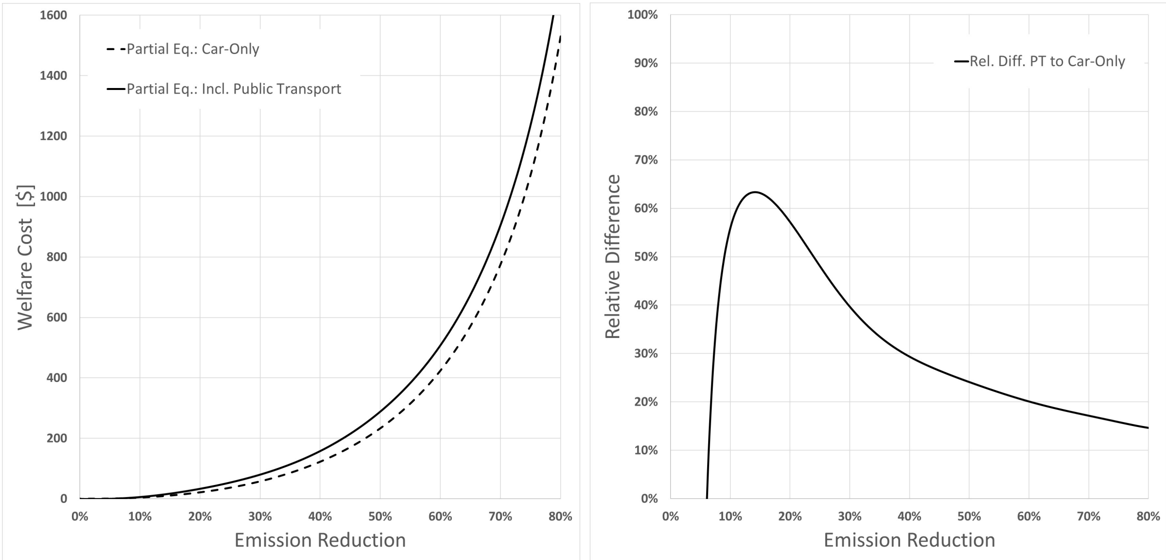
In the medium run, the housing location x with the bid-rent curve $p_0(x, u_0)$, and the population density $D_0(x, u_0)$, is fixed, while optimising its choice of vehicle fuel efficiency according to the introduced CAFE policy. The new vehicle cost curve and the corresponding change in driving costs affects the household's budget constraint as well as its mode choice. Household utility then is then given by

$$u_{1,CAFE}(x) = \frac{\alpha^{\alpha}(1-\alpha)^{(1-\alpha)}}{p_0(x, u_0)}[y - v_{CAFE}(x) - (\mu(x) \cdot t_C\, mpg_{CAFE}(x) + (1-\mu(x)) \cdot t_P + \epsilon)x] \tag{14}$$

Integrating $u_{1,CAFE}(x)$ over the whole city using the population density $D_0(x, u_0)$ and dividing the result by the number of inhabitants L, we obtain the average utility level:

$$\overline{u_{1,CAFE}} = \frac{1}{L}\int_0^{\bar{x}} u_{1,CAFE}(x) D_0(x, u_0) 2\pi x dx \tag{15}$$

Introducing CAFE standards to the model incentivizes the household to buy a more fuel efficient, albeit more expensive, car. Individual and average carbon emissions decrease as well as driving costs, given the fixed commuting distance (cf. Section 2.4). This benefit is countered by higher vehicle costs and a CAFE-induced distortion of the vehicle market, leading to a decrease in average utility. Furthermore, the reduced marginal driving cost by car makes the use of public transport relatively less attractive, shifting the household's mode choice towards car travel, i.e. increasing μ, and reinforcing the household's need for a more expensive, fuel efficient vehicle. Figure 1



(a) (b)

Figure 1: (a) Medium run per-capita welfare costs over emission reduction with (solid) and without (dashed) public transport
(b) Welfare difference between both scenarios rel. to the scenario without public transport.

depicts the welfare cost per capita over aggregate emission reduction levels achieved by a CAFE policy in the medium run in Panel (a). The dashed curve shows the effect of fuel economy standards in a car-only model (corresponding to the setup of Marz and Goetzke (2019)). Welfare costs are low for small reductions and rise convexly for stricter emission goals. Panel (b) shows the relative difference between these two scenarios. The shift of passengers from emission-free public transport to car commuting counteracts the emission reduction goal. Thus, a stricter CAFE standard is necessary to reach a certain emission goal, further distorting the vehicle market and increasing welfare costs. For a goal of reducing carbon emissions by 50 percent, our mode-choice channel increases the welfare cost substantially by 24 percent from 233 USD to 289 USD.

