CESifo WORKING PAPERS

9357
2021

October 2021

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CESifo

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
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Editor: Clemens Fuest
https://www.cesifo.org/en/wp

CESifo *Working Paper No. 9357*

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Abstract

The long-term trend toward more work from home due to digitization has found a strong new driver, the Covid-19 pandemic. The profound change in urban mobility patterns supports the often-held view that reducing the number of commuting trips can lower carbon emissions to a certain degree. We investigate this optimistic view from a long-run perspective in a monocentric urban model with household-level vehicle choice based on fuel efficiency. In the medium run, fewer trips lead to the choice of less fuel-efficient vehicles. In addition, with lower annual driving costs to the city center, households change their location in the long run toward longer commuting trips, but cheaper housing, implying an adjustment in the real-estate market. These changes in vehicle choice and the urban form largely eliminate the initial environmental benefits. Binding fuel economy standards completely prevent the medium-run drop in fuel efficiency, but slightly exacerbate the long-term increase in commuting trip length.

JEL-Codes: H230, L900, Q480, R400.

Keywords: telecommuting, monocentric city, fuel economy, carbon emissions.

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31 July 2021

1 Introduction

The COVID-19 pandemic paved the way for a global surge in telecommuting. In the U.S., the share of people working from home on a regular basis did not increase significantly over the 20 years preceding the pandemic (Mas and Pallais, 2020). On the other hand, during the first wave of the coronavirus pandemic in 2020, almost half of the working population in the U.S. were working from home, including 35% who did not telecommute before the pandemic (Brynjolfsson et al., 2020;Bloom, 2020). The potential for telecommuting is even higher: Alipour et al. (2020) find that 56% of jobs in Germany are suitable for at least partial telecommuting. More and more workers and employers familiarize themselves with the required technologies and the ongoing digitization changes working routines. Furthermore, telecommuting can increase workers' performance (Bloom et al., 2014) and, thus, provide incentives for employers to adapt it permanently. As a result, the outbreak is likely to have persistent effects on the prevalence of telecommuting in the long run. The profound shift toward telecommuting has raised optimism for emission reduction targets in the transport sector due to reduced commuting. This scenario is often expressed in academic and public debates (Büttner and Breitkreuz, 2020).

Evidently, telecommuting can reduce carbon emissions by reducing fossil-fuel intensive commuting to work. However, this point of view focuses on the short run reduction in work trips and neglects subsequent behavioral responses of consumers. In the longer run, a boost in telecommuting also (i) affects household vehicle choice and (ii) changes the urban form through adjustments in household location and in the housing market. These behavioral responses have consequences for carbon emissions as well. We incorporate these mechanisms and investigate whether telecommuting can reduce carbon emissions in the long run by utilizing a monocentric city model where households choose between vehicles with different fuel efficiency. We show that an increase in the share of telecommuting changes carbon emissions not only by affecting the number of commuting days, but also through changes in vehicle choices in the medium-run and a long-term adjustment of real-estate markets and housing consumption. By calibrating our model parameters with empirical data, we find that these adjustments offset the short-run environmental benefits of telecommuting.

The transportation sector is one of the largest sources of greenhouse gas emissions (GHG). It accounts for around 30 percent of the US energy use and it heavily relies on fossil-fuel resources. Hence, it is the largest source of carbon dioxide emissions among all energy using sectors in the US.[1] Commuting to work is one of the most important motives for traveling. According to the 2017 figures, commuting to/from work accounts for 28% of total Miles of passenger travel at the local level in the US.[2] Similarly, 28% of the passenger trips in the Netherlands in 2014 were motivated by work related commuting.[3]. Therefore, reducing the emissions from commuting is an important goal of climate action.

Potential benefits of telecommuting for climate action has been prominent in the public debates, such that an increase in the share of telecommuting for the long-run obviates frequent driving to the city centers which leads to a reduction in commuting related emissions. For example, in a recent report, Büttner and Breitkreuz (2020) show that telecommuting can save 5 to 18% of emissions from commuting due to these short-run adjustments. In the current paper, we investigate two interacting mechanisms that can diminish the immediate carbon savings that telecommuting can bring about. First, telecommuting affects the vehicle choices. The technology costs of fuel efficient cars only pay off in the long-run as they consume less fuel per Mile. But the long-term benefits from higher fuel efficiency decrease with a reduction in the number of trips. Therefore, telecommuters invest less in vehicle fuel economy leading to a dirtier vehicle fleet in the cities. Second, telecommuting affects the housing choices. A structural change towards more telecommuting in the post-corona period can have permanent effects on the ur-

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[1] Source: Transportation Statistics Annual Report 2018, United States Department of Transportation, Bureau of Transportation Statistics. According to the Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2019, the share of transportation sector in total U.S. GHG emissions was 29% in 2019.

[2] Source: Transportation Statistics Annual Report 2018, United States Department of Transportation, Bureau of Transportation Statistics. Local travel is defined as less than 50 Miles of travel which are predominantly made by private vehicles.

[3] Source: Transport and Mobility 2016, Statistics Netherlands, available at `https://www.cbs.nl/en-gb/publication/2016/25/transport-and-mobility-2016`

ban form. Indeed, pandemics have shaped cities throughout the history. For example, modern sanitation systems emerged as a response to the 19th century cholera outbreaks with enduring effects on urban structure. Similarly, in our framework, willingness to pay for living in the close proximity of city centers diminish with more telecommuting and the urban landscape flatten out. Hence, telecommuters drive more Miles for their daily commute. As a result of these two mechanisms, the magnitude of emission reductions due to an increase in telecommuting is not clear.

We build on the urban economic literature in the tradition of monocentric-city modelling[4] and follow Marz and Goetzke (2019) in incorporating consumers' vehicle choices. All households commute to the central business district (CBD) to work and earn their exogenous income. Households choose the quality of their housing and the fuel economy of their cars. Household's budget available for consumption depends on its annual mobility costs which is determined by the household location and the commuting distance. Therefore, households with longer commutes prefer more fuel efficient cars which are cleaner. We go beyond Marz and Goetzke (2019) by incorporating the share of work days spent on working from home. Therefore, the marginal annual cost of driving decreases by the telecommuting share and the vehicle choice takes the telecommuting share into account.

In this setting, we analyze how a reduction in the frequency of work-related commuting affects carbon dioxide emissions. The immediate effect of this shock is a decrease in commuting to work, hence in emissions from commuting to work. We find that vehicle-choice and urban-form adjustments in the longer term counteract this immediate reduction in carbon emissions by 84 to 90 percent. The offsetting effect of the urban-form adjustment turns out between 4 and 6 times larger than the effect of the vehicle-choice adjustment. The results are largely robust to parameter choices and show that a permanent increase in the prevalence of telecommuting is not likely to decrease emissions from commuting.

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[4] See Alonso (1977), Muth (1969), and Mills (1967). Brueckner (2007) provides a detailed discussion of the monocentric city model.

The contribution of our analysis to the literature is to include the role of urban-form adjustments and consumers' vehicle choices in analyzing the role of telecommuting on carbon emissions. Our paper contributes to the nascent literature analyzing environmental concerns in an urban-economic modeling framework. This literature mainly focuses on the effect of fuel economy standards and fuel taxes on environmental outcomes. Marz and Goetzke (2019) incorporates consumers' vehicle choices in the monocentric city model developed by Brueckner (2007) and Kim (2012). We extend their model by introducing the share of work days spent on working from home. Our work is also related to the literature using spatial models to analyze the local labor market effects of telecommuting. Brueckner et al. (2021) studies the effects of telecommuting on the housing market as workers move to cheaper areas.

