

# Policy Instrument Choice with Co-Benefits: The Case of Decarbonizing Transport

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## Abstract

This paper examines alternative regulatory strategies for decarbonizing private transportation in the presence of congestion co-benefits. To capture the behavioral responses of heterogeneous households to regulation and consistently value the monetary and time costs of commuting, we integrate (1) spatial household-level data on the location of residence and work, (2) road network and traffic data from Google, and (3) household survey data on expenditure and income into a dynamic general equilibrium model which features pre-existing fuel taxes and technology choice between internal combustion engine and electric vehicles. Ignoring co-benefits, an emissions intensity standard outperforms carbon pricing because it is a smaller implicit tax on factors of production. With co-benefits, carbon pricing yields aggregate efficiency gains. Moreover, only high-income households with short- to medium-distance commutes or low congestion exposure prefer a standard over carbon pricing. Under both policies, low-income households with long commutes incur the largest costs. Our analysis suggests that carbon pricing, along with targeted measures to alleviate the burden for low-income households, can be an efficient and equitable instrument for decarbonizing private transport.

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# 1 Introduction

Mitigating climate change will require deep carbon dioxide ( $\text{CO}_2$ ) emissions reductions from passenger and freight transport (IPCC, 2018). The transport sector accounts for about 20% of global emissions and currently is the fastest growing contributor to global climate emissions (International Transport Forum, 2017). The issue of policy instrument choice is of fundamental importance for the design of socially acceptable and effective environmental and climate regulation in the transport sector. So far, ex-ante policy assessments have, however, largely focused on evaluating different regulatory options based on their welfare impacts derived from market goods and services (Fullerton et al., 2001; Holland et al., 2009; Goulder et al., 2016; Abrell and Rausch, 2017). Such a narrow perspective can be particularly problematic—and can even lead to misguided policy recommendations—when the regulatory intervention is expected to create significant co-benefits. This is likely to be the case with climate-related regulation in the transport sector, which as a by-product of emission reduction can bring benefits such as reduced local air pollution, congestion, accidents, noise, and oil dependence (Santos et al., 2010).

This paper examines the aggregate and distributional welfare effects of two major regulatory strategies for decarbonizing private transportation in the presence of passenger vehicle externalities: a market-based approach using carbon pricing and a command-and-control approach based on technology or emissions intensity standards for private transportation. To study the behavioral responses of heterogeneous households to such regulation of private transportation and consistently measure welfare costs and co-benefits, we use an analytical and a numerical general equilibrium model. Our numerical model formalizes the key trade-offs of household-level decisions in responding to environmental regulation while satisfying cross-market and aggregate economy restrictions. It includes (1) technology choice between internal combustion engine (ICE) and advanced electric vehicles to account for the endogeneity of fuel economy, (2) derived demand for own-supplied transportation services based on income and prices, including those for other (non-transport) final consumption goods, (3) fiscal interactions with pre-existing fuel taxes, and (4) endogenous labor supply that requires commuting the time cost of which is in turn affected by traffic congestion.

Households heterogeneity reflects differences with respect to income, commuting distance, and exposure to congestion based on rich household data which combines information on the location of residence and work at the ZIP-code level, road network and traffic data from Google, and expenditure and income survey data. To our knowledge, this is the first paper in economics to analyze policy instrument choice for decarbonizing transport in a general equilibrium framework

which incorporates passenger vehicle externalities.

Motivated by the empirical observation that congestion is responsible for a large fraction of external costs of transport in most industrialized countries<sup>1</sup>, we focus on explicitly modelling co-benefits from traffic congestion. By linking labor supply decisions to the demand for commuting, we can provide a consistent valuation of time use as being affected by traffic delays, thus incorporating a congestion externality into a general equilibrium context.

We summarize the results as follows. Our main insight is that taking co-benefits from passenger vehicle externalities into account fundamentally changes the policy comparison between a market-based and a command-and-control approach to decarbonizing the transport sector—both in terms of aggregate welfare and distributional implications. Ignoring any co-benefits and just focusing on welfare derived from market goods, we find that an emissions standard for passenger vehicles outperforms carbon pricing as it distorts factor markets less. Hence, on aggregate and for virtually all household groups, command-and-control regulation is superior to a carbon pricing policy.

Taking co-benefits into account, we find that carbon pricing can yield sizeable aggregate welfare gains as compared to regulation through technology standards for passenger vehicles. The reason is that a carbon price exerts stronger incentives for lowering emissions through reductions in the transportation service demand which leads to less congestion. Compared to a situation where carbon emissions are priced, an emissions standard implicitly subsidizes the services of private transport with adverse consequences for traffic delays. Moreover, only high-income households with short- to medium-distance commutes or low congestion exposure prefer a standard over carbon pricing. Beyond the relative policy comparison, we find that under both policies low-income households with long commutes incur the largest costs.

Overall, our analysis suggests that carbon pricing, along with targeted measures to alleviate the burden for low-income households, can be an efficient and equitable instrument for decarbonizing private transport. While our empirical application focuses on the Swiss economy, we think that the main insights are applicable to and inform policymaking in other countries which seek to decarbonize a highly carbon-based private transport sector in light of a developed but congested road infrastructure.

This paper contributes to the existing literature in several ways. First, there is an abundant literature in environmental economics comparing market-based and command-and-control regulation. Under first-best conditions, a market-based

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<sup>1</sup>See, for example, Parry and Small (2005) for the for the US and UK context. The total external costs of transport in the EU in 2008 amount to 4% of the total GDP. The annual congestion cost of road transport delays amount to 1-2% of the total GDP (van Essen et al., 2011).

approach to regulation through direct emissions pricing (e.g., emissions trading or a tax) is cost-effective but typically viewed as politically highly contentious as the cost of regulation to a large extent fall on consumers whose demand for transportation services is highly inelastic (Goulder and Parry, 2008). Real-world command-and-control regulatory measures in transport (e.g., fuel efficiency standards such as CAFE in the US or emissions regulations in the EU) rather rely on performance or intensity standards which implicitly subsidize the consumer price of transportation services—thereby hiding the costs for consumers—but fail to achieve cost-effectiveness by undermining incentives for energy (demand) conservation and the substitution away from “dirty” inputs or technologies (Fullerton et al., 2001; Holland et al., 2009). Recent studies show that standards can outperform direct emissions pricing in terms of cost-effectiveness due to interaction with broader fiscal policy and pre-existing taxes (Goulder et al., 2016; Landis et al., 2019). We add by investigating the fundamental problem of policy instrument choice in the presence of co-benefits.

Second, we contribute to the literature on evaluating the distributional effects of climate change mitigation policies. While an established body of literature has examined the impacts of market-based approaches such as environmental taxes or emissions permit trading (Bovenberg et al., 2005; Bento et al., 2009; Rausch et al., 2010, 2011a; Sterner, 2012; Fullerton and Monti, 2013), assessments of the distributional impacts of command-and-control approaches to regulation are scarce (see Fullerton and Muehlegger, 2017, for an overview). Previous work, in the context of comparing renewable energy and technology standards focused on electricity and private transport (Rausch and Mowers, 2014; Landis et al., 2019), has ignored second-best effects due to pre-existing tax distortions and assumed a narrow welfare metric which abstracts from co-benefits. The social acceptance of public policy interventions in the transport sector importantly depend on how broadly measured costs and benefits are distributed among heterogeneous consumers.

The remainder of this paper is organized as follows. Section 2 presents a simple analytical framework to compare the effects of a carbon tax and an emissions standard for passenger vehicles. Section 3 describes the numerical model, data, and calibration. Section 4 presents our main simulation results. Section 5 concludes.

## 2 Standards or Taxes in presence of transport externalities?

The purpose of this section is to sharpen the reader's intuition about the trade-offs involved in choosing between a carbon tax and a fuel efficiency standard for reducing emissions in the transport sector. In the first part we look at aggregate national cost-effectiveness in a parsimonious theoretical general equilibrium model. In the second part we discuss the properties of households that determine how exposed they are to policy impacts and build some expectation about which channels determine if a household type is better or worse off under a carbon tax than under a fuel efficiency standard.

### 2.1 Aggregate cost-effectiveness

This section discusses a simple theoretical model that contains the important features that determine the trade-off in terms of cost-effectiveness between reducing emissions by taxing carbon or by regulating car efficiency by fuel efficiency standards. The model is kept close to the model by Goulder et al. (2016), and we will compare the model outcomes to their results and discuss the differences.

The representative household provides production factors labor  $L$  and capital  $K$  to two production sectors that produce a clean ( $X$ ) and a polluting ( $Y$ ) good and consumes their output. Consumption increases and factor provision decreases the households utility function

$$U(K, L, X, Y, C), \quad (1)$$

where  $U$  is continuous, quasi-concave, and twice differentiable and  $C$  is an additional negative externality of the production activity of sector  $Y$ .<sup>2</sup> Market good  $X$  and public good  $G$  are both produced from labor and capital according to the production function

$$X + G = F_X(L_X, K_X), \quad (2)$$

where  $L_X$  and  $K_X$  are labor demand and capital demand for this production process. Production of good  $Y$  is similar but additionally requires pollution  $Z$  (modeled as an input) and creates a negative externality  $C$  along with the valuable output  $Y$ :

$$Y = C = F_Y(L_Y, K_Y, Z). \quad (3)$$

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<sup>2</sup>If you care to call a shovel a shovel and not a gardening tool: By  $X$  we mean economic activity in general, by  $Y$  transportation services.  $C$  corresponds to congestion.

Market clearing conditions require

$$L = L_X + L_Y \quad (4)$$

$$K = K_X + K_Y \quad (5)$$

and budget balance conditions of households and the government are

$$X + p_Y Y = (1 - \tau_L)wL + (1 - \tau_K)rK + (\tau_Z - t_Z)Z + \tau_Y Y \quad (6)$$

$$G = t_Z Z + \tau_L wL + \tau_K rK, \quad (7)$$

where  $p_Y$  is the market price for good  $Y$ ,  $w$  is the wage rate, and  $r$  is the rental value of capital and where  $\tau_L$ ,  $\tau_K$ , and  $t_Z$  are pre-existing revenue raising taxes on labor, capital services, and the polluting good. The government implements policies to reduce pollution  $Z$  to a given level by setting the overall tax on pollution  $\tau_Z > t_Z$ . The revenue from the tax increment  $\tau_Z - t_Z$  is either returned to consumers in a lump-sum fashion (carbon tax;  $\tau_Y = 0$ ) or returned to the sector that generates  $Y$  through a negative tax  $\tau_Y < 0$  on output  $Y$  (efficiency standard).<sup>3</sup> Under these policies, government revenue  $G$  is to be kept constant, and for the efficiency standard,

$$(\tau_Z - t_Z)Z + \tau_Y Y = 0 \quad (8)$$

holds.

In the case of a fuel efficiency standard, perfect competition compels firms to supply good  $Y$  to the market until subsidized revenues  $p_Y - \tau_Y$  equal production costs. Cost minimization of producers together with perfect competition implies equality between marginal productivity and factor-product price ratios

$$\frac{\partial F_X}{\partial K_X} = r \quad \frac{\partial F_X}{\partial L_X} = w \quad (9)$$

$$\frac{\partial F_Y}{\partial K_Y} = \frac{r}{p_Y - \tau_Y} \quad \frac{\partial F_Y}{\partial L_Y} = \frac{w}{p_Y - \tau_Y} \quad \frac{\partial F_Y}{\partial Z} = \frac{\tau_Z}{p_Y - \tau_Y},$$

and utility maximization of consumers imply the first order conditions

$$\begin{aligned} \frac{\partial U}{\partial X} &= \lambda & \frac{\partial U}{\partial Y} &= p_Y \lambda \\ -\frac{\partial U}{\partial K} &= (1 - \tau_K)r\lambda & -\frac{\partial U}{\partial L} &= (1 - \tau_L)w\lambda, \end{aligned} \quad (10)$$

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<sup>3</sup>The equivalence of an efficiency standard with implicit carbon taxes and output subsidies have has been shown by Holland et al. (2009).

where  $\lambda$  is the marginal utility of income. Note that the marginal effect of  $C$  (as well as  $G$ ) on utility is regarded as given by single consumers and thus does not enter the first order conditions of the decentralized equilibrium. While the level of  $C$  is determined by  $Y$ , government spending  $G$  is kept constant and thus not considered in our analysis of consumer utility.

For given government policies  $\tau_Z$ ,  $\tau_Y$ ,  $\tau_K$ , and  $\tau_L$ , equations (2)–(6) and (9)–(10) constitute a general equilibrium model of the decentralized market equilibrium. The government sets its policies under the budget constraint (7) and sets  $\tau_y$  according to (8).

### Derivation of marginal abatement cost

The solutions to the aforescribed model of the market equilibrium implicitly define the market outcome (traded quantities and prices) as functions of the tax rates chosen by the government. In the following, partial derivatives denote derivatives of these functions with respect to the four tax rates.

In order to meet emission targets, the government will increase the cost of polluting by raising  $\tau_Z$ . Depending on the policy version,  $\tau_Y$  is kept 0 or it is set to compensate carbon tax expenditure  $(\tau_Z - t_Z)Z$  according to (8). The only motive for changing  $\tau_K$  and  $\tau_L$  is to balance government budget according to (7). We assume that with each unit that the revenue  $t_Z Z$  from pre-existing taxation decreases, a share  $\alpha_K$  of that loss is recovered by increasing the revenue  $\tau_K r K$  from capital taxation, and the remaining  $\alpha_L = 1 - \alpha_K$  is compensated by increasing revenue from labor taxation. The total derivatives  $\frac{d}{d\tau_Z}$  in the following assume that  $\tau_Y$ ,  $\tau_L$ , and  $\tau_K$  change according to the definitions of  $\alpha_K$  and  $\alpha_L$  as well as the constraints faced by the government.

The derivations of the following expressions for marginal cost of abatement in case of the carbon tax and the efficiency standard are given in Appendix A. The expressions make use of the following definitions: The marginal disutility of  $C$

$$\mu_C := -\frac{1}{\lambda} \frac{\partial U}{\partial C},$$

the (marginal) income tax base eroding effects of increasing taxes  $\tau_Z$  and  $\tau_Y$

$$\begin{aligned}\theta_Z &:= \tau_K \frac{\partial r K}{\partial \tau_Z} + \tau_L \frac{\partial w L}{\partial \tau_Z}, \\ \theta_Y &:= \tau_K \frac{\partial r K}{\partial \tau_Y} + \tau_L \frac{\partial w L}{\partial \tau_Y},\end{aligned}$$

the “non-environmental marginal cost of public funds (MCPF)” of capital and labor

tax<sup>4</sup>

$$\eta_K := \frac{rK}{rK + \tau_K \frac{\partial rK}{\partial \tau_K} + \tau_L \frac{\partial wL}{\partial \tau_K}},$$

$$\eta_L := \frac{wL}{wL + \tau_K \frac{\partial rK}{\partial \tau_L} + \tau_L \frac{\partial wL}{\partial \tau_L}},$$

and the weighted average of the MCPFS

$$\eta_R := \alpha_K \eta_K + \alpha_L \eta_L.$$

Note, that we assume a utility function  $U$  such that  $\mu_C > 0$  and expect that  $\theta_Z$  and  $\theta_Y$  will both be negative. Existing literature on MCPF suggests that we should expect that  $\eta_K$ ,  $\eta_L$ , and  $\eta_R$  are all bigger than 1.