3.2 General Equilibrium: Long Run

In the long run, we allow for an adjustment of location choice, the housing market, and the urban form. Marginal driving costs are lower with higher fuel efficiency and lead to an increase in commuting trip lengths and an overall spatial expansion of the urban form as households try to benefit from lower real-estate prices in the suburbs. Rents in the CBD decrease and rents in the suburbs increase relative to the pre-policy case. As households simultaneously increase their annual share of car commuting μ, they choose an additionally higher level of fuel economy. Therefore, the urban expansion turns out stronger than in a scenario without public transport. The increase in commuting trip lengths x further reinforces the feedback between cleaner cars and a modal shift away from public transport until the new equilibrium is reached. Figure 2 shows the relative

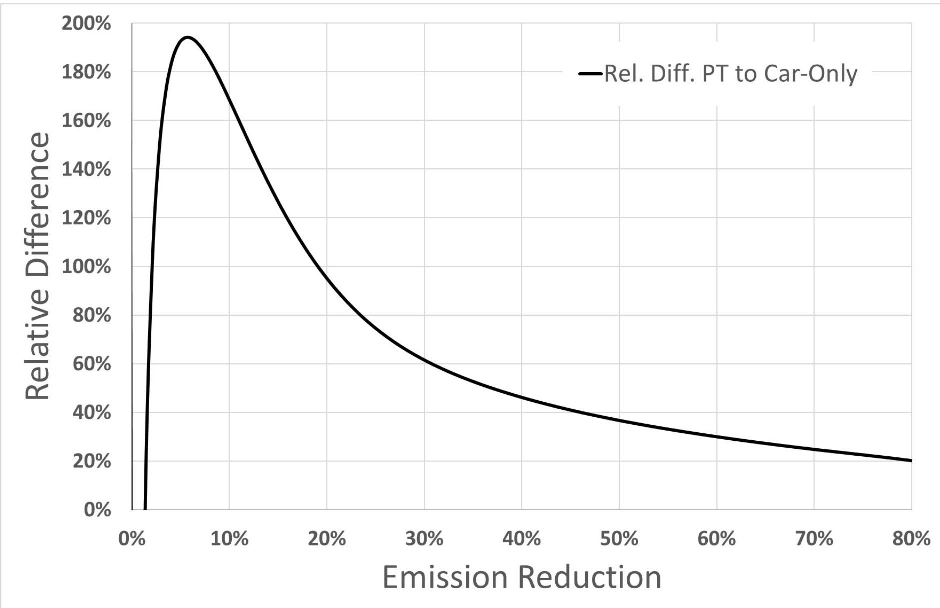


Figure 2: Relative difference of long run per-capita welfare costs between the scenario with public transport and a scenario with car commuting only over emission reduction goals.

difference between the car-only and the public transport scenario (see Appendix A.2, Figure A.1 for absolute values). For an emission reduction of 50 percent, the mode choice channel increases the welfare cost by an additional 36 percent (279 USD vs. 382 USD, see Figure A.1).

Figure 3 depicts the change in the share of car commuting for $m_{CAFE} = 3\frac{\$}{mpg\ a}$, which roughly corresponds to an emission reduction of 50 percent. At the CBD, households are