The rest of the paper is organized as follows: In Section 2, we describe our model. We present our main results in Section 3. In Section 4, we discuss various factors that can potentially be important in our modeling framework. Section 5 concludes.

2 The Model

In the monocentric city model, the urban form is determined by the trade-off between commuting and housing costs. Also, the radial form of the city requires housing-costs to decline as one moves further away from the CBD, as well as the population density gradients. This urban form and the trade-off between commuting and housing costs leads to an equilibrium where lower housing costs at the city boundaries are offset by higher commuting costs. We build on the framework of Marz and Goetzke (2019), who combine a monocentric urban model with household-level vehicle choice based on fuel economy. We extend their framework by incorporating the share of work days spent on working from home. Figure 1 illustrates our model in a stylized fashion.

Telecommuting affects carbon emissions via three channels. First, telecommuting has a direct effect on carbon emissions by reducing the number of trips to work in a year. Second, it affects emissions via the vehicle-choice of households, as the marginal annual

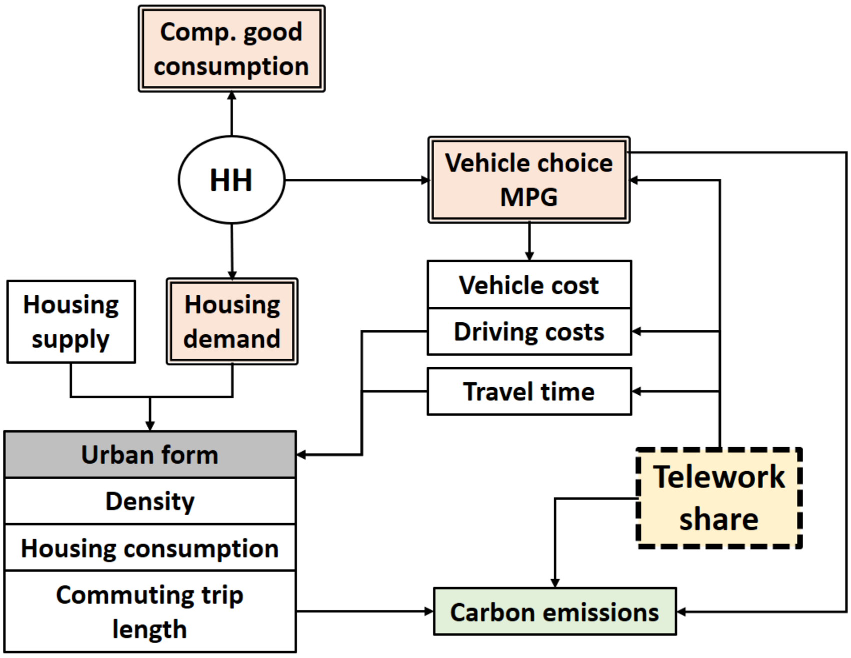

Figure 1: A monocentric city model with endogenous vehicle choices and telecommuting

cost of driving decreases by the telecommuting share and the vehicle choice takes the telecommuting share into account. Finally, telecommuting affects the urban form by changing the driving costs, such that telecommuters move away from the city center as their overall driving costs decrease.

In the rest of the section, we outline the details of our model. We start with formalizing the household's problem and proceed by explaining the details of automobile and housing markets. Finally, we impose the conditions for the general market equilibrium.

2.1 Households

We model a representative urban area as a closed city, such that the population size L is exogenous. Households are characterized with their housing location, i.e., their distance to the CBD, which we denote by x. They earn their income by working in the central business district (CBD).

Households' problem: Households maximize their utility by spending their income on a composite good c, on housing q, and on their car's fuel economy measured in Miles per gallon (mpg).[5] We formulate the households' utility maximization problem as follows:

$$\max_{c,q,mpg} u(c,q) = c^{1-\alpha} q^{\alpha} - \epsilon x \qquad s.t. \qquad c + p(x)q = y - t(mpg)x - v(mpg) \tag{1}$$

where we assume Coub-Douglas utility in the consumption of housing and a composite good. In addition, a fixed linear disutility per unit of distance to the CBD ϵ represents the utility cost of travel time. In maximizing their utility, households face a budget constraint, where y stands for annual per capita income. The annual expenses for commuting consist of two parts: 1) the variable spending on driving depending on the distance driven $t(mpg)x$ and 2) the annualized fixed cost of the vehicle given by $v(mpg)$. Both the fixed vehicle cost v and the unit cost of traveling t depend on fuel efficiency in Miles per Gallon (mpg). Once the commuting costs are deducted from annual income, the rest is spent on the consumption of housing and composite good. The price of the consumption good c is normalized to 1 and $p(x)$ denotes the price of a 'unit' of housing.

Income: Annual per capita income y is uniform across the city. It has three components as follows:

$$y = y_0 + y_{RPC} + y_{Tax} \tag{2}$$

where y_0 is exogenously given, y_{RPC} is lump-sum recycled land rent from the whole city, and y_{Tax} lump-sum recycled revenues from the fuel tax. Rent income y_{RPC} and tax income y_{Tax} will be determined by general market equilibrium which we explain later in this section.

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[5] The maximization problem could also be set up with x as a choice variable. However, this dimension is redundant, as market equilibrium entails that utility is uniform over x to ensure non-arbitrage.

Travel costs and telecommuting share: The annual travel costs per meter of commuting distance $t(mpg)$ is given by:

$$t(mpg) = (1-h)\left(\frac{p_G F}{mpg} + t_{main}\right) \tag{3}$$

where gasoline price per gallon p_G is exogenously given. Here, F is a unit-conversion factor.[6]. Annual vehicle maintenance costs per meter of distance is denoted by t_{main}. The parameter h is the average share of days on which households work at home. For simplicity, we abstract from public transport, which is a good approximation for most U.S. cities.

2.2 Auto Market

The auto industry is perfectly competitive. Therefore, the price of vehicle is equal to its production cost in the absence of binding policies. Following Austin and Dinan (2005), we assume that the production cost of an automobile $v_{tech}(mpg)$ is a linear function of the vehicle efficiency mpg chosen.[7] As a result, annuallized fixed cost of vehicle $v(mpg)$ to the consumer equals the technological vehicle production costs $v_{tech}(mpg)$ as follows:

$$v(mpg) = v_{tech}(mpg) = v_{0,tech} + m_{tech} \cdot mpg \tag{4}$$

The technological cost of a marginal increase in vehicle fuel efficiency, given by m_{tech}, reflects the idea that more advanced technologies such as hybrid or electric engines, are more costly to produce. The first-order condition of household for mpg is given by $-p_G F(1-h)x/mpg^2 + m_{tech} = 0$, which reflects the trade off between the lower driving costs and the cost of a marginal efficiency improvement. The optimal vehicle fuel

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[6] The factor converts the costs of a trip into annual expenses and Miles into meters, and is given by

$$F = \frac{1}{1.6}\frac{Miles}{km}\frac{1}{1000}\frac{km}{m} \cdot 2 \cdot 250 \frac{round-trips}{a} = 0.3125 \frac{Miles}{m \cdot a}.$$

[7] The vehicle cost curve covers potential R&D related cost savings in the future. Hence, its shape is linear.

efficiency is given by:

$$mpg^{*}(x) = \sqrt{\frac{p_G F(1-h)}{m_{tech}} x} \tag{5}$$

By substituting this expression, we obtain following expressions for $t(mpg)$ given by (3) and $v(mpg)$ given by (4):

$$\begin{aligned} t(x) =& \sqrt{\frac{p_G F m_{tech}(1-h)}{x}} + (1-h)t_{main} \\ v(x) =& v_{0,tech} + \sqrt{p_G F m_{tech}(1-h)x}. \end{aligned}$$

If fuel economy is the only criterion for vehicle choice, then households with a longer commute buy cleaner cars.