In the case of the carbon tax, the marginal abatement cost is

$$\frac{\frac{1}{\lambda} \frac{dU}{d\tau_Z}}{\frac{dZ}{d\tau_Z}} = \tau_Z - \mu_C \frac{\frac{dY}{d\tau_Z}}{\frac{dZ}{d\tau_Z}} + (\eta_R - 1) t_Z + \eta_R \frac{\theta_Z}{\frac{dZ}{d\tau_Z}}. \quad (11)$$

This expression of marginal cost can be divided into direct policy cost (first term), co-benefits from reducing  $Y$  (second term), revenue compensation term (third term), and other, general equilibrium effects (last term).

As the carbon tax is bound to decrease  $Z$ ,  $Y$ , and  $rK + wL$ , all terms except the co-benefit one are positive and add to overall marginal cost of abatement. Note that if carbon tax revenues were to be recycled via labor and capital tax reductions rather than lump-sum transfers, the now costly revenue compensation term (costly compensation of revenue lost through reduction in tax base of pre-existing taxes) would turn into a cost-reducing revenue recycling term (by a reduction in distortive taxation of labor and capital in proportion to revenue gains from carbon taxation; see Goulder et al., 2016).

For the fuel efficiency standard, marginal abatement costs are found to be

$$\frac{\frac{1}{\lambda} \frac{dU}{d\tau_Z}}{\frac{dZ}{d\tau_Z}} = \tau_Z + (\tau_Y - \mu_C) \frac{\frac{dY}{d\tau_Z}}{\frac{dZ}{d\tau_Z}} + (\eta_R - 1) t_Z + \eta_R \frac{\theta_Z + \frac{d\tau_Y}{d\tau_Z} \theta_Y}{\frac{dZ}{d\tau_Z}}. \quad (12)$$

Again, we find terms for direct policy cost, co-benefits, the revenue compensation term, and other, general equilibrium effects (last term) in this expression. The term for direct costs is  $\tau_Z + \tau_Y \frac{dY}{d\tau_Z} / \frac{dZ}{d\tau_Z}$ . The second (cost reducing) part of this

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<sup>4</sup>The numerators of  $\eta_K$  and  $\eta_L$  are the cost to the representative agent of a marginal increase in the tax, while the denominators are the marginal revenue from that tax increase in absence of a carbon tax.



arises from the reductions in activity  $Y$  which reduce the distortion caused by the (negative) tax  $\tau_Y$ . Other general equilibrium effects captured by the last term, in the efficiency standard case, are not only driven by changes in the income tax base from carbon tax increases (presumably negative) but also by (presumably positive) changes from further reducing the non-positive tax rate  $\tau_Y$ .

### Comparing the tax with the standard

In order to compare the magnitude of (11) with (12) one has to both account for terms that are only present in one or the other expression and compare the magnitude of terms that appear in both. In particular, the marginal cost of the standard contains the direct-cost reducing term proportional to  $\tau_Y$ , but  $\tau_Z$  at a given level of abatement will be larger such that the total direct cost of the tax is smaller than that of the efficiency standard.<sup>5</sup> Similarly, the co-benefit term is larger for the tax due to the fact that the standard will cause the smaller reduction of activity  $Y$  per reduction in pollution  $Z$ . The comparison of revenue compensating term depends on the comparison of  $\eta_R$ . Initially (at small values of  $\tau_Z - t_Z$  and thus  $\tau_Y$ ),  $\eta_R$  will be the same for both policies, but may differ as policy stringency progresses.  $\frac{dZ}{d\tau_Z}$ , finally, is smaller in the case of the efficiency standard, thus amplifying general equilibrium effects, but those are less costly due to the cost reducing term  $\frac{d\tau_Y}{d\tau_Z}\theta_Y$ .

For small abatement levels (and thus,  $\tau_Z - t_Z \ll t_Z$ ), direct cost of both policies will be close to  $t_Z$ . As the revenue compensation term is initially the same for both policies as well, the cost comparison between the two policies rests solely on the differences in co-benefits and in general equilibrium terms. It is clear that co-benefits (proportional to  $\frac{dY}{d\tau_Z} / \frac{dZ}{d\tau_Z}$ ) favor the carbon tax (it gives the stronger incentive for reducing  $Y$ ), while the general equilibrium effects can go both ways as far as we can tell. Note, however, that if efficient abatement relies on substituting away from pollution in  $Y$ -production more than on reducing use of  $Y$ , both the efficiency standard's reduction in the cost of the general equilibrium term gets more weight and its disadvantage in terms of co-benefits are smaller.

As the abatement target is increased,  $\tau_Z$  and  $\tau_Y$  diverge between the two policies and direct costs of the efficiency standard increase faster than that of the carbon tax. The other terms do not display any features that make it necessary that differences between policies in these terms increase in proportion to  $\tau_Z$ , and thus we would expect that the differences in direct cost eventually dominate the comparison of the two in favor of the carbon tax. Like Goulder et al. (2016) before us (but in a different sector and under different regulatory circumstances), we find in a theoretical model that the efficiency standard *may* have an edge

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<sup>5</sup>The direct cost of the efficiency standard is higher than that of the tax because the standard results in lower market prize of  $Y$  and thus inefficiently high demand for it.

over the carbon tax for low abatement levels, but the carbon tax will likely be the more cost-efficient policy if abatement levels become more stringent.

The fact that our model has been chosen very similarly to Goulder et al.'s theoretical model makes the results of the two directly comparable. On the one hand side, they do not include pre-existing taxes on the polluting good or co-benefits of reducing activity  $Y$ . Thus the corresponding terms (co-benefits and revenue compensation) in the comparison of (11) with (12) do not appear. The loss of the co-benefits term would come at a disadvantage to the carbon tax. On the other hand side, Goulder et al. assume that carbon tax revenues are recycled. The latter leads to an additional (cost reducing) component in the revenue compensation term of the marginal abatement cost with a carbon tax and the above comparison in their case reads

$$\begin{aligned}
& \tau_Z + (\eta_R - 1) \left( \frac{Z + \tau_Z \frac{dZ}{d\tau_Z}}{\frac{dZ}{d\tau_Z}} \right) + \eta_R \frac{\theta_Z}{\frac{dZ}{d\tau_Z}} \\
& \stackrel{?}{\leq} \\
& \tau_Z + \tau_Y \frac{\frac{dY}{d\tau_Z}}{\frac{dZ}{d\tau_Z}} + \eta_R \frac{\theta_Z + \frac{d\tau_Y}{d\tau_Z} \theta_Y}{\frac{dZ}{d\tau_Z}}.
\end{aligned} \tag{13}$$

In summary, only the additional co-benefits of reducing  $Y$  and the decision not to use carbon tax revenues for reducing factor taxes introduce new terms with (opposing) effects on the cost comparison between the efficiency standard and the carbon tax. The introduction of pre-existing taxes introduces a revenue compensating component that is the same for both policies. But it also increases the common terms  $\tau_Z$  and  $(\eta_R - 1)t_Z$  thus making the differences between standards and taxes appear less important relative to total costs.

## 2.2 Distribution of policy cost

After the discussion of cost-effectiveness (based on aggregate national policy cost), we lay out the different household properties that determine if a household of a given type is bound to carry a higher or lower than average part of the burden (in terms of changes in spending power relative to a baseline). In order to build the intuition for understanding the results of the numerical model, we anticipate its structure rather than corresponding to the previously discussed theoretical model.

For discussing households' exposure to policy cost, the partition of effects into those on the expenditure (uses) side and those on the income (sources) side has been found to be instructive (Rausch et al., 2011b). We modify this approach

to decomposing welfare effects by differentiating between impacts on the *budget* with which household utility is achieved (this budget values both time and money and monetary income is reduced by savings expenditures) and *expenditure* side effects that reflect how prices of and demand for inputs to household utility (including leisure) change.

In the following we give an account of how household spending and income patterns determine to what extent households of different characteristics are impacted by policy interventions. We introduce and use the classification of household types that appear in the numerical model in the remainder of the paper. The households in the numerical model are differentiated according to income (low income ( $I_{LO}$ ), medium income ( $I_{MED}$ ), high income ( $I_{HI}$ )), commuting distances (short distance ( $D_{SHORT}$ ), medium distance ( $D_{MED}$ ), long distance ( $D_{LONG}$ )), and exposure to congestion (low congestion ( $C_{LO}$ ), high congestion ( $C_{HI}$ )).

### **Budget side effects**

On the income side, policies will change rates of remuneration of production factors and households that derive a larger share of income from a given factor will be affected more by these changes. In any given time period, all households are endowed with fix quantities of time and capital. While capital is rented to firms at the market rental rate, time is either consumed privately (as leisure) or offered on the labor market in exchange for wage earnings. Observing market wage rates and consumer prices, households make a labor–leisure allocation decision for their time endowment such that their welfare is maximized. In a model with commuting and congestion, labor supply is linked to additional cost in terms of leisure time (time used for commutes), which depends on traffic levels and levels of labor supply. Changes in market wage rates thus change the value of the time endowment, and the useful value of the time endowment is then further modified by the time spent in traffic.

Besides the value of time and capital rents, households get transfers from the government. These are composed of pre-existing transfers and recycling of carbon tax revenue. The relative importance of changes in wages, rental rates, transfers, and congestion for given household classes depends on the relative size of endowments, transfer entitlements, and exposure to congestion.

In addition to these components of total income, savings expenditures reduce the budget for spending on welfare. Our model assumes that households pursue a constant savings rate, and thus percentage changes in monetary incomes result in the same percentage changes in savings outlays. Equal percentage changes in monetary income translate into larger changes of welfare budgets for households with smaller shares of leisure in their full value of endowments.

The left panel of Figure 1 shows how these different components make up

the budget for utility for different household types. Most notably, high income households have higher savings rates and higher shares of labor income.<sup>6</sup> The main difference between households with different exposure to congestion lies in their shares of time and capital rents in total income. Households that live in areas with higher occurrence of traffic jams (urban areas) derive a higher share of their income from labor.

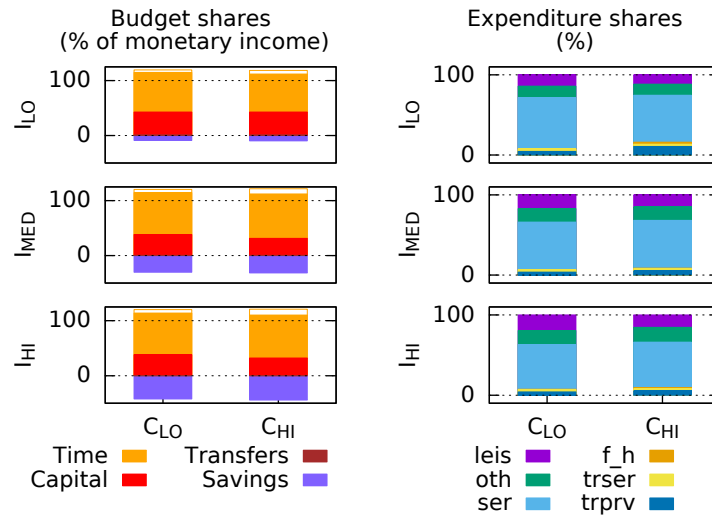


Figure 1: Shares of different components in Swiss households' utility budget and expenditures. Budget shares are compared to monetary income: Value of time beyond 100 percent is leisure time (the empty boxes represent useless time spent in traffic, filled boxes represent useful time) and after subtracting savings, the welfare budget comes to stand at less than 100 percent.

### Expenditure side effects

On the expenditure side, changes in national price levels interact with household expenditure shares. If policies increase prices of certain goods, those households that have a high expenditure share of those goods are generally affected the most.

On the expenditure side, changes in consumer goods prices affect those households most that spend the largest share of their outlays on those goods. In the case of climate policy, fossil fuels (motor and heating fuels) and energy intensive goods such as transportation services become more expensive. Relative to the overall consumer welfare cost index, the goods that are least energy inten-

<sup>6</sup>This reflects the fact that households with heads that are of working age are more prevalent in the higher income quintiles.

sive such as non-transport services become cheaper benefiting those households with a large expenditure share for those goods.

In our numerical model, households also consider leisure consumption to evaluate their welfare and changes in the shadow value of leisure affect their purchasing power as well. Again, households that have high baseline values of leisure consumption compared to their expenditure on commercial goods are affected more by changes in the value of leisure.

The right panel of Figure 1 shows how the utility budget is spent on different inputs to utility by different household types. Spending on heating fuels and private transport is higher for households in congestion exposed areas across income levels, but the difference is most striking for low income households. Spending on non-transport services is higher for low income households which is compensated by spending on leisure (LEIS) and other consumption.

### **Comparing the tax with the standard**

We posit that the switch from a tax to a standard will have four main effects: (i) Remuneration of production factors increases, (ii) recycling of tax revenues to households decreases, (iii) costs of private transportation decrease, and (iv) congestion increases (through both increases in labor supply and reactions to less costly private transportation). For the first point (i) it is at this point unclear if it will affect one type of households more than others. This will depend on which production factors increase in value in particular. The recycling of carbon tax revenues (ii) in Switzerland is in the form of per-capita lump-sum transfers. Such per-capita transfers have the bigger effect on the smaller budgets of low-income households and their reduction under a standard are a disadvantage that hits low-income households harder than it does high-income households. The reduction in the cost of private transportation (iii) that comes from a standard benefits the households that are exposed to congestion and in particular the low-income households in this group (compare expenditure shares for private transportation (TRPRV) in right hand panel of Figure 1). The increases in congestion (iv) on the other hand hurt the congestion exposed (but not the low-income subgroup in particular).

To summarize, the four main effects of a switch from a carbon tax to a fuel efficiency standard impact different households in a range of different patterns and it is unclear at this point if households of a certain income group are at a disadvantage. It seems likely though, that congestion exposed households will not like the increased traffic from the switch to the standard, but within this group, low-income households are likely to profit from cost reductions in their substantial expenditures for private transportation.

### 3 Numerical implementation of the Swiss case

In order to analyze the trade-off between carbon taxes and CO<sub>2</sub> emission standard (CES) in more detail, we employ a computable general equilibrium (CGE) model of the Swiss economy. The model includes the labor–leisure trade-off and explicitly models the commuting requirement linked to labor provision. The time cost of commuting and leisure trips is influenced by congestion and high levels of commuting make commuting itself and thus labor supply more expensive. These effects only exist implicitly in the above theoretical model where the cost of labor supply is given by  $\frac{\partial U}{\partial L}$  and the disutility of congestion by  $\frac{\partial U}{\partial C}$ . The numerical model also keeps track of technological development over time by explicitly modeling the availability of plug-in hybrid electric vehicleless (PHEVs) and battery electric vehicleless (BEVs) on the car market. It thus considers both policy induced (endogenous) and time dependent exogenous changes in fuel intensity of transport and thus give a realistic account of the term  $\frac{dY}{d\tau_Z} / \frac{\partial Z}{\partial \tau_Z}$  over time. In order to indicate what the distribution of policy costs across households of different policy options will be, the model considers eighteen household classes characterized by income levels, commuting distance and exposure to congestion. In the following, we describe the model, the data used for its calibration and the analyzed policy scenarios in more detail.

