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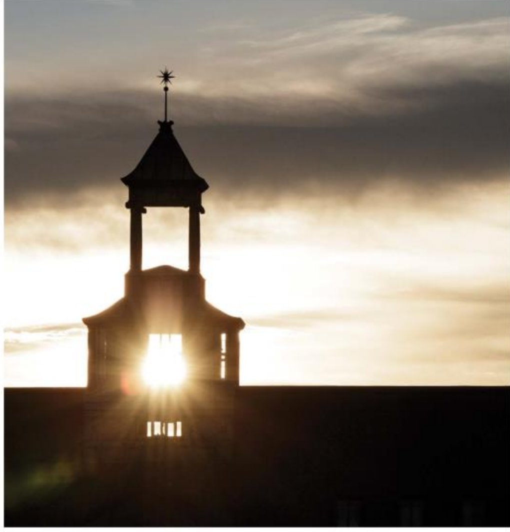

How to road price in a world with electric vehicles and government budget constraints

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Abstract

The road transport market has many market imperfections such as local and global pollution, accidents, noise and road wear. Electric vehicles (EVs) avoid some of these by not having any tailpipe CO2 emissions, but they still contribute to external costs such as congestion. Our research questions are: What characterizes the set of second-best road prices for internalizing external costs from driving EVs and ICEVs when you also have distortionary labor taxes and binding government budget constraints? How are these prices affected by distortions elsewhere in the economy? How does this second-best pricing fit with government set goals of reducing CO2 emissions?

This 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. Expressions for the optimal road prices are derived analytically, and then solved numerically. We find that optimal road prices largely vary with external cost, giving high prices for driving in cities during peak hours, and relatively low prices for driving in rural areas. We also see that the road prices' interactions with the rest of the fiscal system have implications for determining the optimal set of road prices. However, the optimal set of road prices leads to little or no reductions in carbon emissions with the currently recommended social cost of carbon estimates. This implies that any required reduction in CO2-emissions will require a shadow price that exceeds the current social cost estimate.

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1 Introduction

The road transport market is associated with many market imperfections such as local and global pollution, accidents, noise and road wear. Thune-Larsen et al (2014) calculate external costs up to 30 billion NOK (Norwegian Kroner; 1 NOK = 0.11 €) per year from road transport. This figure doesn't even count the CO2-costs, even though road transport in 2015 counted for 19% of national GHG-emissions (Ministry of Finance, 2017). In addition to externalities from road transport, inefficiencies in the economy also arise from distortionary taxes elsewhere in the economy. Both the issues of externalities and inefficiencies in the tax system have recently been put under new scrutiny by 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 2105:15 – *Green Tax Commission.* Looking for ways to mitigate these inefficiencies provide good motivation for this paper.

The "textbook economics" solution would be to find the set of taxes that provide the optimal incentives for the economic agents in order to strike the appropriate balance of costs and benefits in the affected markets. Several papers derive such solutions by finding the optimal gasoline (or diesel) tax. It has for instance been done for the cases UK and USA (Parry & Small, 2005), and Germany (Tscharaktschiew, 2014, 2015).

However, there are several shortcomings to correcting road transport market failures through fuel taxation. First of all, the external costs of driving vary a lot according to where and when the driving takes place. The fuel tax could perhaps internalize some average external cost, but would severely underprice driving in dense cities during peak hour, and overprice driving in rural areas. In addition to this lack of precision, the fuel tax may incentivize more energy efficiency, which may be beneficial with regards to carbon emissions and oil-reliance, but it may lead to higher external costs as lower user costs per kilometer may induce more driving. This has been pointed out in Parry and Small (2005) and Parry, Evans, and Oates (2014).

Second, the possibility for fuel taxes to (imprecisely) correct for externalities and generate government revenue is reduced when EVs (electric vehicles) 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 that they can tax EVs explicitly from their electricity charging.

So are there better taxing instruments than the fuel tax, that both internalize external cost with more precision and allow for the taxation of all cars? We hypothesize that well-designed road pricing scheme (e.g. through satellite-based road-charging) where the external costs based on time, distance, place and vehicle characteristics will approximate a first-best solution. Support for this can be found in the literature. Modelling analysis in the Netherlands from Meurs, Haaijer, and Geurs (2013) suggested that such a scheme can be revenue neutral and have significant environmental benefits compared to the current tax system for car-use and car-ownership. Furthermore, analysis from Parry and Small (2005) and May and Milne (2004) show that distance-based road pricing can generate larger social benefits than e.g. fuel taxation and cordon tolling. Small and Verhoef (2007) and 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 such a scheme. de Palma and Lindsey (2011) argue that a satellite-based road pricing system also has advantages over other technologies in terms of scale economies, potential for value added services and revenue generation. A satellite based road pricing scheme is underway in Singapore (Ong & Siong, 2016), which in time may provide experiences that will bring us closer to confirm or reject our hypothesis.

This paper will investigate how to mitigate economic inefficiencies from transport externalities and a distorted tax system elsewhere in the economy through road pricing: We establish the following research questions: What characterizes the set of second-best road prices for internalizing external costs from driving EVs and ICEVs when you also have distortionary labor taxes and binding government budget constraints? How are these prices affected by distortions elsewhere in the economy? How does this second-best pricing fit with government set goals of reducing CO2-emissions?

We build on analytical framework introduced in Parry and Small (2005). In Parry and Small (2005) they apply this framework to derive the optimal First-Best Pigou-Ramsey tax for gasoline in the UK and the USA. This model has also been used in Lin and Prince (2009) and Antón-Sarabia and Hernández-Trillo (2014) to calculate the optimal gasoline tax in California and Mexico, respectively. A modified version of the model 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 the presence of diesel cars and EVs. It is a fairly simple model that generates insight and intuition. We will to a large degree build on the version from Tscharaktschiew (2015), as it 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-kms (hereafter, road prices). First, we analyze optimal road prices for both EVs and ICEVs, and not just a single policy instrument like the gasoline tax, which is most common in this literature. Secondly, we model how externalities vary geographically and by time of day, which gives us a set of second-best road prices that will 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 reductions 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, McGlivray, & Common, 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), and the marginal cost of public funds (MCF). The estimates of MCF vary greatly between countries, and within a country the MCF will vary depending on which source the government increases or decreases its revenue from. Parry (2009) discusses how recycling gas tax revenues by lowering income taxes would have very large gains and thus increasing the optimal gas tax, but it could be substantially lower if the revenue would be spent on highway maintenance and expansion projects. In Norway, Bjertnæs (2015) find the that the MCF is close to 1.05 from extracting revenue from income tax and VAT, but close to 1.2 from extracting revenue from capital tax and corporate tax. A review of the recent MCF literature can be found in Holtsmark and Bjertnæs (2015). A review of more theoretical discussions about the MCF can be found in Jacobs and de Mooij (2015). The authors here claim that the reason for having distorting taxes in the first place, is for redistributive purposes, stressing the importance of modelling this issue with heterogeneous agents. Hence, the distortions from the non-lump-sum tax system are counteracted by the welfare value of the distribution effects, which in optimum are equal on the margin, thus implying a MCF of one. They further claim that applying a MCF higher than one implicitly reveals a political preference for less income redistribution, since the MCF is larger than one only if the government redistributes too much initially.

This paper does not take sides in this debate. Rather, it constructs a model that will allow for analysis of optimal road prices in an economy with distortionary taxes. Any analyst or decision-maker using the model, may choose to disallow marginal costs of public funds above 1, perhaps as a part of a "moral sensitivity analysis" (see e.g., Mouter, 2016). The model can thus serve a purpose as a flexible and practical tool for analyzing costs and benefits of road prices under varying assumptions.

The paper is constructed as follows. In section 2 we introduce the analytical framework and derive expressions for optimal road prices. The numerical modelling, with parameter values and scenarios, is explained in Section 3. The results from the modelling exercise is given in Section 4, while Section 5 concludes.

2 Analytical framework

As explained above, an important goal of this paper is to emphasize the importance of differentiating between spatiotemporal states, as the estimated value of the externalities vary between these states. In order to avoid too cumbersome notation, we intend to solve the model for a single state that contains all of the externalities. Such a state can be thought of as a large city during peak hours. The numerical model will calculate solutions for all of the considered states.

We will make the simplifying assumption that agents and their cars are constrained to stay within one state only. While 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 many agents. The representative agent has the following utility function:

(1) $$U = u(m_i, v_i, X, l, T, E)$$

All variables are in per household terms. The utility function $u(.)$ is quasi-concave and increasing in arguments m_i, kilometers driven per vehicle i, which could be any passenger car make of any energy source, be it gasoline, diesel or electricity v_i; the vehicle stock of car type i[2], general consumption X, and leisure l. In contrast, utility is decreasing in arguments T, aggregate travel time spent in cars which, in addition to being an activity with some disutility (possibly), it implicitly also lowers household utility by reducing time available for work (and thus income for consumption) and leisure. Utility is also decreasing in E, representing an index of environmental externalities.