2.3 Housing Market

The residual income net of the vehicle expense are spent on housing and the composite consumption good. Given the Coub-Douglas utility function, Households spend $(1-\alpha)$ fraction of this residual income on the composite good and α fraction on the housing consumption. That is, the expenditure on the composite good and rent expenses are given by $c(x) = (1-\alpha)(y - t(x)x - v(x))$ and $p(x)q(x) = \alpha(y - t(x)x - v(x))$, respectively. Using the expenditure functions and (1), we obtain the housing price function:

$$p(x,u) = \Psi(y - t(x)x - v(x))^{\frac{1}{\alpha}}(u + \epsilon x)^{-\frac{1}{\alpha}}, \tag{6}$$

with $\Psi = \alpha(1-\alpha)^{\frac{1}{\alpha}-1}$ and a parametric utility level u. Note that non-arbitrage condition in the urban-economic equilibrium ensures that household utility u is uniform over all households indexed by distances x.[8] Given that utility level is uniform over x in equilibrium, households take into account that higher commuting costs $t(x)x$ at higher distances

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[8] 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 2.4), it appears as a parameter from the perspective of a single household here.

x are compensated by lower housing prices. Substituting $p(x,u)$ into $p(x)q(x)$ leads to housing demand

$$q(x,u) = \Gamma(y - t(x)x - v(x))^{1-\frac{1}{\alpha}}(u + \epsilon x)^{\frac{1}{\alpha}}, \text{ where } \Gamma = (1-\alpha)^{1-\frac{1}{\alpha}}. \tag{7}$$

We follow Brueckner (2007) in specifying the supply side of the housing market. Developers produce housing output with land and housing capital S as inputs. The housing production function per unit of land is given by θS^{β}. The decreasing returns to scale, i.e., the rising marginal cost of building higher buildings, is captured by the exponent $\beta < 1$. Developers are perfectly competitive and maximize profits per unit of land at every distance x.[9]. Their problem is given by $\max_S \Pi(S) = p(x)\theta S^{\beta} - S - r(x)$, where the price of capital S is normalized to 1 and $r(x)$ is the rent per unit of land.[10] When we substitute the housing price function $p(x,u)$ given by equation (6) into the first-order condition for S, we obtain the demand for housing capital $S(x,u) = \Lambda(y - t(x)x - v(x))^{\kappa}(u + \epsilon x)^{-\kappa}$ with the constants $\Lambda = (\theta\beta\Psi)^{\frac{1}{1-\beta}}$ and $\kappa = \frac{1}{\alpha(1-\beta)}$. By setting developers' profits $\Pi(S)$ equal to zero and substituting the functions $S(x,u)$ and $p(x,u)$, we solve for the land rent function

$$r(x,u) = \Omega(y - t(x)x - v(x))^{\kappa}(u + \epsilon x)^{-\kappa}, \tag{8}$$

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

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[9] As in the case of households, developers' profits in equilibrium are equal (and zero) at all distances x.

[10] The term "rent" 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.

2.4 General Market Equilibrium

The land rent at the city boundary $\bar{x}$ must be equal to the exogenous agricultural land rent r_A given by equation (8)), which determines the city limit as follows:

$$r(\bar{x}, u) = \Omega(y - t(\bar{x})\bar{x} - v(\bar{x}))^{\kappa}(u + \epsilon x)^{-\kappa} = r_A \tag{9}$$

The population density is given by $D(x, u) = \frac{\theta S(x,u)^{\beta}}{q(x,u)} = \Phi(y - t(x)x - v(x))^{\kappa-1}(u + \epsilon x)^{-\kappa}$ with $\Phi = \frac{\theta \Lambda^{\beta}}{\Gamma}$. Here, we divide the amount of housing per unit of land by the amount of housing per person $q(x, u)$, and substitute $S(x, u)$. The last condition to solve the model is that the integral of the population density $D(x, u)$ over the inhabited city area must be equal to the exogenous population L as follows:

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

Conditions (9) and (10) close the model and lead to solutions for the city radius $\bar{x}$ and the utility level u.[11] The equilibrium solution is the basis for calculating the aggregate annual carbon emissions E_{CO2} (cf. Appendix A.1) and the sum of excess rent payments. The latter are the land rents r net of the agricultural rent r_A. The excess rents are redistributed to the households as per-capita payments y_{RPC} (cf. Equation (2)):

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

One interpretation of excess rent recycling in the urban economic literature is the following: the citizens collectively own the land of the city through a municipal corporation. This corporation receives and redistributes the excess land rent payments to the citizens in a lump-sum fashion. Hence, further distributional distortions do not arise. Only the

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[11] The model requires a numerical solution due to the integral in (10). Suburban residents have higher mobility expenses than more central residents and, thus, spend less on housing and the composite consumption good. However, as the housing price function ("bid-rent curve") is falling with the CBD distance $\partial p(x)/\partial x < 0$, their higher housing consumption $\partial q(x)/\partial x > 0$ compensates them. In equilibrium, the utility level is uniform over the whole urban area.

excess rent is recycled as the agricultural rent represents the opportunity cost of land and the corresponding payments leave the city. This implies that the original owners of the (agricultural) land reside outside of the city.

3 Results

We investigate the effect of an increase in the share of telecommuting days over the year on commute-related carbon emissions. We calibrate our model to a representative metropolitan area in the US. The reference calibration of the model is summarized in Table 1 and further details are provided in Appendix A.2.

Population, L	845,000
Annual income p.c., y_0	46,380
Annual marginal cost of vehicle fuel efficiency, m_{tech} $[\frac{\$}{MPG\,a}]$[12]	15
Gas price p_G $[\frac{\$}{gal\,a}]$	2.5
Consumption share of housing, α	0.24
Scale exponent in housing production, β	0.826
Scaling constant in housing production, θ	0.0283
Agricultural rent r_A $[\frac{\$}{m^2\,a}]$	0.03123
Automobile maintenance cost t_{main} $[\frac{\$}{m\,a}]$	0.03

Table 1: Parameter setting of the reference city

In the following subsections, we examine the implications of telecommuting for commute-related carbon emissions in three steps by breaking down the total change in emissions into its components: i) in the first step, only the number of commuting trips decreases due to an increase in the share of telecommuting, ii) in the second step, households adjust their vehicle choice and iii) in the last step, also location choices are affected and the urban model reaches a new equilibrium on the real-estate market. These steps reflect the expected timing of these adjustments in reality. Upon the arrival of the shock, the decrease in the number of trips is likely to happen rather quickly, while it takes some years for the households to change their vehicles and even more years to change their houses. For this reason, our narrative will refer to these adjustments also as short-, medium-, and long-run adjustments, although the model itself is static.

In the following analysis, we assume that all households introduce the same share of telecommuting days, irrespective of their location. This seems reasonable as other possible dimensions of heterogeneity like part-time work and their distribution in space are beyond the scope of this paper.