#### Model

We employ the CEPE model, a recursive dynamic CGE model of the global economy with a focus on Switzerland. The following gives an overview over the structure of the model and in particular of the modeling of leisure time, commuting, and congestion. A more formal description of this is given in Appendix B.

A CGE model constitutes a system of equations that comprises market clearing conditions for all commodities in the model, zero-profit conditions for all economic activities, and income balance equations for all economic agents (usually households and regional governments). In a recursive dynamic model all these conditions are satisfied for each time period, investment decisions by households (who own capital stocks) are made based on current information about prices and capital rents, and capital stocks grow according to a discrete-time law of motion taking into account depreciation of existing stocks and new investment.

**PRODUCTION TECHNOLOGIES AND FIRM BEHAVIOR**—In each industry, gross output is produced using primary inputs of labor and capital together with intermediate inputs that are composed of domestically produced goods and imported goods. The model employs constant elasticity of substitution (CES) production functions to characterize the substitutability between inputs of production. Given input prices (gross of taxes and subsidies), firms minimize production

costs subject to physical technology constraints. Capital (except car stocks) and labor are assumed to be mobile across regional industries but not across regions' borders. All industries using mobile production factors are characterized by constant returns to scale. Firms operate in perfectly competitive markets selling their products at a price equal to marginal costs (this is enforced by the zero-profit conditions).

The supply of household type specific private transport services is modeled as regular nested production process that rents capital (cars) from households and sells the services of private transportation back to households. For each drive train technology (namely ICE, PHEV, and BEV) new and old vintages of cars provide the technology specific transport services that are combined in a CES production function to yield total transport services (see Figure 2; for more detail, see Appendix B).

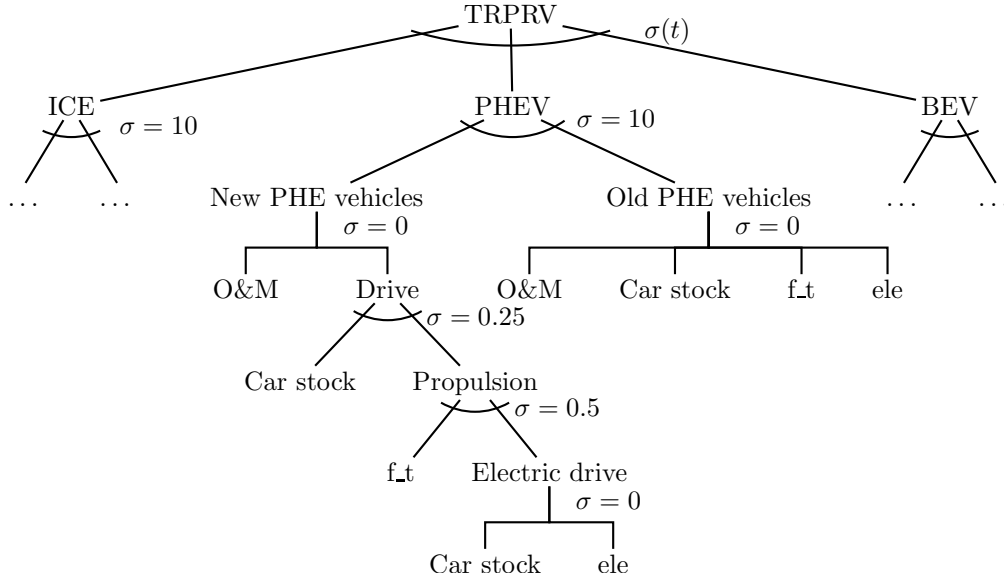


Figure 2: Nesting structure of production of household type specific private transportation services from three technologies ICE, PHEV, and BEV. Technologies differ in value shares (some are zero) in different nests, but not in nesting structure. Operation and maintenance (“O&M”) denotes expenditures related to operating a vehicle besides costs of fuel and energy and besides implicit rent payments on the car stock.

**HETEROGENEOUS HOUSEHOLDS**—The model represents final household consumption by 18 representative households that are differentiated by income, commuting distance, and exposure to congestion. Each household is endowed with an initial stock of capital and by a predefined amount of effective time for each model period. In each period, households observe their capital stock and rent

it out to firms. With regard to the time endowment, households face the trade-off between consuming time as leisure and supplying it in the form of labor to firms in the various economic sectors. Labor supply of each household type requires commuting in fixed proportions (depicted in Figure 3). Commutes can be provided through public transport services (TRPUB; provided through a standard constant-returns-to-scale production activity) or through private transport (TRPRV; provided using technology specific car stocks according to production structure depicted in Figure 2). The model assumes both transport modes to require additional leisure time but only time requirements of private transport are subject to congestion.

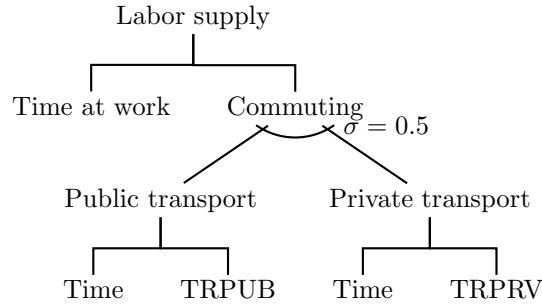


Figure 3: Nesting structure of labor supply and commuting demand. Time requirement for private transportation is subject to congestion.

Together with transfers from the government, wage earnings and rents on capital make up the monetary income of households which is complemented by the remaining leisure time. Monetary income, by virtue of constant and household type specific savings rates, determines the amount of investments in general-purpose capital and car stocks that households make. By observing rental rates on general purpose capital and car stocks, households decide on stock specific investment levels in order to equalize the rental rates. Changes in investments into cars change household-type-specific car stocks, changes in general-purpose investment levels change national capital stocks, the relative changes in which are applied to household type specific capital stocks.<sup>7</sup>

Monetary income minus investments and the value of the remaining time endowment then make up households' budgets for affording their respective levels of utility. Household utility in the model is generated according to a nested CES utility function with leisure, own generated private transportation services

<sup>7</sup>Cars are thus interpreted as rather short lived durable goods which are used by the owners in the same phase of life when they are bought and are household type specific. Earnings from general-purpose capital, on the other hand, reflect rents on long-term savings that are made across different phases of life through which individuals may "move" from one household type to another.



and other commodities from the domestic market as inputs. Utility functions of household types differ in the unit demands of different goods that they generate at benchmark year market prices. Like production sectors, households take prices of commodities as given and adjust the consumption of different goods so as to minimize unit cost of utility.

CONGESTION—Households' demand for transport services are added up to total traffic demand separately for the two levels of exposure to congestion (emulating a spatial differentiation of households) and separately for commuting and leisure-related demand for mobility (emulating a temporal differentiation of demand for transport services). Congestion corresponding to the four traffic levels  $t_{cm,c}$  ( $cm \in \{\text{commute, non-commute}\}$ ,  $c \in \{\text{low, high}\}$ ) is computed according to the congestion function

$$c(t_{cm,c}) = 0.0403 \cdot t_{cm,c}^2 + 0.0597 \cdot t_{cm,c}^5 \quad (14)$$

and denotes the share of benchmark travel time that could be saved if traffic where in free flow. In the benchmark year, traffic levels in areas with low and high exposure to congestion ( $t_{cm,\text{low}}$  and  $t_{cm,\text{high}}$ ) are normalized to 0.561 and 1, such that congestion levels in the two areas are  $c(t_{cm,\text{low}}) = 0.016$  and  $c(t_{cm,\text{high}}) = 0.1$ .

GOVERNMENT ACTIVITY—One government entity per region represents government activities as well as part of the social security system. The government collects taxes to finance transfers and the provision of a public good. Besides value-added taxes, income taxes, corporate profit taxes and social security contributions, the model features industry-specific output taxes and subsidies as well as import and export levies. The public good is a composite of commodities purchased at market prices. The economic impact assessment of different policy scenarios always involves revenue-neutral tax reforms in order to keep the provision of the public good constant. This allows us to provide a meaningful welfare comparison without the need to trade off private and government (public) consumption. Revenue neutrality is achieved by endogenously setting aggregate amounts of lump-sum transfers between the government and households. The lump-sum transfers are allocated among households in proportion to base-year household consumption.

INTERNATIONAL TRADE AND MODEL CLOSURE—Domestic and imported varieties of the same good are differentiated following the Armington (1969) assumption (i.e., for each commodity, its total market supply is a CES composite of a domestically produced variety and an imported variety; the commodity specific elasticity of substitution (EOS) are typically in the order of 2–3 but reach 5.2 and 12.8 for crude oil and gas). The imported variety is made up of a CES composite of imports from different regions and the EOS are typically around twice as big as the EOS between the domestic and the imported variety for the same commodity.

Switzerland trades with the other two regions in the model that are the EU and the Rest of the World. Switzerland holds its balance-of-payments (measured in foreign exchange) constant across policy scenarios and the exchange rate adjusts endogenously to reflect changes in terms of trade.

## Data

This study makes use of a comprehensive data set which combines various data sources. This section describes how these data sources have been combined to calibrate the different parts of the models.

**NATIONAL ECONOMIC ACCOUNTS AND ENERGY DATA**—We calibrate our model of the Swiss economy to the 2011 base year data of version 9 of the Global Trade Analysis Project (Aguiar et al., 2016). The data base provides information about value flows between industries, households and government agents of different countries. These value flows quantify for each industry the inputs of intermediate goods and factors to produce final goods. In addition to this IO data, the tables include taxes payments and physical flows of energy and the associated greenhouse gas emissions. For the purpose of our study, we aggregate the original IO-table into 23 sectors producing sector-specific commodities. Table 1 provides an overview of our commodity aggregation.

**TRANSPORT DEMAND FROM THE MICROCENSUS**—The microcensus on mobility and transport 2015 (Bundesamt für Statistik / Bundesamt für Raumentwicklung, 2017) provides us with data on how transport is distributed between work and non-work related travel for different income groups. We assume either (i) that all households within an income class (different commuting distances and congestion exposures) have the same non-commuting transport demand (in terms of absolute expenditures) or (ii) that they have the same share of commuting transport demand in overall transport demand.

**HOUSEHOLD DATA FROM THE HABE SURVEY**—The Swiss Household Budget Survey “Haushaltsbudgeterhebung” (HABE) is a representative survey of the permanent resident population of Swiss households which is conducted on an annual basis by the Swiss Federal Statistical Office (BFS). For each household in the sample it provides detailed information about expenditures for various consumption goods and different types of income (wages, capital rents, or government transfers). Additionally, the HABE data provides detailed socio-economic information for each household. Each year, about 3’000 households are interviewed. To increase the sample size, our underlying data set aggregates three waves of survey data from the consecutive years 2009–2011 (BFS, 2012a, 2012b, and 2013) using aggregation weights published by BFS (2014). From the HABE data, we use in our model for each household group the level of expenditures by good and income by source.

Table 1: Overview of model resolution: sectors, electricity generation technologies, and household groups.

|                                           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|-------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Sectors ( $i \in I$ )                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| <i>Non-energy</i>                         | Agricultural products (agr), Energy intensive sectors (eit),<br>Vehicles, transport equipment (veh), Others (mac),<br>Services (ser), Other transport (otp), Air transport (atp),<br>Water transport (wtp),                                                                                                                                                                                                                                                                          |
| <i>Energy supply<br/>&amp; conversion</i> | Heating fuels (f_h), Motor fuels (f_t), Crude oil (oil),<br>Coal (col), Natural gas (gas),<br>Transmission and distribution (tnd),<br>Nuclear energy base load (nub), Coal energy base load (cob),<br>Other energy base load (otb), Wind energy base load (wib),<br>Gas energy base load (gab), Gas energy peak load (gap),<br>Hydropower base load (hyb), Hydropower peak load (hyp),<br>Oil energy base load (oib), Oil energy peak load (oip),<br>Solar energy peak load (sop),   |
| <i>Final demand</i>                       | Private consumption by 18 representative households,<br>government consumption, investment demand                                                                                                                                                                                                                                                                                                                                                                                    |
| Household groups                          | $I_{LO}D_{SHORT}C_{HI}$ , $I_{LO}D_{SHORT}C_{LO}$ , $I_{LO}D_{MED}C_{HI}$ , $I_{LO}D_{MED}C_{LO}$ ,<br>$I_{LO}D_{LONG}C_{HI}$ , $I_{LO}D_{LONG}C_{LO}$ ,<br>$I_{MED}D_{SHORT}C_{HI}$ , $I_{MED}D_{SHORT}C_{LO}$ , $I_{MED}D_{MED}C_{HI}$ , $I_{MED}D_{MED}C_{LO}$ ,<br>$I_{MED}D_{LONG}C_{HI}$ , $I_{MED}D_{LONG}C_{LO}$ ,<br>$I_{HI}D_{SHORT}C_{HI}$ , $I_{HI}D_{SHORT}C_{LO}$ , $I_{HI}D_{MED}C_{HI}$ , $I_{HI}D_{MED}C_{LO}$ ,<br>$I_{HI}D_{LONG}C_{HI}$ , $I_{HI}D_{LONG}C_{LO}$ |

HOUSEHOLD DATA FROM THE SHEDS SURVEY—The Swiss Household Energy Demand Survey (SHEDS) is a regularly conducted survey with a focus on energy related household behavior (Weber et al., 2017). It includes observations about socio-economic indicators such as household income and composition as well as postal codes of residence and work place and a rich set of information about energy use and appliance ownership. We take advantage of the postal-code-level information about place of residence and work place and used the application programming interface of Google Maps to get estimates of both the length of commuting trips as well as exposure to congestion during rush hour on these trips.

INTEGRATING HABE AND SHEDS SURVEY DATA AND AGGREGATION—We use the statistical matching method Random Distance Hot Deck with common variables income, spending on public transportation and possession of bicycles (including e-bikes) to add the data on car ownership and commuting habits from the best fitting household group in SHEDS to each of the households in HABE.<sup>8</sup> Thus,

<sup>8</sup>For this, we relied on the package StatMatch in the statistical programming language R

households in the combined data feature both income and expenditure data on the one hand and commuting distance and chosen transport mode as well as fuel efficiency of cars on the other. For the purpose of the model, we aggregate households into 18 representative households (see also Table 1) that are differentiated along the three dimensions income (we differentiate three income levels  $I_{LO}$ ,  $I_{MED}$ , and  $I_{HI}$ ), commuting distances (differentiation  $D_{SHORT}$ ,  $D_{MED}$ , and  $D_{LONG}$ ), and exposure to congestion (differentiating  $C_{LO}$  and  $C_{HI}$ ).

**INTEGRATING HOUSEHOLD SURVEY DATA AND IO DATA**—Integrating the micro-household survey data in the macroeconomic model requires that national aggregates of demands and incomes by representative households and aggregate information on household consumption and revenue according to the national accounts match. National consumption in terms of COICOP (Classification of Individual Consumption According to Purpose) categories according to the IO data was imposed on the household data by scaling household consumption by the appropriate factor for each consumption category. Similarly, we distributed national income from government transfers and investment spendings across representative households, according to the survey data. Wages and capital rents (that is, income from production factors), finally, were allocated to the representative households such that the wage share in factor income is as close to the wage share in factor income according to survey data with the constraint that factor income, together with government transfers, has to add up to representative household's spending on consumption and savings.

