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How to road price in a world with electric vehicles and government budget constraints

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ABSTRACT

In this paper we examine what characterizes second-best road prices targeting external costs from driving electric (EV) and conventional (ICEV) vehicles when there are distortionary labor taxes and binding government budget constraints. Further, we examine how this second-best pricing fits with government set goals of reducing CO_2 emissions. The paper further develops an analytical framework for assessing first- and second-best road prices on vehicle kilometers, extending it to include EVs and externalities that vary geographically and by time of day. We find that optimal road prices largely vary with external cost, but are also significantly affected by the interactions with the rest of the fiscal system. Not surprisingly, the highest road prices should be for ICEVs in large cities during peak hours due to high external costs. More surprisingly, we find that the road price for ICEVs in rural areas should be lower than that for EVs due to large fiscal interaction effects. These road prices give large welfare gains, but they lead to no reduction in carbon emissions when applying the currently recommended social cost of carbon.

1. Introduction

The road transport market is associated with market imperfections such as local and global pollution, accidents, noise and road wear. Thune-Larsen et al. (2014) calculate external costs in Norway of up to NOK 30 billion (Norwegian kroner; 1 NOK = €0.11 = $0.13) per year from road transport – a figure that does not include CO_2 costs, even though road transport in 2015 accounted for 19% of Norway's greenhouse gas (GHG) emissions (Ministry of Finance, 2017). In addition to externalities from road transport, inefficiencies in the economy arise from distortionary taxes elsewhere. Externalities and inefficiencies in the tax system have recently come under renewed scrutiny with government-assigned expert committees publishing so-called Norwegian Official Reports (Norges Offentlige Utredinger – NOU), with NOU 2014:13 – *Capital Taxation in an International Economy* and NOU 2015:15 – *Green Tax Commission.* Looking for ways by which to mitigate these inefficiencies is in itself motivation for this paper.

As recommended by many transport economists before us, we propose a road pricing scheme for mitigating these inefficiencies. More specifically, we propose distance-based road pricing, differentiated across vehicle types and pre-defined areas and time periods according to their external costs, also factoring in revenue recycling through labor taxation.

We raise the following research questions: What characterizes the set of second-best road prices targeting external costs from driving EVs and ICEVs when there are distortionary labor taxes and binding government budget constraints? How are these prices affected by tax distortions in the labor, electricity and car ownership market? How does this second-best pricing fit with government set goals of reducing CO_2 emissions?

Our paper makes the following contributions: First, it extends an established modeling framework for optimal taxation in

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transport with revenue recycling of distortionary labor taxes to include (a) different areas and time periods where external costs vary, and (b) both ICEVs and EVs and their associated taxes. This allows us to take a broad view how a national road pricing scheme optimally would look like. As road prices per combination of vehicle type, area and time period, and the labor tax rate are determined simultaneously, this model also allows us to see the endogeneity of how changes in one road price affects the levels of the others. This can result in road prices that differ from traditional Pigovian solutions in several dimensions. We can also see how costs and benefits of the scheme are distributed geographically. Second, it provides numerical results for the case of Norway, a country where the Ministry of Transport has started investigating the possibilities for distance-based road pricing applying satellite technology. It is also the country with the highest EV share of the car fleet in the world, strengthening both fiscal and externality arguments for moving from fuel tax to a more sophisticated way of road pricing.

Our paper is constructed as follows. In Section 2 we provide some background and literature review. In Section 3 we introduce the analytical framework and derive expressions for optimal road prices. The numerical modeling with parameter values and scenarios is explained in Section 4, while the results from the modeling exercise are given in Section 5. Section 6 concludes.

2. Background and literature

In order to strike the appropriate balance between costs and benefits in the affected markets, the “textbook economics” solution would be to find a set of taxes that provide the incentives for economic agents to do so. The optimal gasoline (or diesel) tax is given as one solution in several papers; for instance, in the cases of the UK and USA (Parry and Small, 2005), and Germany (Tscharaktschiew, 2014, 2015).

However, there are shortcomings to correcting road transport market failures through fuel taxation. First, the external costs of driving vary depending on where and when it takes place, making a fuel tax an imprecise instrument. In addition, a fuel tax provides incentives for more energy efficiency, which could be beneficial with regard to carbon emissions and oil reliance, but lead to higher external costs because lower user costs per kilometer would induce more driving. This has been pointed out in several papers (see e.g., Parry et al., 2014a; Parry and Small, 2005; Proost et al., 2009).

Second, the possibility for fuel taxes to (imprecisely) correct for externalities and generate government revenue is reduced when EVs (electric vehicles)[1] are introduced. EVs have many of the same externalities as ICEVs (internal combustion engine vehicles), but they cannot be captured by a gas tax and it seems implausible they can be taxed explicitly from electricity use.

So, are there better ways of taxing, ways that internalize external cost more precisely and allow for the taxation of all cars? This brings us into the discussion of road pricing. A vast literature on road pricing has accumulated over the decades. Button and Verhoef (1998, p. 4) refer to Pigou (1920) and Knight (1924) as the spiritual fathers of road pricing. Since then, hundreds of theoretical and empirical papers on a wide variety of road pricing schemes have been published, making it useful to specify exactly what kind of road pricing this article will focus on. Levinson (2010) developed a typology with 90 types of road pricing, organizing it along the three dimensions; the spatial resolution, the temporal resolution and the pricing objective. Within the dimensions of this typology, this article focuses on area based,[2] time-varying, second-best road pricing.

We focus on this specific type of road pricing because we believe it has a potential to generate large efficiency improvements for a country like Norway. Support for the merits of the distance-based aspects can be found in the literature. Analysis from Parry and Small (2005) and from May and Milne (2004) shows that distance-based road pricing can generate greater social benefits than, for example, fuel taxation and cordon-tolling. Furthermore, modeling analysis from Meurs et al. (2013) suggests that distance-based road pricing using satellite technology can be beneficial for the Netherlands compared to the current tax system for car-use and car-ownership. Small and Verhoef (2007) along with André de Palma and Lindsey (2011) argue for the potential for high economic efficiency of distance-based road pricing, and note that GPS technology is suitable for a scheme like this. The latter argue that a satellite-based road-pricing system has advantages with regards to scale economies and in the potential for value-added services and revenue generation.

The technologies underlying satellite-based road pricing have matured over the last decades, meaning that the timing is good for research having this in mind. Such technology could in theory enable the theoretically best type of road pricing according to the typology from Levinson (2010); dynamic marginal cost pricing on differentiated links. However, both privacy concerns and the understandability of the system for the general public sets a limit on spatial and temporal granularity. It will probably not be permissible for the road pricing authority to monitor car users at the finest level of detail, and a large number of car users cannot be expected to understand a system with a wide variety of dynamically changing road prices. This makes distance-based prices differentiated across pre-defined areas and time periods a promising alternative. Finally, because of the new emphasis on reducing inefficiencies in the Norwegian tax system, we want to focus on second-best road prices as a part of a tax reform where revenues are recycled back into the economy through reduced distortionary labor taxes.

Many of the aspects included in this specific form of road pricing have been covered in previous literature. The term road pricing has primarily been associated with road traffic congestion (Button and Verhoef, 1998, p. 6), and this has been the study of numerous papers. Over time, several papers have included environmental and/or accident externalities along with congestion (De Borger and Mayeres, 2007; De Borger and Wouters, 1998; André De Palma et al., 2004; Munk, 2008). Several papers have considered how road

[1] In this paper, when we refer to electric vehicles (EVs) we consistently mean pure battery electric vehicles (BEVs), without any hybrid technology.

[2] More specifically, distance-based road pricing that vary by a small number of areas; large city, small city and rural.

prices should differ across areas, e.g., between the urban and the non-urban setting (Munk, 2008; Proost and Van Dender, 1998) or across the diesel and gasoline cars (De Borger and Mayeres, 2007), and an integrated transport and land-use model that can e.g., simulate the effects of distance-based road pricing differentiated by area and gasoline, diesel and electric cars is under development in the OECD (Tikoudis and Oueslati, 2017). Finally, many influential papers have considered road prices in interaction with other distortionary taxes (see e.g., De Borger, 2009; André De Palma and Lindsey, 2004; Mayeres and Proost, 1997; Munk, 2008; Parry and Bento, 2001; Parry and Small, 2005; Van Dender, 2003).

We build on an analytical framework introduced by Parry and Small (2005), who applied it in deriving the optimal First-Best Pigou-Ramsey tax for gasoline in the UK and USA. This model was also used by Lin and Prince (2009) and by Antón-Sarabia and Hernández-Trillo (2014) in calculating the optimal gasoline tax in California and Mexico, respectively. A modified version is used in Parry (2009) and Tscharaktschiew (2015). Parry (2009) uses it to calculate optimal gasoline and diesel taxes, and Tscharaktschiew (2015) uses it to calculate optimal gasoline taxes in a model with both electric and diesel cars. It is a fairly simple model that generates insight and intuition. To a large extent, we build on the Tscharaktschiew (2015) version, which contains EV considerations. In this paper, we extend these model exercises in several dimensions in order to assess the optimal second-best tax for vehicle kilometers (hereafter, road prices). First, we analyze optimal road prices for both EVs and ICEVs and not just a single policy instrument such as gasoline tax. Second, we model how externalities vary geographically and by time of day, which gives us a set of second-best road prices that differ across four different stylized spatiotemporal states, large cities during peak hours, large cities off-peak, small cities and in rural areas. Third, we apply the model to analyze the shadow price for reaching a (sector-specific) GHG emissions reduction target at least cost.

The Pigovian solution of setting the corrective tax equal to marginal external cost (MEC) is well known (see e.g., Perman, Ma et al., 2003). In this paper, we place ourselves in a second-best world with binding budget constraints and distortionary labor taxes, so we want to find second-best road prices. This is related to the debate on how to correctly assess optimal environmental taxation in the presence of distortionary taxation elsewhere in the economy (see e.g., Bovenberg, 1999; Jacobs and de Mooij, 2015) and the marginal cost of public funds (MCF) (for a recent review, see Holtsmark and Bjertnæs, 2015). This literature shows that the debates on these topics are far from settled. We construct a model for analyzing optimal road prices in an economy with distortionary taxes, and any analyst using it may choose to disallow MCF above 1, perhaps as part of a "moral sensitivity analysis" (see e.g., Mouter, 2016). The model can thus serve as a practical tool for analyzing the costs and benefits of road prices under varying assumptions.

3. Analytical framework

As explained above, we emphasize the importance of differentiating between spatiotemporal states, because the estimated value of the externalities varies between them. In order to avoid cumbersome notation, we attempt to solve the model for a single state containing all of the externalities, a state that can be thought of as a large city during peak hours. The numerical model calculates solutions for all of the states under consideration.

We make the simplifying assumption that agents and their cars are constrained to remain within one state only. Although this constraint is fairly strict, it should still cover the main purpose each agent has with her car.

We consider a static, closed economy model with a representative household with the following utility function:

$$U = u(m_F, v_F, m_P, v_P, X, l, T, E) \tag{1}$$

The utility function $u(.)$ considers goods in per household terms. It is quasi-concave and increasing in arguments m_F and m_P, kilometers driven per car of type ICEV (F) and EV (P). It is also increasing in v_F and v_P; the number of cars per type.[3] This also applies for general consumption X, and leisure l. In contrast, utility is decreasing in arguments T, total in-vehicle travel time that, in addition to being an activity with some disutility (possibly), also reduces household utility through taking away time potentially used for working (and earning for consumption) and leisure. Utility is also decreasing in E, representing an index of environmental externalities.

Total travel time for a household depends on aggregate vehicle kilometrage $\bar{M}$ in a particular area. We use bar notation to denote economy-wide variables perceived as exogenous by travelers. The total per-period travel time for a household is given by:

$$T_i = t(\bar{M})M \tag{2}$$

The average travel time per kilometer $t(\bar{M})$ is increasing in the aggregate vehicle kilometers travelled ($t' > 0$) as higher economy-wide kilometrage leads to time delays due to congestion (in our stylized model we assume that such large traffic volumes in one area only occur in large cities during rush hours) and

$$M = M_P + M_F = m_P v_P + m_F v_F \tag{3}$$

is the per-household distance traveled by car per period.

Environmental externalities $E_i = \{E_F(\bar{F}), E_P(\bar{P}), E_{M_F}(\bar{M}_F), E_{M_P}(\bar{M}_P)\}$ cover traffic externalities stemming from energy consumption E_F and E_P (increasing in the use of fossil fuels and electricity, F and P) and from vehicle kilometrage E_{M_i} (increasing in $\bar{M}_i$ for each vehicle type i). The partial derivatives of E translate into marginal external damage (in units) from energy usage and kilometers traveled by car. We assume in this paper that there are no externalities associated with producing and consuming electricity for EVs,

[3] We look at average ownership rates of vehicle types per household, treating it as a continuous variable.

i.e., $E_P(\bar{P}) = 0$. In regard to GHGs, this assumption may hold for Norway, whose electricity generation consists overwhelmingly of hydro (95.8% hydro in 2015) (IEA, 2017). The argument is further strengthened by the fact that Norway is a part of the EU ETS market, as discussed in Bjertnæs (2016).