For modelling purposes, we will assume that there are two types of vehicles. These are the average fossil-fueled car and the average electric car, with subscripts *F* and *P*, respectively. This gives us a slightly simpler utility function:

(2) $$U = u(m_F, v_F, m_P, v_P, X, l, T, E)$$

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

(3) $$T_i = t(\overline{M})M \quad ,$$

where $t\left(\overline{M}\right)$ is (average) travel time per kilometer depending on aggregate vehicle kilometrage ($t' > 0$ implies time delays due to an increase in kilometrage, and in our stylized model, we assume that such large traffic volumes in one area only occurs in the state cities during rush hours) and

(4) $$M = M_P + M_F = m_P v_P + m_F v_F$$

is aggregate distance traveled (vehicle kilometrage) by the representative household. The externality index $E_i = \left\{E_F(\overline{F}), E_P(\overline{P}), E_{M_F}(\overline{M_F}), E_{M_P}(\overline{M_P})\right\}$ covers traffic externalities stemming from energy consumption E_F and E_P (increasing in the use of fossil fuels and electric power, F and P) and from vehicle kilometrage E_{M_i} (increasing in $\overline{M}_i$). The partial derivatives of E then denote the various marginal external damages (in units) related to energy consumption and vehicle kilometrage. We assume in this paper that there are no externalities associated with producing and consuming electricity for EVs $E_P(\overline{P}) = 0$. With regards to greenhouse gases (GHGs), this assumption may hold for countries like Norway that are within the EU ETS-market, as discussed in Bjertnæs (2016). However, whether this assumption holds for local pollution may deserve some closer discussion, as highlighted in Holland, Mansur, Muller, and Yates (2016), but that will not take place in this paper.

[2] Vehicle stock and corresponding vehicle choice per household is taken as a continuous variable because we are averaging over a large number of households.

The assumption of no externalities associated with producing and consuming electricity will in any case save space in this paper[3].

The monetary budget constraint of the household – equating expenditures for travel activities and general consumption with net income – can be written as follows:

(5)

$$\left[\left(P_F f + c_F\right)m_F + \tau_{m_F} m_F + c(f) + \Gamma_F\right]v_F + \left[\left(P_P p + c_P\right)m_P + \tau_{m_P} m_P + c(p) + \Gamma_P\right]v_P + P_X X = (1-\tau_L)wL$$

where $P_i = (p_i + \tau_i)$ denote the consumer price per unit of energy type *i*. All consumer prices contain the pure fixed producer energy supply price p_i and the energy tax τ_i. Energy intensity for cars, expressed in units per kilometer, is denoted f for ICEVs and p for EVs. The lower the energy intensity, the more energy efficient is the car. The terms c_F and c_P denote the other distance dependent costs (repair, service etc.). Tolls are averaged to per-km road prices (τ_{m_F} and τ_{m_P}). The terms $c(f)$ and $c(p)$ denote the other costs of owning a car, independent of distance. This would mainly be an annuity of the pre-tax purchase cost. These costs are assumed to depend on energy efficiency, so they capture how increasing energy efficiency comes at a cost (otherwise everyone 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 the annual ownership tax and the annuity of the purchase tax for the vehicle type. The consumer price of the general consumption goods basket is $P_X X$.

Monetary household net (labor) income is $(1-\tau_L)wL$, where τ_L is the labor tax rate. Finally, w is the hourly gross wage and L is labor supply (hours per year). Total pre-tax labor income is denoted W.

The relationship between fuel usage and energy intensity and km driven is given by:

(6) $$F = fM_F = fm_F v_F$$

(7) $$P = pM_P = pm_P v_P$$

In addition to the monetary budget constraint the individual is also subject to the following time constraint

(8) $$L + l + t(\overline{M})M = \overline{L}$$

[3] A version of the derivation of optimal taxes where more parameters are included can be obtained from the author on request.

This shows that the total time endowment $\overline{L}$ can be spent on labor, leisure and travel.

The following government budget constraint equates fixed public spending *GOV* with net tax revenue:

(9) $$GOV = \tau_F F + \tau_P P + \tau_{m_F} m_F v_F + \tau_{m_P} m_P v_P + \tau_L wL + \Gamma_P v_P + \Gamma_F v_F \quad ,$$

On the production side, it is assumed that goods are all produced under constant returns to scale by competitive firms using labor as the only primary input. Therefore, there are no pure economic profits, and producer prices are fixed. Firms pay a gross wage of *w* equal to the constant value marginal product of labor.

Optimization

The household's optimization program is to maximize the utility function Eq. (1) with respect to the choice variables $m_F, v_F, f, m_P, v_P, p, X$ and l subject to the monetary budget constraint Eq. (5) and time constraint Eq. (8). The per kilometer travel time, externalities, and taxes are treated as given by the household. We form the Lagrangian – denoting μ as the Lagrange multiplier of the household's (full economic) budget constraint (the marginal utility of income) and obtain the first-order conditions (FOCs). We then use the FOCs to obtain the household's indirect utility function, that yields maximized utility given prices, taxes and income, but also travel time and externalities that are determined by the *aggregate* level of driving.

The government's optimization program then is to maximize the household's indirect utility function with respect to a set of parameters $\Omega \equiv \left\{\tau_{m_F}, \tau_{m_P}, \tau_P, \Gamma_F, \Gamma_P, \tau_L, t, E\right\}$ that are exogenous to the household (policy variables and time and environmental externalities).

(10)

$$V(\Omega) \equiv \max_{m_F, v_F, f, m_P, v_P, p, X, l} u(m_F, v_F, m_P, v_P, X, l, T, E)$$
$$-\mu \left(\begin{array}{l} \left[\left(P_F f + c_F\right) m_F + \tau_{m_F} m_F + c(f) + \Gamma_F\right] v_F + \left[\left(P_P p + c_P\right) m_P + \tau_{m_P} m_P + c(p) + \Gamma_P\right] v_P \\ + P_X X - (1-\tau_L) w(\overline{L} - l + t(\overline{M})M) \end{array} \right)$$

We will show the analytical exercise of deriving the optimal tax on EV-km, τ_{m_P}. All the steps of the analytical derivations are given in the appendix. Here in the main part of the paper, we only show the most central equations before we get to the analytical results. The analytical exercise starts by total differentiation of the household's indirect utility function with respect to τ_{m_P}. After some algebra, and redefining the externality terms we get the following expression for the marginal welfare effect of the km-tax:

$$\frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = \underbrace{e_F\left\{-\frac{dF}{d\tau_{m_P}}\right\}}_{\textit{energy related externalities}} + \underbrace{e_m^c\left\{-\frac{dM}{d\tau_{m_P}}\right\}}_{\textit{congestion externalities}} + \underbrace{e_{m_F}^{nc}\left\{-\frac{dM_F}{d\tau_{m_P}}\right\} + e_{m_P}^{nc}\left\{-\frac{dM_P}{d\tau_{m_P}}\right\}}_{\substack{\textit{kilometrage related} \\ \textit{non-congestion externalities}}}$$

$$(11)\quad -\underbrace{\left[\tau_{m_P}\left\{-\frac{dM_P}{d\tau_{m_P}}\right\} + \tau_{m_F}\left\{-\frac{dM_F}{d\tau_{m_P}}\right\}\right]}_{\textit{km-tax revenue}} - \underbrace{\left[\tau_F\left\{-\frac{dF}{d\tau_{m_P}}\right\} + \tau_P\left\{-\frac{dP}{d\tau_{m_P}}\right\}\right]}_{\textit{energy tax revenue}}$$

$$\underbrace{+D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}}}_{\substack{\textit{direct/indirect tax revenue/cost from} \\ \textit{vehicle stock}}} + \underbrace{\tau_L\frac{dW}{d\tau_{m_P}}}_{\textit{labor tax revenue}}$$

The parameter e_F represents the MEC stemming from the consumption of fossil fuel. Similarly, the parameters $e_m^c, e_{m_F}^{nc}$, and $e_{m_P}^{nc}$ represents the MEC from driving a km, with regards to congestion, and km-based environmental externalities from ICEVs and EVs respectively. The parameters D_F and D_P represent the per vehicle annual tax revenue $\tau_{m_F} m_F + \tau_F f m_F + \Gamma_F$ and $\tau_{m_P} m_P + \tau_P f m_P + \Gamma_P$. As we see, the EV-km tax causes a number of different changes in Eq.(11), which shows that the km-tax affects overall welfare through many different channels.

Derivation of the optimal km-tax

Setting the marginal welfare change as displayed in Eq.(11) to zero and solving for τ_{m_P} yields

$$(12)\quad \begin{aligned} \tau_{m_P}^* &= e_F\left\{\frac{dF/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + e_m^c\left\{\frac{dM/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + e_{m_F}^{nc}\left\{\frac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + e_{m_P}^{nc} \\ &+ \left[\tau_{m_F}\frac{dM_F}{d\tau_{m_P}} + \tau_F\frac{dF}{d\tau_{m_P}} + \tau_P\frac{dP}{d\tau_{m_P}} + D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}} + \tau_L\frac{dW}{d\tau_{m_P}}\right]\frac{1}{-dM_P/d\tau_{m_P}} \end{aligned}$$

After more algebra, which is shown in the Appendix, we finally get the final expression for the optimal km-tax

$$(13)\quad \tau_{m_P}^* = \tau_{m_P}^C + \tau_{m_P}^I = \tau_{m_P}^C + \tau_{m_P}^{RR} + \tau_{m_P}^{TI} = \tau_{m_P}^C + \tau_{m_P}^{RR} + \tau_{m_P}^{(TI)} + \tau_{m_P}^{CF}$$

The first term is the corrective component

$$(14)\quad \tau_{m_P}^C = e_{m_P}^{nc} + e_m^c + \eta_F(e_m^c + e_{m_F}^{nc}) + \chi_F e_F \;.$$

The parameters η_F and χ_F are parameters for how consumption of ICEV-kms and fossil fuel consumption 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 (13) is the revenue recycling component

(15) $$\tau_{m_P}^{RR} = \Omega_{\tau_L}\left(\frac{\left(P_P p + c_P + \tau_{m_P}\right)}{-\varepsilon_{M_P}} - \tau_{m_P}\right).$$

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 component in (13) is the tax interaction component (not including the congestion feedback component):