**CALIBRATION OF THE CONGESTION CURVE**—We make plausible assumptions about the ratio of labor time spent on commuting. We assume people to spend 8 hours at work per working day and use the fact that Swiss commuters, on average, spend 30 minutes commuting in each direction. Therefore, households spend leisure time of one eighth of their working time on commuting. But how much of that time is spent in slow traffic and how will this congestion intensity change if traffic on the roads increases? We follow (Suter et al., 2002) and derive the following stylized facts for traffic levels in the congestion-exposed area from their tables 3-6 and 3-9: commuting time without congestion would be 10 percent smaller, and if traffic increases 1.4-fold, time spent in traffic due to congestion quadruples. We reproduce these stylized facts with a congestion function  $c(t) = at^2 + bt^e$  mapping traffic levels  $t$  to congestion measured as share of time spent in traffic due to congestion. We choose the exponent  $e$  as the smallest possible integer that gives the function  $c(t)$  sufficient curvature to reach both  $c(1) = 0.1$  and  $c(1.4) = 0.4$  and find  $e = 5$ ,  $a = 0.0403$ , and  $b = 0.0597$ .<sup>9</sup>

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(D'Orazio, 2016).

<sup>9</sup>The additional requirements that  $c(0) = 0$  and  $c'(0) = 0$  are guaranteed by the omission of a constant term and a linear coefficient.

## Scenarios

While the base year calibration of our model is given by historical data, the analysis of stringent climate policy is most plausibly made in the intermediate future (we decided to consider the period up to 2050) and likely socio-economic developments until that future point in time must be anticipated.

Our business as usual (BAU) scenario assumes that currently decided carbon taxes are continued and that population growth, gross domestic product (GDP), autonomous energy efficiency improvements (AEEI), transport demand and sales shares of different technologies (viz. ICE, PHEV, and BEV) in vehicle sales develop according to Table 2. Road capacity is assumed to be stagnating at current levels. The model endogenously determines congestion and the resulting effects on transport demand.

Table 2: BAU assumptions about socio-economic developments in the Swiss economy up to 2050.

|                                                            | 2020 | 2030 | 2040 | 2050 |
|------------------------------------------------------------|------|------|------|------|
| GDP (2010 = 1)                                             | 1.20 | 1.38 | 1.56 | 1.66 |
| Population (million)                                       | 8.68 | 9.43 | 9.97 | 10.3 |
| AEEI electricity (2010 = 1)                                | 1.14 | 1.28 | 1.39 | 1.47 |
| AEEI other energy (2010 = 1)                               | 1.19 | 1.47 | 1.75 | 2.03 |
| PHEV sales share (percent)                                 | 2.40 | 13.5 | 20.4 | 21.3 |
| BEV sales share (percent)                                  | 4.22 | 37.7 | 56.3 | 60.7 |
| Carbon tax (2010 CHF / tcarbon dioxide (CO <sub>2</sub> )) | 61.9 | 102  | 115  | 116  |
| Carbon emissions (MtCO <sub>2</sub> ) <sup>†</sup>         | 39.2 | 35.8 | 32.4 | 29.1 |
| Transport demand (2010 = 1) <sup>†</sup>                   | 1.14 | 1.25 | 1.33 | 1.36 |
| Congestion (2010 = 1) <sup>†</sup>                         | 1.28 | 1.36 | 1.36 | 1.35 |

<sup>†</sup>: While rows one to seven are exogenous parameters that the model is calibrated to, transport demand and carbon emissions are endogenous model outcomes that are reported here for comparison with policy scenarios.

Over time, sales shares for the private passenger drive train technologies ICE, PHEV, and BEV trend toward higher sales of BEV and lower sales of ICE. Our assumptions about BAU trends for these developments are given in Figure 4.

In our policy scenarios we implement the Swiss climate policy target of reducing per capita greenhouse gas (GHG) emissions to 1 metric tonne CO<sub>2</sub> equivalent by 2050. The resulting 10.3 million tonnes (Mt) CO<sub>2</sub> equivalent (CO<sub>2</sub>e) are 18.9 percent of 2010 GHG emissions, which amounted to 54.37 Mt CO<sub>2</sub>e.<sup>10</sup> Out of the total GHG emissions, this model only captures energy related CO<sub>2</sub> emissions and

<sup>10</sup>Taken from the 2016 Switzerland's National Inventory Report under the United Nations

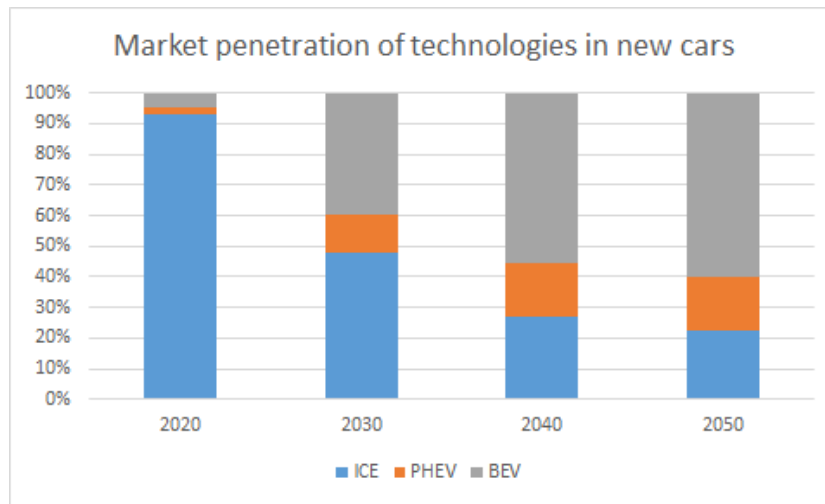


Figure 4: Technology shares for ICE, PHEV, and BEV in new cars.

we model the GHG emission reduction target as a 81.1 percent reduction in energy related CO<sub>2</sub> emissions compared to 2010 levels. In the years up to 2050, 2010 emissions are assumed to be linearly decreased to meet this target. Table 3 displays the emission targets for the policy scenarios.

Table 3: Reduction targets for energy related CO<sub>2</sub> emissions relative to 2010 and in absolute numbers.

|                                        | 2020  | 2030  | 2040  | 2050  |
|----------------------------------------|-------|-------|-------|-------|
| Emissions target (2010=1)              | 0.824 | 0.615 | 0.403 | 0.189 |
| Emissions target (MtCO <sub>2</sub> e) | 35.1  | 26.7  | 17.8  | 8.28  |

In the ‘tax emissions in all sectors’ (*tax*) scenario, these annual targets are met by endogenously setting a uniform carbon tax on energy related CO<sub>2</sub> emissions of all sectors such that emissions are reduced by the required amount.

In the ‘set efficiency standards on vehicles, tax emissions in all other sectors’ (*standard*) scenario, a carbon tax reduces the emissions outside the private transport activities, but within the transport sector, emission reductions are achieved by emission standards on vehicles. The standards are endogenously chosen by the model such that emissions in the private transport sector remain the same as in the *tax* scenario. Standards are implemented by a revenue-neutral combina-

Framework Convention on Climate Change, see <https://www.bafu.admin.ch/bafu/en/home/topics/climate/state/data/climate-reporting/most-recent-ghg-inventory.html>.

tion of an implicit tax on emissions related to the fuel of private transportation and an implicit subsidy on the final service of private transportation activities. The carbon tax on non-transport related emissions is set such that the same overall emission reduction target is met as in *tax*.

## 4 Results

Here we present the results for the two counterfactual policy scenarios *tax* and *standard* and compare them to the BAU. We first discuss aggregate national cost and the aspects of the results that explain those costs. This discussion is followed by our observations of how policy cost is distributed across household types.

### 4.1 Aggregate national policy costs

First we want to establish the fact that without considering congestion, the outcome that the CES can achieve Swiss emission reduction targets in the transport sector at lower cost than a carbon tax is replicable in our model. For this we run the model without the interdependence of traffic levels and travel times. In this case we find that the policy cost in terms of equivalent variation (EV)<sup>11</sup> of meeting the targets in 2020 to 2050 with a carbon tax is consistently higher than the policy cost with a CES (see first half of Table 4). More detailed results for the model runs without congestion can be found in Appendix D.

The second half of Table 4 shows welfare outcomes in terms of EV if congestion is included in the model. Two notable differences in the results can be observed. First, costs in terms of EV for all years are lower in the model version that considers congestion. This is due to the fact that both climate policies reduce traffic and thus congestion, which creates co-benefits that are only captured by the model that considers this. Secondly, the comparison of the two policies in terms of EV makes the *tax* the preferable policy if congestion is included contrary to what the comparison of model results without congestion indicate.

These results for household utility are partly driven by impacts on household income and by changes in market value of consumption goods and leisure. Besides these differences in market valuation, the traffic levels, through congestion, determine the availability of useful leisure time. As posited in Section 2.2, we observe that the switch from a carbon tax to a CES increases labor and capital productivity, decreases the cost of private transportation, increases traffic and congestion levels, and decreases carbon tax recycling volumes. Table 5 shows how the factor productivities compare across the scenarios in the years 2030 and

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<sup>11</sup>Our particular implementation of EV includes the value of leisure corresponding to the market wage rate.

Table 4: Welfare results for 2020 to 2050. Results indicate EV (including leisure at market wage rate) with respect to BAU for the two scenarios *tax* and *standard* with or without congestion in the model.

|                          | 2020  | 2030  | 2040  | 2050  |
|--------------------------|-------|-------|-------|-------|
| Model without congestion |       |       |       |       |
| <i>tax</i>               | -0.12 | -0.59 | -1.49 | -3.73 |
| <i>standard</i>          | -0.12 | -0.56 | -1.47 | -3.67 |
| Model with congestion    |       |       |       |       |
| <i>tax</i>               | -0.08 | -0.40 | -1.06 | -2.89 |
| <i>standard</i>          | -0.10 | -0.48 | -1.20 | -2.99 |

2050 as well as the implicit user price for private transport and the volumes of carbon tax revenue that is recycled to households. Figure 5 shows traffic and congestion levels for the different scenarios over time.

Table 5: Macroeconomic key figures. Numbers reflect percent changes from BAU for the respective years and policy scenarios.

|                                | 2030       |                 | 2050       |                 |
|--------------------------------|------------|-----------------|------------|-----------------|
|                                | <i>tax</i> | <i>standard</i> | <i>tax</i> | <i>standard</i> |
| Marginal product of labor      | -0.95      | -0.63           | -4.00      | -3.65           |
| Marginal product of capital    | -0.82      | -0.45           | -2.78      | -2.24           |
| User cost of private transport | 2.95       | -3.98           | 6.59       | -2.70           |
| Volume of carbon tax recycling | 76.40      | 16.23           | 155.68     | 99.71           |

Even though the marginal product of labor increases, changes in households' reward for giving up leisure time for working is not immediately determined, as the requirement for commuting adds (household type specific) monetary and temporal costs to labor provision. Under the switch from a carbon tax to a CES, households observe a reduction in the monetary cost of commuting but spend more time in traffic due to increases in congestion. Overall, the effective wage per hour spent away from home still increases. This coincides with an increase of time spent away from home for working but due to time losses in traffic, the supply of useful labor to production sectors is reduced: In 2050 it goes from 0.72 percent above BAU for the carbon tax scenario to 0.65 percent above for the CES.

Similarly, revenue from capital is not only determined by the factor's productivity, but also depends on the capital stock in the different scenarios. The capital stocks in the recursive dynamic model depend on past monetary income and on the cost of the investment good. In 2050, the stock is 1.5 percent below BAU levels



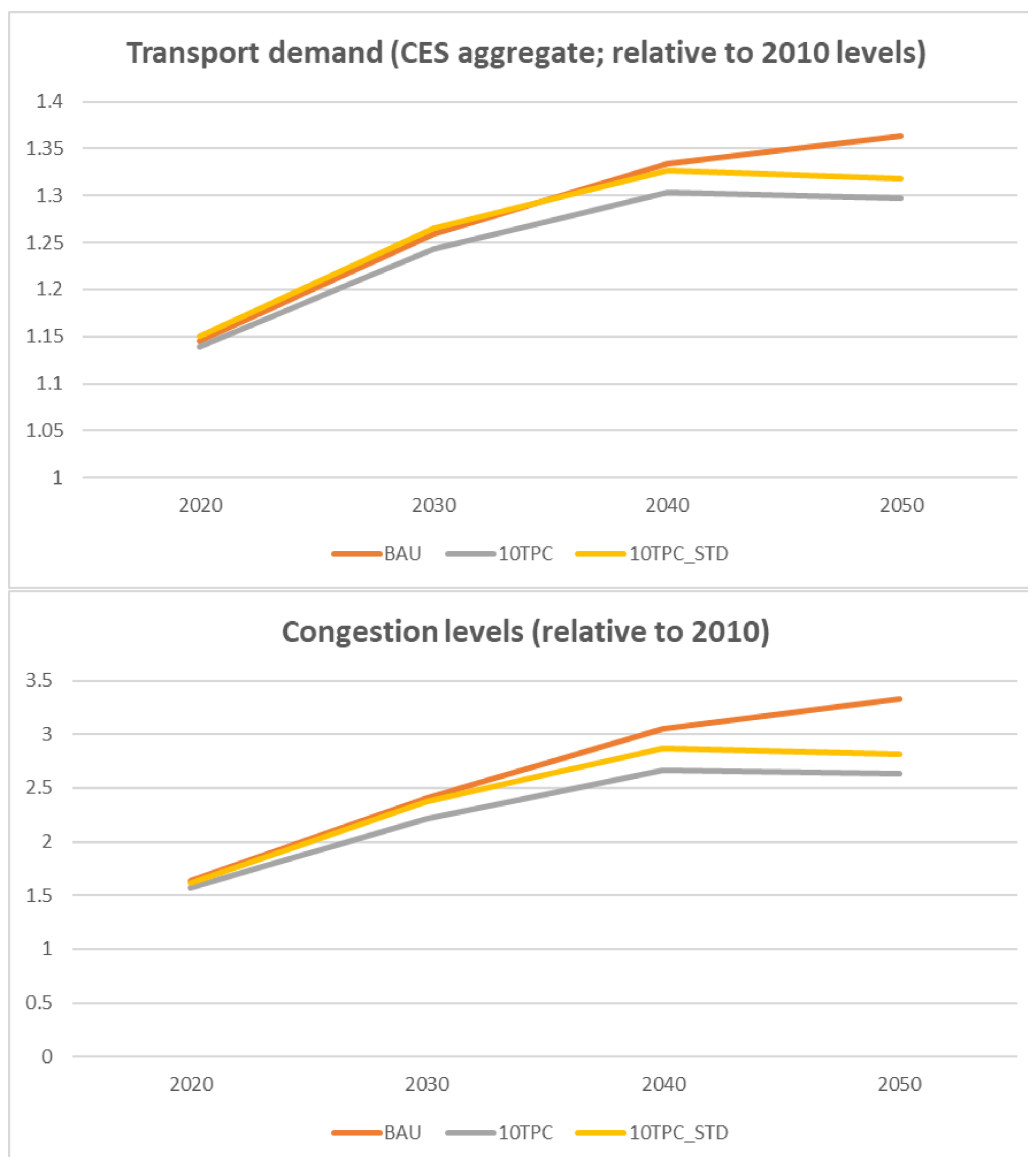


Figure 5: Traffic and resulting congestion relative to 2010 in Switzerland under different scenarios

in the *tax* scenario and decreases to 1.9 percent below BAU in *standard*.