3.1 Adjustments in Vehicle Choice

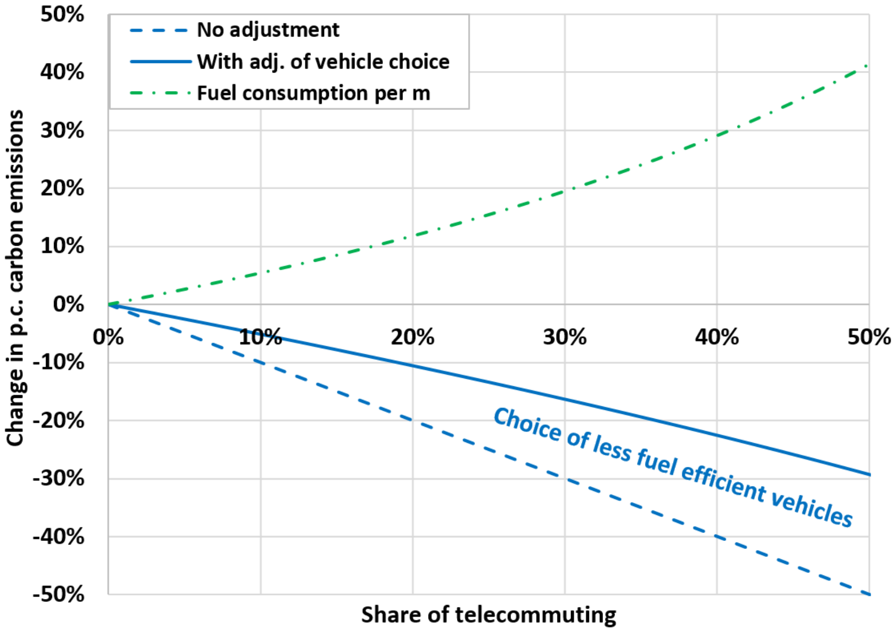

Figure 2: Medium-run change in carbon emissions

Notes: Medium-run percentage change in carbon emissions per capita over the share of telecommuting in the total annual working days. The medium-run adjustment after the change in vehicle choices is depicted by the blue solid line. The blue dashed line represents the short-run adjustments due to the change in the number of commuting days to the CBD in a year. The green dash-dotted line shows the medium-run change in the average vehicle fuel consumption.

We start our analysis by analyzing the short to medium term reactions to an increase in the share of telecommuting. Figure 2 illustrates our results. The immediate effect of an increase in telecommuting is a one-to-one decrease in commuting trips and, hence, in commute-related emissions. A higher share of telecommuting days in the total number of working days leads to a higher emission reduction. The blue dashed line in Figure 2 represents this linear relationship.

In the second step, we allow for vehicle-choice adjustments, such that households renew their cars by taking their new permanent commuting schedule into account. At this stage, household locations remain unchanged. The changes in carbon emissions after the vehicle-choice adjustments are depicted by the solid blue line in Figure 2. These adjustments in the vehicle choices offset between 40 and 50 percent of the initial carbon emission reduction.

The intuition underlying this result is straightforward. The annual monetary benefits of a marginal improvement in fuel economy is experienced in the form of lower gasoline expenses. These benefits decrease with fewer commuting trips per year. However, the marginal costs of fuel economy, in the form of vehicle purchasing costs, remain the same. Therefore, households choose less fuel-efficient vehicles. The change in fuel economy in terms of Gallons of consumed fuel per Mile is shown in the upper panel of Figure 2 for different telecommuting levels. The average fuel consumption per Mile increases with higher shares of telecommuting. This mechanism reduces the immediate carbon savings from fewer trips to the city center.

In Figure 2, the amount of carbon emissions which is offset through the choice of dirtier vehicles is not rising as steeply as the average vehicle fuel consumption per Mile. The reason is that fuel efficiency is an average characteristic of the vehicles. In order to obtain the implication of this vehicle-choice adjustment for aggregate carbon emissions, each household's fuel consumption per Mile is weighted with the distance driven. This gives a higher weight to more efficient vehicles of households with long commutes.

3.2 Adjustment of Location Choices and the Urban Form

We continue our analysis by additionally allowing adjustments in household location choice and the urban form. The annual costs of "distance to the CBD" in terms of monetary driving costs and disutility of time spent traveling decrease with a rising telecommuting share. Therefore, households move further away from the CBD to take advantage of lower real-estate prices. This urban expansion affects emissions in two ways: First, the driving distance to the CBD increases as illustrated in Figure 3. This figure shows that the change in commuting distances due to telecommuting is large. For example, a

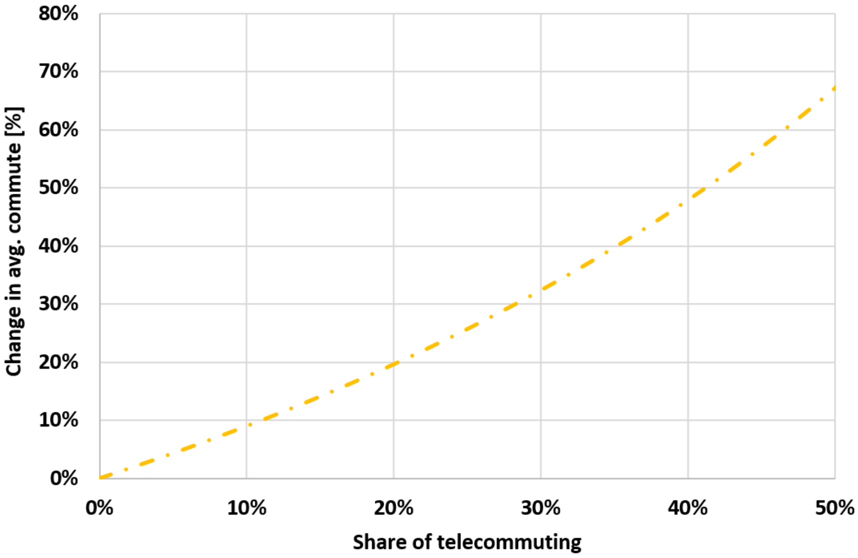

Figure 3: Long-run change in average commuting trip length

Notes: Long-run change in commuting trip lengths over the share of telecommuting in the total annual working days.

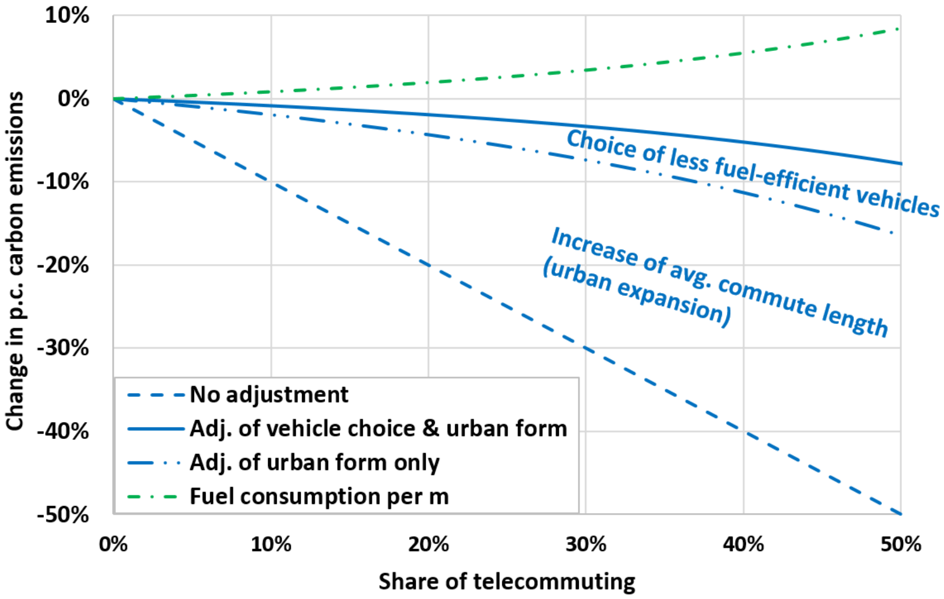

Figure 4: Long-run change in carbon emissions

Notes: This figure illustrates the long-run percentage change in carbon emissions per capita over the share of telecommuting in the total annual working days. The long-run change after all adjustments in the vehicle choice and in the urban form is depicted with blue-solid line. The blue dashed line represents the short-run adjustments due to the change in the annual number of trips to the CBD. The blue dash-double-dotted line represents the effect on emissions of only the extension in commute lengths is considered. The green dash-dotted line shows the long-run change in the average vehicle fuel consumption per Mile.