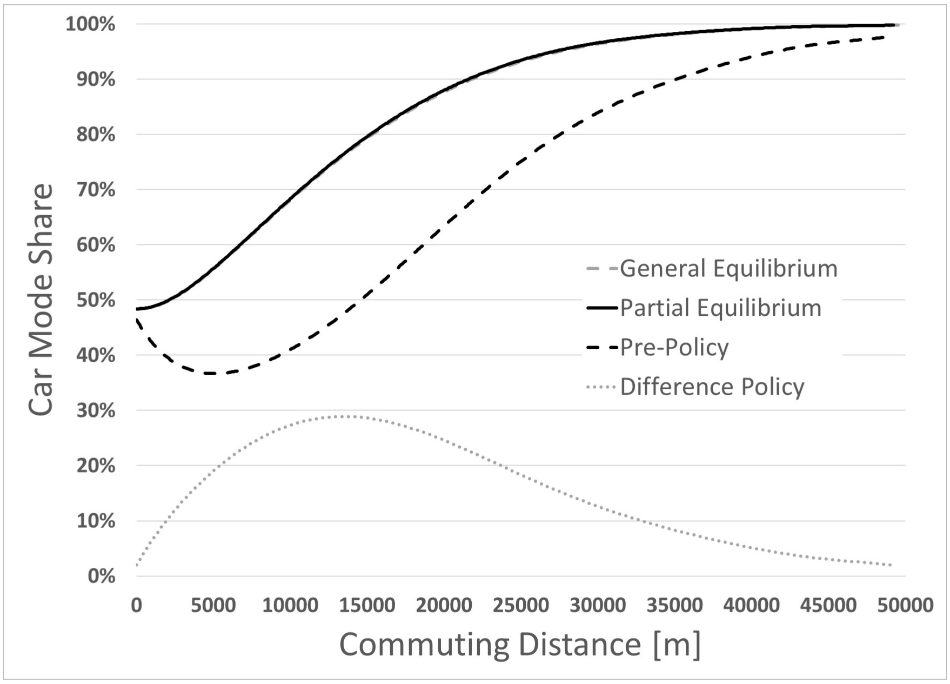


Figure 3: Change of mode choice due to the introduction of a CAFE policy with $m_{CAFE} = 3\ \frac{\$}{mpg\ a}$

virtually indifferent between modes ($\mu \approx 50\%$) due to very short commuting distances. With a rising distance to the CBD, households choose increasingly cleaner cars with more and more decreasing marginal driving costs. Since marginal PT ticket prices per m and year are constant in the whole city, the share of car use rises with higher x (except for a small area close to the CBD where the increase in x dominates the fuel-economy improvement).

In the depicted partial equilibrium (solid line), cars are more fuel efficient due to the CAFE policy and commuting costs by car are lower per distance for all households in the city due to the CAFE policy. Therefore, at each commuting distance car travel is relatively more attractive than public transport than without the policy. Table 2 directly compares the different scenarios quantitatively by welfare costs, city radius, average commuting distance, CO_2 emissions and miles per gallon of the average car.

The sizeable difference when including public transport in the model highlights the relevance of the mode choice effect we discuss for policy design.

		CAFE Policy $m_{CAFE} = 3\frac{\$}{mpg\ a}$		
Model Outcomes	**Pre-Policy**	**PE: Car**	**PE: PT**	**GE: PT**
City radius $\bar{x}$ $[m]$		48,733.4		51,456.4
Avg. commuting distance $[m]$		19,689.9		21,392.3
CO_2 Emissions $[tons/a]$	1.17	0.65	0.6	0.63
Avg. Miles per Gallon	24.8	68	62.8	66.2
Ticket Price Public Transport $[\$/m\ a]$	0.07	-	0.076	0.076

Table 2: Model outcomes for different scenarios under CAFE compliance without (PE: Medium Run) and with (GE: Long Run) adjustment of the urban form relative to the pre-policy and the car-only case

4 Fuel Tax

In our model, a fuel tax increases the households' incentive to invest in fuel economy. Burke and Nishitateno (2013) and Klier and Linn (2013) show that higher gasoline prices indeed trigger the purchase of more fuel efficient vehicles. Vehicle choice in the tax case, thus, changes from (3) to

$$mpg_{Tax}(x) = \sqrt{\frac{(p_G + \tau)F}{m_{tech}}\mu(x)x} \tag{16}$$

The resulting increase in Miles per Gallon also reduces driving costs. Overall, however, the marginal driving cost increases with the fuel tax. In contrast to CAFE, vehicle prices remain equal to production costs in the tax case, yielding the vehicle cost as $v_{Tax}(x) = v(x) = v_0 + \sqrt{m_{tech}\,(p_G + \tau)\,F\,x}$. The fuel tax revenues are given back to the households as lump-sum payments:

$$y_{Tax} = \frac{1}{L}\int_0^{\bar{x}} \frac{\tau\,F\,\mu(x)\,x}{mpg^*_{Tax}(x)} D(x,u) 2\pi x\,dx \tag{17}$$

The fuel tax triggers the choice of more fuel efficient vehicles. But, at the same time, it increases marginal driving costs and the incentive to switch mode more often to public transport. This fosters emission reductions without the distortion of the vehicle market associated with fuel economy standards. Moreover, the rising number of PT passengers distributes the fixed cost of the PT system over more shoulders and PT ticket prices decrease. Consequently, the mode shift towards public transport is reinforced by a similar feedback loop as in the CAFE case, only in the opposite direction.