(16)

$$\tau_{m_P}^{(TI)} = -\left(1+\Omega_{\tau_L}\right)\left[\left(\frac{\tau_L\left(P_P p + c_P + \tau_{m_P}\right)(\varepsilon_{MI}^c + \varepsilon_{LI})}{\left(-\varepsilon_{M_P}\right)\left(1-\tau_L\right)}\right) + \eta_F \tau_{m_F} + \chi_F \tau_F + p\tau_P + \kappa_P D_P + \varphi_F D_F\right]$$

The fourth component is the congestion feedback component:

(17) $$\tau_{m_P}^{CF} = \left(1+\Omega_{\tau_L}\right)\frac{\tau_L}{\left(1-\tau_L\right)}\left(\varepsilon_{LI}(1-\varepsilon_{MI})\varepsilon_{LL}^c\right)e_{m_P}^c\left[\eta_F + 1\right],$$

The previously unmentioned parameters in these expressions are ε_{MI}^c and ε_{MI}, the compensated and uncompensated income elasticities for vehicle kms, ε_{LI}, the income elasticity of labor supply, and ε_{LL}^c, the compensated elasticity of labor supply. Ω_{τ_L} represents the marginal cost of public funds, which is defined as

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

It represents the efficiency cost of raising an extra NOK of revenue through labor taxes (or the efficiency gain of recycling one NOK through cuts in labor taxes). $\varepsilon_{LL} > 0$ is the (uncompensated) labor supply elasticity. The numerator in Eq. (18) reflects the efficiency cost from an incremental increase in the labor tax whereas the denominator is the marginal change in tax revenue. We have that $\Omega_{\tau_L} > 0$ 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 beyond the peak of the Laffer curve, i.e. marginal revenue is positive.

The components of the optimal tax is thoroughly described in Tscharaktschiew (2014, 2015), but we will give brief explanation here.

The corrective tax component accounts for the externalities associated with driving an EV-km. It includes the km-related externalities related to congestion (same for all vehicles), and other externalities like 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 reducing the level of the corrective component.

The second component is the revenue recycling effect. It represents the efficiency gain from using additional EV-km tax revenue to cut the distortionary labor tax and so to 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 to the government from raising the EV-km tax.

The third component is the tax interaction effect. It accounts for the efficiency loss in the labor market from the higher tax on kms. On one hand, higher taxes reduce the real household wage and has a discouraging effect on labor supply. On the other hand, it also includes the income effect from a higher km-tax on labor supply. The further terms reflect the interaction of the EV-km tax with the other (secondary) tax distorted markets, e.g., the electricity market.

The fourth component is the congestion feedback effect. Raising the cost of travel through km-taxes may reduce vehicle kilometrage and congestion. This induces a feedback effect on labor supply, leading workers to allocate their time towards less time spent on travel and more spent on labor or leisure. Because labor is taxed, this feedback effect is welfare improving and *ceteris paribus* causes an upward adjustment of the optimal km tax. When we present our numerical results, this component will be included in the tax interaction component where relevant, i.e. in the state large cities during peak hours.

We solve the model the exact same way for $\tau^*_{m_F}$, and obtain analogous expressions that look like the following:

(19) $$\tau^*_{m_F} = \tau^C_{m_F} + \tau^I_{m_F} = \tau^C_{m_F} + \tau^{RR}_{m_F} + \tau^{TI}_{m_F} = \tau^C_{m_F} + \tau^{RR}_{m_F} + \tau^{(TI)}_{m_F} + \tau^{CF}_{m_F}$$

With the corrective component

(20) $$\tau^C_{m_F} = e^{nc}_{m_F} + e^c_m + \left(f + \sigma_F \right) e_F + \eta_P (e^c_m + e^{nc}_{m_P}) \ ,$$

the revenue recycling component

(21) $$\tau^{RR}_{m_F} = \Omega_{\tau_L} \left(\frac{\left(P_F f + c_F + \tau_{m_F} \right)}{-\varepsilon_{M_F}} - \tau_{m_F} \right),$$

the tax interaction component (not including the congestion feedback component)[4]

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

(22) $$\tau_{m_F}^{(TI)} = -\left(1+\Omega_{\tau_L}\right)\left[\begin{array}{l}\left(\dfrac{\tau_L\left(P_F f + c_F + \tau_{m_F}\right)(\varepsilon_{MI}^c + \varepsilon_{LI})}{\left(-\varepsilon_{M_F}\right)\left(1-\tau_L\right)}\right) \\ +\eta_P\tau_{m_P} + \chi_P\tau_P + \left(f+\sigma_F\right)\tau_F + \kappa_F D_F + \varphi_P D_P\end{array}\right],$$

and finally the congestion feedback component,

(23) $$\tau_{m_F}^{CF} = \left(1+\Omega_{\tau_L}\right)\frac{\tau_L}{\left(1-\tau_L\right)}\left(\varepsilon_{LI}(1-\varepsilon_{MI})\varepsilon_{LL}^c\right)e_m^c\left[\eta_F + 1\right],$$

The expressions for τ_{m_F} mirror those for τ_{m_P}, and the applied parameters 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.

Functional relationships

Parameters like $\eta_F = \dfrac{dM_F / d\tau_{m_P}}{dM_P / d\tau_{m_P}}$ quantify our assumptions on how households respond to changes in tax parameters. These parameters can be expressed in terms of elasticities, e.g., $\eta_F = \dfrac{M_F \varepsilon_{M_F}^{M_P}}{M_P \varepsilon_{M_P}}$, where $\varepsilon_{M_F}^{M_P}$ 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 $m_F = m_F^0\left(\dfrac{P_{m_P} + \tau_{m_P}^*}{P_{m_P} + \tau_{m_P}^0}\right)^{\varepsilon_{M_F}^{M_P}}$ and $m_P = m_P^0\left(\dfrac{P_{m_P} + \tau_{m_P}^*}{P_{m_P} + \tau_{m_P}^0}\right)^{\varepsilon_{M_P}}$, where we assume constant elasticity of demand. This is common practice in these kinds of analyses of optimal pricing in the transport sector, see e.g., Parry and Small (2005), Parry (2009) and Tscharaktschiew (2014, 2015). We have similar expressions for responses in vehicle stock. The parameter P_{m_P} is the pre-tax cost of a km, $P_P p + c_P$, as seen in the budget equation, Eq. (5). The parameters m_F^0 and m_P^0 are the per-vehicle kilometrage in the initial equilibrium. The levels in the new equilibrium depends on the road prices in the new equilibrium. If e.g. $\tau_{m_P}^*$ does not differ from $\tau_{m_P}^0$, then there will be no change in the new equilibrium, as m_P would equal m_P^0.

As we see from the equations that comprise the optimal taxes, the tax levels are on both the left-hand and the right-hand side of the equation, so we must solve it numerically. In addition, we want to 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 calculate the optimal tax rates.

3 Numerical model description and parameter values

In this section, we explain the scenario for calculating optimal levels of taxes for EV-kms and ICEV-kms. The thought experiment for the baseline calculation can be summarized as: 1) We assume the optimal km taxes are implemented in the time of writing in 2017. 2) There is a medium-run adjustment from agents towards 2020. 3) Based on these medium-run adjustments, we get values for the optimal taxes in 2020.

Our calculations ignore dynamics in the adjustments, and 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 in cost-benefit analysis conducted in Norway, see e.g., NOU 2012:16 (2012)). All monetary values are given in 2015-prices. Applied values for vehicle kms and levels of labor and electricity taxes are also based on 2015 values.

Ideally, one would want to have individual tax levels for the hundreds of car types, based on the car types' individual characteristics. In our model, we make the drastic simplification of working 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 kms in 2015[5], based on the BIG-model[6] at the Institute of Transport Economics.

In the theoretical framework we have taxes on labor, fossil fuel, electricity, vehicle purchase and ownership taxes, ICEV-km and EV-km. In the numerical model, the current tax on fossil fuels, along with average tolls in the various states, are 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 the drivers incentives to economize their kilometrage 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 is derived from the social cost of CO2. This cost component gives not only incentives to economize kilometrage but also 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 into the road price. Parts of the road price for a particular car would then differ according to the fuel intensity of that car, and hence contain an implicit fuel tax. This model technicality becomes apparently 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

[5] Gasoline had 59 % of the ICEV kms travelled in 2015 and diesel had 41%

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

ownership taxes, must be offset by changes in the labor tax. This makes the equilibrium labor tax rate endogenous.

The scenario can mimic a reform where fuel taxes and tolls are shifted over to road prices, which then are optimized, taking into account that labor tax rates change to maintain revenue neutrality. A situation where the optimal road prices lead to a reduction in labor tax rates, corresponds to a net shift in tax burden from labor income to transport.

With regards to transport variables, the representative household in the model is considered as a weighted average of values for the three different geographical areas we consider. The areas are large cities (larger than 100 000 inhabitants), small cities (between 15 000 and 100 000 inhabitants) and rural areas (less than 15 000 inhabitants), which contains 28%, 32% and 40% of Norwegian households, respectively. This classification of areas corresponds to the one done for external costs of road transport in Thune-Larsen, Veisten, Rødseth, and Klæboe (2014).