50 percent telecommuting share increases the average commuting distance by almost 70 percent. This mechanism implies an increase in carbon emissions. Second, the larger driving distances incentivize the choice of more fuel efficient vehicles. This adjustment counteracts vehicle-choice adjustments towards dirtier cars illustrated in the previous subsection. As a result, the change in fuel consumption per Mile in the long run after all adjustments take place is smaller than that in the medium run, for which we only allow for vehicle-choice adjustment. Figure 4 shows that this partial effect is quite strong, such that fuel consumption per Mile after the urban-form adjustments almost reverts back to the initial levels with no telecommuting.

Figure 4 summarizes our results from allowing for long-term adjustments in the urban form. Additionally, Table 2 gives an overview over the magnitudes of the offsetting effects the telecommuting shares of 20 percent and 50 percent. The offsetting effect from the choice of dirtier vehicles (wedge between solid and dash-double-dotted line, Figure 4) decreases by a factor of 2.5 to 4 as the longer commuting trips increase the benefits of higher fuel economy again. But the strong extension of commute lengths itself (cf. Figure 3) plays a more dominant role and offsets an additional 67 to 78 percent of the initial decrease in carbon emissions through telecommuting. This component of the total effect is represented in Figure 4 by the wedge between the dashed line and the dash-double-dotted line, which shows the outcome if only the commute extension is considered. Overall, the initial carbon emission reduction is offset to a very large degree (84-90 percent), as illustrated by the solid-blue line.

		Telecommuting share	
		20%	50%
Medium run offset	Vehicle choice	**47%**	**41%**
Long run offset	Vehicle choice	12%	17%
	Commute adjustment	78%	67%
	Σ	**90%**	**84%**

Table 2: Magnitudes of the effects offsetting the intitial carbon emission reduction from a higher share of telecommuting

3.3 Robustness

We describe the empirical basis for our model parameters in Appendix A.2. In addition, we provide a sensitivity analysis w.r.t. a few parameters whose empirical justification is not as clear-cut as the gasoline price or the income level. In Appendix B, we show that our results are qualitatively and quantitatively very robust to variations in the marginal technological cost of fuel economy m_{tech}, the housing production parameter θ and the elasticity of utility w.r.t. housing α. Here, we show that two further parameters have a slightly larger, but overall still limited, influence on the results: the value of travel time and the agricultural rent r_A.

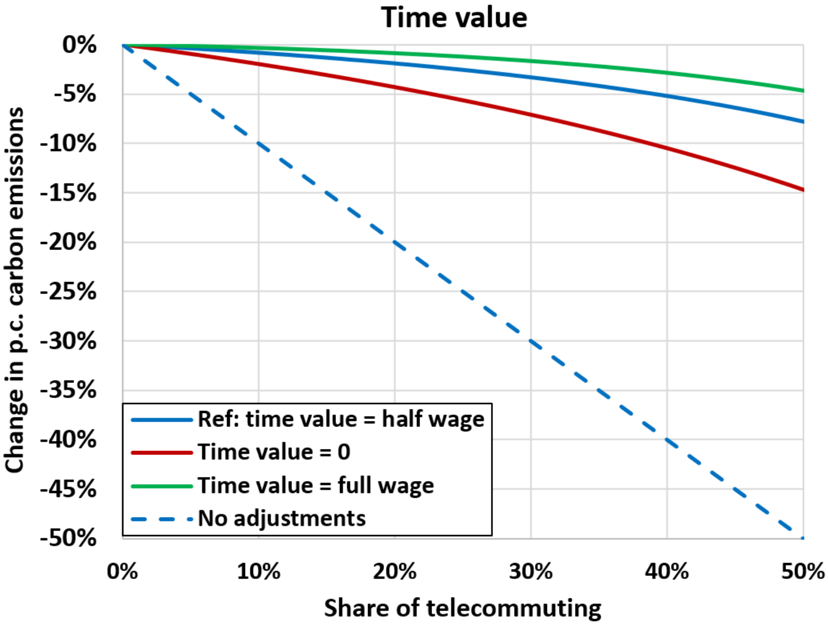

Figure 5: Effect of the value of travel time on the overall offset of initial carbon emission reductions through telecommuting

We base our reference calibration on the standard assumption in the literature (e.g., Small and Verhoef (2007); Shires and de Jong, 2009; Small, 2012) that the value of travel time is equal to half the gross hourly wage. In Figure 5, we additionally apply two extreme values for the value of travel time: zero and a fully hourly wage. Assuming a full hourly wage for the value of travel time implies that additional work-from-home days reduce the annual cost of distance to the the CBD more than if a lower value of travel time is assumed. This leads to a stronger urban expansion in the long run and a stronger offset of the initial carbon emission reductions (green curve in Figure 5). In the other extreme scenario, we assume away the value of travel time (red curve in Figure 5). In this case, the urban expansion is weaker and the offset of initial carbon emission reductions is smaller. But even in this unrealistically conservative scenario, between 70 and 80 percent of the initial emission savings through telecommuting are lost to the adjustments in household location and vehicle choice. The U.S. metropolitan areas differ substantially in the wage level and, consequently in the value of travel time for their citizens. However, this heterogeneity does not seem to affect our overall results.

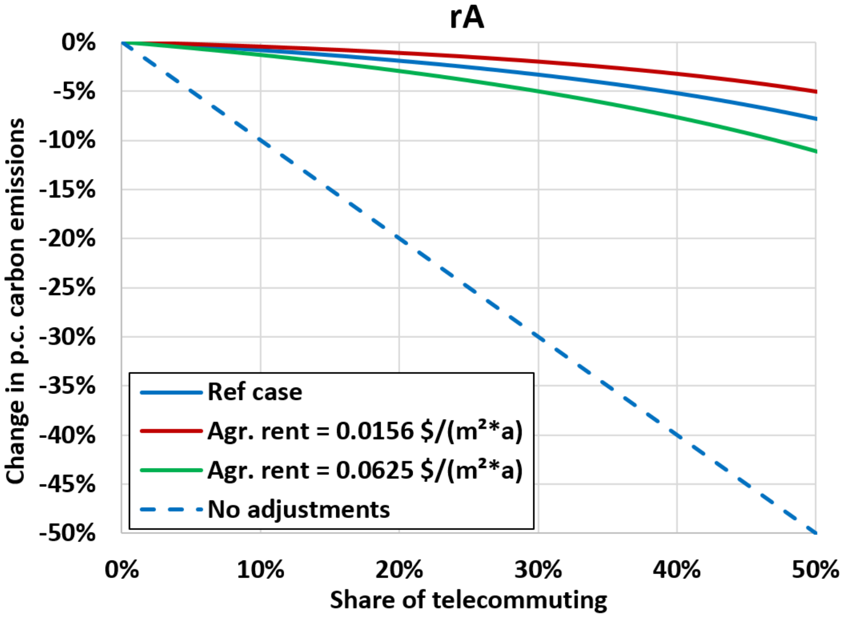

Figure 6: Effect of the agricultural rent r_A on the overall offset of initial carbon emission reductions through telecommuting

The agricultural rent in the regions surrounding the U.S. metropolitan areas is not as much uncertain as it is heterogeneous. Still, the overall outcome is fairly robust w.r.t. different levels of the agricultural rent, as Figure 6 shows. For cities with lower land values, the increase in commuting distances is stronger. But the quantitative effect on the results is, again, moderate. Therefore, our results overall indicate that the decrease in carbon emissions through a higher prevalence of telecommuting is not likely to be as substantial as is commonly expected.