In the medium-run PE perspective before an adjustment of the real estate market and the urban form takes place, therefore, the welfare cost for reaching an emission reduction goal is lower in the scenario with public transport than in a scenario without public transport.

A fuel tax also triggers a contraction of the urban form instead of the expansion that takes place for fuel economy standards, because it increases the marginal driving cost instead of reducing it (similarly as in Marz and Goetzke, 2019). The urban contraction reduces average commuting distances, making emission reduction goals attainable at lower welfare costs.

The interaction of fuel economy standards and fuel taxes with mode choice reinforces the welfare advantage of the fuel tax compared to fuel economy standards. The behavioral responses of mode choice, location choice and vehicle choice reinforce each other and increase the total welfare difference between the policies.

5 Discussion: Subsidy to Prevent Collapse of the Public Transport System

The shift of passengers away from public transport (PT) towards cars raises ticket prices, reinforcing the mode shift. If this feedback loop is strong enough (if the CAFE policy shock reaches a certain level and/or the share of fixed costs is high enough in the

PT system), then it can lead to a collapse of the PT system. The numerical analysis shows that such collapse is more likely to occur with higher emission reduction goals, with higher variable costs and a higher fixed-cost share in the PT cost structure.

In reality, public transport systems are usually heavily subsidized up to two-thirds of total costs or more. The share of fixed costs in public transport systems lies on a similar level. To prevent ticket prices from rising and the public transport system from collapsing, it will be necessary to raise the subsidies. In our model, the subsidy to reduce transit ticket prices is funded by a lump-sum income tax on all household incomes. In this sense, it is the "opposite-sign" counterpart to the fuel tax that makes driving more expensive at the margin while providing lump-sum revenue recycling payments to the households. In the following, we examine which mix of CAFE standards and public-transport subsidies reduces carbon emissions at the lowest welfare cost.

Results to be added...

6 Conclusion

Our research shows that fuel economy standards not only trigger the choice of more fuel-efficient vehicles, but also incentivize households to switch more often from commuting by public transport to commuting by car. This channel counteracts the intended reduction in greenhouse gas (GHG) emissions. Furthermore, by decreasing the marginal cost of driving, fuel economy standards induce a long-run expansion of the urban form as households see a stronger incentive to benefit from lower real estate prices in the suburbs. The mode choice channel reinforces this urban expansion and exacerbates the increase in commuting trip lengths. Thus, the choice of cleaner vehicles, the mode shift away from public transport towards car commuting, and the households' moving away from the CBD reinforce each other, leading to additional GHG emissions. This requires an additional tightening of the fuel economy standard with additional welfare costs from the associated vehicle market distortion to reach certain emission reduction goals. Overall, the examined mode choice channel leads to substantially larger welfare costs in the medium run, as well as in the long run. Moreover, fuel economy standards undermine the economics of public transport systems which are in danger of collapse without an increase in subsidies.

By contrast, the described interaction of vehicle choice, mode choice, and location choice also occurs for a carbon tax on gasoline, but with opposite signs: As the fuel tax raises marginal driving costs, households switch more often to public transport, decreasing ticket prices, emissions and welfare costs. The urban form reacts by a contraction that facilitates reaching certain emission reduction goals. The interactions of both environmental policies, mode choice and the urban form, thus, lead to an even larger gap in total welfare costs between fuel economy standards and the first-best instrument, a fuel tax. Our analysis shows how interactions of environmental policy instruments in the transport sector with mode choices can substantially affect their welfare balance and that they should be accounted for in policy design.

Our framework abstracts from several issues such as income heterogeneity and non-work trips. We also do not account for congestion, which is likely to change with mode shifts between car commuting and public transport. However, a large share of mode switching occurs in medium-range distances from the CBD which are not as congested as the center. Moreover, in the long run that we are looking at, road capacity can increase. Finally, congestion is not only driven by commuting traffic. Overall, accounting for congestion would add complexity to the model without a big impact on the magnitude of the results.