In the household monetary budget constraint, expenditures related to car transport and other consumption are set equal to after-tax income in the following way:

$$[(R_F\widetilde{f} + c_F^d)m_F + \tau_{mF}m_F + c(\widetilde{f}) + \Gamma_F]v_F + [(R_P\widetilde{p} + c_P^d)m_P + \tau_{mp}m_P + c(\widetilde{p}) + \Gamma_P]v_P + P_XX = (1-\tau_L)wL \tag{4}$$

Here, $R_i = (r_i + \tau_i)$ denotes the consumer price per unit of energy type *i*. All consumer prices contain the pure fixed producer energy supply price r_i and the energy tax τ_i. Energy intensity for cars, expressed in units per kilometer, is denoted $\widetilde{f}$ for ICEVs and $\widetilde{p}$ for EVs – lower energy intensity means higher energy efficiency. The terms c_F^d and c_P^d denote the other distance-dependent costs (repairs, service, etc.). We assume away any costs related to range anxiety or waiting time at charging stations for EVs.[4] Tolls are averaged to per-kilometer road prices (τ_{mF} and τ_{mp}). The terms $c(\widetilde{f})$ and $c(\widetilde{p})$ denote the other costs of owning a car, independently of distance. This would mainly be an annuity of the pre-tax purchase cost – costs assumed to depend on energy efficiency. These capture how increasing energy efficiency comes at a cost (otherwise every-one would choose the highest level of energy efficiency). As we will see later, the model agent has an elasticity of fuel efficiency and can thus respond to changes in consumer fuel costs by choosing higher or lower fuel intensity. Γ_i represents the sum of the annual ownership tax and the annuity of the purchase tax for vehicle type. The cost of the general consumption goods basket is given by P_XX.

Net labor income per household is given by $(1-\tau_L)wL$, where τ_L is the tax rate on labor. Finally, w represents hourly gross wage, while L represents labor supply (total per-year working hours). Total pre-tax labor income is denoted as W.

The relationship between fuel use, energy intensity and kilometers driven is given by:

$$F = \widetilde{f}M_F = \widetilde{f}m_Fv_F \tag{5}$$

$$P = \widetilde{p}M_P = \widetilde{p}m_Pv_P \tag{6}$$

Households also have a time constraint that can be written as follows:

$$L + l + t(\bar{M})M = \bar{L} \tag{7}$$

Available time $\bar{L}$ is distributed between the activities labor, leisure and car travel.

The government is subject to the following budget constraint, where fixed public spending *GOV* is set equal to net revenue from all taxes:

$$GOV = \tau_FF + \tau_PP + \tau_{mF}m_Fv_F + \tau_{mp}m_Pv_P + \tau_LwL + \Gamma_Pv_P + \Gamma_Fv_F, \tag{8}$$

We make the simplifying assumptions that general consumption goods are produced by firms under perfect competition and with constant returns to scale technology, where labor is the only production input. This means that the firms generate no pure economic profits and all producer prices are fixed. The gross wage for workers, *w,* equates the value of the marginal product of labor, which is assumed to be constant.

3.1. Maximizing utility

Households are assumed to maximize their utility function given in Eq. (1) with respect to the choice variables $m_F, v_F, \widetilde{f}, m_P, v_P, \widetilde{p}, X$ and l. The optimization is subject to Eqs. (4) and (7), representing the monetary budget constraint and time constraint, respectively. Households treat travel times (affected by aggregate kilometrage), external environmental damages and all tax levels as given. We form the Lagrangian – where μ is the Lagrange multiplier for the complete economic household budget constraint and can be interpreted as the marginal utility of income. We get first-order conditions from the optimization and use these to obtain the household's indirect utility function, which yields maximized utility given prices, taxes and income, but also travel time and externalities determined by the *aggregate* level of driving.

The households' indirect utility function can be expressed by the following set of parameters $\Omega \equiv \{\tau_{mF}, \tau_{mp}, \tau_P, \Gamma_F, \Gamma_P, \tau_L, t, E\}$. These parameters (policy variables and time and environmental externalities) are, as previously mentioned, treated as given by the households. The government's aim is to maximize the indirect utility function using the road pricing scheme policy variables.

$$\begin{aligned} V(\Omega) \equiv \max_{m_F,v_F,\widetilde{f},m_P,v_P,\widetilde{p},X,l} & u(m_F, v_F, m_P, v_P, X, l, T, E) - \mu([(R_F\widetilde{f} + c_F^d)m_F + \tau_{mF}m_F + c(\widetilde{f}) + \Gamma_F]v_F \\ & + [(R_P\widetilde{p} + c_P^d)m_P + \tau_{mp}m_P + c(\widetilde{p}) + \Gamma_P]v_P + P_XX - (1-\tau_L)w(\bar{L} - l + t(\bar{M})M)) \end{aligned} \tag{9}$$

We show the analytical exercise of deriving the optimal tax on EV-km, τ_{mp}. Government revenues from τ_{mp} are recycled through reducing labor taxes, and all other transport and energy taxes are kept constant. All the steps of the analytical derivations are given in

[4] A standard range of 190 km would be sufficient for most daily commuters that charge the car at home. According to Figenbaum (2018), there are about 1000 fast-chargers in Norway, amounting to one fast-charger per 140 BEV owners. The fast-chargers are mainly located in and around the cities, and along the highways between cities. In addition, there are about 7500 slow or semi-fast chargers that are public (and/or work place), making coverage adequate for most trip purposes in most parts of the country, but not all.

Appendix A. Here, in the main part of the paper, only the most central equations are noted before we get to the analytical results. The analytical exercise starts with total differentiation of the household's indirect utility function with respect to τ_{mp}. After some algebra and redefining of the externality terms we get the following expression for the marginal welfare effect of the kilometer tax:

$$\frac{1}{\mu}\frac{\partial V}{\partial \tau_{mp}} = \underbrace{e_F\left\{-\frac{dF}{d\tau_{mp}}\right\}}_{\text{energy related externalities}} + \underbrace{e_m^c(M)\left\{-\frac{dM}{d\tau_{mp}}\right\}}_{\text{congestion externalities}} + \underbrace{e_{mF}^{nc}\left\{-\frac{dM_F}{d\tau_{mp}}\right\} + e_{mp}^{nc}\left\{-\frac{dM_P}{d\tau_{mp}}\right\}}_{\substack{\text{kilometrage related}\\ \text{non-congestion externalities}}} - \underbrace{\left[\tau_{mp}\left\{-\frac{dM_P}{d\tau_{mp}}\right\} + \tau_{mF}\left\{-\frac{dM_F}{d\tau_{mp}}\right\}\right]}_{\text{km-tax revenue}}$$
$$-\underbrace{\left[\tau_F\left\{-\frac{dF}{d\tau_{mp}}\right\} + \tau_P\left\{-\frac{dP}{d\tau_{mp}}\right\}\right]}_{\text{energy tax revenue}} \underbrace{+D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}}}_{\substack{\text{direct/indirect tax revenue/cost from}\\ \text{vehicle stock}}} + \underbrace{\tau_L\frac{dW}{d\tau_{mp}}}_{\text{labor tax revenue}} \tag{10}$$

Parameter e_F represents the MEC stemming from the consumption of fossil fuel. We also have MEC of driving 1 km when contributing to congestion $e_m^c(M)$, which is increasing in traffic volumes. Similarly, parameters e_{mF}^{nc}, and e_{mp}^{nc} represent the environmental MEC from driving 1 km from ICEVs and EVs, respectively (assumed to be constant within a given state). Parameters D_F and D_P represent the per vehicle annual tax revenue $\tau_{mF}\,m_F + \tau_F\widetilde{f}\,m_F + \Gamma_F$ and $\tau_{mp}\,m_P + \tau_P\widetilde{f}\,m_P + \Gamma_P$. As we can see, the EV-km tax brings about a number of different changes in Eq. (10), which shows that the kilometer tax affects overall welfare through several channels.

3.2. Deriving second-best road prices

We set the marginal welfare change (given by Eq. (10)) equal to zero and solve for τ_{mp}. This gives us the following expression:

$$\tau_{mp}^* = e_F\left\{\frac{dF/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\} + e_m^c(M)\left\{\frac{dM/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\} + e_{mF}^{nc}\left\{\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\} + e_{mp}^{nc}$$
$$+\left[\tau_{mF}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}}\right]\frac{1}{-dM_P/d\tau_{mp}} \tag{11}$$

After more algebra, which is shown in Appendix A, we get the final expression for the optimal kilometer tax:

$$\tau_{mp}^* = \tau_{mp}^C + \tau_{mp}^I = \tau_{mp}^C + \tau_{mp}^{RR} + \tau_{mp}^{TI} = \tau_{mp}^C + \tau_{mp}^{RR} + \tau_{mp}^{(TI)} + \tau_{mp}^{CF} \tag{12}$$

The first term is the corrective component:

$$\tau_{mp}^C = e_{mp}^{nc} + e_m^c(M) + \eta_F\left(e_m^c(M) + e_{mF}^{nc}\right) + \chi_F e_F \tag{13}$$

Parameters η_F and χ_F are for how consumption of ICEV-kms and fossil fuel react to the EV-km tax. Note that in our second-best world we have to look at the total effect of the road price, and not simply equate the corrective tax to MEC.

The second term in (12) is the revenue recycling component:

$$\tau_{mp}^{RR} = \Omega_{\tau_L}\left(\frac{(R_P\widetilde{p} + c_P + \tau_{mp})}{-\varepsilon_{M_P}} - \tau_{mp}\right) \tag{14}$$

The term consists of the marginal cost of public funds, Ω_{τ_L}, times the net tax revenue from marginally increasing the EV-km tax. The parameter ε_{M_P} is the own-price elasticity of EV-kms.

The third term in (12) is the tax interaction component (excluding the congestion feedback component):

$$\tau_{mp}^{(TI)} = -(1 + \Omega_{\tau_L})\left[\left(\frac{\tau_L(R_P\widetilde{p} + c_P^d + \tau_{mp})(\varepsilon_{MI}^c + \varepsilon_{LI})}{(-\varepsilon_{M_P})(1-\tau_L)}\right) + \eta_F\tau_{mF} + \chi_F\tau_F + \widetilde{p}\,\tau_P + \kappa_P D_P + \varphi_F D_F\right] \tag{15}$$

The fourth term is the congestion feedback component:

$$\tau_{mp}^{CF} = (1 + \Omega_{\tau_L})\frac{\tau_L}{(1-\tau_L)}(\varepsilon_{LI}(1-\varepsilon_{MI})\varepsilon_{LL}^c)e_m^c(M)[\eta_F + 1] \tag{16}$$

The previously unmentioned parameters in these expressions are ε_{MI}^c and ε_{MI}, the compensated and uncompensated income elasticities for vehicle kilometers, ε_{LI}, the income elasticity of labor supply, and ε_{LL}^c, the compensated elasticity of labor supply. Ω_{τ_L} is the marginal cost of public funds (MCF), which has the following formula:

$$\Omega_{\tau_L} \equiv \frac{-\tau_L w\frac{\partial L}{\partial \tau_L}}{W + \tau_L w\frac{\partial L}{\partial \tau_L}} = \frac{\frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}}{1 - \frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}} \tag{17}$$

This term reflects the marginal efficiency cost of raising public funds through taxing labor. On the flip side, it also reflects the marginal efficiency gain from cutting tax on labor, which could be done by, e.g., raising funds from road pricing. The numerator in this expression represents the efficiency cost from an incremental increase in labor taxation, while the denominator gives us the marginal change in public revenue. $\varepsilon_{LL} > 0$ represents the elasticity of labor supply (uncompensated). We have $\Omega_{\tau_L} > 0$ as a consequence of $\varepsilon_{LL} > 0$ and $1 > \frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}$. The latter implies that τ_L is not so large that we find ourselves on the right side of the Laffer curve's peak, meaning that government revenue from increasing labor taxation will, on the margin, be positive.

Components of the optimal tax have been described thoroughly in Tscharaktschiew (2014, 2015), but here is a brief explanation.

The corrective tax component addresses the external environmental damages from driving an EV-km. It includes the kilometer-related externalities in relation to congestion (same for all vehicles), and externalities such as pollution, noise and accident risk (differs between EVs and ICEVs). Note that the tax on EV-kms may induce more driving of ICEVs, which contributes to a reduction in the level of the corrective component.

The revenue recycling component is the efficiency gain from using additional EV-km tax revenue to cut the distortionary labor tax and increase the efficiency of the tax system. The effect is equal to the marginal cost of public funds times the marginal net EV-km tax revenue gains due to the increase in EV-km taxation.

The tax interaction component accounts for the efficiency loss in the labor market from the higher tax on kilometers. On the one hand, higher taxes reduce the real household wage and have a discouraging effect on labor supply. On the other, they include the income effect on labor supply from a higher km-tax. The other terms cover how the EV-km tax interacts with secondary markets, e.g., the electricity market, and the tax distortions there.

The congestion feedback component accounts for how raising the cost of travel through road prices may reduce vehicle kilometers and congestion, and in that way affect labor supply through reductions in travel time. Workers may then allocate less of their time on travel, and more of their time on either working or enjoying leisure activities. Since labor is subject to taxation, such a feedback effect would improve welfare and *ceteris paribus* cause upward adjustments to the second-best kilometer tax. When we present our numerical results, this is included in the tax interaction component where relevant, i.e. in the state large cities during peak hours.

3.3. Functional relationships

Parameters such as $\eta_F = \frac{dM_F\,/\,d\tau_{mp}}{dM_P\,/\,d\tau_{mp}}$ quantify our assumptions on how households respond to changes in tax parameters. These parameters can be expressed in terms of elasticities, e.g., $\eta_F = \frac{M_F\varepsilon_{MF}^{MP}}{M_P\varepsilon_{MP}}$, where ε_{MF}^{MP} is the cross-price elasticity for ICEV-km, with respect to price change for EV-km. Furthermore, the *direct* response in per-vehicle demand for vehicle-kms when the EV-km tax changes can be expressed through $m_F = m_F^0\left(\frac{R_P\widetilde{p} + c_P^d + \tau_{mp}^*}{R_P\widetilde{p} + c_P^d + \tau_{mF}^0}\right)^{\varepsilon_{MF}^{MP}}$ and $m_P = m_P^0\left(\frac{R_P\widetilde{p} + c_P^d + \tau_{mp}^*}{R_P\widetilde{p} + c_P^d + \tau_{mp}^0}\right)^{\varepsilon_{mp}}$, where we assume constant elasticity of demand. This is common in these kinds of analysis of optimal pricing in the transport sector, as can be seen in for example Parry and Small (2005), Parry (2009) and Tscharaktschiew (2014, 2015). We have similar expressions for responses in vehicle stock. The parameters m_F^0 and m_P^0 are the per-vehicle kilometrage in the initial equilibrium. The levels in the new equilibrium depend on the road prices in the new equilibrium. If, for example, τ_{mp}^* does not differ from τ_{mp}^0, then there will be no change in the new equilibrium, as m_P would equal m_P^0.