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

Table 1: Parameter values for baseline calculations

Description	**Name of symbol**	**Value**	**Dimension**	**Sources used**
Transport and other data				
Initial "fossil" fuel intensity	f^0	0.079	l/km	Institute of Transport Economics, BIG-model
EV el intensity (average of winter and summer)	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) [These kms per car per area numbers are weighted according to areas share of households. In sum, this results in a national average of 12 230 km per car]
Initial vehicle kilometrage per car (EV & ICEV), large cities, off-peak (lo)	m_{ilo}^0	10806	km	
Initial vehicle kilometrage per car (EV & ICEV), small cities (s)	m_{is}^0	12004	km	
Initial vehicle kilometrage per car (EV & ICEV), rural (r)	m_{ir}^0	12761	km	
ICEVs per household, large cities (Fl)	v_{Fl}^0	0.960	cars	Statistics Norway (StatBank: link) [These cars per household per area numbers are weighted according to areas 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, small cities (Fs)	v_{Fs}^0	1.128	cars	
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	p_F	6.82	NOK/l	Statistics Norway (StatBank: link)
Corresponding initial fossil-km producer price	p_{M_F}	0.54	NOK/km	
Other private km costs for ICEVs	c_F	1.32	NOK/km	Vegdirektoratet (2015)
Electricity consumer price (includes VAT and electricity tax)	p_P	0.81	NOK/kWh	Statistics Norway (StatBank: link)
Corresponding EV-km price (includes VAT and electricity tax)	p_{M_P}	0.20	NOK/km	
Other private km costs for EVs	c_P	1.13	NOK/km	Vegdirektoratet (2015), smartepenger.no
Initial fossil fuel tax	τ_F^0	6.58	NOK/l	Finansdepartementet (2016)
Corresponding initial fossil-km tax	$\tau_{m_F}^0$	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 personal 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		164892	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 Norwegian inflation target is 2.5%.
Average marginal labor tax rate (benchmark)	τ_L	40%		Bjertnæs (2015)
<u>Behavioral responses</u>				
Own-price elasticity of fossil intensity	ε_f	-0.092		Norsk Petroleumsinstitutt (2011)
Own-price elasticity of ICEV kilometrage	ε_{M_F}	-0.152		Steinsland, Østli, and Fridstrøm (2016)
Own-price elasticity of EV kilometrage	ε_{M_P}	-0.152		Steinsland et al. (2016)
Own-price elasticity of ICEV ownership wrt costs per km	$\varepsilon_{M_F}^{v_F}$	-0.121		Boug, Dyvi, Johansen, and Naug (2002)
Own-price elasticity of EV ownership wrt costs per km	$\varepsilon_{M_P}^{v_P}$	-0.121		
Cross-price elasticity of EV kilometrage i.e. how ICEV ownership increases when the cost of EV- km increases	$\varepsilon_{M_P}^{v_F}$	0.0015		Institute of Transport Economics, BIG-model
Cross-price elasticity of ICEV kilometrage i.e. how EV ownership increases when the cost of ICEV- km increases	$\varepsilon_{M_F}^{v_P}$	0.486		Institute of Transport Economics, BIG-model
Income elasticity of vehicle kilometrage	ε_{MI}	0.185		Steinsland and Madslien (2007)
Compensated income elasticity of vehicle kilometrage	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)
Labor supply elasticity (compensated)	ε_{LL}^{c}	0.208		$\varepsilon_{LL}^{c} = \varepsilon_{LL} - \varepsilon_{LI}$
<u>External costs of cars</u>				
Kilometrage related external congestion costs, initially, large cities, peak	e_{m}^{c}	6.339	NOK/vkm	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		
Kilometrage related external non-congestion costs ICEV, large cities, peak (lp)	$e_{m_F lp}^{nc}$	0.958	NOK/vkm	
Kilometrage related external non-congestion costs EV, large cities, peak (lp)	$e_{m_P lp}^{nc}$	0.423	NOK/vkm	
Kilometrage related external non-congestion costs ICEV, large cities, off-peak (lo)	$e_{m_F lo}^{nc}$	0.823	NOK/vkm	
Kilometrage related external non-congestion costs EV, large cities, off-peak (lo)	$e_{m_P lo}^{nc}$	0.423	NOK/vkm	
Kilometrage related external non-congestion costs ICEV, small cities (s)	$e_{m_F s}^{nc}$	0.492	NOK/vkm	
Kilometrage related external non-congestion costs EV, small cities (s)	$e_{m_P s}^{nc}$	0.419	NOK/vkm	
Kilometrage related external non-congestion costs fossil car, rural (r)	$e_{m_F r}^{nc}$	0.171	NOK/vkm	
Kilometrage related external non-congestion costs EV, rural (r)	$e_{m_P r}^{nc}$	0.161	NOK/vkm	
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)

The values for the external costs from driving are all taken from Thune-Larsen et al. (2014). The external non-congestion costs consist of external cost estimates for local pollution, noise, accident risk, road wear and winter management. In Table 1 it is clear to see that the external costs vary significantly between the states city during peak hours, city in off-peak hours and rural areas.

4 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.

Baseline second-best road pricing

The model calculates road prices that vary significantly between states, largely reflecting the variation in external costs. This can be seen in Table 2. The highest price is placed on driving an ICEV in a large city during peak hours, mainly because of the relatively high 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 hour have been reduced significantly, both for EVs and ICEVs. It is still worth noting that the tax per km is more than five time higher than the current sum of average toll and fuel tax per km during peak hour.

The lowest price is placed on driving an ICEV in rural areas. The tax per km is actually 60% lower in the new equilibrium, than the sum of average toll and fuel tax per km was initially. It is also worth noting that the optimal road price for ICEVs in rural areas is actually lower than for EVs in the corresponding area. This is the case for driving in small cities as well.

This brings us over to another important observation from Table 2. In all cases there is a markup from the revenue recycling component, showing the efficiency gain from replacing revenue from labor taxation with revenue from road pricing. We also see that the tax interaction component lowers the final road prices. This is because of the negative impact 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 quite large. Incentivizing EV driving over ICEV driving in these states will result in lower tax revenues from e.g. 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 the 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. For all cases the final road price is larger than the corrective component that targets the internalization of externalities, with the exception of driving ICEV in rural areas. For this case the tax interaction component has a larger impact on the final price than the revenue recycling component.

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[7]**	**Tax interaction component – other taxes**	**Total**	**Initial (tolls and fuel tax per km)**

[7] Including congestion feedback where relevant, i.e. in the state City peak hours

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**

In all the states, the optimal km-taxes are higher than their current levels for EVs. However, for ICEVs 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 km travelled per household, from 14 129 to 14 150 km per year, in spite of 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 go in the opposite direction. On average, EV ownership rates increase by about 11%, but the corresponding 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. The total increase in labor taxes corresponds to an increase in the average marginal tax rate from 40% to 40.1%.

In order to calculate the welfare effect of this road pricing scheme, we numerically integrate the marginal welfare impact, shown in eq. (11) and rewritten in eq. (84). When numerically integrating the marginal welfare effect for all the road prices, we end up with an annual welfare gain of 255 NOK (or about 32 € per household). For comparison, Tscharaktschiew (2014) finds a welfare gain of 13 € per household when optimizing gasoline taxation.

What are the GHG emission implications when such values are applied in the model and second-best road prices are calculated? As emphasized in Section 3, the applied social cost of carbon (SCC) of 420 NOK per ton is a parameter in the corrective component in Eq. (20), that gives a direct incentive to economize fuel, while the road price as a whole gives incentive to economize kilometrage. It is equivalent to moving the fuel tax from the pump, but incorporating it into the 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 optimized equilibrium. This leads to agents choosing about 5% lower average fuel efficiency. With almost unchanged travel demand in the nation as a whole, the annual GHG emissions from transport increases 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.

Optimal road prices and a shadow price on CO_2

The Norwegian government has a goal to reduce GHG-emissions from 1990-levels by 40% within 2030. By 2016, annual emissions were about 3% higher than in 1990. For the road transport sector, it was even worse, where the emissions were about 28% higher[8]. In our next modelling exercise, we consider a binding emission reduction requirement for personal road transport from 2015 levels (the initial situation in the model) to 2020, about 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 in order to fulfill the emission reduction requirement.

For this exercise, we set a constraint on equilibrium emissions, and we allow the carbon price component in the road price (in effect, the fuel tax) to vary freely, and not be set equal to the recommended SCC. The model will solve for the optimal road pricing scheme given constraints, 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.

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**

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

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**

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

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

We see from Table 4 that the shadow price of the emission constraint is about 16 times the SCC. This corresponds to a carbon price of 7057 NOK/ton. We also see that carbon cost component surpasses the initial fuel tax, by about 150%. This means that in order to achieve the emissions reductions target at least cost alongside an optimized road pricing scheme it would not be a question of "shifting from fuel tax and tolls to road price". It would require increasing the tax burden *both* on fossil fuel and on kilometers.

So *how* do the agents reduce their emissions at least cost? The agents can drive ICEVs less and/or drive them more efficiently (or replacing them with more efficient ICEVs). The results show an about 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 materialize in a shift from ICEV ownership to EV ownership. The results show that they drive about 9.6% fewer km in total, when EVs are included. EV ownership has increased by about 33% nationwide (and 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 opens up for 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 219 NOK per year. This welfare calculation assumes that the actual welfare cost of a ton of GHG is 420 NOK, the SCC, even though a higher shadow price has been forced upon the transport sector. The high shadow price for the emission constraint reflects high welfare costs from large-scale CO2-abatement within the transport sector. For the Norwegian economy as a whole, the shadow price of such a CO2-constraint would probably be lower. This is 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.

Sensitivity analysis and alternative scenarios

The model results rely on the parameter values, which in some cases are derived from fairly noisy and uncertain estimates (see e.g., Thune-Larsen et al., 2014). We therefore provide sensitivity analysis to show how the uncertainty in the underlying parameters reflect the uncertainty in the results. This applies for both estimates of external costs and behavioral relationships, i.e. elasticities. We will mainly focus on testing the sensitivity of the elasticity values. The implications for road price levels of higher/lower external cost values are easier to imagine, and we have already shown the implications of higher carbon costs. It will also save space in the article.

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

Two of our focus on the uncertainty on 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.