3.4 Telecommuting under Fuel Economy Standards

In many countries like the U.S. or in the E.U., the fuel efficiency of vehicles is regulated with fuel economy standards. With these regulations, it is the responsibility of automakers to make sure that their fleet of sold vehicles in each year fulfills an average fuel-economy standard. If customers are reluctant to buy more fuel efficient vehicles, producers must provide the necessary incentives. Binding fuel economy standards can be expected to counteract the shift toward less fuel efficient vehicles in the medium and long run.

Figure 7 confirms that the reduction in fuel economy is completely prevented with binding fuel economy standards (cf. flat green dash-dotted curve). The wedge in Figure 4 which depicts the offsetting of emission reductions through lower fuel economy is eliminated. At the same time, the marginal cost of driving is lower than the one in the scenario without fuel economy standards, as equilibrium fuel economy is higher in the long run. This situation provides an additional incentive for households to move further away from the CBD to benefit from cheaper housing. However, reduction in carbon emission savings from an increase in the commuting distance with CAFE standards (Figure 7) is only slightly larger than the one in the baseline scenario without CAFE standards (Figure 4). Overall, about 43% of the initial carbon emission reduction through telecommuting in the short run can be preserved in the long run with CAFE standards for a high telecommuting share of 50%. Without CAFE standards, only about 16% can be preserved, a relative improvement by a factor of 2.7.

4 Discussion

In this section, we discuss policy options in the face of potential urban sprawl caused by a surge in telecommuting and its implications for CO_2 emissions, and we elaborate on the roles of some potential factors which we omit in our analysis.

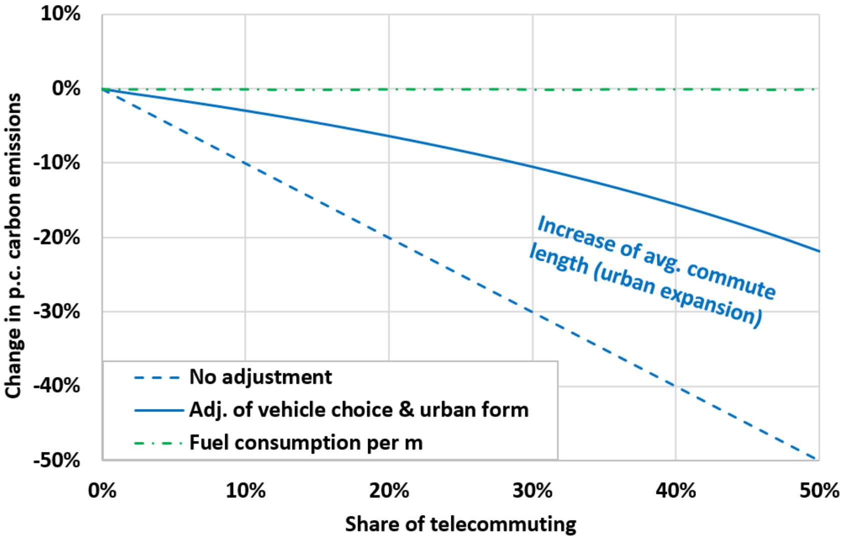

Figure 7: Long-run change in carbon emissions with CAFE standards

Notes: This figure illustrates the long-run percentage changes in carbon emissions per capita over the share of telecommuting in the total working days in a year in the presence of binding fuel economy standards. The long-run changes after the adjustment in the urban form are depicted with the blue solid line. The blue dashed line represents the short-run adjustments due to the change in the number of trips to the CBD in a year. The green dash-dotted line shows the change in the average vehicle fuel consumption in the long term, i.e. it remains flat for binding CAFE standards.

Urban growth boundaries. Our analysis shows that telecommuting can lead to substantially longer commutes resulting from an expansion of metropolitan areas into the surrounding countryside. For decades, the detrimental effects of urban sprawl and possible countermeasures have been central in the urban economic literature (see, for example, Nechyba and Walsh, 2004). In addition to transport policies, such as CAFE standards which we analyzed in the previous section, regulators may apply land-use policies to prevent urban sprawl. One such measure, urban growth boundaries, could in principle limit the expansion of urban areas due to a shift toward telecommuting. However, such policies can increase housing costs, and households could still increase their commuting distance to the CBD within the boundary. In addition they can still move to suburbs and exurbs outside of the jurisdiction of the municipal center. Thus, the potential to prevent the resulting increase in commuting distances due to telecommuting seems limited if demand in the real estate market shifts accordingly.

Public transport In general, the major means of commuting is car travel rather than public transit. According to the Census Bureau's American Community Survey (ACS), the main mode of commuting in the US to work is car travel. In 2018, more than 80% of commuters drove alone to work. The share of public transportation was only 1.3%.[13]. Even in European countries where the public transport infrastructure is more prominent, the main mode of commuting to work is still car transport. For example, the share of personal cars in total commute in Germany in 2016 was 68%, while public transportation accounts only for 14%.[14]

Our analysis, which abstracts from public transport, represents a rather conservative view on the effect of telecommuting on commuting emissions. The reason is that the operation of public transport systems is better characterized with cost coverage motives rather than profit maximization motives. If a higher share of telecommuting reduces the number of trips to work and more households move beyond the area covered by public transport, then the utilized capacity of public transport is likely to decrease. The substantial fixed costs and operation and maintenance costs of public transit then have to be covered by fewer passengers. This situation can lead to higher ticket prices which could trigger an additional shift of passengers from public transport to commuting by car. This shift would likely further increase carbon emissions of commuting on top of that implied by our analysis.

Non-commute travel In our analysis, we abstract from non-commute travel, such as traveling for shopping, recreational activities, education, or religion. Since Tiebout (1956), it is argued that people choose their residential location based on such local public amenities in addition to commuting motives. However, in our long-run perspective, it is plausible that shopping malls, schools, churches and recreational facilities are also provided at the new neighborhoods and exurbs. Market forces (demand), as well as political-economic processes can drive the provision of non-work facilities. Consequently,

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[13] Source: US Department of Commerce, Bureau of Census, American Community Survey, table B08006. Also see the figures provided by the US Department of Transportation available at `https://www.bts.gov/browse-statistical-products-and-data/state-transportation-statistics/commute-mode`.

[14] Source: Germany's Federal Statistical Office (Destatis). Also see the press release by Destatis availabl at `https://www.destatis.de/EN/Press/2017/08/PE17_288_12211.html;jsessionid=3AD98E11EAB553F3F2A9E2604815A547.live742`.

in the long run, the average driving distance to these places are not likely to increase as much as the movement of household locations alone would suggest. Our focus on work-related trips, thus, also yields a conservative estimate of the effect of telecommuting on carbon emissions in this regard. The actual long-run increase in carbon emissions is likely to be even higher.

Congestion In this paper, we focus on the role of two important mechanisms, urban-form and vehicle-choice adjustments, in the relationship between telecommuting and commute-related emissions. In order to keep this focus, we have to leave some interesting elements out in our analysis, such as congestion and housing emissions. The relationship between congestion and urban sprawl is complex. The first order effect of incorporating congestion in our analysis would be that the urban-form adjustments due to higher telecommuting would reduce congestion, which can reduce congestion-related emissions.[15] On the other hand, less congestion reduces the utility cost of driving, which incentivizes longer commuting distances. The overall role of congestion for our results is not clear and it should be addressed by future research.