As we can see from the equations that comprise the optimal taxes, the tax levels are on both the left-hand and right-hand sides of the equation, so they must be solved numerically. In addition, we solve the model for road prices for both ICEVs and EVs, and for all the stylized states simultaneously. The next step involves inserting parameter values into the model and calculating the optimal tax rates.

4. Numerical model description and parameter values

In this section, we explain the scenario for calculating optimal tax levels for EV- and ICEV-kms. The thought experiment for the calculation can be summarized as: (1) an assumption that the optimal kilometer taxes were implemented at the time of writing in 2017; (2) there is a medium-run adjustment from agents towards 2020[5]; and (3) based on these medium-run adjustments, we get values for the optimal taxes in 2020.

Our calculations ignore dynamics in the adjustments. We simply calculate the tax rates for 2020 with 2020 values on externalities (i.e. values applied today are real-price adjusted for future years, as is recommended practice for CBA conducted in Norway; see, e.g., NOU 2012:16 (2012)). All monetary values are given in 2015 prices. Applied values for vehicle kilometers and levels of labor and electricity taxes are also based on 2015 values.

Ideally, one would want to have individual tax levels for hundreds of car types based on the car's individual characteristics. In our model, we work with two types of car, an ICEV and an EV. The numerical values applied to the ICEVs are based on a weighted average of diesel and gasoline-powered vehicles, weighted by their estimated aggregate vehicle kilometers in 2015,[6] based on the BIG model[7] at the Institute of Transport Economics.

In the theoretical framework we have taxes on labor, fossil fuel, electricity, vehicle purchase and vehicle ownership, ICEV-km and

[5] This is reflected in the choice of elasticities in the model. A way to think of the changes in a medium -run equilibrium in e.g., the transport market, households are able to adjust their driving style, choices of destinations and frequencies, and a small fraction of them have had time to change vehicle ownership. We would expect e.g., little change in the choice of residential and work place location.

[6] Gasoline had 59% of the ICEV kms travelled in 2015, while diesel had 41%. To use the weighted average of gasoline and diesel as "fossil fuel" is a simplification that allows us to focus on the differences between EVs and ICEVs. While there are large differences between diesel and gasoline both with regards to external costs and current tax policy (Harding, 2014), the differences between electricity and any of the fossil fuels are even larger.

[7] The acronym is derived from "bilgenerasjonsmodell", meaning "car cohort model".

EV-km. In the numerical model, the current tax on fossil fuels, along with average tolls in the various states, is converted to a corresponding tax on ICEV-kms. When we optimize road prices, drivers will face a price that strikes a balance between costs and benefits from mitigating transport externalities and distortions in the labor market. That price will give drivers the incentive to economize their kilometers appropriately. However, in the corrective component of the road prices we find both the distance-dependent external costs (e.g., accident risk, local pollution, noise, etc.) and the external cost from fuel usage, which in this analysis derives from the social cost of CO_2. This cost component gives not only incentives for economizing on kilometers but also on fuel use. Changes in the external cost of fuel use would induce changes to both kilometers driven and fuel efficiency. It can be thought of as if taxes on fuel have been removed from the pump, but incorporated within the road price. Parts of the road price for a particular car would then differ according to its fuel intensity and be an implicit fuel tax. This model technicality is useful when we calculate the shadow price of reaching a GHG emissions reduction target at least cost using this road pricing scheme.

The government budget constraint must hold in equilibrium. The sum of changes from optimized km-tax revenue (that in the initial condition contains current fuel taxes and tolls), and subsequent changes in electricity, vehicle purchase and ownership tax revenue,[8] must be offset by changes in the labor tax. This makes the equilibrium labor tax rate endogenous.

The scenario mimics a reform where fuel taxes and tolls are shifted over to distance-based road prices, differentiated across area, time of day and vehicle type (almost exactly the reform recommended for Europe in De Borger and Proost (2015)), which are then optimized, taking into account that labor tax rates change to maintain revenue neutrality. A situation where optimal road prices lead to a reduction in labor tax rates corresponds to a net shift in tax burden from labor income to transport.

For the transport variables, the representative household in the model is considered as a weighted average of values for the different geographical areas we consider. The areas are large cities (more than 100 000 inhabitants), small cities (between 15 000 and 100 000 inhabitants), and rural areas (fewer than 15 000 inhabitants), which contain 28%, 32%, and 40% of Norwegian households, respectively. This is the same classification as in Thune-Larsen et al. (2014).

The applied parameter values for the model are given in Table 1.

Values for the external costs from road transport are all taken from Thune-Larsen et al. (2014), a report made for the Ministry of Finance, Ministry of Transport and Communications and The Ministry of Climate and Environment, that now serves as official guideline parameters for conducting CBA in Norway.[9] The congestion costs in this report are estimated for both freight and passenger car transport. We only apply the estimates for passenger car transport, implicitly assuming a constant level of freight transport. The external non-congestion costs consist of (with each component's share of the national average estimate in parenthesis) external cost estimates for local pollution (25%), noise (3%), accident risk (55%), road wear (< 1%) and winter management (16%). The component that causes the largest differences between large cities, small cities and rural areas is the local pollution component. This component is set to zero for EVs, and is the only difference between EVS and ICEVs with regards to non-congestion costs per km.[10] More information about the parameter values is given in Appendix C.

5. Model results

Here we present the calculations of the second-best distance-based road prices differentiated by vehicle and spatiotemporal state. Main results are given in Table 2.

5.1. Baseline second-best road pricing

The model calculates road prices that vary significantly between states and car types, largely reflecting the variation in external costs. This can be seen in Table 2. The highest price is on driving an ICEV in a large city during peak hours, mainly because of the external congestion costs. However, the marginal external congestion costs are lower in the new equilibrium than in the initial situation, as the transport volumes during peak hours have been reduced significantly for both EVs and ICEVs. It is still worth noting that the tax per kilometer is more than five times higher than the current sum of average toll and fuel tax per kilometer during peak hours.

The lowest price is on driving an ICEV in rural areas. The tax per kilometer is actually 60% lower in the new equilibrium than the sum of average toll and fuel tax per kilometer was initially. It is also worth noting that the optimal road price for ICEVs in rural areas is actually lower than for EVs in these areas. This is also the case for driving in small cities. Hence, the current preferential treatment of EV use, essentially facing zero taxation (except for general electricity taxation), is way below optimal road pricing.

In all cases there is a markup from the revenue recycling component, showing the efficiency gain from replacing revenue from

[8] The purchase and ownership taxes per ICEV is assumed to remain constant in this model. This is a caveat, as the purchase tax is progressive in both type approved CO_2-emissions and NO_X-emissions per km. Any increase in fuel efficiency in the car fleet will result in a decrease in purchase tax revenue, *ceteris paribus*. On the other hand, with a higher pre-tax cost of more fuel efficient cars, the VAT revenue will increase.

[9] Other possible external cost estimates could include estimates from the IMF (Parry et al., 2014b), but they only provide a national average for external costs, and we make a point of using estimates that vary across areas and times of day. Applying the parameters specifically estimated for the Norwegian context and recommended by official guidelines, also makes this exercise more relevant for a Norwegian policy discussion. This is also discussed in the sensitivity analysis.

[10] Note that EVs are assumed to have the same noise cost per km as ICEVs in spite of the higher engine noise from the latter. This is because noise from tires on asphalt dominates at speeds over 30 km/h according to Thune-Larsen et al. (2014). In any case, noise makes up a relatively small portion of the external costs, even in large cities.

Table 1
Parameter values for baseline calculations.

Model parameters	Symbol	Value	Denomination	Sources used and additional information
Vehicle technology, usage and ownership				
Initial "fossil" fuel intensity	$\widetilde{f}^0$	0.079	l/km	Institute of Transport Economics, BIG model
EV electricity intensity (average of winter and summer)	$\widetilde{p}^0$	0.25	kWh/km	Institute of Transport Economics, BIG model
Initial vehicle kilometrage per car (EV & ICEV), large cities, peak (lp)	m_{ilp}^0	940	km	Institute of Transport Economics, Thune-Larsen et al. (2014) and Statistics Norway StatBank (2018c)
Initial vehicle kilometrage per car (EV & ICEV), large cities, off-peak (lo)	m_{ilo}^0	10,806	km	[These kms per car per area numbers are weighted according to area's share of households. In sum, this results in a national average of 12 230 km per car]
Initial vehicle kilometrage per car (EV & ICEV), small cities (s)	m_{is}^0	12,004	km	
Initial vehicle kilometrage per car (EV & ICEV), rural (r)	m_{ir}^0	12,761	km	
ICEVs per household, large cities (Fl)	v_{Fl}^0	0.960	cars	Statistics Norway StatBank (2018f), Statistics Norway StatBank (2018a), Statistics Norway StatBank (2018b)
ICEVs per household, small cities (Fs)	v_{Fs}^0	1.128	cars	[These cars per household per area numbers are weighted according to area's share of households. In sum, this results in on average 1.112 ICEVs per household and 0.029 EVs per household, implying on average 1.141 cars in total per Norwegian household]
ICEVs per household, rural (Fr)	v_{Fr}^0	1.123	cars	
EVs per household, large cities (Pl)	v_{Pl}^0	0.046	cars	
EVs per household, small cities (Ps)	v_{Ps}^0	0.033	cars	
EVs per household, rural (Pr)	v_{Pr}^0	0.015	cars	
Car life-span		16.5	years	Fridstrøm, Østli, and Johansen (2016)
Prices and taxes				
"Fossil fuel" producer price	r_F	6.82	NOK/l	Statistics Norway (2015)
Corresponding initial fossil-km producer price		0.54	NOK/km	
Other private km costs for ICEVs	c_F^d	1.32	NOK/km	Vegdirektoratet (2015)
Electricity consumer price (includes VAT and electricity tax)	R_P	0.81	NOK/kWh	Statistics Norway StatBank (2018e)
Corresponding EV-km price (includes VAT and electricity tax)		0.20	NOK/km	
Other private km costs for EVs	c_P^d	1.13	NOK/km	Vegdirektoratet (2015)
Initial fossil fuel tax	τ_F^0	6.58	NOK/l	Finansdepartementet (2016)
Corresponding initial fossil-km tax	τ_{mF}^0	0.52	NOK/km	
Electricity tax per kWh	τ_P	0.18	NOK/kWh	Finansdepartementet (2016)
Corresponding electricity tax EVs pay per km		0.045	NOK/km	
Average toll, large cities		0.47	NOK/km	Calculated from National Public Road Administration's toll statistics and Statistics Norway's passenger car transport statistics. Users pay per passing of tolling station, but the numbers have been normalized to per km
Average toll, small cities		0.25	NOK/km	
Average toll, rural		0.11	NOK/km	
Purchase tax + VAT for ICEV		164,892	NOK	Based on disaggregate car sales data provided by Norwegian Road Federation (OVF)
Purchase tax + VAT for EV		0	NOK	
Annual ownership tax for ICEV		3565	NOK	Finansdepartementet (2016)
Annual ownership tax for EV		435	NOK	
Real discount rate for purchase tax annuity		2%		Risk-free component in real discount rate applied in CBA (NOU 2012:16, 2012). In addition, car loans are usually given at 4–5% and the Norwegian inflation target is 2.5%
Average marginal labor tax rate (benchmark)	τ_L	40%		Bjertnæs (2015)
Household behavior parameters				
Own-price elasticity of fossil fuel intensity (i.e. the isolated elasticity component for fuel efficiency w.r.t. consumer fuel price)	$\varepsilon_{\widetilde{f}}$	−0.092		Norsk Petroleumsinstituutt (2011)
Own-price elasticity of ICEV kilometers	ε_{MF}	−0.152		Rekdal and Larsen (2008)
Own-price elasticity of EV kilometers	ε_{MP}	−0.152		Rekdal and Larsen (2008)
Own-price elasticity of ICEV ownership w.r.t. costs per km	ε_{MF}^{vF}	−0.121		Boug, Dyvi, Johansen, and Naug (2002)
Own-price elasticity of EV ownership w.r.t. costs per km	ε_{MP}^{vP}	−0.121		
Cross-price elasticity of EV kilometers i.e. how ICEV ownership increases when the cost of EV-km increases	ε_{MP}^{vF}	0.0015		Institute of Transport Economics, BIG-model
Cross-price elasticity of ICEV kilometers, i.e. how EV ownership increases when the cost of ICEV-km increases	ε_{MF}^{vP}	0.486		Institute of Transport Economics, BIG-model
Income elasticity of vehicle kilometers	ε_{MI}	0.185		Steinsland and Madslien (2007)
Compensated income elasticity of vehicle kilometers	ε_{MI}^c	0.151		Weighting estimates from West and Williams III (2007) on average Norwegian household demographics
Income elasticity of labor supply	ε_{LI}	−0.03		Correspondence with Thor-Olav Thoresen on LOTTE-model at Statistics Norway, documented in Dagsvik, Jia, Kornstad, and Thoresen (2007)
Labor supply elasticity (uncompensated)	ε_{LL}	0.178		Dagsvik et al. (2007)

(*continued on next page*)

Table 1 (*continued*)

Model parameters	Symbol	Value	Denomination	Sources used and additional information
Labor supply elasticity (compensated)	ε_{LL}^{c}	0.208		$\varepsilon_{LL}^{c} = \varepsilon_{LL} - \varepsilon_{LI}$
Externalities from car transport				
External congestion costs per kilometer, initially, large cities, peak	$e_m^c(M^0)$	6.339	NOK/veh-km	Thune-Larsen et al. (2014)
Calibrated congestion function parameter – marginal congestion cost per km as a linear function of total vehicle km driving in peak hours. This can be considered a sub-component of e_m^c		0.0237		
External non-congestion costs per km ICEV, large cities, peak (lp)	e_{mFlp}^{nc}	0.958	NOK/veh-km	
External non-congestion costs per km EV, large cities, peak (lp)	e_{mplp}^{nc}	0.423	NOK/ veh-km	
External non-congestion costs per km ICEV, large cities, off-peak (lo)	e_{mFlo}^{nc}	0.823	NOK/ veh-km	
External non-congestion costs per km EV, large cities, off-peak (lo)	e_{mplo}^{nc}	0.423	NOK/ veh-km	
External non-congestion costs per km ICEV, small cities (s)	e_{mFs}^{nc}	0.492	NOK/ veh-km	
External non-congestion costs per km EV, small cities (s)	e_{mps}^{nc}	0.419	NOK/ veh-km	
External non-congestion costs per km ICEV, rural (r)	e_{mFr}^{nc}	0.171	NOK/ veh-km	
External non-congestion costs per km EV, rural (r)	e_{mpr}^{nc}	0.161	NOK/ veh-km	
Fossil fuel related external costs	e_F	1.034	NOK/l	Based on recommended social cost of carbon (420 NOK/ton) from NOU 2015:15 (2016)

labor taxation with revenue from road pricing. We can also see that the tax interaction component lowers the final road prices. This is because of the negative impact that the total changes in road prices and labor taxes have on labor supply. The impact on other tax revenue leads to higher total road price levels. The exception is for ICEV driving in rural areas, small cities and cities off peak, as the negative impact on other tax revenue becomes greater. Incentivizing EV driving over ICEV driving in these states will result in lower tax revenues from, for example, purchase taxes, with inadequate substitution from EV road prices. This is why the impact on other tax revenue drives the EV road price upwards. This shows some of the endogeneity between road prices, and how they affect the size of each other's tax interaction component, which again will affect the revenue recycling component and the total road price level. In all cases the final road price is greater than the corrective component that targets the internalization of externalities, with the exception of driving ICEV in rural areas, where the final road price is even lower than its direct external cost. For this case, the tax interaction component has a larger impact on the final price than the revenue recycling component.