Figure 6 shows how the difference in 2050 EV changes from BAU between *tax* and *standard* (compare Table 6) are composed of different income and expenditure side effects. On the budget side (first nine items in Figure 6), we notice that the increase in labor productivity overcompensates the reduction in effective labor hours spent on the job and nominal wage earnings increase (category “Time: wages”). The appreciation of the value of leisure (“Time: leisure”) is largely compensated by the fact that, under *standard*, a bigger part of non-working hours are spent in traffic (“Congestion”). The reductions in revenue recycling (“Recycling”) weigh heavy on the budget of households and are somewhat aggravated by the need to cut transfers (“Transfers”) from the government in order to balance the budget of the latter. The decrease in capital stock is compensated by the higher valuation of capital and rents from investments in general-purpose capital and in the car park produce higher rents under the *standard* scenario than under *tax*. The observed increase in spending on the investment good (eighth item in Figure 6) does not translate into an increase in capital stock due to a more expensive investment good in the *standard* scenario: Real investment is decreasing from 2.48 percent below BAU levels to 2.84 below when switching from *tax* to *standard*.

On the cost-of-utility side (last six items in Figure 6), there is a noticeable benefit from cheaper private transportation (TRPRV) which is compensated by other monetary expenditures.<sup>12</sup> The increased value of time makes the consumption of time in the form of leisure (LEIS) more expensive and the cost of overall household utility ends up being more expensive than the national consumption basket afforded from monetary expenditures.

## 4.2 Distribution of policy cost across household types

Now that it is established that the carbon tax will outperform the CES if co-benefits such as congestion are included in the comparison, we want to analyze how policy costs are distributed among different household types in order to judge if either of the policies lead to particularly unjust outcomes with regard to distribution of cost.

The welfare results in terms of EV for the different household types in the model for 2050 are given in Table 6.<sup>13</sup> It becomes evident that, on average, high income households would prefer scenario *standard* but middle and low income households (again on average) prefer the outcome in the *tax* scenario. But while

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<sup>12</sup>All income and cost indices are in terms of the national index of purchasing power. Monetary expenditure effects (approximately) add up to the change in this purchasing power index, thus netting out to (approximately) zero.

<sup>13</sup>The corresponding results for 2030 are given in Table 8 of Appendix C. They display more or less the same patterns but at lower policy cost for either scenario.

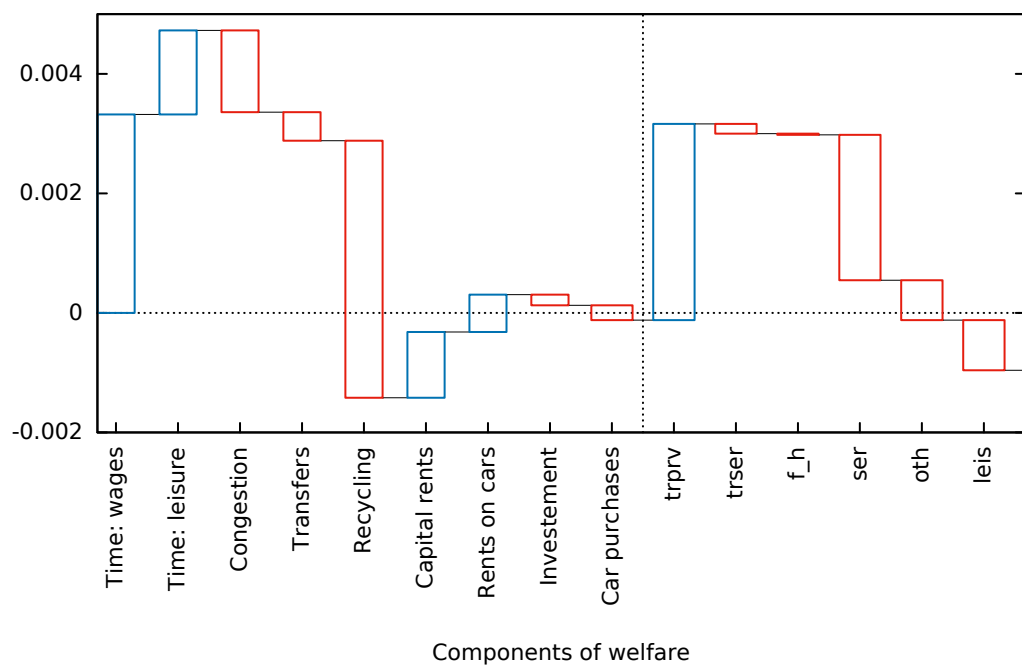


Figure 6: Decomposition of welfare impacts per household for switching from scenario *tax* to *standard* in 2050. Changes are in percentage point changes in policy cost relative to BAU welfare and add up to differences in welfare changes between *standard* and *tax* in Table 4.

households with different commute lengths and different exposures to congestion show different results it does not become evident that households that are exposed to congestion *always* prefer the *tax* scenario even though that scenario is better at reducing congestion.

Table 6: Welfare results (EV including leisure at market wage rate) for 2050. Rows differentiate income levels, columns differentiate different types of commutes. Results in **bold** font indicate household groups that prefer the respective policy option for the given year.

| Scenario <i>tax</i>      |                                    |                                    |                                  |                                  |                                   |                                   |              |
|--------------------------|------------------------------------|------------------------------------|----------------------------------|----------------------------------|-----------------------------------|-----------------------------------|--------------|
|                          | D <sub>SHORT</sub> C <sub>LO</sub> | D <sub>SHORT</sub> C <sub>HI</sub> | D <sub>MED</sub> C <sub>LO</sub> | D <sub>MED</sub> C <sub>HI</sub> | D <sub>LONG</sub> C <sub>LO</sub> | D <sub>LONG</sub> C <sub>HI</sub> | avg          |
| I <sub>LO</sub>          | <b>-3.63</b>                       | <b>-6.85</b>                       | <b>-6.77</b>                     | -9.12                            | -11.76                            | -21.93                            | <b>-5.94</b> |
| I <sub>MED</sub>         | <b>-2.24</b>                       | <b>-4.30</b>                       | <b>-2.50</b>                     | <b>-0.81</b>                     | <b>-3.30</b>                      | <b>-1.23</b>                      | <b>-2.33</b> |
| I <sub>HI</sub>          | -2.24                              | -7.64                              | -2.65                            | <b>-2.31</b>                     | -3.59                             | <b>-4.30</b>                      | -2.76        |
| avg                      | <b>-2.43</b>                       | -5.65                              | <b>-2.95</b>                     | <b>-1.99</b>                     | -4.15                             | <b>-4.68</b>                      | <b>-2.89</b> |
| Scenario <i>standard</i> |                                    |                                    |                                  |                                  |                                   |                                   |              |
|                          | D <sub>SHORT</sub> C <sub>LO</sub> | D <sub>SHORT</sub> C <sub>HI</sub> | D <sub>MED</sub> C <sub>LO</sub> | D <sub>MED</sub> C <sub>HI</sub> | D <sub>LONG</sub> C <sub>LO</sub> | D <sub>LONG</sub> C <sub>HI</sub> | avg          |
| I <sub>LO</sub>          | -3.92                              | -6.96                              | -6.88                            | <b>-8.98</b>                     | <b>-11.50</b>                     | <b>-20.44</b>                     | -6.07        |
| I <sub>MED</sub>         | -2.37                              | -4.34                              | -2.65                            | -1.32                            | -3.36                             | -2.07                             | -2.51        |
| I <sub>HI</sub>          | <b>-2.18</b>                       | <b>-7.10</b>                       | <b>-2.56</b>                     | -2.49                            | <b>-3.51</b>                      | -4.46                             | <b>-2.71</b> |
| avg                      | -2.52                              | <b>-5.58</b>                       | -3.02                            | -2.33                            | <b>-4.13</b>                      | -4.98                             | -2.99        |

Figure 7 decomposes the welfare effects in scenario *tax* compared to BAU. The first nine items add up to *full income* (encompassing the value of all available time and the rental value of households' car parks) and deduct investments and car purchases to arrive at the *full consumption budget* (where consumption includes leisure). Note that values are normalized to a national average consumption price index (CPI). The second set of components of welfare changes weigh how price changes of consumption goods influence the household class specific cost of utility from consumption and leisure.<sup>14</sup>

Household class specific full income is influenced by the value of time, time losses through congestion, capital rents, and transfer payments from the government. Between BAU and *tax* the wage rate drops along with the value of time and this is reflected by the negative sum of effects from *time: wages* and *time: leisure* in households' budgets. All households reduce their free time in order to work more and thus compensate some of the wage losses. Reductions in traffic and

<sup>14</sup>Appendix C explains how the decomposition of welfare changes works.

Table 7: Congestion in the policy scenarios under different circumstances for 2030 and 2050 (percentage changes from BAU).

|                     | <b>Low congestion</b> |                 | <b>High congestion</b> |                 |
|---------------------|-----------------------|-----------------|------------------------|-----------------|
|                     | <i>tax</i>            | <i>standard</i> | <i>tax</i>             | <i>standard</i> |
| <b>2030</b>         |                       |                 |                        |                 |
| <b>Commutes</b>     | 0.06                  | 1.16            | 2.95                   | 2.13            |
| <b>Non-commutes</b> | −4.82                 | 2.77            | −15.64                 | −7.39           |
| <b>2050</b>         |                       |                 |                        |                 |
| <b>Commutes</b>     | 1.80                  | 3.11            | 14.59                  | 13.74           |
| <b>Non-commutes</b> | −20.56                | −12.41          | −44.98                 | −37.00          |

thus congestion frees up time and largely compensates households for their additional work time (the sum of effects from *time: leisure* and *congestion* add up to the net change of the value of useful leisure time). The effects on capital revenue (*capital rents*) is negative throughout the population. This is due to both sinking rental rates as well as lower capital stocks. Changes in both existing transfers and receipts from the recycling of transport related carbon taxes have only small effects on the budget of households. Note that one household category, *mlc*, ends up with more full income in *tax* than under BAU. This is due to the big reduction in congestion which makes possible an increase in labor supply that compensates the wage rate reduction in scenario *tax*.

From full income, the items *investment*, *rents on cars*, and *car purchases* are deducted to receive households' full utility budget. Investments drop along with income for all households except *mlc*, the effect on the consumption budget of which is positive. Accounting for car purchases and implicit rents on the utility of the car stock, we can say that most household classes find their car parks less valuable and low income and congestion exposed households tend to increase their spending on cars in *tax* compared to BAU.

The household classes' budgets for full consumption (sum of effects up to the dotted vertical line in Figure 7) has decreased for all households except *mlc*. But household specific consumption preferences and the resulting class specific cost of utility from (full) consumption create additional deviation from this income effects (the latter are normalized to the *national average* CPI). Therefore, household classes with relatively high expenditure shares for commodities with prices that increase more than the national average CPI will face increasing costs of utility even relative to the national average CPI. In particular, low income households that are exposed to congestion seem to suffer from increases in costs of heating fuel and private transport. Also, while the consumption budget of *mlc* is increasing relative to the CPI, the increase in the household class's cost of utility means

it is worse off under scenario *tax* than under BAU.

Figure 8 compares the outcomes in scenarios *tax* with *standard* and decomposes the changes. The differences between the two counterfactual scenarios are given relative BAU values and they thus add up to differences in welfare changes between *standard* and *tax* in Table 6.

Common to all households are the following two effects. Under the CES, cars become more expensive and expenditures for cars increase. Also, the value of time increases and before effects of congestion, all households are better off for that.<sup>15</sup>

Effects of switching from *tax* to *standard* that affect household classes differently include increased congestion, changes in government transfers, and household class specific cost of utility from consumption and leisure. While congestion increases for all households, those who are more exposed to it suffer bigger losses in useful time. At the same time, these households tend to profit more from the overall cheaper private transport that the switch from taxes to standards makes possible. The reduction in transfers, finally, are felt most by low income households.

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<sup>15</sup>Due to the prolonged tedium of commuting, most households react with a decrease in labor supply, but that is not shown conclusively in Figure 8. Aggregate labor supply falls by 0.07 percentage points relative to BAU levels from 0.72 percentage points above BAU to 0.65 above BAU.

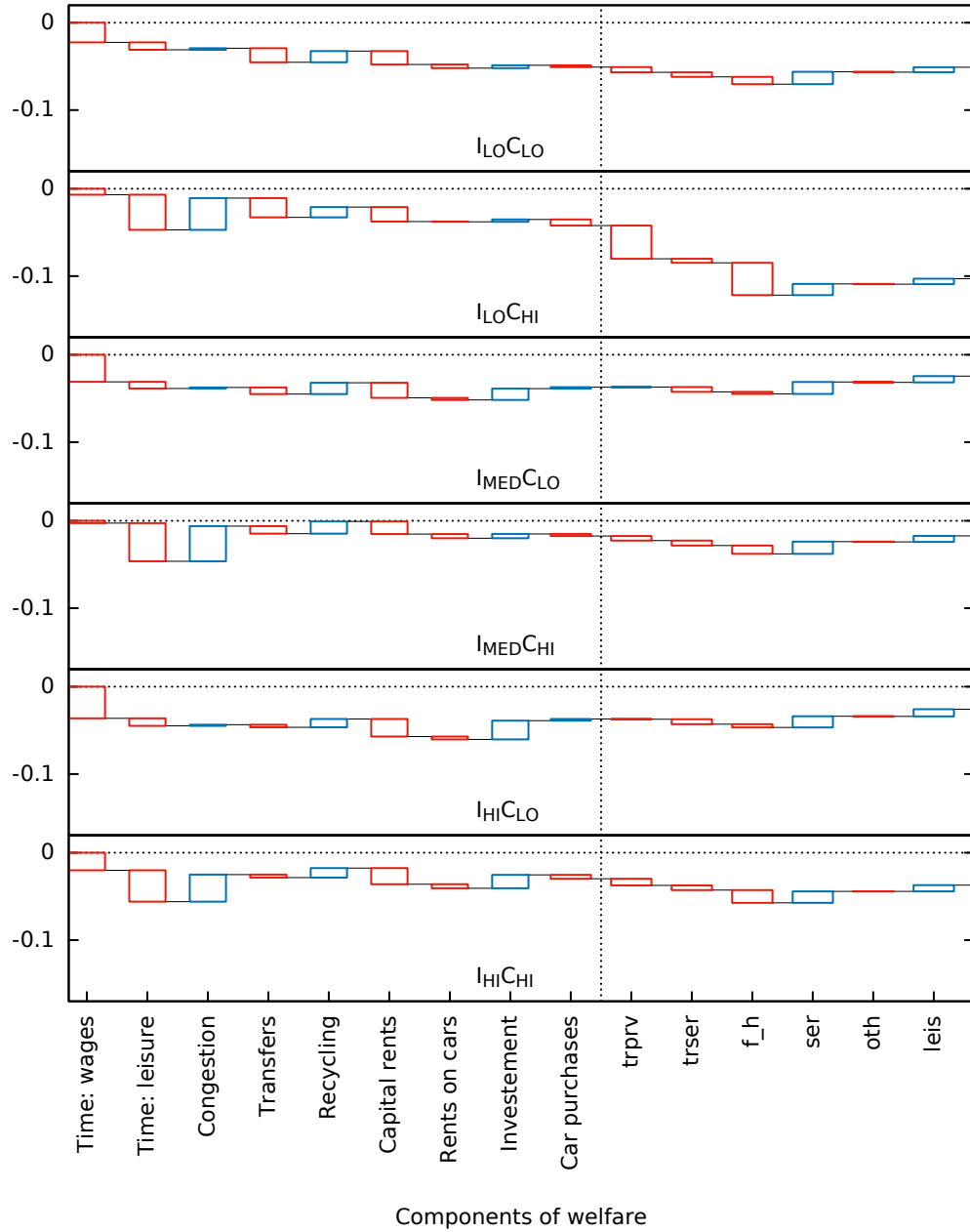


Figure 7: Decomposition of welfare impacts per household for scenario *tax* in 2050. Changes are relative to BAU welfare and add up to total welfare changes in Table 6.