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Appendix

A Numerical Analysis

A.1 Aggregate Carbon Emissions

Annual carbon emissions E_{CO2} are calculated based on the total amount of consumed gasoline. The amount of consumed gasoline is calculated by integrating the product of individual driving distances x over the corresponding vehicle fuel economy in Miles per Gallon and the population density $D(x, u)$ over the city area.

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

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 and meters of distance to the CBD to annual Miles driven.[6]

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

A.2 Additional Figures

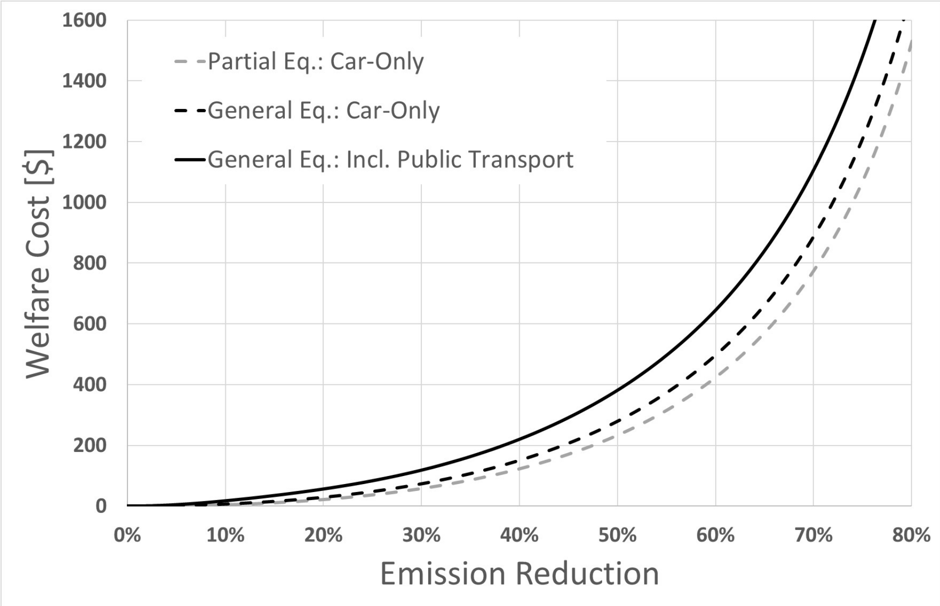

Figure A.1: Long run per capita welfare costs per emission reduction including/excluding public transport with medium run as reference case

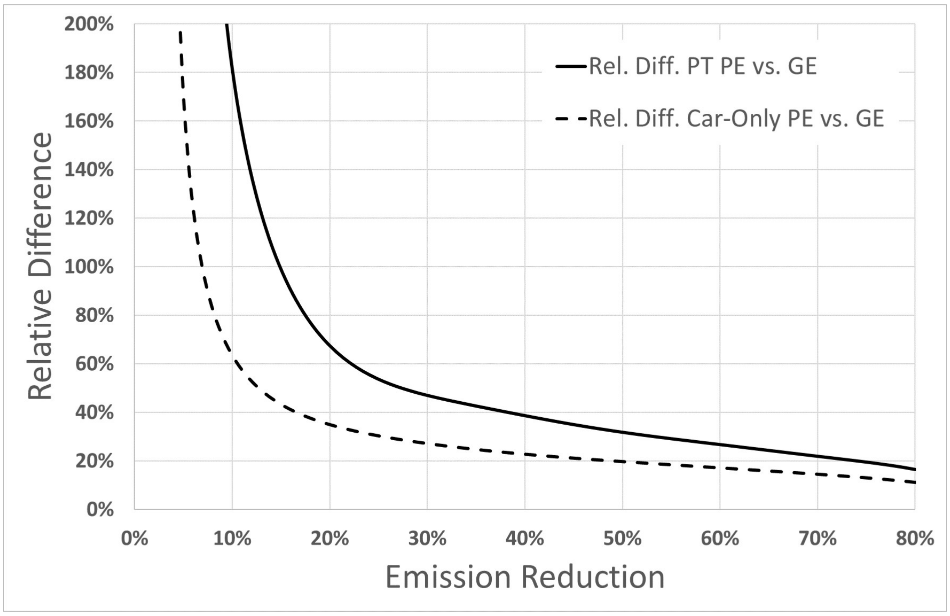

Figure A.2: Relative difference between medium and long run per capita welfare costs per emission reduction including/excluding public transport

A.3 Calibration

To be added...

B Sensitivity Analysis

To be added...