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 wrt ICEV km-cost	+ 30%	- 30%
Own-price elasticity of EV purchase wrt. EV km-cost	+ 30%	- 30%
Cross-price elasticity of ICEV purchase wrt. EV km-cost	+ 30%	- 30%
Cross-price elasticity of EV purchase wrt. ICEV km-cost	+ 30%	- 30%

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

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%

We further add two more scenarios. These scenarios test the implications of different developments for EV purchases and EV purchase taxes. The first of these scenarios 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 quite large since the 2015, the base year of the analysis. This scenario is denoted 2X EV.

The last scenario considers the case where the government relaxes the largest incentive for purchasing EVs, namely the exemption from VAT. A 25% VAT on the average EV sold in Norway would correspond to a 91 558 NOK addition to 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 455 NOK to 3 565 NOK per year. This scenario is denoted EV VAT.

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

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	**Base-line**	**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 four scenarios that test the 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 lead to 45% to 87% lower optimal road prices compared to the baseline. The direction is not surprising, as more responsiveness makes it a less attractive to tax, as 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 the revenue recycling component and the tax interaction component becomes smaller, but it is the reduced revenue recycling component that dominates. The corresponding road prices in the LRTM-scenario are 27% to 96% higher than the baseline.

The more responsive the agents are in the labor market, the higher the road price. 30% larger elasticities for own-price and income elasticity with respect to labor supply, resulted in 49% to 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, which drives up the revenue recycling component, and the income elasticity drives up the value of the tax interaction component (makes it less negative). In the opposite end, the road prices in the LRLM-scenario are 31% to -184% lower than the baseline. The labor elasticity and income elasticity of labor are estimated to be relatively small in the Norwegian LOTTE-modelling system at Statistics Norway (see e.g., Dagsvik et al., 2007), namely 0.178 and -0.03, respectively. This makes the optimal prices quite sensitive to changes in these parameters.

In the 2X EV scenario we see that a doubled initial stock of EVs implies higher road prices for ICEVs in large and small cities, but somewhat lower in rural areas. As for EVs, the optimal road price becomes lower, with the exception of cities during peak hour. This is mainly because for given elasticities[9], the absolute changes related to EV stock will be larger, and lower for the ICEV stock. This increases the absolute value of parameters for household responses to shift to EV-km and EV-ownership when ICEV road prices increase and reducing 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 road prices for ICEVs.

In the EV VAT scenario we see that removing the VAT exemption for EVs would imply a 1% to 4% higher road price for ICEVs. 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 a VAT on EVs, a higher road price on ICEVs become, on the margin, less of a fiscal problem, as the government revenue loss from a switch to EVs becomes smaller. This is similar to the finding from Tscharaktschiew (2015), where he shows that introducing EV purchase subsidies, reduces the optimal gasoline tax.

[9] 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

5 Discussion and conclusion

We start this section by going through the research questions and how they have been answered.

What characterizes the set of second-best road prices for internalizing external costs from driving EVs and ICEVs when you also have distortionary labor taxes and binding government budget constraints?

The short answer to the question is that it is characterized by 1) large price differences between states, 2) ICEVs face a higher cost in large cities, but lower costs in most parts of the country compared to the initial situation and 3) EVs should not go untaxed. The highest price, 7.97 NOK per km, is placed on driving an ICEV in large cities during peak hours, while the lowest price, 0.23 NOK per km, is placed on driving an ICEV in rural areas. Since we find that ICEVs are overtaxed in most parts of the country in the initial situation, we find that in optimum it is better to have slight increase in the labor tax rate, and allow for reduced tax burdens on ICEVs outside large cities. In sum, the road pricing scheme leads to higher welfare.

It has been common to find that driving is undertaxed and that labor is overtaxed in previous literature using the analytical framework developed by Parry and Small (2005) and the other authors referenced in the introduction. In our paper, we find that only driving in large cities is undertaxed, while driving in the rest of the country is overtaxed. This demonstrates how analyzing a road pricing scheme that differs over four spatiotemporal states, and over two car types adds more nuance and insight than e.g., analyzing a single gasoline tax. It also takes the large 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.

How are these prices affected by distortions elsewhere in the economy?

We find that the interaction with the rest of the fiscal system leads generally to a price markup on the external costs. The differences between states and car types largely reflects the differences in external costs per km, the corrective component, but also an interaction component that reflects how the km-tax in that given state with that given car type interacts with the rest of the fiscal system. Within this interaction component there are two opposing forces. The revenue recycling through reducing labor taxation drives the road prices upwards, while the road prices' interaction with the labor market and the rest of the tax system generally drives the price downwards. We 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.

How does this second-best pricing fit with government set goals of reducing CO2-emissions?

The second-best road pricing scheme applies the recommended social cost of carbon of 420 NOK 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 second-best road pricing scheme gives strong incentives to economize on travel distance (depending on state), the net effect on carbon 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 CO2-emissions from personal road transport implies a higher carbon price than the recommended SCC.

We run the model again with a 15% emission reduction requirement. In order to reach this target at least cost, a shadow price of carbon 16 times the SCC is required. 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. The adaptation to these prices comes mainly through driving the ICEVs less, but also through increased fuel efficiency. Some of the reduced driving of ICEVs is reflected in a large increase in people driving EVs. The large-scale CO2-abatement within the transport sector comes at a high welfare cost, but it is worth noting that for the Norwegian economy as a whole, the cost would probably be lower as cheaper abatement opportunities outside the transport sector would be exploited.

Concluding remarks

There are good efficiency reasons to look closer at road pricing as the future main instrument for regulating transport. The fuel tax is imprecise for internalizing externalities, its signals of external costs get weakened through more fuel efficiency, and it provides no signals to people driving EVs. A satellite-based road pricing system could bring precision to the regulation of transport demand, and provide efficient price signals to all drivers. The modeling framework, that has been used by several authors focusing on fuel taxes, has in this paper been reconfigured and extended to mimic such a future road pricing system.

These results suggest that a satellite-based road pricing scheme is likely to be welfare enhancing, as it improves both efficiency in the transport market, but it also could alleviate some the burden of distortionary labor taxes. For 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 modelling 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 of the model could include heterogeneous agents, public transport and the opportunity so 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. It can also look closer at distributional impacts and political feasibility. The modelling involves moving from one static equilibrium to another. The numerical modelling is based on 2015 being an equilibrium situation, although in many respects it could be considered a transitory situation, at least with regards to the EV stock. We try to incorporate this into the analysis through the sensitivity testing.

The numerical results also have their caveats as they are based on estimates obtained from noisy data. We stress the uncertainty in how agents would respond to the road pricing system, and our sensitivity analysis shows us that changes in these 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 very mindful of these uncertainties with regards to design and implementation planning.

The development of satellite-based road pricing for personal transport 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, but many steps need to be taken before it can be widely seen in the real world. Citizens may be skeptical, for instance about privacy concerns (Duncan, Nadella, Giroux, Bowers, & Graham, 2017). However, the Data Protection Agency in Norway claim that a satellite-based road pricing scheme could be designed to respect (and maybe even enhance) privacy protection[10]. Principles such as that ownership of the data belongs to the car owner, and that the scheme cannot be used 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 its implantation (Anthoff & Hahn, 2010). We saw in the case of the Dutch attempt to design a national road pricing scheme between 2007 and 2011, that politics was the main reason for the project to be stopped after years of progress, seemingly close to the finish line (Geerlings, Shiftan, & Stead, 2012).

Attempts to develop satellite-based road pricing schemes may finally be successful, or they could continue to fail. In any case it will offer valuable learning experiences. And contributing to the body of knowledge on road pricing is a worthy pursuit of any transport economist.

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[10] http://www.ofv.no/artikler-2017/dynamisk-veiprising-kan-fjerne-bomstasjonene-article515-299.html (in Norwegian, easily translated by translation software)

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Appendix

A1 Derivation of optimal tax

The household's optimization program is to maximize the utility function Eq. (1) with respect to the choice variables $m_F, v_F, f, m_P, v_P, p, X$ and l subject to the monetary budget constraint Eq. (5) and time constraint Eq. (8). The per kilometer travel time, externalities, and government variables (taxes), are treated as given by the household. We form the Lagrangian – denoting μ as the Lagrange multiplier of the household's (full economic) budget constraint (the marginal utility of income) and obtain the first-order conditions (FOCs). We then use the FOCs to obtain the household's indirect utility function, that yields maximized utility given prices, taxes and income, but also travel time and externalities that are determined by the *aggregate* level of driving.

The government's optimization program then is to maximize the household's indirect utility function with respect to a set of parameters $\Omega \equiv \left\{\tau_{m_F}, \tau_{m_P}, \tau_P, \Gamma_F, \Gamma_P, \tau_L, t, E\right\}$ that are exogenous to the household (policy variables and time and environmental externalities).

(24)

$$V(\Omega) \equiv \max_{m_F, v_F, f, m_P, v_P, p, X, l} u(m_F, v_F, m_P, v_P, X, l, T, E)$$
$$-\mu\left(\begin{array}{l}\left[\left(P_F f + c_F\right)m_F + \tau_{m_F} m_F + c(f) + \Gamma_F\right]v_F + \left[\left(P_P p + c_P\right)m_P + \tau_{m_P} m_P + c(p) + \Gamma_P\right]v_P \\ +P_X X - (1-\tau_L)w(\overline{L} - l + t(\overline{M})M)\end{array}\right)$$

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

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_{m_P}.