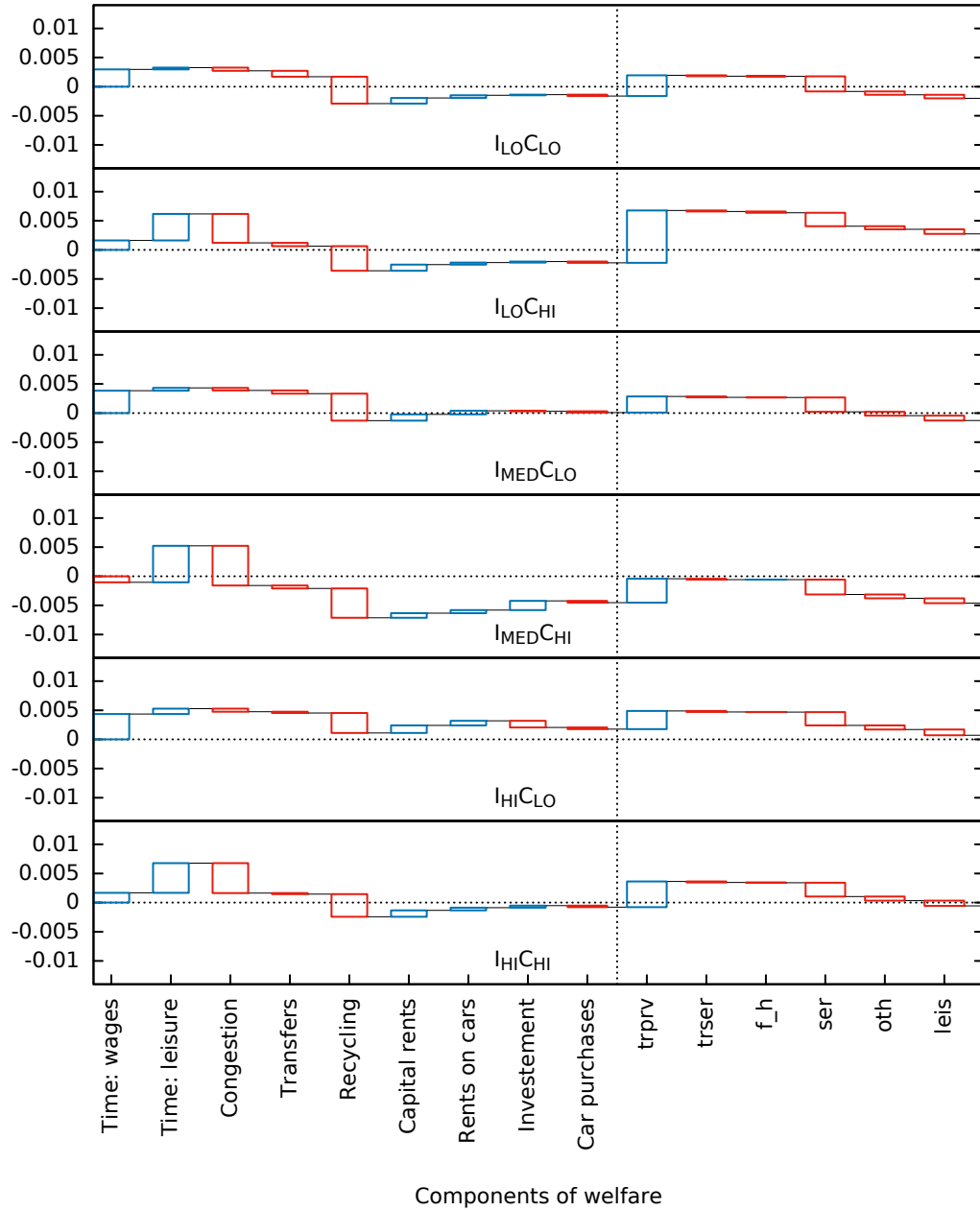


Figure 8: Decomposition of welfare impacts per household for scenario *standard* in 2050. Changes are compared to scenario *tax*, relative to BAU welfare and add up to differences in welfare changes between *standard* and *tax* in Table 6.



## 5 Discussion

This paper compares different instruments for reducing emissions in private transportation. It considers a carbon tax alongside a CES that achieves the same emission levels. The carbon tax increases the consumer cost of motor fuels and thus the cost of transportation services. The CES leaves the cost of transportation lower and reduces traffic to a lesser degree than the carbon tax but achieves higher average fuel efficiency in the car park.

If congestion and other co-benefits of traffic reduction are not included in the modeling, we find that a CES can achieve the emission target at lower aggregate cost. We attribute this to strong interaction effects between the carbon tax and pre-existing factor taxation. If co-benefits of traffic reduction are explicitly included in the model, however, the stronger traffic reduction of the carbon tax makes this the more desirable policy than the CES in terms of aggregate policy cost.

When we compare the distribution of policy costs across household types we find that the carbon tax gives better outcomes for lower income households on average. We do, however, identify the low income long distance commuters as a group that is particularly exposed to increases in costs of transportation (under either policy scenario).

Our model is calibrated to Swiss data and the situation in other European countries is similar in many aspects but can differ in others. When we compare Switzerland with other European countries we find that there are high pre-existing taxes on fossil fuels as well and the EU also currently regulates emissions in private transportation with CES. Congestion is more of a problem in many European countries than it is in Switzerland. This suggests, that the taxation of carbon emissions can be expected to be superior to CO<sub>2</sub> emission standards in most EU member states (assuming absence of congestion pricing). Unlike Switzerland, many EU member states produce cars domestically rather than just importing them. This may constitute a factor that makes a CES more attractive to such countries as it will increase the sale of highly efficient cars and thus will promote the industry.

The model is closely calibrated to real world data and as such makes plausible statements about magnitudes of impacts and interactions of policies. Some caveats still apply. For one, data about the exposure of households to congestion on non-commuting trips and estimates for the responsiveness of agents to transport costs in all the particular situations is not available. Also, our model does not consider household's choice of place of residence (mobility between areas with different commuting lengths and different exposures to congestion).

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## Appendix A Derivations for analytical model

We consciously decided to design our theoretical model in analogy to Goulder et al.'s theoretical model (2016). The procedure for deriving marginal costs is equally similar and the formulations in the following closely resemble the Appendix of their paper. Sorry for the lazy copying.

Taking the total derivative of (1) with respect to  $\tau_Z$ , substituting in the consumer first-order conditions (10), taking total derivatives of the production functions (2) and (3) with respect to  $\tau_Z$ , substituting in the firm first-order conditions (9), substituting in total derivatives of the factor-market clearing conditions (4) and (5) and rearranging yield<sup>16</sup>

$$\begin{aligned} \frac{1}{\lambda} \frac{dU}{d\tau_Z} &= \tau_Z \frac{dZ}{d\tau_Z} + \tau_Y \frac{dY}{d\tau_Z} + \tau_K \frac{d(rK)}{d\tau_Z} + \tau_L \frac{dwL}{d\tau_Z} + \frac{1}{\lambda} \frac{\partial U}{\partial C} \frac{dC}{d\tau_Z} \\ &= \tau_Z \frac{dZ}{d\tau_Z} + \left( \tau_Y + \frac{1}{\lambda} \frac{\partial U}{\partial C} \right) \frac{dY}{d\tau_Z} + \tau_K \frac{d(rK)}{d\tau_Z} + \tau_L \frac{dwL}{d\tau_Z} \\ &= \tau_Z \frac{dZ}{d\tau_Z} + (\tau_Y - \mu_C) \frac{dY}{d\tau_Z} + \tau_K \frac{d(rK)}{d\tau_Z} + \tau_L \frac{dwL}{d\tau_Z}, \end{aligned} \quad (15)$$

where  $\mu_C := -\frac{1}{\lambda} \frac{\partial U}{\partial C} > 0$  denotes the marginal cost from changes in  $C$ . From this general expression we derive expressions for marginal abatement cost for the carbon tax on the one hand and for the efficiency standard on the other hand side.

### Derivation of marginal abatement costs under the carbon tax

Expanding the total derivatives of  $rK$  and  $wL$  with respect to  $\tau_Z$  allows (15) to be rewritten as

$$\begin{aligned} \frac{1}{\lambda} \frac{dU}{d\tau_Z} &= \tau_Z \frac{dZ}{d\tau_Z} + \tau_K \frac{\partial(rK)}{\partial\tau_Z} + \tau_L \frac{\partial(wL)}{\partial\tau_Z} - \mu_C \frac{dY}{d\tau_Z} \\ &\quad + \frac{d\tau_K}{d\tau_Z} \left[ \tau_K \frac{\partial(rK)}{\partial\tau_K} + \tau_L \frac{\partial(wL)}{\partial\tau_K} \right] \\ &\quad + \frac{d\tau_L}{d\tau_Z} \left[ \tau_K \frac{\partial(rK)}{\partial\tau_L} + \tau_L \frac{\partial(wL)}{\partial\tau_L} \right]. \end{aligned} \quad (16)$$

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<sup>16</sup>Note that  $\frac{p_Y}{p_Y - \tau_Y} = 1 + \frac{\tau_Y}{p_Y - \tau_Y}$ .

The next step is to derive expressions for  $\frac{d\tau_K}{d\tau_Z}$  and  $\frac{d\tau_L}{d\tau_Z}$ . Taking the total derivative of the government budget constraint (7) and substituting in  $dG = 0$  yields

$$\begin{aligned} 0 = & \left( t_Z \frac{dZ}{d\tau_Z} + \tau_L \frac{\partial(wL)}{\partial\tau_Z} + \tau_K \frac{\partial(rK)}{\partial\tau_Z} \right) d\tau_Z \\ & + \left( rK + \tau_L \frac{\partial(wL)}{\partial\tau_K} + \tau_K \frac{\partial(rK)}{\partial\tau_K} \right) d\tau_K \\ & + \left( wL + \tau_L \frac{\partial(wL)}{\partial\tau_L} + \tau_K \frac{\partial(rK)}{\partial\tau_L} \right) d\tau_L. \end{aligned} \quad (17)$$

The share  $\alpha_K$  of budget imbalance from reducing pollution (the first term in (17)) is compensated by changing the capital tax and the share  $\alpha_L$  compensated by changing the labor tax. Together with (17), this implies

$$\frac{d\tau_K}{d\tau_Z} = -\alpha_K \frac{t_Z \frac{dZ}{d\tau_Z} + \tau_L \frac{\partial(wL)}{\partial\tau_Z} + \tau_K \frac{\partial(rK)}{\partial\tau_Z}}{rK + \tau_L \frac{\partial(wL)}{\partial\tau_K} + \tau_K \frac{\partial(rK)}{\partial\tau_K}} \quad (18)$$

and

$$\frac{d\tau_L}{d\tau_Z} = -\alpha_L \frac{t_Z \frac{dZ}{d\tau_Z} + \tau_L \frac{\partial(wL)}{\partial\tau_Z} + \tau_K \frac{\partial(rK)}{\partial\tau_Z}}{wL + \tau_L \frac{\partial(wL)}{\partial\tau_L} + \tau_K \frac{\partial(rK)}{\partial\tau_L}}. \quad (19)$$

Substituting (18) and (19) into (17) and rearranging, using the definitions of  $\eta_R$ ,  $\eta_K$  and  $\eta_L$ , yields

$$\begin{aligned} \frac{1}{\lambda} \frac{dU}{d\tau_Z} = & [\tau_Z + (\eta_R - 1)t_Z] \frac{dZ}{d\tau_Z} - \mu_C \frac{dY}{d\tau_Z} \\ & + \eta_R \left[ \tau_K \frac{\partial(rK)}{\partial\tau_Z} + \tau_L \frac{\partial(wL)}{\partial\tau_Z} \right]. \end{aligned}$$

Inserting the definition of  $\theta_Z$  and dividing by  $\frac{dZ}{d\tau_Z}$  gives (11).

## Derivation of marginal abatement costs under the efficiency standard

In the case of the efficiency standard, expanding the total derivatives of  $rK$  and  $wL$  in (15) gives

$$\begin{aligned} \frac{1}{\lambda} \frac{dU}{d\tau_Z} &= \tau_Z \frac{dZ}{d\tau_Z} + \tau_K \frac{\partial(rK)}{\partial\tau_Z} + \tau_L \frac{\partial(wL)}{\partial\tau_Z} + (\tau_Y - \mu_C) \frac{dY}{d\tau_Z} \\ &+ \frac{d\tau_K}{d\tau_Z} \left[ \tau_K \frac{\partial(rK)}{\partial\tau_K} + \tau_L \frac{\partial(wL)}{\partial\tau_K} \right] \\ &+ \frac{d\tau_L}{d\tau_Z} \left[ \tau_K \frac{\partial(rK)}{\partial\tau_L} + \tau_L \frac{\partial(wL)}{\partial\tau_L} \right] \\ &+ \frac{d\tau_Y}{d\tau_Z} \left[ \tau_K \frac{\partial(rK)}{\partial\tau_Y} + \tau_L \frac{\partial(wL)}{\partial\tau_Y} \right]. \end{aligned} \quad (20)$$

The same application of equations (17)–(19) as in the case of the carbon tax yields

$$\begin{aligned} \frac{1}{\lambda} \frac{dU}{d\tau_Z} &= [\tau_Z + (\eta_R - 1)t_Z] \frac{dZ}{d\tau_Z} + (\tau_Y - \mu_C) \frac{dY}{d\tau_Z} \\ &+ \eta_R \left[ \tau_K \frac{\partial(rK)}{\partial\tau_Z} + \tau_L \frac{\partial(wL)}{\partial\tau_Z} + \frac{d\tau_Y}{d\tau_Z} \left( \tau_K \frac{\partial(rK)}{\partial\tau_Y} + \tau_L \frac{\partial(wL)}{\partial\tau_Y} \right) \right]. \end{aligned}$$

Applying definitions of  $\theta_Z$  and  $\theta_Y$  and division by  $\frac{dZ}{d\tau_Z}$  gives (12).