In all states, the optimal km-taxes are higher than their current levels for EVs. For ICEVs, however, the optimal km-taxes are lower than current levels of fuel taxes and tolls with the exception of large cities. It seems that ICEVs are taxed higher than optimal in most parts of the country. Hence, the optimal car travel volumes are higher than current volumes in these areas. This results in total 0.2% more vehicle kilometers travelled per household, from 14 129 to 14 150 km per year, despite a large reduction in city driving. The model also finds 0.5% lower rates of average vehicle ownership, from 1.152 to 1.146 cars per household. The impacts differ greatly between states. In large cities, EV ownership rates increase by 36% as the cross-price effect from the road price on ICEVs dominates the own-price effect for EVs. At the same time, ownership rates of ICEVs drop by 8% in large cities. For the rest of the country, the effects are in the opposite direction. On average, ownership rates for EVs increase by about 11%, while the rates for ICEVs fall by 0.8%.

Because the model results indicate over-taxation of ICEVs in most parts of the country in the initial situation, the net revenue from the road-pricing scheme is lower than the initial revenue. This indicates that in optimum it is better with a slightly higher labor tax burden than a higher tax burden from road pricing, given the same government budget constraint. The total increase in labor taxes corresponds to an increase in the average marginal tax rate from 40% to 40.1%. This could be an effect of Norway currently having among the world's highest taxes on gasoline and diesel, but it is worth noting that there are several European countries with similar or higher fuel taxes (U.S. Department of Energy, 2018).

In order to calculate the welfare effect of this road pricing scheme, we numerically integrate the marginal welfare impact (shown in Eq. (10) and rewritten in Eq. (B.7)). When numerically integrating the marginal welfare effect for all road prices, we end up with an annual welfare gain of NOK 255 (about €28 or $33) per household. By comparison, Tscharaktschiew (2014) finds a welfare gain of €13 per household when optimizing gasoline taxation. It is worth noting that the welfare gain is the *national* per capita average. The gain will be higher in large cities where congestion would be curbed (making it comparable to welfare gains found in urban road pricing case studies such as André De Palma et al. (2006)), and somewhat lower in rural areas.

What are the GHG emission implications when values such as these are applied in the model and second-best road prices are calculated? The applied social cost of carbon (SCC) of NOK 420 per ton (about €47 or $53) is the parameter e_F in the corrective component in the ICEV road price that gives a direct incentive to economize fuel, while the road price as a whole gives an incentive to economize kilometers. It is equivalent to moving fuel tax from the pump, but incorporating it in road pricing that would differ with the vehicle's fuel intensity. The SCC is lower than the current tax on fuel, so fuel efficiency incentives become weaker in the new

Table 2
Results from model calculations of second-best road prices in 2020. Road prices are given in 2015 NOK per km for a given state.

Vehicle type and state	Corrective component – own vehicle	Corrective component – indirect impact	Revenue recycling component	Tax interaction component – labor market and congestion[a]	Tax interaction component – other taxes	Total	Initial (tolls and fuel tax per km)
EV cities peak hours	5.33	−0.89	6.66	−5.17	1.30	7.24	0.00
ICEV cities peak hours	6.01	−1.10	7.68	−5.93	1.33	7.97	0.99
EV cities off-peak	0.42	−0.13	1.93	−1.40	0.16	0.97	0.00
ICEV cities off-peak	0.96	−0.09	2.65	−1.92	−0.28	1.31	0.99
EV small cities	0.42	−0.22	1.85	−1.34	0.16	0.88	0.00
ICEV small cities	0.63	−0.03	2.17	−1.54	−0.53	0.68	0.77
EV rural areas	0.16	−0.25	1.64	−1.17	0.22	0.59	0.00
ICEV rural areas	0.31	−0.01	1.83	−1.27	−0.61	0.23	0.63

[a]Including congestion feedback where relevant, i.e. in cities peak hours.

optimized equilibrium. This leads to agents choosing ca 5% lower average fuel efficiency. With almost unchanged travel demand in the nation as a whole, the annual GHG emissions from transport increase by 5.1% in optimum. It is clear that reducing GHG emissions through an optimal road-pricing scheme implies that the carbon price would have to be higher than the recommended values.

5.2. Optimal road prices and a shadow price on CO_2

The Norwegian government's goal by 2030 is to reduce GHG emissions from 1990 levels by 40%. In 2016, annual emissions were about 3% higher than in 1990. For the road transport sector, emissions were about 28% higher.[11] We consider now a binding emission reduction requirement for passenger car transport from 2015 levels (the initial situation in the model) to about 2020, when the new equilibrium following the policy change would be reached. We consider a 15% reduction to be roughly in line with the necessary trajectory for the emission reduction requirement to be met.

For this exercise, we set a constraint on equilibrium emissions. We allow the carbon price component in the road price (in effect, the fuel tax) to not be set equal to the recommended SCC, but to vary freely. The model will solve given constraints for the optimal road pricing scheme where the carbon price component will serve as a shadow price for the emission constraint. We then have the case of achieving the emission reductions in the most efficient pricing scheme available, i.e. reducing emissions at least cost. The results are given in Table 3.

The most notable difference in Table 3 compared to Table 2 is that the road price for ICEVs increases for driving in all states. The increase is between 20% (driving in large cities during peak hours) and 550% (driving in rural areas). The same comparison for EVs results in reductions for all states. The reduction is between 7% (driving in large cities in off-peak hours) and 24% (driving in small cities). These road price changes working against the ICEV arise from a substantial increase in the carbon price component, now the shadow price of the emission constraint. This shadow price is given in Table 4 alongside the social cost of carbon (SCC) and the initial fuel tax (59% gasoline, 41% diesel) measured in NOK per liter.

It can be seen from Table 4 that the shadow price of the emission constraint is about 16 times the SCC, which corresponds to a carbon price of NOK 7057/ton (about €784 or $882). We can also see that the carbon cost component exceeds the initial fuel tax by about 150%. This means that to achieve the emissions reduction target at least cost alongside an optimized road pricing scheme would not just be a question of "shifting from fuel tax and tolls to road price", it would require increasing the tax burden on *both* fossil fuel and kilometers.

So *how* do agents reduce their emissions at least cost? They could drive ICEVs less and/or more efficiently (or replace them with more efficient ICEVs). The results show an approximate 10.3% drop in total household driving with ICEVs and average fuel intensity drops by about 5.3%. Some of the reduction in ICEV kilometers materializes in a shift from ICEV to EV ownership. The results show about 9.6% fewer kilometers driven in total when EVs are included. EV ownership has increased by about 33% nationwide (even higher in cities). On the ICEV side, ownership rates have dropped by about 5.5% nationwide.

The increase in road pricing in this scenario means larger cuts in labor taxation. The total reduction in labor taxes corresponds to a drop in the average marginal tax rate from 40% to 37%. However, this is not enough to save the scenario from substantially less welfare compared to the initial situation. In this scenario, each household gets a welfare decrease of NOK 219 per year. The calculation assumes that the actual welfare cost of a ton of GHG is NOK 420, the SCC, even though a higher shadow price has been forced on the transport sector. The high shadow price for the emission constraint reflects high welfare costs from large-scale CO_2 abatement within the transport sector. For the Norwegian economy as a whole, the shadow price of a CO_2 constraint like this would probably be lower, because the existing emissions taxation is generally lower than in the transport sector (see e.g., NOU 2015:15, 2016), so cheaper abatement opportunities would be exploited.

5.3. Sensitivity analysis and alternative scenarios

The model results are reliant on the parameter values, which in some cases derive from uncertain estimates (see e.g., Thune-Larsen et al., 2014). We therefore provide sensitivity analysis to show how uncertainty in the underlying parameters creates uncertainty in the results. This applies for estimates of both external costs[12] and behavioral relationships, i.e. elasticities. We focus mainly on testing the sensitivity of the elasticity values. The implications for road price levels of higher/lower external cost values are easier to imagine; we have already shown the implications of higher carbon costs.

There are many ways to do sensitivity analysis. A common practice is varying the central parameters one-by-one to show how a change in one parameter affects the result. We often find it more rewarding to vary a set of variables simultaneously in a consistent scenario, which is useful in showing the range of outcomes, and helps the reader see the uncertainty in terms of different "stories".

Two of our scenarios focus on uncertainty about how the agents will respond in the transport market, i.e. uncertainty in transport-related elasticity parameters. In one of the scenarios, the agents turn out to be less responsive to transport policies, and vice versa for the other. The parameters we vary in the two scenarios are given in Table 5.

[11] Statistics Norway: StatBank: Table: 08940: Greenhouse gases, by source, energy product and pollutant 1990–2016 (retrieved November 2017).

[12] Many of the uncertainties underlying these estimates are discussed in Thune-Larsen et al. (2014), and the external cost estimates for Norway in this report differ somewhat from those found in Parry et al. (2014b). For example, the latter finds national average marginal accident costs per km to be about the same as the former, but finds lower local pollution costs per liter of fuel (about half) than in the former, mostly due to lower average emission factors.

Table 3
Results from model calculations of second-best road prices in 2020 under a GHG emission constraint of 15% reduction from 2015 levels. Road prices are given in 2015 NOK per km for a given state.

Vehicle type and state	Corrective component – own vehicle	Corrective component – indirect impact	Revenue recycling component	Tax interaction component – labor market and congestion	Tax interaction component – other taxes	Total
EV cities peak hours	5.10	−0.82	5.39	−4.18	1.22	6.72
ICEV cities peak hours	7.72	−1.33	7.71	−5.99	1.56	9.65
EV cities off-peak	0.42	−0.24	1.63	−1.18	0.30	0.94
ICEV cities off-peak	2.91	−0.12	3.29	−2.46	−0.74	2.86
EV small cities	0.42	−0.48	1.46	−1.04	0.32	0.67
ICEV small cities	2.58	−0.05	2.71	−2.00	−1.25	1.97
EV rural areas	0.16	−1.05	1.35	−0.96	1.00	0.50
ICEV rural areas	2.26	−0.01	2.27	−1.65	−1.55	1.30

Table 4
Fuel taxes/carbon cost component in road price. 2015 NOK per liter.

	Initial fuel tax (including VAT)	Social cost of carbon (SCC)	Shadow price of emission constraint
NOK per liter fossil fuel	6.58	1.034	17.37

Table 5
Direction and relative change of parameter values in two scenarios for sensitivity analysis on responsiveness in transport markets.

Elasticity parameter	More responsive transport market (MRTM)	Less responsive transport market (LRTM)
Own-price elasticity of fossil intensity	+30%	−30%
Own-price elasticity of ICEV kilometrage	+30%	−30%
Own-price elasticity of EV kilometrage	+30%	−30%
Own-price elasticity of ICEV purchase w.r.t. ICEV km cost	+30%	−30%
Own-price elasticity of EV purchase w.r.t. EV km cost	+30%	−30%
Cross-price elasticity of ICEV purchase w.r.t. EV km cost	+30%	−30%
Cross-price elasticity of EV purchase w.r.t. ICEV km cost	+30%	−30%

The next two scenarios focus on the uncertainty concerning how agents will respond in the labor market. In one of them, we look at the case where agent behavior in the labor market is less responsive to changes, and vice versa in the other scenario. The parameters we vary in the two scenarios are given in Table 6.

We add two more scenarios that test the implications of different developments for EV purchases and EV purchase taxes. The first considers the case where the stock of EVs has doubled at the expense of ICEVs, i.e. a doubling of the EV share under the same car fleet size. This is particularly relevant since the growth of EV's has been fairly large since 2015, the base year of the analysis. This scenario is denoted 2X EV.

The last scenario considers the case where the government relaxes the biggest incentive for purchasing EVs, namely the exemption from VAT. A 25% VAT on the average EV sold in Norway would correspond to NOK 91 558 on top of the sales price. This is implemented in the model as an increase in the purchase tax annuity for EVs. In addition, EVs will pay the same annual ownership tax as ICEVs, which corresponds to an increase from NOK 455 to NOK 3565 NOK per year. This scenario is denoted EV VAT.

The resulting second-best road price levels in these scenarios are given in Table 7.