(25)
$$\frac{dV}{d\tau_{m_P}} = \frac{\partial V}{\partial \tau_{m_P}} + \frac{\partial V}{\partial \tau_{m_F}}\frac{d\tau_{m_F}}{d\tau_{m_P}} + \frac{\partial V}{\partial \tau_F}\frac{d\tau_F}{d\tau_{m_P}} + \frac{\partial V}{\partial \tau_P}\frac{d\tau_P}{d\tau_{m_P}} + \frac{\partial V}{\partial \Gamma}\frac{d\Gamma}{d\tau_{m_P}} + \frac{\partial V}{\partial \tau_L}\frac{d\tau_L}{d\tau_{m_P}}$$
$$+\frac{\partial V}{\partial t}\frac{dt}{d\tau_{m_P}} + \frac{\partial V}{\partial E}\frac{dE}{d\tau_{m_P}}$$

where

(26)
$$\frac{\partial V}{\partial E}\frac{dE}{d\tau_{m_P}} = \frac{\partial V}{\partial E_F(\overline{F})}\frac{\partial E_F(\overline{F})}{\partial F}\frac{dF}{d\tau_{m_P}} + \frac{\partial V}{\partial E_P(\overline{P})}\frac{\partial E_P(\overline{P})}{\partial P}\frac{dP}{d\tau_{m_P}}$$
$$+\frac{\partial V}{\partial E_{M_F}(\overline{M_F})}\frac{\partial E_{M_F}(\overline{M}_F)}{\partial M_F}\frac{dM_F}{d\tau_{\tau_{mp}}} + \frac{\partial V}{\partial E_{M_P}(\overline{M_P})}\frac{\partial E_{M_P}(\overline{M}_P)}{\partial M_P}\frac{dM_P}{d\tau_{\tau_{mp}}}$$

represents the (dis-)utility stemming from a marginal change in aggregate externalities via changes in cars' energy consumption and kilometrage that are caused by a marginal increase in the km-tax for EVs. We assume from here on out that there are no externalities associated with producing and consuming electricity for EVs, i.e. $E_P(\overline{P}) = 0$. This is further discussed in section 2.

For the optimization of $V(\Omega)$ through τ_{m_P}, we can consider τ_{m_F} as exogenously given, implying that $d\tau_{m_F}/d\tau_{m_P} = 0$. The same argument holds when we later show the results of optimizing $V(\Omega)$ through τ_{m_F}, where we can consider τ_{m_P} exogenous and thus $d\tau_{m_P}/d\tau_{m_F} = 0$. In the later expressions for optimal taxes, $\tau^*_{m_P}$ will be a function of τ_{m_F}, and $\tau^*_{m_F}$ will be a function of τ_{m_P}, which will lead us to a set of two equations with two unknowns.

Since the policy instruments τ_F, τ_P and Γ are held fixed in this exercise we can also simplify our expressions with $d\tau_F/d\tau_{m_P} = d\tau_P/d\tau_{m_P} = d\Gamma/d\tau_{m_P} = 0$. This gives

(27)
$$\frac{\partial V}{\partial \tau_{m_P}} = \frac{\partial V}{\partial \tau_{m_P}} + \frac{\partial V}{\partial \tau_L}\frac{d\tau_L}{d\tau_{m_P}} + \frac{\partial V}{\partial t}\frac{dt}{d\tau_{m_P}} + V_{E_F}E'_F\frac{dF}{d\tau_{m_P}}$$
$$+V_{E_{M_F}}E'_{M_F}\frac{dM_F}{d\tau_{m_P}} + V_{E_{M_P}}E'_{M_P}\frac{dM_P}{d\tau_{m_P}}$$

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

(28)
$$\frac{dV}{d\tau_{m_P}} = -\mu m_P v_P - \mu wL\frac{d\tau_L}{d\tau_{m_P}} + \frac{\partial V}{\partial T}M\frac{dt}{d\tau_{m_P}} - \mu(1-\tau_L)wM$$
$$+V_{E_F}E'_F\frac{dF}{d\tau_{m_P}} + V_{E_{M_F}}E'_{M_F}\frac{dM_F}{d\tau_{m_P}} + V_{E_{M_P}}E'_{M_P}\frac{dM_P}{d\tau_{m_P}}$$

Dividing both sides by μ, the marginal utility of income, gives us the welfare change in monetary terms

$$\begin{aligned}(29)\quad &\frac{1}{\mu}\frac{dV}{d\tau_{m_P}} = -m_P v_P - wL\frac{d\tau_L}{d\tau_{m_P}} + \frac{1}{\mu}\frac{\partial V}{\partial T}M\frac{dt}{d\tau_{m_P}} - (1-\tau_L)wM\frac{dt}{d\tau_{m_P}} \\ &+\frac{1}{\mu}V_{E_F}E'_F\frac{dF}{d\tau_{m_P}} + \frac{1}{\mu}V_{E_{M_F}}E'_{M_F}\frac{dM_F}{d\tau_{m_P}} + \frac{1}{\mu}V_{E_{M_P}}E'_{M_P}\frac{dM_P}{d\tau_{m_P}}\end{aligned}$$

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

$$\begin{aligned}(30)\quad &\frac{dGOV}{d\tau_{m_P}} = \frac{\partial GOV}{\partial \tau_{m_P}} + \frac{\partial GOV}{\partial M_P}\frac{dM_P}{d\tau_{m_P}} + \frac{\partial GOV}{\partial M_F}\frac{dM_F}{d\tau_{m_P}} + \frac{\partial GOV}{\partial F}\frac{dF}{d\tau_{m_P}} \\ &+\frac{\partial GOV}{\partial P}\frac{dP}{d\tau_{m_P}} + \frac{\partial GOV}{\partial v_P}\frac{dv_P}{d\tau_{m_P}} + \frac{\partial GOV}{\partial v_F}\frac{dv_F}{d\tau_{m_P}} + \frac{\partial GOV}{\partial \tau_L}\frac{d\tau_L}{d\tau_{m_P}} + \frac{\partial GOV}{\partial W}\frac{dW}{d\tau_{m_P}}\end{aligned}$$

yielding

(31)

$$\begin{aligned}&\frac{dGOV}{d\tau_{m_P}} = M_P + \tau_{m_P}\frac{dM_P}{d\tau_{m_P}} + \tau_{m_F}\frac{dM_F}{d\tau_{m_P}} + \tau_F\frac{dF}{d\tau_{m_P}} + \tau_P\frac{dP}{d\tau_{m_P}} \\ &+\left(\tau_{m_P}m_P + \tau_P pm_P + \Gamma_P\right)\frac{dv_P}{d\tau_{m_P}} + \left(\tau_{m_F}m_F + \tau_F fm_F + \Gamma_F\right)\frac{dv_F}{d\tau_{m_P}} + W\frac{d\tau_L}{d\tau_{m_P}} + \tau_L\frac{dW}{d\tau_{m_P}}\end{aligned}$$

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

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

$$(32)\quad \frac{d\tau_L}{d\tau_{m_P}} = -\frac{M_P + \tau_{m_P}\frac{dM_P}{d\tau_{mp}} + \tau_{m_F}\frac{dM_F}{d\tau_{mp}} + \tau_F\frac{dF}{d\tau_{mp}} + \tau_P\frac{dP}{d\tau_{mp}} + D_P\frac{dv_P}{d\tau_{mp}} + D_F\frac{dv_F}{d\tau_{mp}} + \tau_L\frac{dW}{d\tau_{mp}}}{W}$$

Plugging Eq. (32) into Eq.(29), recalling $M = m_P v_P + m_F v_F$ (see Eq.(4)), gives

$$\begin{aligned}&\frac{1}{\mu}\frac{dV}{d\tau_{m_P}} = \tau_{m_P}\frac{dM_P}{d\tau_{m_P}} + \tau_{m_F}\frac{dM_F}{d\tau_{m_P}} + \tau_F\frac{dF}{d\tau_{m_P}} + \tau_P\frac{dP}{d\tau_{m_P}} + D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}} \\ (33)\quad &+\tau_L\frac{dW}{d\tau_{m_P}} + \frac{1}{\mu}\frac{\partial V}{\partial T}M\frac{dt}{d\tau_{m_P}} - (1-\tau_L)wM\frac{dt}{d\tau_{m_P}} \\ &+\frac{1}{\mu}V_{E_F}E'_F\frac{dF}{d\tau_{m_P}} + \frac{1}{\mu}V_{E_{M_F}}E'_{M_F}\frac{dM_F}{d\tau_{m_P}} + \frac{1}{\mu}V_{E_{M_P}}E'_{M_P}\frac{dM_P}{d\tau_{m_P}}\end{aligned}$$

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. We also have from (3) that $\frac{dt}{d\tau_{m_p}} = t'\frac{dM}{d\tau_{mp}}$. When we replace both of these expressions in Eq. (33), we get

(34)

$$\frac{1}{\mu}\frac{dV}{d\tau_{m_P}} = \tau_{m_P}\frac{dM_P}{d\tau_{m_P}} + \tau_{m_F}\frac{dM_F}{d\tau_{m_P}} + \tau_F\frac{dF}{d\tau_{m_P}} + \tau_P\frac{dP}{d\tau_{m_P}} + D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}} + \tau_L\frac{dW}{d\tau_{m_P}}$$

$$-\theta t' M\frac{dM}{d\tau_{m_P}} + \frac{1}{\mu}V_{E_F}E'_F\frac{dF}{d\tau_{m_P}} + \frac{1}{\mu}V_{E_{M_F}}E'_{M_F}\frac{dM_F}{d\tau_{m_P}} + \frac{1}{\mu}V_{E_{M_P}}E'_{M_P}\frac{dM_P}{d\tau_{m_P}}$$

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

(35) $$e_F \equiv \frac{1}{\mu}V_{E_F}E'_F$$

(36) $$e_m^c \equiv \theta t' M$$

(37) $$e_{m_F}^{nc} \equiv \frac{1}{\mu}V_{E_{M_F}}E'_{M_F}$$

(38) $$e_{m_P}^{nc} \equiv \frac{1}{\mu}V_{E_{M_P}}E'_{M_P}$$

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

$$\frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = \underbrace{e_F\left\{-\frac{dF}{d\tau_{m_P}}\right\}}_{\text{energy related externalities}} + \underbrace{e_m^c\left\{-\frac{dM}{d\tau_{m_P}}\right\}}_{\text{congestion externalities}} + \underbrace{e_{m_F}^{nc}\left\{-\frac{dM_F}{d\tau_{m_P}}\right\} + e_{m_P}^{nc}\left\{-\frac{dM_P}{d\tau_{m_P}}\right\}}_{\substack{\text{kilometrage related} \\ \text{non-congestion externalities}}}$$

(39) $$-\underbrace{\left[\tau_{m_P}\left\{-\frac{dM_P}{d\tau_{m_P}}\right\} + \tau_{m_F}\left\{-\frac{dM_F}{d\tau_{m_P}}\right\}\right]}_{\text{km-tax revenue}} - \underbrace{\left[\tau_F\left\{-\frac{dF}{d\tau_{m_P}}\right\} + \tau_P\left\{-\frac{dP}{d\tau_{m_P}}\right\}\right]}_{\text{energy tax revenue}}$$

$$\underbrace{+D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}}}_{\substack{\text{direct/indirect tax revenue/cost from} \\ \text{vehicle stock}}} + \underbrace{\tau_L\frac{dW}{d\tau_{m_P}}}_{\text{labor tax revenue}}$$

As we see, the EV-km tax causes numerous different changes in Eq. (39), which shows that the km-tax affects overall welfare through various channels.