Housing emissions Telecommuting might also effect housing emissions as the urban expansion due to a permanent surge in teleworking reduces the overall population density of urban areas. A lower population density can induce a change in building structures with less floors and more single-family homes instead of larger apartment buildings and condominiums. On the one hand, the construction of new buildings according to recent technological and regulation standards, e.g. concerning heating and cooling, could reduce energy consumption and emissions. On the other hand, the associated increase in housing area per capita and shift to buildings with a higher surface area relative to floorspace implies an increase in heating and cooling demand and related emissions.The overall

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[15] The direct effect of reduced congestion on pollution depends on the type of congestion. In the case of nitrogen oxides, there is a U-shaped relation between per vehicle mile traveled and car speed. See Nechyba and Walsh, 2004 for a detailed discussion.

effect on building emissions and how it interacts with endogenous vehicle choices is an important avenue for future research.

5 Conclusion

The Covid-19 pandemic is expected to permanently boost the prevalence of telecommuting, as it accelerates structural shifts in digitization and work organization. This can can have profound effects on CO_2 emissions. To examine the effect of telecommuting on carbon dioxide emissions, we model behavioral responses of consumers in the vehicle and housing market in a monocentric city model. In our model, households change their vehicles based on their fuel efficiency and the location of their houses due to a structural increase in the share of telecommuting.

An increase in the frequency of work from home leads to an immediate reduction in CO_2 emissions in the short-run. However, we show that these immediate savings in carbon emissions are more than offset as households switch to less efficient cars and move away from the city center benefiting from lower real-estate prices. In our reference scenario, about 84 to 90 percent of the initial carbon emission reduction are offset by the vehicle and housing market adjustments. Therefore, our findings indicate that the decrease in carbon emissions due to a higher prevalence of telecommuting is not as substantial as is commonly expected. Furthermore, our analysis provides a rather conservative view on behavioral responses which can offset short-term benefits of telecommuting. Our discussion of additional aspects such as non-work trips, interaction with public transport, congestion, and building emissions suggests that more telecommuting likely triggers additional offsetting effects which could further diminish emission savings, or even lead to overall rising emissions. In this case, telecommuting might even turn out as counterproductive in reaching carbon emission goals in the transport sector. We further show that a policy response which mandates fuel economy standards on the producers prevents the medium-run drop in fuel efficiency, but slightly exacerbates the long-term increase in commute lengths.

Our results show that even the potential carbon savings from a higher share of telecommuting are not granted in the long run, even for the narrowly defined commuting related emissions. Therefore, telecommuting cannot be considered an effective strategy to reach climate targets in the transport sector and it is not likely to be a substitute for environmental policies to reduce carbon emissions. However, as we illustrate for the case of fuel economy standards, environmental policy are still required to at least reap the limited benefits of teleworking for emission targets.

The attention of policy makers is now on the recovery plans from the global recession caused by the COVID-19 pandemic. These recovery plans entail large scale economic stimulus packages which will be spent on infrastructure and capital investments with long-term implications. Based on our results, we believe that maintaining the subsidies for electrical vehicles and ambitious emission standards for combustion cars is important as transport related emissions are not likely to decrease much due to telecommuting.

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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.[16]

A.2 Calibration

The model is calibrated to the U.S. When U.S. metropolitan areas are ranked by population (cf. 2019 data from USCB (2020b)), then the median U.S. citizen lives in a metropolitan area of 1,625,000 inhabitants (Providence, RI). Assuming a realistic average of 2.5 persons and 1.3 earners per household (cf. BLS (2020)), this translates into 845,000 earners. We take this number as our model population "L", who are all individual commuters. We also use the factor $\frac{1.3}{2.5}$ to translate the U.S. median household income of 60,293$ to an income of $y_0 = 46,380\$$ per earner/commuter (cf. USCB (2020c)). The parameter α (cf. (1)) is the elasticity of consumption utility w.r.t. housing. With our assumption of Cobb-Douglas utility in consumption, α also captures the share of income spent on housing. We use the value of $\alpha = 0.24$, which Davis and Ortalo-Magné (2011)

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

obtain as a fairly robust result for the U.S. For determining the agricultural rent r_A, we follow the approach of Borck and Brueckner (2018) and Bertaud and Brueckner (2005): we take the average value of farm real estate of 3,160\$ per acre ($4,047m^2$) from USDA (2019) and convert it with an interest rate of 4 percent to an annual agricultural rent of $r_A = 0.03123\$/m^2$.

Our choice of $\theta = 0.0283$ in the housing production function (Section 2.3) implies that building an average U.S. new single-family home of $241.5m^2$ (2600 square feet, cf. NAHB, 2020) on an average single-family-home lot size of $1634m^2$ (17,590 square feet, cf. USCB, 2020a) incurs realistic costs of 250,000\$ when we again assume an interest rate of 4% to relate value and annual rent (cf. Liaison Ventures, 2020).

Empirical estimates for the value of travel time in commuting according to an overview by Small (2012), who refers, among others, to Small and Verhoef (2007) and Shires and de Jong (2009), are close to one-half of the gross hourly wage rate. For the U.S., one-half of the median hourly wage of 19.33\$ in 2019 (EPI, 2020) yields 9.67\$ for the value of one hour of commute travel. With the average duration of a commute in the U.S. of 27.6 minutes (Burd et al., 2021), an average commuting trip length of $19.7km$ (12.22 Miles; USDT, 2017) and 500 one-way trips between home and work per year, each meter of household distance to the CBD adds 0.01168 hours of commuting time per year. Multiplied with the value of travel time per hour above, we obtain 0.1129\$ per meter and year for the value of commuting time. We have to translate this Dollar value into utility units to obtain the annual disutility from commuting over another meter of distance ϵ in the utility function. To this end, we 1) observe the utility difference caused by an increase in exogenous income by one Dollar in the numerical equilibrium and 2) multiply the result with the Dollar value of travel time $0.1129\frac{\$}{m \cdot a}$. Thus, we obtain a value for ϵ, which plays a significant role for the geographical size of the city. 3) To make sure that the model yields realistic distances, we then choose the degree of decreasing returns to scale in building high β such that the model reproduces the average U.S. commuting trip length of $19.7km$ (12.22 Miles, cf. USDT, 2017) in the pre-policy equilibrium. The literature does not provide a clear empirical estimate of β and its choice is our last degree of freedom in the calibration. As this choice again slightly affects the marginal utility of one dollar of income in the model, steps 1)-3) are iterated until the values converge, finally yielding the values $\epsilon = 0.0257$ and $\beta = 0.826$. The value for β is well in the range of previous studies which use a calibrated monocentric city model.

Assuming an average vehicle lifetime of 10 years, our choice of $m_{tech} = 15\frac{\$}{MPG \cdot a}$ implies that a fuel efficiency improvement by one percent induces a total (not annual) increase in vehicle production costs of 46.36$. This is well in the range of 25 to 100$ that National Research Council (2015, p. 270) estimates. We set the intercept of our annualized vehicle cost curve to $v_{0,tech} = 1480$. With a slope of the linear vehicle cost curve of $15\frac{\$}{MPG \cdot a}$, an average fuel economy of 30.44 MPG in the pre-policy equilibrium and vehicle lifetime of 10 years, this is equivalent to an average vehicle purchasing cost of approx. 19,400$. This is very close to the average used-car value in 2017 (Ulitskaya, 2019). Finally, an average maintenance and repair cost per Mile driven of 0.0956$ (AAA, 2020) implies an annual (500 one-way trips) maintenance cost per meter of distance to the CBD of $t_{main} = 0.03\frac{\$}{m \cdot a}$.