The four scenarios that test sensitivity to elasticity values show that relatively moderate ranges (± 30%) for these values lead to relatively large ranges for optimal taxes; 30% larger transport-related elasticity values leads to 45–87% lower optimal road prices compared to baseline. The direction is not surprising, as more responsiveness makes it less attractive to tax because the agents are more willing to reduce kilometrage and ownership and/or switch to another vehicle in response to prices. The absolute value of both

Table 6
Direction and relative change of parameter values in two scenarios for sensitivity analysis on responsiveness in labor markets.

Elasticity parameter	More responsive labor market (MRLM)	Less responsive labor market (LRLM)
Labor supply elasticity (uncompensated)	+30%	−30%
Income elasticity of labor	+30%	−30%

Table 7
Results from model calculations of second-best road prices in 2020 under various scenarios. Road prices are given in 2015 NOK per km for a given state.

Vehicle type and state	Baseline	MR-TM	LR-TM	MR-LM	LR-LM	2X EV	EV VAT
EV cities peak hours	7.24	6.27	9.21	10.78	4.97	8.95	7.21
ICEV cities peak hours	7.97	6.89	10.20	13.64	5.33	39.90	8.01
EV cities off-peak	0.97	0.78	1.40	2.19	0.23	0.62	0.96
ICEV cities off-peak	1.31	1.08	1.79	3.04	0.44	5.50	1.35
EV small cities	0.88	0.67	1.32	2.06	0.16	0.72	0.88
ICEV small cities	0.68	0.53	1.00	1.56	0.10	1.53	0.70
EV rural areas	0.59	0.32	1.16	2.51	−0.34	0.50	0.60
ICEV rural areas	0.23	0.13	0.45	0.83	−0.20	0.21	0.24

the revenue recycling and tax interaction components becomes smaller, but it is the reduced revenue recycling component that is predominant. The corresponding road prices in the LRTM scenario are 27–96% higher than the baseline.

The more responsive the agents are in the labor market, the higher the road price; 30% greater elasticities for own-price and income elasticity with respect to labor supply resulted in 49–320% higher road prices compared to the baseline. This is because larger own-price elasticity of labor supply drives up the marginal cost of public funds and in turn the revenue recycling component; income elasticity drives up the value of the tax interaction component (makes it less negative). At the opposite end, road prices in the LRLM scenario are 31–184% lower than the baseline. The labor supply elasticity and income elasticity of labor are estimated to be relatively small in the Norwegian LOTTE modeling system at Statistics Norway (see e.g., Dagsvik et al., 2007), namely 0.178 and −0.03, respectively.[13] This makes the optimal prices quite sensitive to changes in these parameters.

In the 2X EV scenario it can be seen that a doubled initial stock of EVs implies higher road prices for ICEVs in large and small cities, but lower in rural areas. As for EVs, the optimal road price becomes lower, with the exception of cities during peak hours. This is mainly because for given elasticities[14] the absolute changes related to EV stock will be larger and for ICEV stock lower. This increases the absolute value of parameters for household shifting to EV km and EV ownership when ICEV road prices increase, and shifting from EV ownership when EV road prices increase (parameters η_P, φ_P and κ_P). Conversely, the corresponding parameters for ICEVs decrease in absolute value. This will tend to lower road prices for EVs and increase for ICEVs.

In the EV VAT scenario we can see that removing the VAT exemption for EVs would imply a 1–4% higher road price for ICEVs, while for EVs there is hardly any change (1% or less). The changes are driven by the impact the annual tax revenue per vehicle has on the tax interaction component of the road price. When there is VAT on EVs, a higher road price on ICEVs is, on the margin, less of a fiscal problem, as the government revenue loss from a switch to EVs becomes smaller. This is similar to Tscharaktschiew (2015) finding that introducing EV purchase subsidies reduces the optimal gasoline tax.

We also find that removing the VAT exemption for EVs increases the welfare potential for the second-best road pricing scheme by about 1% compared to the baseline results. This welfare increase would be in addition to whatever gains made from alternative use of the revenue the government would have earned if EVs had the same VAT rate as other cars. In 2017, the VAT exempted from EV purchases added up to 3.2 bn. NOK (Ministry of Finance, 2018).

These sensitivity tests give some indication of how this model would produce different optimal road prices for different countries. Elasticity estimates in the transport market are a bit on the low side for Norway (further discussed in Appendix C) compared to other countries, leading one to expect that optimal road prices will be higher in Norway, than in most other countries. Norway also seems to put a higher value on external costs, and also has relatively high fuel taxes and tolls as a part of government revenue compared to other countries, which also leads us to expect that Norwegian road prices would be higher than in most countries. On the other hand, elasticities in the Norwegian labor market seems to be in the lower end. If other countries' labor force is more responsive to labor tax changes, it would drive road prices upwards and labor taxes downwards, compared to Norway.

6. Discussion and conclusion

Here we go through the research questions and how they have been answered.

6.1. What characterizes the set of second-best road prices targeting external costs from driving EVs and ICEVs when there are distortionary labor taxes and binding government budget constraints?

The short answer to this question is that it is characterized by (1) large price differentials between states, (2) ICEVs face a higher

[13] These elasticity values are well within the normal range found in the meta-study by Bargain and Peichl (2016), although somewhat in the lower end in absolute value. The labor supply elasticity is a national average, and it is lower for men and higher for women in absolute value, as is common. The study mentions how the labor supply elasticity for women in Nordic countries seem to be relatively low (closer to those of men), as seems to be a pattern in countries with relatively high participation rates for women in the labor force.

[14] A large change in shares for the two car types would probably imply changes to their respective cross-price elasticities, but this was not included in the sensitivity analysis.

cost in large cities but lower costs in most parts of the country compared to the initial situation, even if it leads to a slightly higher labor tax rate, and (3) EVs should not be untaxed. In sum, the road pricing scheme leads to higher welfare.

It is common to find that driving is undertaxed and labor overtaxed in previous literature using the analytical framework developed by Parry and Small (2005) and other authors referenced in the Introduction. In our study, we found that driving in large cities is undertaxed, and in the rest of the country the opposite. This demonstrates how analyzing a road pricing scheme that differs over four spatiotemporal states and two car types adds more nuance and insight than, for example, analyzing a single gasoline tax. It also takes the big differences in external costs between spatiotemporal states seriously. The extended analytical framework can serve as a tool for calculating second-best road prices in other countries as well, but, as the calculations and the sensitivity analysis show, using parameters relevant for the national context is important.

6.2. How are these prices affected by tax distortions in the labor, electricity and car ownership market?

We find that interaction with the rest of the fiscal system generally leads to a price markup on the external costs. The differences between states and car types largely reflect the differences in external costs per kilometer, the corrective component, but also an interaction component that reflects how the km-tax in a given state with a given car type interacts with the rest of the fiscal system. Within this interaction component there are two opposing forces. Revenue recycling through reducing labor taxation drives up road prices, while road price interaction with the labor market and the rest of the tax system generally drives the price down. We can also see that VAT exemption for EVs drives the optimal road price for ICEVs downwards in order to reduce the shift to EVs and the subsequent loss of government revenue. The VAT exemption also reduces the overall welfare potential from the road pricing scheme.

6.3. How does this second-best pricing fit with government-set goals of reducing CO_2 emissions?

The second-best road pricing scheme applies the recommended social cost of carbon of NOK 420 per ton, which in turn reflects the part of the road price that directly concerns fossil fuel. Using the SCC, the direct tax on fuel becomes lower than in the initial situation, giving less incentive to strive towards fuel efficiency. So even though the road pricing scheme gives incentives to economize on travel distance (depending on the state), the net effect on GHG emissions is actually an increase. The short answer to the research question is: as long as the optimal road pricing scheme applies the recommended SCC, it will not contribute much to reaching the government emission target. This means that the goal of reducing CO_2 emissions from passenger car transport implies a higher carbon price than the recommended SCC.

In order to reach a 15% emission reduction requirement at least cost, a shadow price of carbon 16 times the SCC is needed. This is reflected in road prices that are between 20% and 550% higher for ICEVs and between 7% and 24% lower for EVs compared to the second-best optimum. Adaptation to these prices comes mainly through the ICEVs being driven less, but also through increased fuel efficiency. Some of the reduced driving of ICEVs is reflected in a big increase in EV driving.

The large-scale CO_2 abatement within the transport sector comes at a high welfare cost, which reveals a large mismatch between the SCC and the government's emission target. This can be interpreted as a goal conflict between welfare maximization and ambitious emission targets. This is in line with De Borger and Proost (2015), who claim that too much emphasis has been put on climate issues, compared to the other market imperfections related to the transport sector. It is worth noting that for the Norwegian economy as a whole the cost would lower as cheaper abatement opportunities outside the transport sector would be exploited. This was the conclusion for Belgium in Proost et al. (2009). Mayeres and Proost (2013) also find marginal abatement costs of many hundred Euros when pursuing narrow measures within the transport sector.

6.4. Concluding remarks

As many great transport economists have suggested before, there are good reasons for policy makers to look closely at road pricing as a future main instrument for regulating transport. We make the case for distance-based road pricing, differentiated across vehicle types and pre-defined areas and time periods using satellite technology.

These results suggest that such a road pricing scheme is likely to be welfare enhancing. In the case of Norway, a policy implication would be to start the formal process of investigating how to design and implement such a road pricing scheme. This paper and the extended modeling framework can serve as input for analysis in such a process.

There are some caveats worth mentioning. Even though the model expressions are a bit messy and a bit tedious to derive, it is still a fairly simple static model with one representative household. Future extensions could include heterogeneous agents, public transport, freight transport, and a more comprehensive treatment of the car purchase tax system, which already provides incentives for lower emission vehicles. The opportunity to substitute driving in one state with another (in particular driving in peak and off-peak hours in large cities), and the cost of establishing and running such a road pricing scheme would also be promising extension. Distributional impacts and political feasibility could also be looked at more closely. The modeling involves moving from one static equilibrium to another, and the numerical modeling is based on 2015 being an equilibrium situation, although in many respects it could be considered transitory, at least with regard to the EV stock. We try to incorporate this within the analysis through sensitivity testing.

The numerical results also have their caveats, as they are based on estimates obtained from noisy data. Our sensitivity analysis shows us that changes in uncertain behavioral parameters could imply a wide range of different optimal road prices. This brings us to another policy implication: If a formal process of investigating satellite-based road pricing is undertaken, the process should be mindful of these uncertainties with regard to design and implementation planning.

The development of satellite-based road pricing for passenger cars in Singapore and the trials in Oregon and California are exciting developments in real-world transport economics. Theory and numerical simulations make a good case for such a scheme. As the share of EVs grow, the case will get even better.[15] However, many steps need to be taken before satellite-based road pricing can be seen widely in the real world. Citizens may be skeptical, for instance about privacy concerns (Duncan et al., 2017). However, the Data Protection Agency in Norway claims that a satellite-based road pricing scheme could be designed to respect (and maybe even enhance) privacy protection.[16] Principles such as ownership of the data belonging to the car owner, and the scheme not being useable for detailed tracking without informed consent, would to a large degree align such a scheme with privacy concerns.

Another important real-world factor is how the scheme would take form after a political process. Politics and other constraints could easily reduce the efficiency of such schemes (see e.g., Anthoff and Hahn, 2010; Evans, 1992), and could hinder them from being implemented in the first place. We saw in the case of the Dutch attempt to design a national road pricing scheme that politics was the main reason for the project being stopped in 2011 after years of progress, seemingly close to the finishing line (Geerlings et al., 2012).

Attempts to develop satellite-based road pricing schemes may finally be successful, or they could continue to fail. In any case, valuable learning experiences will be gained, and we strongly believe contributing to the body of knowledge on road pricing is a worthy pursuit.

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Declarations of interest

None.

Appendix A. Deriving second-best road prices

We follow many of the same analytical steps as in Tscharaktschiew (2015) when we here derive optimal road prices.

The household's optimization program is to maximize the utility function Eq. (1) with respect to the choice variables m_F, v_F, $\widetilde{f}$, m_P, v_P, $\widetilde{p}$, X and l subject to monetary budget Eq. (4) and time constraints Eq. (7). Households treat travel times (affected by aggregate kilometrage), external environmental damages and all tax levels as given. We form the Lagrangian where μ is the Lagrange multiplier for the complete economic household budget constraint and can be interpreted as the marginal utility of income. We get first-order conditions (FOCs) from the optimization and use these to obtain the household's indirect utility function, which yields maximized utility given prices, taxes and income, but also travel time and externalities determined by the *aggregate* level of driving.

The government's optimization program is then to maximize the household's indirect utility function with respect to a set of parameters $\Omega \equiv \{\tau_{mF}, \tau_{mp}, \tau_P, \Gamma_F, \Gamma_P, \tau_L, t, E\}$. These parameters, policy variables and time and environmental externalities, are treated as given by the households.

$$\begin{aligned} V(\Omega) \equiv \max_{m_F, v_F, \widetilde{f}, m_P, v_P, \widetilde{p}, X, l} & u(m_F, v_F, m_P, v_P, X, l, T, E) - \mu([(R_F\widetilde{f} + c_F^d)m_F + \tau_{mF}m_F + c(\widetilde{f}) + \Gamma_F]v_F \\ & + [(R_P\widetilde{p} + c_P^d)m_P + \tau_{mp}m_P + c(\widetilde{p}) + \Gamma_P]v_P + P_X X - (1-\tau_L)w(\bar{L} - l + t(\bar{M})M)) \end{aligned} \tag{A.1}$$

The policy instrument subject to change in its level is the km-tax for EVs. At the same time, changes in governmental tax revenue, per kilometer travel time, and external costs are considered explicitly.