Derivation of the optimal km-tax

Setting the marginal welfare change as displayed in Eq. (39) to zero and solving for τ_{m_P} yields

$$
\begin{aligned}
\tau_{m_P}^{*} &= e_F\left\{\frac{dF/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + e_m^c\left\{\frac{dM/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + e_{m_F}^{nc}\left\{\frac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + e_{m_P}^{nc} \\
&+\left[\tau_{m_F}\frac{dM_F}{d\tau_{m_P}} + \tau_F\frac{dF}{d\tau_{m_P}} + \tau_P\frac{dP}{d\tau_{m_P}} + D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}} + \tau_L\frac{dW}{d\tau_{m_P}}\right]\frac{1}{-dM_P/d\tau_{m_P}} \\
&= e_F\left\{\frac{dF/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + (e_m^c + e_{m_F}^{nc})\left\{\frac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + e_{m_P}^{nc} + e_m^c \\
&+\left[\tau_{m_F}\frac{dM_F}{d\tau_{m_P}} + \tau_F\frac{dF}{d\tau_{m_P}} + \tau_P\frac{dP}{d\tau_{m_P}} + D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}} + \tau_L\frac{dW}{d\tau_{m_P}}\right]\frac{1}{-dM_P/d\tau_{m_P}}
\end{aligned} \tag{40}
$$

We simplify the following expressions to reaction parameters.

(41) $$\eta_F = \frac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}$$

(42) $$\chi_F = \frac{dF/d\tau_{m_P}}{dM_P/d\tau_{m_P}}$$

(43) $$\kappa_P = \frac{dv_P/d\tau_{m_P}}{dM_P/d\tau_{m_P}}$$

(44) $$\varphi_F = \frac{dv_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}$$

The expression in (40) can be aggregated to the following expression for the optimal km-tax.

(45) $$\tau_{m_P}^{*} = \tau_{m_P}^{C} + \tau_{m_P}^{I}$$

The optimal km-tax is here expressed by a corrective component, $\tau_{m_P}^{C}$, and a "fiscal interaction" component $\tau_{m_P}^{I}$. We apply the definitions in (41) to (42) to the first part of the expression in (40) and get the following expression for the corrective component.

(46) $$\tau_{m_P}^{C} = \chi_F e_F + \eta_F(e_m^c + e_{m_F}^{nc}) + e_{m_P}^{nc} + e_m^c$$

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

The remaining part of (42) is the fiscal interaction component.

(47)

$$\tau_{m_P}^{I}=\left[\tau_{m_F}\frac{dM_F}{d\tau_{m_P}}+\tau_F\frac{dF}{d\tau_{m_P}}+\tau_P\frac{dP}{d\tau_{m_P}}+D_P\frac{dv_P}{d\tau_{m_P}}+D_F\frac{dv_F}{d\tau_{m_P}}+\tau_L\frac{dW}{d\tau_{m_P}}\right]\frac{1}{-dM_P/d\tau_{m_P}}$$

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

We proceed in this exercise by totally differentiating the terms in brackets in (47):

(48) $$\frac{dM_F}{d\tau_{m_P}}=\frac{\partial M_F}{\partial\tau_{m_P}}+\frac{\partial M_F}{\partial\tau_L}\frac{d\tau_L}{d\tau_{m_P}}$$

(49) $$\frac{dF}{d\tau_{m_P}}=\frac{\partial F}{\partial\tau_{m_P}}+\frac{\partial F}{\partial\tau_L}\frac{d\tau_L}{d\tau_{m_P}}$$

(50) $$\frac{dP}{d\tau_{m_P}}=\frac{\partial P}{\partial\tau_{m_P}}+\frac{\partial P}{\partial\tau_L}\frac{d\tau_L}{d\tau_{m_P}}$$

(51) $$\frac{dv_P}{d\tau_{m_P}}=\frac{\partial v_P}{\partial\tau_{m_P}}+\frac{\partial v_P}{\partial\tau_L}\frac{d\tau_L}{d\tau_{m_P}}$$

(52) $$\frac{dv_F}{d\tau_{m_P}}=\frac{\partial v_F}{\partial\tau_{m_P}}+\frac{\partial v_F}{\partial\tau_L}\frac{d\tau_L}{d\tau_{m_P}}$$

(53) $$\frac{dW}{d\tau_{m_P}}=\frac{\partial W}{\partial\tau_{m_P}}+\frac{\partial W}{\partial\tau_L}\frac{d\tau_L}{d\tau_{m_P}}+\frac{\partial W}{\partial t}\frac{dt}{d\tau_{m_P}}=w\left(\frac{\partial L}{\partial\tau_{m_P}}+\frac{\partial L}{\partial\tau_L}\frac{d\tau_L}{d\tau_{m_P}}+\frac{\partial L}{\partial t}\frac{dt}{d\tau_{m_P}}\right)$$

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 & Dyvi, 2008). This means that the largest part of any compensation through revenue recycling will be spent on other goods. This makes it reasonable to use uncompensated elasticities (see Willig, 1976) in order to parameterize demand elasticities for vehicle kms, 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.(53) into $d\tau_L/d\tau_{m_P}$ as displayed in Eq. (32) and grouping terms gives

(54)
$$\frac{d\tau_L}{d\tau_{m_P}} = -\frac{B_1}{B_2}$$

where

(55)
$$B_1 = M_P + \tau_{m_P}\frac{dM_P}{d\tau_{m_P}} + \tau_{m_F}\frac{dM_F}{d\tau_{m_P}} + \tau_F\frac{dF}{d\tau_{m_P}} + \tau_P\frac{dP}{d\tau_{m_P}}$$
$$+\left(D_P - \Gamma\right)\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}} + \tau_L w\left(\frac{\partial L}{\partial\tau_{m_P}} + \frac{\partial L}{\partial t}\frac{dt}{d\tau_{m_P}}\right)$$

and

(56)
$$B_2 = W + \tau_L w\frac{\partial L}{\partial\tau_L}$$

The expression in (53) can be manipulated further by applying the following expression for the marginal cost of public funds:

(57)
$$\Omega_{\tau_L} \equiv \frac{-\tau_L w\frac{\partial L}{\partial\tau_L}}{W + \tau_L w\frac{\partial L}{\partial\tau_L}} = \frac{\frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}}{1-\frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}}$$

It represents the efficiency cost of raising an extra Euro of revenue through labor taxes (or the efficiency gain of recycling one Euro through cuts in labor taxes). $\varepsilon_{LL} > 0$ is the (uncompensated) labor supply elasticity. The numerator in Eq.(57) reflects the efficiency cost from an incremental increase in the labor tax whereas the denominator is the marginal change in tax revenue. We have that $\Omega_{\tau_L} > 0$ as a consequence of $\varepsilon_{LL} > 0$ and $1 > \frac{\tau_L}{(1-\tau_L)}\varepsilon_{LL}$, i.e. marginal revenue is positive. The latter implies that τ_L is not so large that we find ourselves beyond the peak of the Laffer curve.

We the substitute $d\tau_L/d\tau_{m_P} = -B_1/B_2$ into Eq.(53). Then we plug the resulting expressions into Eq.(47), where we also regroup terms and use the definition of Ω_{τ_L} in Eq.(57). We then get

(58)
$$\tau_{m_P}^I = \left[\begin{array}{l}\tau_{m_F}\frac{dM_F}{d\tau_{m_P}} + \tau_F\frac{dF}{d\tau_{m_P}} + \tau_P\frac{dP}{d\tau_{m_P}} + D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}} \\ +\tau_L w\left(\frac{\partial L}{\partial\tau_{m_P}} + \frac{\partial L}{\partial t}\frac{dt}{d\tau_{m_P}}\right) + \Omega_{\tau_L} B_1\end{array}\right]\frac{1}{-dM_P/d\tau_{m_P}}$$

Multiplying each term by $\frac{1}{-dM_i/d\tau_{m_i}}$, and using the definitions of η_F (Eq.(41)), χ_F (Eq.(42)), κ_P (Eq.(43)) and φ_F (Eq.(44)) gives

(59)
$$\tau^I_{m_P} = -\eta_F \tau_{m_F} - \chi_F \tau_F - \chi_P \tau_P - \kappa_P D_P - \varphi_F D_F$$
$$+\tau_L w \left(\frac{\partial L}{\partial \tau_{m_P}} + \frac{\partial L}{\partial \tau_L} \frac{d\tau_L}{d\tau_{m_P}} \right) \frac{1}{-dM_P/d\tau_{m_P}} + \Omega_{\tau_L} B_1 \frac{1}{-dM_P/d\tau_{m_P}}$$

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 do some manipulations to Eq.(59). First we obtain the following expressions from the own-price demand elasticity of EV-km.