B Sensitivity Analysis

In the calibration section above, we have explained the empirical justification for all model parameters. Here, we examine how sensitively our results react to changes in model parameters for which there is no clear estimation in the literature or for which there is a range of plausible values. Changing the technology cost of a marginal increase in fuel economy (cf. Section A.2 above) to half of or twice its value of $15\frac{\$}{(MPG*a)}$ in the reference calibration virtually does not affect the carbon emission reduction through telecommuting at all. The technology cost plays an important role for the choice of fuel economy and, therefore, for the marginal driving cost. But this effect is compensated by and adjustment of the parameter β in the housing production function in the calibration so that the average U.S. commuting distance of 12.2 Miles (cf. Section A.2) is reproduced. As long as the model fulfills this condition, the marginal technology cost does not play an important role.

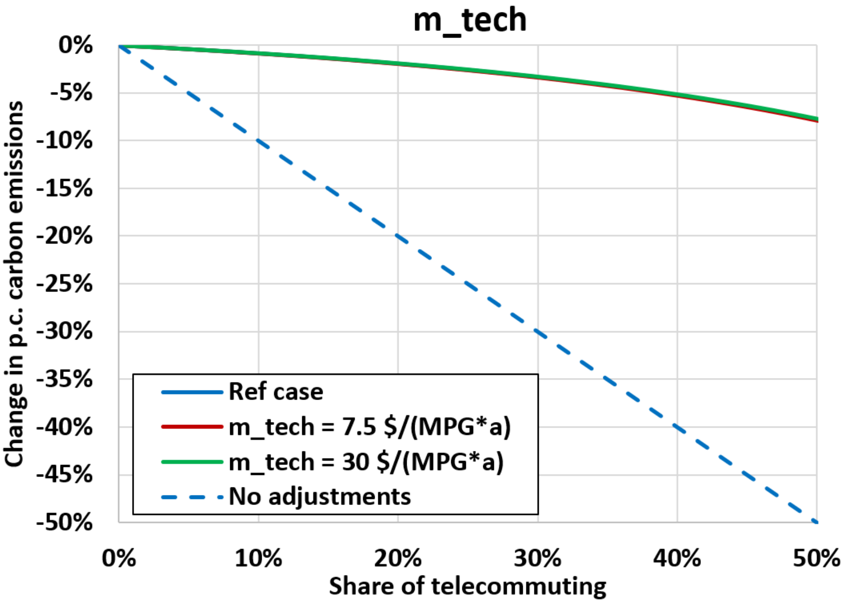

Figure B.8: Effect of the marginal technology cost m_{tech} on the overall offset of initial carbon emission reductions through telecommuting.

The parameter θ in the housing production function plays a role for how much housing is produced with a certain amount of land and housing capital and, therefore, for the citizens' utility level. Without any value of travel time, it would not at all affect the city

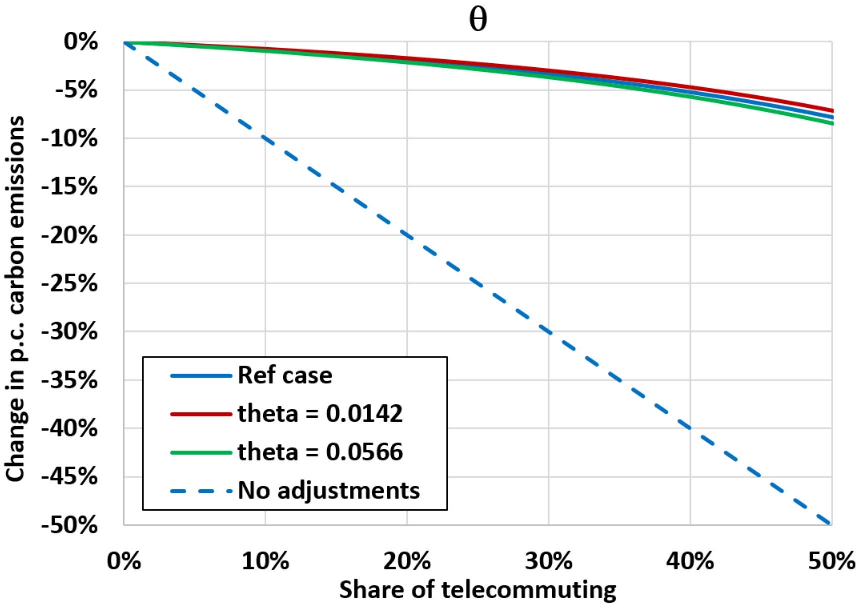

Figure B.9: Effect of the housing production parameter θ on the overall offset of initial carbon emission reductions through telecommuting.

geography and carbon emissions, but just scale the utility. As we are considering the value of travel time, this parameter does interact with the urban economic equilibrium. But, similarly to the influence of the marginal technology cost m_{tech}, an adjustment of β to match the average U.S. commuting distance counteracts most of the change in θ. Consequently, the simulation result is very robust to reducing its value to half or increasing it to double the initial value.

For the elasticity of consumption utility w.r.t. housing α there are good empirical estimates in the literature. With Cobb-Douglas utility (and also with our accounting for the value of travel time) it is also the share of available income spent on housing. If we, nevertheless, vary α within a very large range between 0.14 and 0.34, and adjust β to still reproduce the average commuting distance, the effect on the simulation result is only very modest. So, even with potentially large recent movements on the U.S. real estate market and in the income share households spend on housing, our result that most of the initial carbon emission reduction through telecommuting is offset is robust.

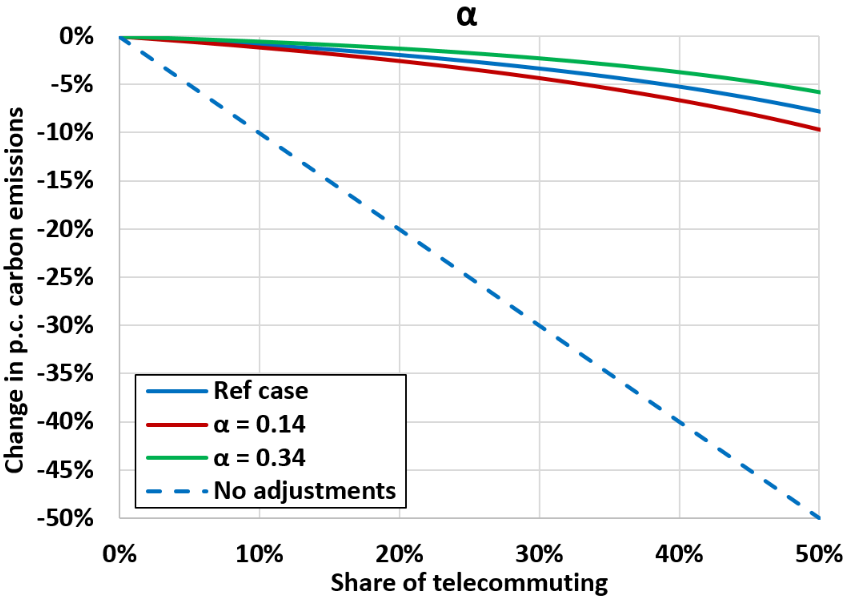

Figure B.10: Effect of the elasticity of consumption utility w.r.t. housing α on the overall offset of initial carbon emission reductions through telecommuting.