The analytical exercise of deriving the optimal tax on EV-km, τ_{m_p}. starts by total differentiation of the household's indirect utility function with respect to τ_{mp}. For optimization of $V(\Omega)$ through τ_{mp}, with revenue recycling through τ_L we can consider the policy instruments τ_{mF}, τ_F, τ_P, Γ_P and Γ_F as fixed in this exercise. Assuming $d\tau_{mF}/d\tau_{mp} = d\tau_F/d\tau_{mp} = d\tau_P/d\tau_{mp} = d\Gamma_P/d\tau_{mp} = d\Gamma_F/d\tau_{mp} = 0$, we

[15] In a future with autonomous cars, where the generalized travel cost could get greatly reduced, and the average occupancy rate of cars could drop (e.g., if autonomous cars drive people to work, drive back home empty, and drive empty to the workplace at the end of the day to pick up again), regulating transport demand with distance-based road pricing using satellite technology could be essential.

[16] http://www.ofv.no/artikler-2017/dynamisk-veiprising-kan-fjerne-bomstasjonene-article515-299.html (in Norwegian, easily translated using translation software) [last accessed April 5th 2018].

get:

$$\frac{dV}{d\tau_{mp}} = \frac{\partial V}{\partial \tau_{mp}} + \frac{\partial V}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} + \frac{\partial V}{\partial t}\frac{dt}{d\tau_{mp}} + \frac{\partial V}{\partial E}\frac{dE}{d\tau_{mp}} \tag{A.2}$$

where

$$\frac{\partial V}{\partial E}\frac{dE}{d\tau_{mp}} = \frac{\partial V}{\partial E_F(\bar{F})}\frac{\partial E_F(\bar{F})}{\partial F}\frac{dF}{d\tau_{mp}} + \frac{\partial V}{\partial E_P(\bar{P})}\frac{\partial E_P(\bar{P})}{\partial P}\frac{dP}{d\tau_{mp}} + \frac{\partial V}{\partial E_{M_F}(\bar{M}_F)}\frac{\partial E_{M_F}(\bar{M}_F)}{\partial M_F}\frac{dM_F}{d\tau_{\tau_{mp}}} + \frac{\partial V}{\partial E_{M_P}(\bar{M}_P)}\frac{\partial E_{M_P}(\bar{M}_P)}{\partial M_P}\frac{dM_P}{d\tau_{\tau_{mp}}} \tag{A.3}$$

represents (dis-)utility stemming from a marginal change in aggregate externalities via changes in a car's energy consumption and kilometrage caused by a marginal increase in the km-tax for EVs. From here on, we assume that there are no externalities associated with producing and consuming electricity for EVs, i.e.$E_P(\bar{P}) = 0$. This is further discussed in Section 2. (A.2) can then be rewritten as:

$$\frac{\partial V}{\partial \tau_{m_p}} = \frac{\partial V}{\partial \tau_{m_p}} + \frac{\partial V}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} + \frac{\partial V}{\partial t}\frac{dt}{d\tau_{m_p}} + V_{E_F}E_F'\frac{dF}{d\tau_{mp}} + V_{E_{M_F}}E_{M_F}'\frac{dM_F}{d\tau_{mp}} + V_{E_{M_P}}E_{M_P}'\frac{dM_P}{d\tau_{mp}} \tag{A.4}$$

Replacing partial derivative terms $\frac{\partial V}{\partial \tau_{mp}}, \frac{\partial V}{\partial \tau_L}, \frac{\partial V}{\partial t}$ yields:

$$\frac{dV}{d\tau_{mp}} = -\mu m_P v_P - \mu wL\frac{d\tau_L}{d\tau_{mp}} + \frac{\partial V}{\partial T}M\frac{dt}{d\tau_{mp}} - \mu(1-\tau_L)wM + V_{E_F}E_F'\frac{dF}{d\tau_{mp}} + V_{E_{M_F}}E_{M_F}'\frac{dM_F}{d\tau_{mp}} + V_{E_{M_P}}E_{M_P}'\frac{dM_P}{d\tau_{mp}} \tag{A.5}$$

We divide both sides by μ, the marginal utility of income, and get the welfare change in monetary terms:

$$\frac{1}{\mu}\frac{dV}{d\tau_{mp}} = -m_P v_P - wL\frac{d\tau_L}{d\tau_{mp}} + \frac{1}{\mu}\frac{\partial V}{\partial T}M\frac{dt}{d\tau_{mp}} - (1-\tau_L)wM\frac{dt}{d\tau_{mp}} + \frac{1}{\mu}V_{E_F}E_F'\frac{dF}{d\tau_{mp}} + \frac{1}{\mu}V_{E_{M_F}}E_{M_F}'\frac{dM_F}{d\tau_{mp}} + \frac{1}{\mu}V_{E_{M_P}}E_{M_P}'\frac{dM_P}{d\tau_{mp}} \tag{A.6}$$

In order to derive $d\tau_L/d\tau_{mp}$ we totally differentiate the government budget constraint (remember $W = wL$ and only electric cars receive tax benefits):

$$\frac{dGOV}{d\tau_{mp}} = \frac{\partial GOV}{\partial \tau_{mp}} + \frac{\partial GOV}{\partial M_P}\frac{dM_P}{d\tau_{mp}} + \frac{\partial GOV}{\partial M_F}\frac{dM_F}{d\tau_{mp}} + \frac{\partial GOV}{\partial F}\frac{dF}{d\tau_{mp}} + \frac{\partial GOV}{\partial P}\frac{dP}{d\tau_{mp}} + \frac{\partial GOV}{\partial v_P}\frac{dv_P}{d\tau_{mp}} + \frac{\partial GOV}{\partial v_F}\frac{dv_F}{d\tau_{mp}} + \frac{\partial GOV}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} + \frac{\partial GOV}{\partial W}\frac{dW}{d\tau_{mp}} \tag{A.7}$$

yielding

$$\frac{dGOV}{d\tau_{mp}} = M_P + \tau_{mp}\frac{dM_P}{d\tau_{mp}} + \tau_{m_F}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + (\tau_{mp}m_P + \tau_P\widetilde{p}\,m_P + \Gamma_P)\frac{dv_P}{d\tau_{mp}} + (\tau_{m_F}m_F + \tau_F\widetilde{f}\,m_F + \Gamma_F)\frac{dv_F}{d\tau_{mp}} + W\frac{d\tau_L}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}} \tag{A.8}$$

We set the expressions $\tau_{m_i}m_i + \tau_i\widetilde{p}\,m_i + \Gamma_i$ equal to D_i for notational simplicity.

Equating $dGOV/d\tau_{mp}$ to zero and solving for $d\tau_L/d\tau_{mp}$ yields:

$$\frac{d\tau_L}{d\tau_{mp}} = -\frac{M_P + \tau_{mp}\frac{dM_P}{d\tau_{mp}} + \tau_{m_F}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}}}{W} \tag{A.9}$$

Plugging Eq. (A.9) into Eq.(A.6), recalling $M = m_P v_P + m_F v_F$ (see Eq. (3)), gives:

$$\frac{1}{\mu}\frac{dV}{d\tau_{mp}} = \tau_{mp}\frac{dM_P}{d\tau_{mp}} + \tau_{m_F}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}} + \frac{1}{\mu}\frac{\partial V}{\partial T}M\frac{dt}{d\tau_{mp}} - (1-\tau_L)wM\frac{dt}{d\tau_{mp}} + \frac{1}{\mu}V_{E_F}E_F'\frac{dF}{d\tau_{mp}} + \frac{1}{\mu}V_{E_{M_F}}E_{M_F}'\frac{dM_F}{d\tau_{mp}} + \frac{1}{\mu}V_{E_{M_P}}E_{M_P}'\frac{dM_P}{d\tau_{mp}} \tag{A.10}$$

We define the value of travel time as $-\frac{1}{\mu}\frac{\partial V}{\partial T} + (1-\tau_L)w \equiv \theta$, where $\frac{\partial V}{\partial T} < 0$ is the household's disutility from aggregate travel time. It also follows from Eq. (2) that $\frac{dt}{d\tau_{mp}} = t'\frac{dM}{d\tau_{mp}}$. When we replace both of these expressions in Eq. (A.10) we get:

$$\frac{1}{\mu}\frac{dV}{d\tau_{mp}} = \tau_{mp}\frac{dM_P}{d\tau_{mp}} + \tau_{m_F}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}} - \theta t'M\frac{dM}{d\tau_{mp}} + \frac{1}{\mu}V_{E_F}E_F'\frac{dF}{d\tau_{mp}} + \frac{1}{\mu}V_{E_{M_F}}E_{M_F}'\frac{dM_F}{d\tau_{mp}} + \frac{1}{\mu}V_{E_{M_P}}E_{M_P}'\frac{dM_P}{d\tau_{mp}} \tag{A.11}$$

For notational simplicity we rewrite the expressions for marginal external costs (marginal external damage expressed in monetary terms) stemming from the consumption of fuel and kilometrage

$$e_F \equiv \frac{1}{\mu}V_{E_F}E_F' \tag{A.12}$$

$$e_m^c(M) \equiv \theta t'M \tag{A.13}$$

$$e_{mF}^{nc} \equiv \frac{1}{\mu} V_{E_{M_F}} E'_{M_F} \tag{A.14}$$

$$e_{mp}^{nc} \equiv \frac{1}{\mu} V_{E_{M_P}} E'_{M_P} \tag{A.15}$$

We also reorganize the expression to get a clearer view of the marginal welfare effect of the km-tax:

$$\frac{1}{\mu}\frac{\partial V}{\partial \tau_{mp}} = \underbrace{e_F\left\{-\frac{dF}{d\tau_{mp}}\right\}}_{\text{energy related externalities}} + \underbrace{e_m^c(M)\left\{-\frac{dM}{d\tau_{mp}}\right\}}_{\text{congestion externalities}} + \underbrace{e_{mF}^{nc}\left\{-\frac{dM_F}{d\tau_{mp}}\right\} + e_{mp}^{nc}\left\{-\frac{dM_P}{d\tau_{mp}}\right\}}_{\substack{\text{kilometrage related}\\ \text{non-congestion externalities}}} - \underbrace{\left[\tau_{mp}\left\{-\frac{dM_P}{d\tau_{mp}}\right\} + \tau_{mF}\left\{-\frac{dM_F}{d\tau_{mp}}\right\}\right]}_{\text{km-tax revenue}}$$
$$- \underbrace{\left[\tau_F\left\{-\frac{dF}{d\tau_{mp}}\right\} + \tau_P\left\{-\frac{dP}{d\tau_{mp}}\right\}\right]}_{\text{energy tax revenue}} \underbrace{+D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}}}_{\substack{\text{direct/indirect tax revenue/cost from}\\ \text{vehicle stock}}} + \underbrace{\tau_L\frac{dW}{d\tau_{mp}}}_{\text{labor tax revenue}} \tag{A.16}$$

As we can see, the EV-km tax causes numerous different changes in Eq. (A.16), which shows that the km-tax affects overall welfare through various channels.

A.1. Deriving second-best road prices

We set the marginal welfare change seen in Eq. (A.16) equal to zero and solve for τ_{mp}. This gives us the following expression:

$$\begin{aligned}\tau_{mp}^* &= e_F\left\{\frac{dF/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\} + e_m^c(M)\left\{\frac{dM/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\} + e_{mF}^{nc}\left\{\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\} + e_{mp}^{nc}\\
&+\left[\tau_{mF}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}}\right]\frac{1}{-dM_P/d\tau_{mp}}\\
&= e_F\left\{\frac{dF/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\} + (e_m^c(M) + e_{mF}^{nc})\left\{\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\} + e_{mp}^{nc} + e_m^c(M)\\
&+\left[\tau_{mF}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}}\right]\frac{1}{-dM_P/d\tau_{mp}}\end{aligned} \tag{A.17}$$

We simplify the following expressions into reaction parameters.

$$\eta_F = \frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}} \tag{A.18}$$

$$\chi_F = \frac{dF/d\tau_{mp}}{dM_P/d\tau_{mp}} \tag{A.19}$$

$$\kappa_P = \frac{dv_P/d\tau_{mp}}{dM_P/d\tau_{mp}} \tag{A.20}$$

$$\varphi_F = \frac{dv_F/d\tau_{mp}}{dM_P/d\tau_{mp}} \tag{A.21}$$

The expression in (A.17) can be aggregated to the following expression for the optimal km-tax:

$$\tau_{mp}^* = \tau_{mp}^C + \tau_{mp}^I \tag{A.22}$$

The optimal km-tax is expressed here by both a corrective component, τ_{mp}^C and a "fiscal interaction" component τ_{mp}^I. We apply the definitions in (A.18) and (A.19) to the first part of the expression in (A.17) and get the following expression for the corrective component.

$$\tau_{mp}^C = \chi_F e_F + \eta_F\left(e_m^c(M) + e_{mF}^{nc}\right) + e_{mp}^{nc} + e_m^c(M) \tag{A.23}$$

This component accounts for traffic-related externalities from EVs, but also the impact the km-tax for EVs may have on externalities (through kilometers driven) from ICEVs.

The remaining part of the expression in (A.17) is the fiscal interaction component.

$$\tau_{mp}^I = \left[\tau_{mF}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}}\right]\frac{1}{-dM_P/d\tau_{mp}} \tag{A.24}$$

This component represents interaction of EV-km tax with the broader fiscal system in the economy. The first, second and third terms denote how a change in τ_{mp} affects tax revenue from ICEV km-tax, fossil fuel tax and electricity tax, respectively. The fourth and fifth terms denote how a change in τ_{mp} affects revenue from annual ownership and purchase taxes. The sixth term denotes how a change in τ_{mp} affects labor tax revenue.