## Appendix B Additional detail on congestion

Here we document the features of our numerical model that set it apart from standard recursive dynamic CGE models in more detail.

**COMMUTING REQUIREMENT OF LABOR PROVISION**—In contrast to regular CGE models with a labor–leisure choice, labor supply requires expenses for commuting. Thus, household-type and region specific wage rates  $PF_{\text{labor},hht,r}$  after taxes and social security contributions are related to effective value of time to households and other cost related to commuting by

$$\begin{aligned} PF_{\text{labor},hht,r} &= \theta_{\text{labor},hht,r} PFE_{\text{labor},hht,r} + (1 - \theta_{\text{labor},hht,r}) C_{\text{commute},hht,r} \\ C_{\text{commute},hht,r} &:= [\theta_{\text{publ},hht,r} C_{\text{publ},hht,r}^{0.5} + \theta_{\text{priv},hht,r} C_{\text{priv},hht,r}^{0.5}]^2 \\ C_{\text{publ},hht,r} &:= \theta_{\text{TRPUB},hht,r} P_{\text{TRPUB},r} + (1 - \theta_{\text{TRPUB},hht,r}) PFE_{\text{labor},hht,r} \\ C_{\text{priv},hht,r} &:= \theta_{\text{TRPRV},hht,r} P_{\text{TRPRV},hht,r} \\ &\quad + (1 - \theta_{\text{TRPRV},hht,r}) PFE_{\text{labor},hht,r} (1 + c(t_{hht,r}) - c(t_{hht,r}^{\text{BAU}})) , \end{aligned}$$

where  $PFE_{\text{labor},hht,r}$  is the effective value of time to household type  $hht$  in region  $r$ ,  $P_{\text{TRPUB},r}$  the price of commercially provided transport services in region  $r$ ,  $P_{\text{TRPRV},hht,r}$  the monetary cost of privately generated transport services by household  $hht$  in region  $r$ . The share parameters  $\theta_{\dots}$  denote benchmark expenditure shares of the respective cost category and add up to one within each equation,  $c(t)$  is the congestion function in equation (14), and  $t_{hht,c}$  the traffic levels experienced by household type  $hht$  in region  $r$ .

Assuming that in the benchmark, all prices and cost indices are unity and supply of productive labor to firms is  $F_{\text{labor},hht,r} = \bar{F}_{\text{labor},hht,r}$ , time on the job is  $FE_{\text{labor,work},hht,r} = \bar{FE}_{\text{labor,work},hht,r}$ , time spent on public-transport commuting  $FE_{\text{labor,pub},hht,r} = \bar{FE}_{\text{labor,pub},hht,r}$ , and time spent on private-transport commuting  $FE_{\text{labor,priv},hht,r} = \bar{FE}_{\text{labor,priv},hht,r}$ , the demand of total time to households related to labor provision is

$$\begin{aligned} FE_{\text{labor, total},hht,r} &= \frac{F_{\text{labor},hht,r}}{\bar{F}_{\text{labor},hht,r}} \left[ \bar{FE}_{\text{labor, work},hht,r} \right. \\ &\quad + \bar{FE}_{\text{labor, pub},hht,r} \left( \frac{C_{\text{commute},hht,r}}{C_{\text{publ},hht,r}} \right)^{0.5} \\ &\quad \left. + \bar{FE}_{\text{labor, priv},hht,r} \left( \frac{C_{\text{commute},hht,r}}{C_{\text{priv},hht,r}} \right)^{0.5} \right] . \end{aligned}$$

While the commercially provided transport services are produced by a run-of-the-mill production sector using general-purpose capital, labor, and intermediate

inputs from domestic markets, the privately generated transport services use household and technology specific car stocks in analogy to capital. Cost of such private transport is given by

$$\begin{aligned}
PTRPRV_{hht,r} &= \left[ \sum_{tec \in \{ICE, PHEV, BEV\}} \theta_{tec} C_{tec,hht,r}^{1-eoscar_{hht}} \right]^{1/(1-eoscar_{hht})} \\
C_{tec,hht,r} &:= \left[ \theta_{old,tec,hht,r} PCARO_{tec,hht,r}^{-9} \right. \\
&\quad \left. + \theta_{new,tec,hht,r} PCARN_{tec,hht,r}^{-9} \right]^{-1/9} \\
PCARO_{tec,hht,r} &:= \theta_{cars,tec,hht,r}^{old} RCARO_{tec,hht,r} \\
&\quad + \theta_{ele,tec,hht,r}^{old} PA_{ele,c,r} \\
&\quad + \theta_{f_t,tec,hht,r}^{old} PA_{f_t,c,r} \\
&\quad + \sum_{i \neq f_t,ele} \theta_{i,tec,hht,r}^{old} PA_{i,c,r} \\
PCARN_{tec,hht,r} &:= \sum_{i \neq f_t,ele} \theta_{i,tec,hht,r}^{new} PA_{i,c,r} \\
&\quad + \left( 1 - \sum_{i \neq f_t,ele} \theta_{i,tec,hht,r}^{new} \right) C_{Drive,tec,hht,r} \\
C_{Drive,tec,hht,r} &:= \left[ \theta_{cars,tec,hht,r}^{new} RCARN_{tec,hht,r}^{3/4} \right. \\
&\quad \left. + (1 - \theta_{cars,tec,hht,r}^{new}) C_{Propulsion,tec,hht,r}^{3/4} \right]^{4/3} \\
C_{Propulsion,tec,hht,r} &:= \left[ \theta_{f_t,tec,hht,r}^{new} PA_{f_t,c,r}^{1/2} + (1 - \theta_{f_t,tec,hht,r}^{new}) C_{e-drive,tec,hht,r}^{1/2} \right]^2 \\
C_{e-drive,tec,hht,r} &:= \theta_{ele,tec,hht,r}^{new} PA_{ele,c,r} \\
&\quad + (1 - \theta_{ele,tec,hht,r}^{new}) RCARN_{tec,hht,r},
\end{aligned}$$

where  $PA_{i,c,r}$  are regional consumer prices of commodities  $i$ ,  $RCARO_{tec,hht,r}$  and  $RCARN_{tec,hht,r}$  are the implicit rental rates on old and new cars that households pay themselves,  $\theta$ s are benchmark expenditure share and add up to one in each equation, and price and cost indices in the benchmark situation are normalized to unity.

Demands for old and new cars are

$$\begin{aligned}
\text{CARN}_{tec,hht,r} &= \overline{\text{CARN}}_{tec,hht,r} \\
&\cdot \left[ \frac{\theta_{cars,tec,hht,r}^{\text{new}}}{\theta_{cars,tec,hht,r}^{\text{new}} + \theta_{e-drive,tec,hht,r}^{\text{new}}} \frac{C_{\text{Drive},tec,hht,r}^{1/4}}{\text{RCARN}_{tec,hht,r}} \right. \\
&\quad + \frac{\theta_{e-drive,tec,hht,r}^{\text{new}}}{\theta_{cars,tec,hht,r}^{\text{new}} + \theta_{e-drive,tec,hht,r}^{\text{new}}} \frac{C_{\text{Propulsion},tec,hht,r}^{1/2}}{C_{e-drive,tec,hht,r}} \\
&\quad \left. \cdot \frac{C_{\text{Drive},tec,hht,r}^{1/4}}{C_{\text{Propulsion},tec,hht,r}} \right] \\
&\cdot \frac{C_{tec,hht,r}}{\text{PCARN}_{tec,hht,r}} \frac{{}^9\text{PTRPRV}_{hht,r}^{e\text{oscar}_{hht}}}{C_{tec,hht,r}} \frac{\text{TRPRV}_{hht,r}}{\overline{\text{TRPRV}}_{hht,r}} \\
\text{CARO}_{tec,hht,r} &= \overline{\text{CARO}}_{tec,hht,r} \\
&\cdot \frac{C_{tec,hht,r}}{\text{PCARO}_{tec,hht,r}} \frac{{}^9\text{PTRPRV}_{hht,r}^{e\text{oscar}_{hht}}}{C_{tec,hht,r}} \frac{\text{TRPRV}_{hht,r}}{\overline{\text{TRPRV}}_{hht,r}},
\end{aligned}$$

where

$$\theta_{e-drive,tec,hht,r}^{\text{new}} := (1 - \theta_{cars,tec,hht,r}^{\text{new}})(1 - \theta_{f\_t,tec,hht,r}^{\text{new}})(1 - \theta_{ele,tec,hht,r}^{\text{new}})$$

and (benchmark) demand for private transport services is  $\text{TRPRV}_{hht,r}$  ( $\overline{\text{TRPRV}}_{hht,r}$ ) and  $\overline{\text{CARO}}_{tec,hht,r}$  and  $\overline{\text{CARN}}_{tec,hht,r}$  are benchmark availabilities of old and new cars.

Given transport service demands  $\text{TRPRV}_{hht,r}$ , traffic levels  $t_{hht,r}$  to which households  $hht$  are exposed to during commutes are computed by

$$\begin{aligned}
t_{hht,r} &= 0.561 \frac{\sum_{hh \in \text{C}_{\text{Lo}}} \text{TRPRV}_{hh,r}}{\sum_{hh \in \text{C}_{\text{Lo}}} \overline{\text{TRPRV}}_{hh,r}} && \text{if } hht \in \text{C}_{\text{Lo}} \text{ and} \\
t_{hht,r} &= \frac{\sum_{hh \in \text{C}_{\text{Hi}}} \text{TRPRV}_{hh,r}}{\sum_{hh \in \text{C}_{\text{Hi}}} \overline{\text{TRPRV}}_{hh,r}} && \text{if } hht \in \text{C}_{\text{Hi}}.
\end{aligned}$$

## Appendix C Detailed welfare decomposition

This appendix complements the per-household-type results in Table 6 with the results for 2030 (see Table 8) and gives a graphical welfare composition of all results in Table 6.

Table 8: Welfare results (EV including leisure at market wage rate) for 2030. Rows differentiate income levels, columns differentiate different types of commutes. Results in **bold** font indicate household groups that prefer the respective policy option for the given year.

| Scenario <i>tax</i>      |                                    |                                    |                                  |                                  |                                   |                                   |              |
|--------------------------|------------------------------------|------------------------------------|----------------------------------|----------------------------------|-----------------------------------|-----------------------------------|--------------|
|                          | D <sub>SHORT</sub> C <sub>LO</sub> | D <sub>SHORT</sub> C <sub>HI</sub> | D <sub>MED</sub> C <sub>LO</sub> | D <sub>MED</sub> C <sub>HI</sub> | D <sub>LONG</sub> C <sub>LO</sub> | D <sub>LONG</sub> C <sub>HI</sub> | avg          |
| I <sub>LO</sub>          | <b>-0.38</b>                       | <b>-1.35</b>                       | <b>-0.94</b>                     | <b>-1.57</b>                     | -1.89                             | -5.32                             | <b>-0.89</b> |
| I <sub>MED</sub>         | <b>-0.22</b>                       | <b>-0.67</b>                       | <b>-0.30</b>                     | <b>0.11</b>                      | <b>-0.49</b>                      | <b>0.36</b>                       | <b>-0.23</b> |
| I <sub>HI</sub>          | -0.37                              | -1.86                              | -0.50                            | <b>-0.41</b>                     | -0.74                             | <b>-0.64</b>                      | -0.50        |
| avg                      | <b>-0.28</b>                       | <b>-1.10</b>                       | <b>-0.43</b>                     | <b>-0.20</b>                     | -0.71                             | <b>-0.64</b>                      | <b>-0.40</b> |
| Scenario <i>standard</i> |                                    |                                    |                                  |                                  |                                   |                                   |              |
|                          | D <sub>SHORT</sub> C <sub>LO</sub> | D <sub>SHORT</sub> C <sub>HI</sub> | D <sub>MED</sub> C <sub>LO</sub> | D <sub>MED</sub> C <sub>HI</sub> | D <sub>LONG</sub> C <sub>LO</sub> | D <sub>LONG</sub> C <sub>HI</sub> | avg          |
| I <sub>LO</sub>          | -0.57                              | -1.58                              | -1.04                            | -1.73                            | <b>-1.81</b>                      | <b>-4.56</b>                      | -1.01        |
| I <sub>MED</sub>         | -0.30                              | -0.75                              | -0.39                            | -0.28                            | -0.52                             | -0.40                             | -0.36        |
| I <sub>HI</sub>          | <b>-0.32</b>                       | <b>-1.58</b>                       | <b>-0.43</b>                     | -0.56                            | <b>-0.67</b>                      | -0.86                             | <b>-0.48</b> |
| avg                      | -0.34                              | -1.14                              | -0.47                            | -0.49                            | <b>-0.69</b>                      | -1.01                             | -0.48        |

If household utility  $u$  is determined by budget  $m$  and the cost of utility  $p$ , relative changes in utility can be decomposed by

$$\begin{aligned}
 \frac{du}{u} &= \frac{d(m/p)}{m/p} = \frac{\frac{m+dm}{p+dp} - \frac{m}{p}}{m/p} = \frac{(m+dm)\frac{p}{p+dp} - m}{m} \\
 &= \frac{(m+dm)\left(1 - \frac{p}{p+dp} - 1\right) - m}{m} = \frac{dm}{m} - \frac{m+dm}{m} \frac{dp}{p+dp}.
 \end{aligned}$$

The first set of nine items in the graphical decompositions in this paper are the parts that make up the first budget term ( $dm/m$ ) and the second set of items are contributions of commodity price changes to the second term. The decomposition of  $dp$  into its components relies on the nested CES structure of the utility

function. Minimization of unit cost of utility implies unit nest cost functions of

$$c_n = \bar{c}_n \left[ \sum_{i(n)} \theta_i^n \left( \frac{p_i}{\bar{p}_i} \right)^{1-\sigma_n} + \sum_{sn(n)} \theta_{sn}^n \left( \frac{c_{sn}}{\bar{c}_{sn}} \right)^{1-\sigma_n} \right]^{1/(1-\sigma_n)},$$

where  $c_n$  ( $\bar{c}_n$ ) are the (BAU) unit costs of nest  $n$ ,  $i(n)$  are direct inputs to nest  $n$  and  $sn(n)$  are subnests entering nests  $n$ .  $p_i$  ( $\bar{p}_i$ ) are the (BAU) prices of direct inputs  $i$ , and  $\theta_i^n$  the BAU expenditure shares of  $i$  in nest  $n$ . In the following we abstract from the difference between direct inputs  $i$  and subnests  $sn$  and decompose the changes in cost of one nest into the impact shares from price changes of the different inputs into that nest.

The decomposition of  $dp$  (that is, the change in utility cost) into its components (that are, changes in consumer costs of the consumed commodities and leisure) is achieved by defining the contribution of changes in commodity prices  $p_i$  to changes in  $p$  as  $\gamma_i dp$ , where

$$\gamma_i = \theta_i \frac{\left( \frac{p_i + dp_i}{p_i} \right)^{1-\sigma} - 1}{\left( \frac{p + dp}{p} \right)^{1-\sigma} - 1}$$

and  $\theta_i$  are the BAU expenditure shares for commodity  $i$  in total expenditures on household utility. If changes in price  $j$  contribute with share  $\gamma_j$  to a cost increase of subnest  $sn$  and the cost increase contributes with share  $\gamma_{sn}$  to the change in cost of nest  $n$ , the impact share of price change  $j$  to cost change  $n$  is  $\gamma_{sn} \gamma_j$ .<sup>17</sup>

Figures 9 and 10 show the corresponding information of Figures 7 and 8 for all household types in the model.