We proceed in this exercise by totally differentiating the terms in brackets in:

$$\frac{dM_F}{d\tau_{mp}} = \frac{\partial M_F}{\partial \tau_{mp}} + \frac{\partial M_F}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} \tag{A.25}$$

$$\frac{dF}{d\tau_{mp}} = \frac{\partial F}{\partial \tau_{mp}} + \frac{\partial F}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} \tag{A.26}$$

$$\frac{dP}{d\tau_{mp}} = \frac{\partial P}{\partial \tau_{mp}} + \frac{\partial P}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} \tag{A.27}$$

$$\frac{dv_P}{d\tau_{mp}} = \frac{\partial v_P}{\partial \tau_{mp}} + \frac{\partial v_P}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} \tag{A.28}$$

$$\frac{dv_F}{d\tau_{mp}} = \frac{\partial v_F}{\partial \tau_{mp}} + \frac{\partial v_F}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} \tag{A.29}$$

$$\frac{dW}{d\tau_{mp}} = \frac{\partial W}{\partial \tau_{mp}} + \frac{\partial W}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} + \frac{\partial W}{\partial t}\frac{dt}{d\tau_{mp}} = w\left(\frac{\partial L}{\partial \tau_{mp}} + \frac{\partial L}{\partial \tau_L}\frac{d\tau_L}{d\tau_{mp}} + \frac{\partial L}{\partial t}\frac{dt}{d\tau_{mp}}\right) \tag{A.30}$$

Concerning the demand for vehicle kilometers, fossil fuels, electricity and car ownership, it is assumed that *indirect* changes in labor taxation (through the government budget constraint) have a small impact on corresponding demands relative to the *direct* impact of the km-tax. This is a reasonable approximation since Norwegian household income shares and income elasticities for operating costs and purchase costs for own car are relatively small (Boug and Dyvi, 2008). This means that the largest part of any compensation through revenue recycling will be spent on other goods. It is therefore reasonable to use uncompensated elasticities (see Willig, 1976) in order to parameterize demand elasticities for vehicle kilometers, transport related energy and car ownership. The total differential of $W \equiv wL$ decomposes the change in labor income (labor supply) into three effects: The first component arises from the labor supply effect of raising the price of EV-kms relative to leisure which depends on the degree of substitution or complementarity between EV-kms and leisure. The second term is the effect of revenue recycling, i.e. using EV-km tax revenues to reduce τ_L will increase labor supply. The third effect is the change in labor supply due to a change in commuting travel time caused by a EV-km tax induced change in vehicle kilometrage and, thus, congestion levels.

Plugging Eq. (A.30) into $d\tau_L/d\tau_{mp}$ as displayed in Eq. (A.9) and grouping terms gives

$$\frac{d\tau_L}{d\tau_{mp}} = -\frac{B_1}{B_2} \tag{A.31}$$

where

$$B_1 = M_P + \tau_{mp}\frac{dM_P}{d\tau_{mp}} + \tau_{m_F}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L w\left(\frac{\partial L}{\partial \tau_{mp}} + \frac{\partial L}{\partial t}\frac{dt}{d\tau_{mp}}\right) \tag{A.32}$$

and

$$B_2 = W + \tau_L w\frac{\partial L}{\partial \tau_L} \tag{A.33}$$

The expression in (A.30) can be manipulated further by applying the following expression for the marginal cost of public funds:

$$\Omega_{\tau_L} \equiv \frac{-\tau_L w\frac{\partial L}{\partial \tau_L}}{W + \tau_L w\frac{\partial L}{\partial \tau_L}} = \frac{\frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}}{1-\frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}} \tag{A.34}$$

This term reflects the marginal efficiency cost of raising public funds through taxing labor. On the flip side, it also reflects the marginal efficiency gain from cutting tax on labor, which could be done by, e.g., raising funds from road pricing. The numerator in this expression represents the efficiency cost from an incremental increase in labor taxation, while the denominator gives us the marginal change in public revenue. $\varepsilon_{LL} > 0$ represents the elasticity of labor supply (uncompensated). We have $\Omega_{\tau_L} > 0$ as a consequence of $\varepsilon_{LL} > 0$ and $1 > \frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}$. The latter implies that τ_L is not so large that we find ourselves on the right side of the Laffer curve's peak, meaning that government revenue from increasing labor taxation will, on the margin, be positive.

We substitute $d\tau_L/d\tau_{mp} = -B_1/B_2$ into Eq. (A.30), then plug the resulting expressions into Eq. (A.24), where we regroup terms and use the definition of Ω_{τ_L} in Eq. (A.34). We then get:

$$\tau_{mp}^I = \left[\tau_{m_F}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L w\left(\frac{\partial L}{\partial \tau_{mp}} + \frac{\partial L}{\partial t}\frac{dt}{d\tau_{mp}}\right) + \Omega_{\tau_L}B_1\right]\frac{1}{-dM_P/d\tau_{mp}} \tag{A.35}$$

Multiplying each term by $\frac{1}{-dM_i/d\tau_{m_i}}$, and using the definitions of η_F (Eq. (A.18)), χ_F (Eq. (A.19)), κ_P (Eq. (A.20))) and φ_F(Eq. (A.21)) gives

$$\tau^{I}_{mp} = -\eta_F \tau_{mF} - \chi_F \tau_F - \chi_P \tau_P - \kappa_P D_P - \varphi_F D_F + \tau_L w \left(\frac{\partial L}{\partial \tau_{mp}} + \frac{\partial L}{\partial \tau_L} \frac{d\tau_L}{d\tau_{mp}} \right) \frac{1}{-dM_P/d\tau_{mp}} + \Omega_{\tau_L} B_1 \frac{1}{-dM_P/d\tau_{mp}} \tag{A.36}$$

The fiscal interaction component can be broken down into a revenue recycling component and a tax-interaction component. To obtain a clear expression for the former, we need to manipulate Eq. (A.36). First, we obtain the following expressions from the own-price demand elasticity of EV-km:

$$\varepsilon_{M_P} = \frac{dM_P}{d\tau_{mp}} \frac{(R_P \widetilde{p} + c_P^d + \tau_{mp})}{M_P} \Rightarrow \frac{M_P}{dM_P/d\tau_{mp}} = \frac{(R_P \widetilde{p} + c_P^d + \tau_{mp})}{\varepsilon_{M_P}} \tag{A.37}$$

The term $R_P \widetilde{p} + c_P^d + \tau_{mp}$ is the private cost of a vehicle-km by electric car.

We multiply the expression $\Omega_{\tau_L} B_1$ by $\frac{1}{-dM_P / d\tau_{mp}}$ and apply the definitions of η_F (Eq. (A.18), χ_F (Eq. (A.19)), κ_P (Eq. (A.20)) and φ_F(Eq. (A.21)), and we get:

$$\Omega_{\tau_L} B_1 \frac{1}{-dM_P/d\tau_{mp}} = \Omega_{\tau_L} \left(\begin{array}{c} \frac{(R_P \widetilde{p} + c_P^d + \tau_{mp})}{-\varepsilon_{M_P}} - \tau_{mp} - \eta_F \tau_{mF} - \chi_F \tau_F - \widetilde{p}\, \tau_P - \\ \kappa_P D_P - \varphi_F D_F - \tau_L w \left(\frac{\partial L}{\partial \tau_{mp}} + \frac{\partial L}{\partial t} \frac{dt}{d\tau_{mp}} \right) \frac{1}{-dM_P / d\tau_{mp}} \end{array} \right) \tag{A.38}$$

We can now define the following expression for the revenue recycling effect of the EV-km tax:

$$\tau^{RR}_{mp} = \Omega_{\tau_L} \left(\frac{(R_P \widetilde{p} + c_P^d + \tau_{mp})}{-\varepsilon_{M_P}} - \tau_{mp} \right) \tag{A.39}$$

We thus can rearrange Eq. (A.36) to:

$$\tau^{I}_{mp} = \tau^{RR}_{mp} + (1 + \Omega_{\tau_L})[-\eta_F \tau_{mF} - \chi_F \tau_F - \widetilde{p}\, \tau_P - \kappa_P D_P - \varphi_F D_F] + (1 + \Omega_{\tau_L}) \left(\tau_L w \frac{\partial L}{\partial \tau_{m_i}} + \tau_L w \frac{\partial L}{\partial t} \frac{dt}{d\tau_{m_i}} \right) \frac{1}{-dM_i/d\tau_{m_i}} \tag{A.40}$$

From the Slutsky equation it follows that:

$$\frac{\partial L}{\partial \tau_{mp}} = \frac{\partial L^c}{\partial \tau_{mp}} - \frac{\partial L}{\partial I} M_P \tag{A.41}$$

where superscript c indicates the compensated elasticity and $\partial L/\partial I$ is the income effect on labor supply. From the Slutsky symmetry property and after some manipulation we get:

$$\begin{aligned} \frac{\partial L}{\partial \tau_{mp}} &= \frac{\partial L^c}{\partial \tau_{mp}} - \frac{\partial L}{\partial I} M_P = \frac{\partial M_P^c}{\partial (1-\tau_L) w} - \frac{\partial L}{\partial I} M_P \Rightarrow \\ \frac{(1-\tau_L) w}{M_P} \frac{\partial L}{\partial \tau_{mp}} &= \frac{(1-\tau_L) w}{M_P} \frac{\partial M_P^c}{\partial (1-\tau_L) w} - \frac{(1-\tau_L) w}{M_P} \frac{\partial L}{\partial I} M_P \\ &= -\varepsilon^c_{MI} - \frac{L(1-\tau_L) w}{L} \frac{\partial L}{\partial I} = -\varepsilon^c_{MI} - \varepsilon_{LI} \\ \Rightarrow \frac{\partial L}{\partial \tau_{mp}} &= -\varepsilon^c_{MI} \frac{M_P}{(1-\tau_L) w} - \varepsilon_{LI} \frac{M_P}{(1-\tau_L) w} \end{aligned} \tag{A.42}$$

ε^c_{MI} represents the income elasticity for vehicle kilometers (alternatively the compensated cross-price elasticity of leisure). ε_{LI} represents the income elasticity for labor.

Plugging Eq. (A.42) into Eq. (A.40) and using Eq. (A.37) gives:

$$\begin{aligned} \tau^{I}_{mp} &= \tau^{RR}_{mp} + (1 + \Omega_{\tau_L})[-\eta_F \tau_{mF} - \chi_F \tau_F - \widetilde{p}\, \tau_P - \kappa_P D_P - \varphi_F D_F] + \\ & (1 + \Omega_{\tau_L}) \left(\tau_L w \left(-\varepsilon^c_{MI} \frac{M_P}{(1-\tau_L) w} - \varepsilon_{LI} \frac{M_P}{(1-\tau_L) w} \right) + \tau_L w \frac{\partial L}{\partial t} \frac{dt}{d\tau_{mp}} \right) \frac{1}{-dM_P / d\tau_{mp}} \\ &= \tau^{RR}_{m_i} + (1 + \Omega_{\tau_L}) \left[\left(\frac{\tau_L M_P (-\varepsilon^c_{MI} - \varepsilon_{LI})}{(-dM_P / d\tau_{mp})(1-\tau_L)} \right) - \eta_F \tau_{mF} - \chi_F \tau_F - \widetilde{p}\, \tau_P - \kappa_P D_P - \varphi_F D_F \right] \\ & + (1 + \Omega_{\tau_L}) \left(\tau_L w \frac{\partial L}{\partial t} \frac{dt}{d\tau_{mp}} \right) \frac{1}{-dM_P / d\tau_{mp}} \\ &= \tau^{RR}_{mp} - (1 + \Omega_{\tau_L}) \left[\left(\frac{\tau_L (R_P \widetilde{p} + c_P^d + \tau_{mp})(\varepsilon^c_{MI} + \varepsilon_{LI})}{(-\varepsilon_{M_P})(1-\tau_L)} \right) + \eta_F \tau_{mF} + \chi_F \tau_F + \widetilde{p}\, \tau_P + \kappa_P D_P + \varphi_F D_F \right] \\ & + (1 + \Omega_{\tau_L}) \left(\tau_L w \frac{\partial L}{\partial t} \frac{dt}{d\tau_{mp}} \right) \frac{1}{-dM_P / d\tau_{mp}} \\ &= \tau^{RR}_{mp} + \tau^{(TI)}_{mp} + (1 + \Omega_{\tau_L}) \tau_L w \frac{\partial L}{\partial t} \frac{dt}{d\tau_{mp}} \frac{1}{-dM_P / d\tau_{mp}} \\ &= \tau^{RR}_{mp} + \tau^{TI}_{mp} \end{aligned} \tag{A.43}$$

The terms τ^{RR}_{mp}, τ^{TI}_{mp} and $\tau^{(TI)}_{mp}$ are the road price components for revenue recycling, tax interaction and pure tax interaction, respectively.