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<sup>17</sup>It is straightforward to show that this decomposition into contribution shares  $\gamma_i$  satisfies the following conditions.

- The sum of the contribution shares  $\gamma_i$  sum up to 1 at each nesting level,
- contribution shares for utility inputs without price changes are 0,
- contribution shares for homogeneous price increases across all inputs are  $\gamma_i = \theta_i$ , and
- contribution shares due to changes in one input price at constant other input prices are monotonously increasing in price changes.

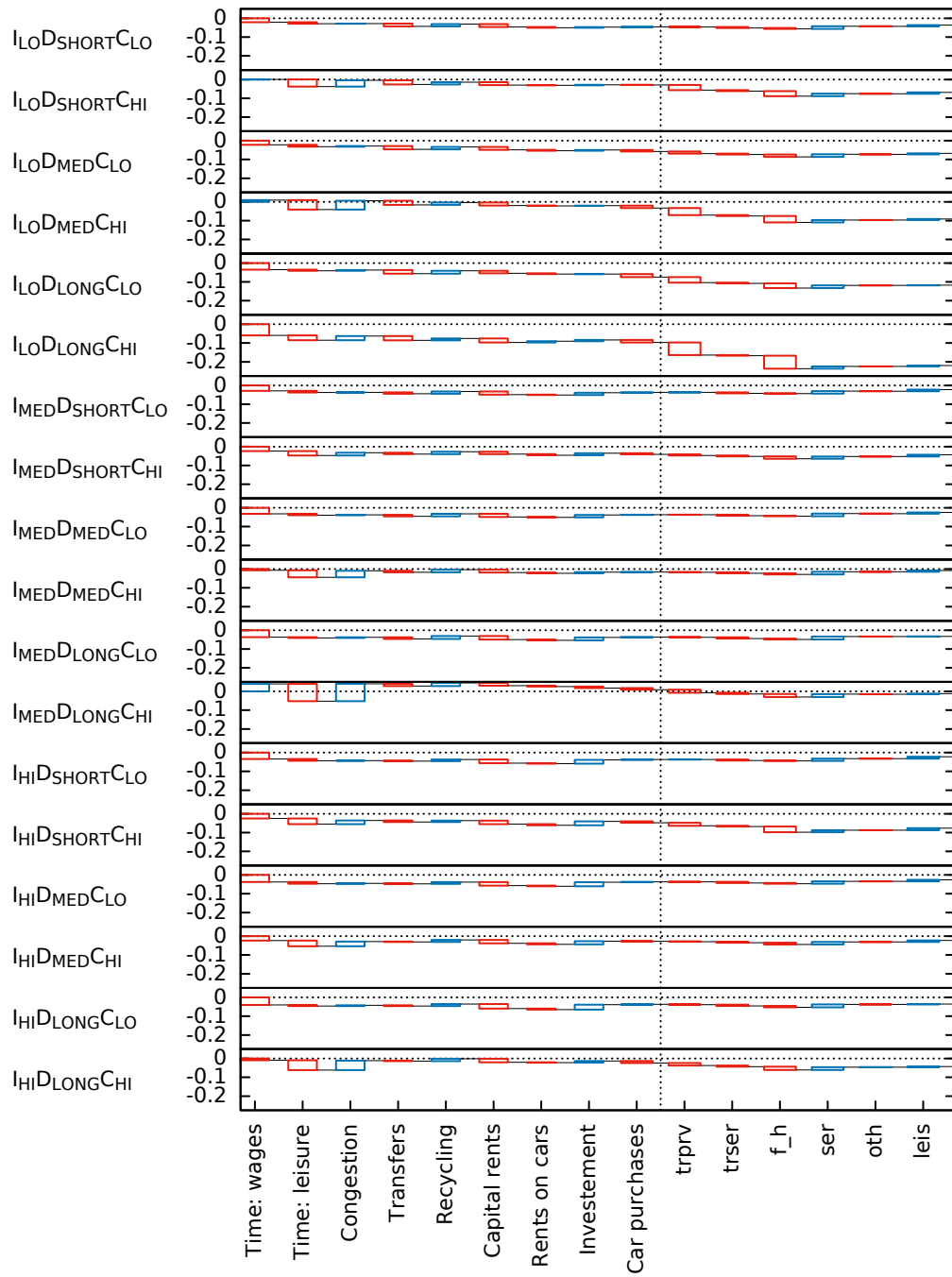


Figure 9: Decomposition of welfare impacts per household type for scenario *tax* in 2050. Changes are relative to BAU welfare and add up to total welfare changes in Table 6.

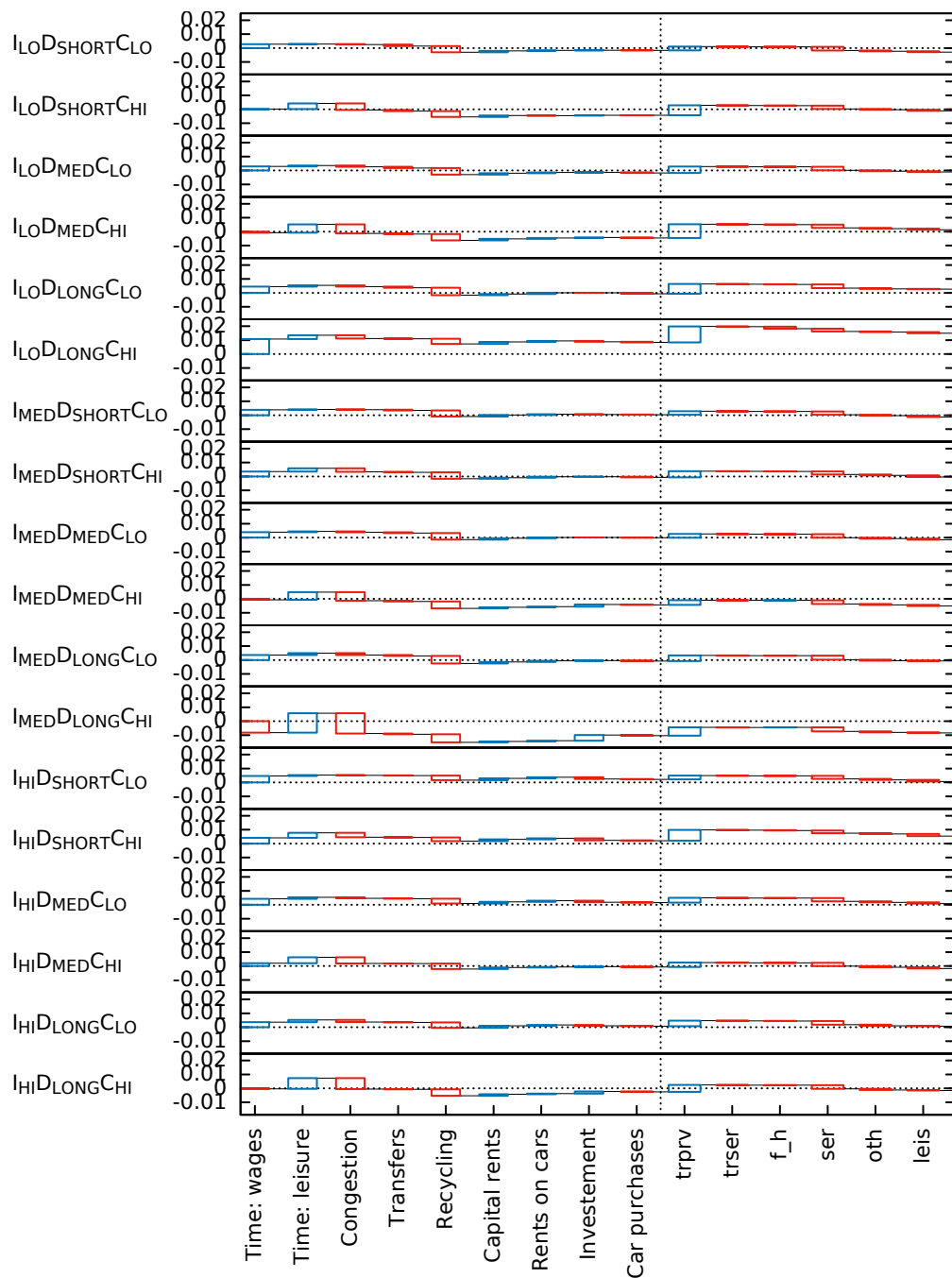


Figure 10: Decomposition of welfare impacts per household type for scenario *standard* in 2050. Changes are compared to scenario *tax*, relative to BAU welfare and add up to differences in welfare changes between *standard* and *tax* in Table 6.

## Appendix D Results without congestion

Tables 9 and 10 show results if we assume that time spent in traffic does depend on the aggregate traffic levels. It becomes apparent that under this assumption, the fuel efficiency standard achieves higher aggregate cost-efficiency. Also the lowest income quintile as a whole, and the medium and long range commuters in particular, prefer the fuel efficiency standard if congestion is not part of the model.

Table 9: Welfare results (EV including leisure at market wage rate) for 2030. Rows differentiate income levels, columns differentiate different types of commutes. Results in **bold** font indicate household groups that prefer the respective policy option for the given year.

| Scenario <i>tax</i>      |                                    |                                    |                                  |                                  |                                   |                                   |              |
|--------------------------|------------------------------------|------------------------------------|----------------------------------|----------------------------------|-----------------------------------|-----------------------------------|--------------|
|                          | D <sub>SHORT</sub> C <sub>LO</sub> | D <sub>SHORT</sub> C <sub>HI</sub> | D <sub>MED</sub> C <sub>LO</sub> | D <sub>MED</sub> C <sub>HI</sub> | D <sub>LONG</sub> C <sub>LO</sub> | D <sub>LONG</sub> C <sub>HI</sub> | avg          |
| I <sub>LO</sub>          | <b>-0.53</b>                       | -2.26                              | -1.12                            | -2.74                            | -2.08                             | -5.89                             | -1.18        |
| I <sub>MED</sub>         | <b>-0.29</b>                       | -1.01                              | <b>-0.38</b>                     | -0.58                            | -0.60                             | -1.31                             | <b>-0.43</b> |
| I <sub>HI</sub>          | -0.42                              | -2.24                              | -0.56                            | -0.83                            | -0.83                             | -1.42                             | -0.64        |
| avg                      | <b>-0.36</b>                       | -1.59                              | -0.51                            | -0.84                            | -0.82                             | -1.80                             | -0.59        |
| Scenario <i>standard</i> |                                    |                                    |                                  |                                  |                                   |                                   |              |
|                          | D <sub>SHORT</sub> C <sub>LO</sub> | D <sub>SHORT</sub> C <sub>HI</sub> | D <sub>MED</sub> C <sub>LO</sub> | D <sub>MED</sub> C <sub>HI</sub> | D <sub>LONG</sub> C <sub>LO</sub> | D <sub>LONG</sub> C <sub>HI</sub> | avg          |
| I <sub>LO</sub>          | -0.63                              | <b>-2.08</b>                       | <b>-1.10</b>                     | <b>-2.35</b>                     | <b>-1.89</b>                      | <b>-4.91</b>                      | <b>-1.15</b> |
| I <sub>MED</sub>         | -0.34                              | <b>-0.92</b>                       | -0.42                            | -0.58                            | <b>-0.54</b>                      | <b>-1.20</b>                      | -0.45        |
| I <sub>HI</sub>          | <b>-0.35</b>                       | <b>-1.78</b>                       | <b>-0.45</b>                     | <b>-0.75</b>                     | <b>-0.68</b>                      | <b>-1.24</b>                      | <b>-0.54</b> |
| avg                      | -0.38                              | <b>-1.40</b>                       | <b>-0.50</b>                     | <b>-0.79</b>                     | <b>-0.71</b>                      | <b>-1.57</b>                      | <b>-0.56</b> |

This results from the missing benefit of the carbon tax's reduction of congestion and the difference between household welfare under the standard and under the tax change in favor of the standard for *all* household types.



Table 10: Welfare results (EV including leisure at market wage rate) for 2050. Rows differentiate income levels, columns differentiate different types of commutes. Results in **bold** font indicate household groups that prefer the respective policy option for the given year.

| Scenario <i>tax</i>      |                                    |                                    |                                  |                                  |                                   |                                   |              |
|--------------------------|------------------------------------|------------------------------------|----------------------------------|----------------------------------|-----------------------------------|-----------------------------------|--------------|
|                          | D <sub>SHORT</sub> C <sub>LO</sub> | D <sub>SHORT</sub> C <sub>HI</sub> | D <sub>MED</sub> C <sub>LO</sub> | D <sub>MED</sub> C <sub>HI</sub> | D <sub>LONG</sub> C <sub>LO</sub> | D <sub>LONG</sub> C <sub>HI</sub> | avg          |
| I <sub>LO</sub>          | <b>-4.35</b>                       | -10.02                             | -7.59                            | -13.08                           | -12.49                            | -23.39                            | -7.12        |
| I <sub>MED</sub>         | <b>-2.66</b>                       | -5.68                              | <b>-2.98</b>                     | -3.57                            | -3.92                             | -7.60                             | -3.21        |
| I <sub>HI</sub>          | -2.53                              | -8.87                              | -2.99                            | -4.02                            | -4.10                             | -7.24                             | -3.39        |
| avg                      | <b>-2.85</b>                       | -7.45                              | -3.42                            | -4.50                            | -4.74                             | -8.98                             | -3.73        |
| Scenario <i>standard</i> |                                    |                                    |                                  |                                  |                                   |                                   |              |
|                          | D <sub>SHORT</sub> C <sub>LO</sub> | D <sub>SHORT</sub> C <sub>HI</sub> | D <sub>MED</sub> C <sub>LO</sub> | D <sub>MED</sub> C <sub>HI</sub> | D <sub>LONG</sub> C <sub>LO</sub> | D <sub>LONG</sub> C <sub>HI</sub> | avg          |
| I <sub>LO</sub>          | -4.49                              | <b>-9.62</b>                       | <b>-7.50</b>                     | <b>-12.29</b>                    | <b>-12.03</b>                     | <b>-21.65</b>                     | <b>-7.02</b> |
| I <sub>MED</sub>         | -2.71                              | <b>-5.48</b>                       | -3.02                            | <b>-3.56</b>                     | <b>-3.82</b>                      | <b>-7.36</b>                      | -3.21        |
| I <sub>HI</sub>          | <b>-2.42</b>                       | <b>-8.09</b>                       | <b>-2.82</b>                     | <b>-3.90</b>                     | <b>-3.88</b>                      | <b>-6.89</b>                      | <b>-3.22</b> |
| avg                      | -2.87                              | <b>-7.07</b>                       | <b>-3.38</b>                     | <b>-4.38</b>                     | <b>-4.57</b>                      | <b>-8.55</b>                      | <b>-3.67</b> |