Because $\frac{dt}{d\tau_{mp}} = t'\frac{dM}{d\tau_{mp}}$ and $\frac{\partial L}{\partial t} = \frac{\partial L}{\partial R_M}\theta$ with R_M as the full economic price (private cost) of vehicle kilometrage, we can write:

$$(1+\Omega_{\tau_L})\tau_L w\frac{\partial L}{\partial t}\frac{dt}{d\tau_{mp}}\frac{1}{-dM_P/d\tau_{mp}} = -(1+\Omega_{\tau_L})\tau_L w\frac{\partial L}{\partial R_M}\theta t'\left[\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}+1\right] \tag{A.44}$$

It follows from the Slutsky equation applied to the demand function that:

$$\frac{\partial L}{\partial R_M} = \frac{\partial L^c}{\partial R_M} - \frac{\partial L}{\partial I}M \tag{A.45}$$

and from the Slutsky symmetry property for goods in the utility function:

$$\frac{\partial L^c}{\partial R_M} = \frac{\partial M^c}{\partial \tau_L} = \frac{\partial M}{\partial \tau_L}(1-\tau_L)w\frac{\partial L^c}{\partial \tau_L} \tag{A.46}$$

where $(1-\tau_L)w\partial L^c/\partial\tau_L$ is the change in disposable income following a compensated increase in the labor tax. After some manipulation, we get:

$$\begin{aligned}\frac{(1-\tau_L)w}{M}\frac{\partial L}{\partial R_M} &= \frac{(1-\tau_L)w}{M}\frac{\partial M}{\partial \tau_L}(1-\tau_L)w\frac{\partial L^c}{\partial \tau_L} - \frac{(1-\tau_L)w}{M}\frac{\partial L}{\partial I}M = -\varepsilon_{MI}\varepsilon_{LL}^c - \varepsilon_{LI}\\ \Rightarrow \frac{\partial L}{\partial R_M} &= -\varepsilon_{MI}\varepsilon_{LL}^c\frac{M}{(1-\tau_L)w} - \varepsilon_{LI}\frac{M}{(1-\tau_L)w}\end{aligned} \tag{A.47}$$

Plugging Eq. (A.47) into Eq. (A.44) gives:

$$\begin{aligned}&(1+\Omega_{\tau_L})\tau_L w\frac{\partial L}{\partial t}\frac{dt}{d\tau_{mp}}\frac{1}{-dM_P/d\tau_{mp}}\\ &= -(1+\Omega_{\tau_L})\tau_L w\left(-\varepsilon_{MI}\varepsilon_{LL}^c\frac{M}{(1-\tau_L)w} - \varepsilon_{LI}\frac{M}{(1-\tau_L)w}\right)\theta t'\left[\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}+1\right]\\ &= -(1+\Omega_{\tau_L})\frac{\tau_L}{(1-\tau_L)}(-\varepsilon_{MI}\varepsilon_{LL}^c - \varepsilon_{LI})\theta t' M\left[\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}+1\right]\end{aligned} \tag{A.48}$$

Substituting $\varepsilon_{LI} = \varepsilon_{LL} - \varepsilon_{LL}^c$ and $e_m^c(M) \equiv \theta t' M$ and $\eta_F = \frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}$, after regrouping terms we obtain the congestion feedback effect:

$$\tau_{mp}^{CF} = (1+\Omega_{\tau_L})\tau_L w\frac{\partial L}{\partial t}\frac{dt}{d\tau_{mp}}\frac{1}{-dM_P/d\tau_{mp}} = (1+\Omega_{\tau_L})\frac{\tau_L}{(1-\tau_L)}(\varepsilon_{LI}(1-\varepsilon_{MI})\varepsilon_{LL}^c)e_m^c(M)[\eta_F+1] \tag{A.49}$$

We thus get the final expression for the optimal km-tax:

$$\begin{aligned}\tau_{mp}^* &= \tau_{mp}^C + \tau_{mp}^I = \tau_{mp}^C + \tau_{mp}^{RR} + \tau_{mp}^{TI}\\ \tau_{mp}^* &= \tau_{mp}^C + \tau_{mp}^{RR} + \tau_{mp}^{(TI)} + \tau_{mp}^{CF}\end{aligned} \tag{A.50}$$

It has the components:

$$\tau_{mp}^C = e_{mp}^{nc} + e_m^c(M) + \eta_F\left(e_m^c(M) + e_{mF}^{nc}\right) + \chi_F e_F \tag{A.51}$$

$$\tau_{mp}^{RR} = \Omega_{\tau_L}\left(\frac{(R_P\widetilde{p} + c_P^d + \tau_{mp})}{-\varepsilon_{M_P}} - \tau_{mp}\right) \tag{A.52}$$

$$\tau_{mp}^{(TI)} = -(1+\Omega_{\tau_L})\left[\left(\frac{\tau_L(R_P\widetilde{p} + c_P^d + \tau_{mp})(\varepsilon_{MI}^c + \varepsilon_{LI})}{(-\varepsilon_{M_P})(1-\tau_L)}\right) + \eta_F\tau_{mF} + \chi_F\tau_F + \widetilde{p}\tau_P + \kappa_P D_P + \varphi_F D_F\right] \tag{A.53}$$

$$\tau_{mp}^{CF} = (1+\Omega_{\tau_L})\frac{\tau_L}{(1-\tau_L)}(\varepsilon_{LI}(1-\varepsilon_{MI})\varepsilon_{LL}^c)e_m^c(M)[\eta_F+1] \tag{A.54}$$

We solve the model in exactly the same way for τ_{mF}^*, and obtain analogous expressions that look like the following:

$$\tau_{mF}^* = \tau_{mF}^C + \tau_{mF}^I = \tau_{mF}^C + \tau_{mF}^{RR} + \tau_{mF}^{TI} = \tau_{mF}^C + \tau_{mF}^{RR} + \tau_{mF}^{(TI)} + \tau_{mF}^{CF} \tag{A.55}$$

with the corrective component

$$\tau_{mF}^C = e_{mF}^{nc} + e_m^c(M) + (\widetilde{f} + \sigma_F)e_F + \eta_P\left(e_m^c(M) + e_{mp}^{nc}\right) \tag{A.56}$$

the revenue recycling component

$$\tau_{mF}^{RR} = \Omega_{\tau_L}\left(\frac{(R_F\widetilde{f} + c_F^d + \tau_{mF})}{-\varepsilon_{M_F}} - \tau_{mF}\right) \tag{A.57}$$

the tax interaction component (excluding the congestion feedback component).[17]

$$\tau_{mF}^{(TI)} = -(1+\Omega_{\tau_L})\left[\left(\frac{\tau_L(R_F\widetilde{f}+c_F^d+\tau_{mF})(\varepsilon_{MI}^c+\varepsilon_{LI})}{(-\varepsilon_{M_F})(1-\tau_L)}\right)+\eta_P\tau_{mp}+\chi_P\tau_P+(\widetilde{f}+\sigma_F)\tau_F+\kappa_F D_F+\varphi_P D_P\right] \tag{A.58}$$

and, finally, the congestion feedback component,

$$\tau_{mF}^{CF} = (1+\Omega_{\tau_L})\frac{\tau_L}{(1-\tau_L)}(\varepsilon_{LI}(1-\varepsilon_{MI})\varepsilon_{LL}^c)e_m^c(M)[\eta_F+1] \tag{A.59}$$

The expressions for τ_{mF} mirror those for τ_{mp}. The parameters applied are given the same symbol, but with subscript *F,* and illustrate the mechanisms for the agents' responses to a change in the tax on ICEV-kms.

Appendix B. Deriving the welfare measure

As can be seen in Eq. (A.16), we have the following marginal welfare effect of increasing the road price:

$$\frac{1}{\mu}\frac{\partial V}{\partial\tau_{mp}} = \underbrace{e_F\left\{-\frac{dF}{d\tau_{mp}}\right\}}_{\text{energy related externalities}} \underbrace{e_m^c(M)\left\{-\frac{dM}{d\tau_{mp}}\right\}}_{\text{congestion externalities}} + \underbrace{e_{mF}^{nc}\left\{-\frac{dM_F}{d\tau_{mp}}\right\} + e_{mp}^{nc}\left\{-\frac{dM_P}{d\tau_{mp}}\right\}}_{\text{kilometrage related non-congestion externalities}} - \underbrace{\left[\tau_{mp}\left\{-\frac{dM_P}{d\tau_{mp}}\right\}+\tau_{mF}\left\{-\frac{dM_F}{d\tau_{mp}}\right\}\right]}_{km-\text{tax revenue}}$$
$$-\underbrace{\left[\tau_F\left\{-\frac{dF}{d\tau_{mp}}\right\}+\tau_P\left\{-\frac{dP}{d\tau_{mp}}\right\}\right]}_{\text{energy tax revenue}} \underbrace{+D_P\frac{dv_P}{d\tau_{mp}}+D_F\frac{dv_F}{d\tau_{mp}}}_{\text{direct/indirect tax revenue/cost from vehicle stock}} + \underbrace{\tau_L\frac{dW}{d\tau_{mp}}}_{\text{labor tax revenue}} \tag{B.1}$$

The next step is to factor out $-\frac{dM_P}{d\tau_{mp}}$ and rearrange. This gives us:

$$\frac{1}{\mu}\frac{\partial V}{\partial\tau_{mp}} = \left[(e_{mp}^{nc}-\tau_{mp})+(e_F-\tau_F)\left\{\frac{dF/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}-\tau_P\left\{\frac{dP/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}+(e_{mF}^{nc}-\tau_{mF})\left\{\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}+e_m^c(M)\left\{\frac{dM/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}\right.$$
$$\left.+\left(D_P\frac{dv_P}{d\tau_{mp}}+D_F\frac{dv_F}{d\tau_{mp}}+\tau_L\frac{dW}{d\tau_{mp}}\right)\frac{1}{-dM_P/d\tau_{mp}}\right]\left\{-\frac{dM_P}{d\tau_{mp}}\right\} \tag{B.2}$$

Further rearranging gives:

$$\frac{1}{\mu}\frac{\partial V}{\partial\tau_{mp}} = \left[e_{mp}^{nc}-\tau_{mp}+\chi_F e_F-\chi_F e_F-\tau_P\left\{\frac{dP/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}+\eta_F\left(e_m^c(M)+e_{mF}^{nc}\right)+e_m^c(M)-\tau_{mF}\left\{\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}\right.$$
$$\left.+\left(D_P\frac{dv_P}{d\tau_{mp}}+D_F\frac{dv_F}{d\tau_{mp}}+\tau_L\frac{dW}{d\tau_{mp}}\right)\frac{1}{-dM_P/d\tau_{mp}}\right]\left\{-\frac{dM_P}{d\tau_{mp}}\right\} \tag{B.3}$$

Parts of this expression can be converted to the corrective component:

$$\frac{1}{\mu}\frac{\partial V}{\partial\tau_{mp}} = \left[\tau_{mp}^C-\tau_{mp}-\tau_F\left\{\frac{dF/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}-\tau_P\left\{\frac{dP/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}-\tau_{mF}\left\{\frac{dM_F/d\tau_{mp}}{dM_P/d\tau_{mp}}\right\}+\left(D_P\frac{dv_P}{d\tau_{mp}}+D_F\frac{dv_F}{d\tau_{mp}}+\tau_L\frac{dW}{d\tau_{mp}}\right)\frac{1}{-dM_P/d\tau_{mp}}\right]\left\{-\frac{dM_P}{d\tau_{mp}}\right\} \tag{B.4}$$

Other parts can be converted into the interaction component (see Eq. (A.24))

$$\frac{1}{\mu}\frac{\partial V}{\partial\tau_{mp}} = [\tau_{mp}^C-\tau_{mp}+\tau_{mp}^I]\left\{-\frac{dM_P}{d\tau_{mp}}\right\} \tag{B.5}$$

This gives us:

$$\frac{1}{\mu}\frac{\partial V}{\partial\tau_{mp}} = [\tau_{mp}^*-\tau_{mp}]\left\{-\frac{dM_P}{d\tau_{mp}}\right\} \tag{B.6}$$

We can rewrite $\left\{-\frac{dM_P}{d\tau_{mp}}\right\}$ using Eq. (A.37). This gives us:

$$\frac{1}{\mu}\frac{\partial V}{\partial\tau_{mp}} = [\tau_{mp}-\tau_{mp}^*]\frac{M_P\varepsilon_{M_P}}{(R_P\widetilde{p}+c_P^d+\tau_{mp})} \tag{B.7}$$

We numerically integrate this expression to find the change in welfare from a non-marginal change in the km-tax.

[17] This expression has a term that is not present for determining road prices for EVs, namely $\sigma_F = M_F\frac{d\widetilde{f}\,/\,d\tau_{mF}}{dM_F\,/\,d\tau_{mF}}$. This term is related to induced changes in fuel efficiency.

Appendix C. About the parameter values

Some of the parameter values in Table 1 require further explanation.

Initial vehicle kilometrage per car (EV & ICEV): Statistics Norway provides data of average kilometers driven annually per car on a municipal level. We aggregate these to averages on the analysis area level, large cities, small cities and rural areas, according to definitions from Thune-Larsen et al. (2014). This report finds that 8% of vehicle kilometers driven in large cities are spent in congested peak traffic, which is used to divide between peak and off-peak kilometrage.

Car ownership per household: Statistics Norway provides data on car ownership on a municipal level, and separates between ICEVs and EVs. We aggregate these to average car ownership per household on the analysis area level, large cities, small cities and rural areas, according to definitions from Thune-Larsen et al. (2014). These numbers are again weighted according to each area's share of total households, so we get the weighted average car ownership per household.

Average toll: Data on toll paid by passenger cars to toll companies have been provided by the National Public Road Administration's toll statistics. Statistics on passenger car traffic volumes are given by Statistics Norway StatBank (2018d). Users pay per passing of tolling station, but the numbers have been normalized to per kilometer by dividing passenger car toll revenue by passenger car traffic volumes at county level. The national average was 0.31 NOK per km. The average tolls per kilometer for large cities, small cities and rural areas were then approximated by dividing toll revenue by traffic volumes for counties where these area types dominate.

Purchase tax and VAT: The Norwegian Roads Federation (OVF) provides disaggregated car sales data from which the average price, purchase tax and VAT for the average ICEV can be calculated for any given year.

Own-price elasticity of car kilometrage: The newest estimates of elasticity values for the National and Regional Transport Modeling system (NTM and RTM) in Norway give an own price elasticity w.r.t. all kilometer costs and tolls together of -0.152 (documented in Rekdal and Larsen (2008)). When putting this elasticity (adjusted for the ca. 40% fuel share of total kilometer costs and tolls) together with the own-price elasticity of fossil fuel intensity (i.e. the isolated elasticity component for fuel efficiency w.r.t. consumer fuel price), valuated at -0.092 (Norsk Petroleumsinstitutt, 2011) we get the relatively more familiar own price elasticity for fuel. This sums up to -0.153. This is lower than the elasticity for gasoline applied for the US in Parry and Small (2005) (-0.55) and Lin and Prince (2009) (-0.221) and the German case with Tscharaktschiew (2015), that totaled up to -0.5. Fridstrøm (2017) argues that car transport in Norway has a quite low price sensitivity on a national level because most Norwegians do not live in dense, urban areas with public transport as an alternative. In addition, Norwegians have for years gotten used to having both relatively high average incomes, and high costs of car transport.

Cross-price elasticity of kilometer costs with respect to car ownership, i.e. how ownership of one car type increases when the kilometer costs of another increases. This is obtained by simulating the effect of increasing energy costs on new car sales in the BIG-model for the simulation year 2015, which then gives us a counterfactual change in the car stock. We extend this effect over 3 years and convert the implied elasticity measure for energy into an elasticity measure for kilometer costs.

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