(60)
$$\varepsilon_{M_P} = \frac{dM_P}{d\tau_{m_P}} \frac{\left(P_P p + c_P + \tau_{m_P}\right)}{M_P} \Rightarrow \frac{M_P}{dM_P/d\tau_{m_P}} = \frac{\left(P_P p + c_P + \tau_{m_P}\right)}{\varepsilon_{M_P}}$$

The term $P_P p + c_P + \tau_{m_P}$ 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.(41), χ_F (Eq.(42)), κ_P (Eq.(43)) and φ_F (Eq.(44)), and we get

(61)
$$\Omega_{\tau_L} B_1 \frac{1}{-dM_P/d\tau_{m_P}} =$$
$$\Omega_{\tau_L} \left(\begin{array}{l} \dfrac{\left(P_P p + c_P + \tau_{m_P}\right)}{-\varepsilon_{M_P}} - \tau_{m_P} - \eta_F \tau_{m_F} - \chi_F \tau_F - p\tau_P - \\ \kappa_P D_P - \varphi_F D_F - \tau_L w \left(\dfrac{\partial L}{\partial \tau_{m_P}} + \dfrac{\partial L}{\partial t} \dfrac{dt}{d\tau_{m_P}} \right) \dfrac{1}{-dM_P/d\tau_{m_P}} \end{array} \right)$$

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

(62)
$$\tau^{RR}_{m_P} = \Omega_{\tau_L} \left(\frac{\left(P_P p + c_P + \tau_{m_P}\right)}{-\varepsilon_{M_P}} - \tau_{m_P} \right)$$

We thus can rearrange Eq.(59) to

(63)
$$\tau^I_{m_P} = \tau^{RR}_{m_P} + \left(1 + \Omega_{\tau_L}\right)\left[-\eta_F \tau_{m_F} - \chi_F \tau_F - p\tau_P - \kappa_P D_P - \varphi_F D_F \right]$$
$$+\left(1 + \Omega_{\tau_L}\right)\left(\tau_L w \frac{\partial L}{\partial \tau_{m_i}} + \tau_L w \frac{\partial L}{\partial t} \frac{dt}{d\tau_{m_i}} \right) \frac{1}{-dM_i/d\tau_{m_i}}$$

From the Slutsky equation it follows

$$\frac{\partial L}{\partial \tau_{m_P}} = \frac{\partial L^c}{\partial \tau_{m_P}} - \frac{\partial L}{\partial I} M_P \tag{64}$$

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 manipulations we get

$$\begin{aligned}
&\frac{\partial L}{\partial \tau_{m_P}} = \frac{\partial L^c}{\partial \tau_{m_P}} - \frac{\partial L}{\partial I} M_P = \frac{\partial M_P{}^c}{\partial \left(1-\tau_L\right) w} - \frac{\partial L}{\partial I} M_P \Rightarrow \\
&\frac{\left(1-\tau_L\right) w}{M_P} \frac{\partial L}{\partial \tau_{m_P}} = \frac{\left(1-\tau_L\right) w}{M_P} \frac{\partial M_P{}^c}{\partial \left(1-\tau_L\right) w} - \frac{\left(1-\tau_L\right) w}{M_P} \frac{\partial L}{\partial I} M_P \\
&= -\varepsilon_{MI}^c - \frac{L\left(1-\tau_L\right) w}{L} \frac{\partial L}{\partial I} = -\varepsilon_{MI}^c - \varepsilon_{LI} \\
&\Rightarrow \frac{\partial L}{\partial \tau_{m_P}} = -\varepsilon_{MI}^c \frac{M_P}{\left(1-\tau_L\right) w} - \varepsilon_{LI} \frac{M_P}{\left(1-\tau_L\right) w}
\end{aligned} \tag{65}$$

ε_{MI}^c denotes the income elasticity for vehicle kms (alternatively the compensated cross-price elasticity of leisure). ε_{LI} denotes the income elasticity for labor.

Plugging Eq.(65) into Eq.(63) and using Eq.(60) gives

(66)

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

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

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

$$(67)\ \left(1+\Omega_{\tau_L}\right)\tau_L w\frac{\partial L}{\partial t}\frac{dt}{d\tau_{m_P}}\frac{1}{-dM_P/d\tau_{m_P}} = -\left(1+\Omega_{\tau_L}\right)\tau_L w\frac{\partial L}{\partial P_{M_P}}\theta t'\left[\frac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}} + 1\right]$$

From the Slutsky equation applied to the demand function it follows

$$(68)\qquad \frac{\partial L}{\partial \tau_{m_P}} = \frac{\partial L^c}{\partial P_{M_P}} - \frac{\partial L}{\partial I}M_P$$

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

$$(69)\qquad \frac{\partial L^c}{\partial P_{M_P}} = \frac{\partial M^c_P}{\partial \tau_L} = \frac{\partial M_P}{\partial \tau_L}(1-\tau_L)w\frac{\partial L^c}{\partial \tau_L}$$

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 manipulations, we get

(70)

$$\frac{(1-\tau_L)w}{M_P}\frac{\partial L}{\partial P_{M_P}}=\frac{(1-\tau_L)w}{M_P}\frac{\partial M_P}{\partial \tau_L}(1-\tau_L)w\frac{\partial L^c}{\partial \tau_L}-\frac{(1-\tau_L)w}{M}\frac{\partial L}{\partial I}M_P=-\varepsilon_{MI}\varepsilon_{LL}^c-\varepsilon_{LI}$$

$$\Rightarrow \frac{\partial L}{\partial P_{M_P}}=-\varepsilon_{MI}\varepsilon_{LL}^c\frac{M_P}{(1-\tau_L)w}-\varepsilon_{LI}\frac{M_P}{(1-\tau_L)w}$$

Plugging Eq. (70) into Eq. (67) gives

$$\left(1+\Omega_{\tau_L}\right)\tau_L w\frac{\partial L}{\partial t}\frac{dt}{d\tau_{m_P}}\frac{1}{-dM_P/d\tau_{m_P}}$$

(71) $$=-\left(1+\Omega_{\tau_L}\right)\tau_L w\left(-\varepsilon_{MI}\varepsilon_{LL}^c\frac{M_P}{(1-\tau_L)w}-\varepsilon_{LI}\frac{M_P}{(1-\tau_L)w}\right)\theta t'\left[\frac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}+1\right]$$

$$=-\left(1+\Omega_{\tau_L}\right)\frac{\tau_L}{(1-\tau_L)}\left(-\varepsilon_{MI}\varepsilon_{LL}^c-\varepsilon_{LI}\right)\theta t' M_P\left[\frac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}+1\right]$$

Substituting $\varepsilon_{LI}=\varepsilon_{LL}-\varepsilon_{LL}^c$ and $e_{m_P}^c\equiv\theta t' M_P$ and $\eta_F=\frac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}$, after regrouping terms we obtain the congestion feedback effect

(72)

$$\tau_{m_P}^{CF}=\left(1+\Omega_{\tau_L}\right)\tau_L w\frac{\partial L}{\partial t}\frac{dt}{d\tau_{m_P}}\frac{1}{-dM_P/d\tau_{m_P}}=\left(1+\Omega_{\tau_L}\right)\frac{\tau_L}{(1-\tau_L)}\left(\varepsilon_{LI}(1-\varepsilon_{MI})\varepsilon_{LL}^c\right)e_m^c\left[\eta_F+1\right]$$

$$=\left(1+\Omega_{\tau_L}\right)\boldsymbol{F}$$

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

(73) $$\begin{aligned}\tau_{m_P}^* &= \tau_{m_P}^C+\tau_{m_P}^I=\tau_{m_P}^C+\tau_{m_P}^{RR}+\tau_{m_P}^{TI}\\ \tau_{m_P}^* &= \tau_{m_P}^C+\tau_{m_P}^{RR}+\tau_{m_P}^{(TI)}+\tau_{m_P}^{CF}\end{aligned}$$

With the components

(74) $$\tau_{m_P}^C=e_{m_P}^{nc}+e_m^c+\eta_F(e_m^c+e_{m_F}^{nc})+\chi_F e_F$$

(75) $$\tau_{m_P}^{RR}=\Omega_{\tau_L}\left(\frac{\left(P_P p+c_P+\tau_{m_P}\right)}{-\varepsilon_{M_P}}-\tau_{m_P}\right)$$

(76)

$$\tau_{m_P}^{(TI)} = -\left(1+\Omega_{\tau_L}\right)\left[\left(\frac{\tau_L\left(P_P\,p + c_P + \tau_{m_P}\right)(\varepsilon_{MI}^c + \varepsilon_{LI})}{\left(-\varepsilon_{M_P}\right)\left(1-\tau_L\right)}\right) + \eta_F \tau_{m_F} + \chi_F \tau_F + p\tau_P + \kappa_P D_P + \varphi_F D_F\right]$$

(77) $$\tau_{m_P}^{CF} = \left(1+\Omega_{\tau_L}\right)\frac{\tau_L}{\left(1-\tau_L\right)}\left(\varepsilon_{LI}(1-\varepsilon_{MI})\varepsilon_{LL}^c\right)e_m^c\left[\eta_F + 1\right]$$

A2 Deriving the welfare measure

As seen in equation (39) we have the following marginal welfare effect of increasing the road price:

(78)
$$\begin{aligned}\frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = {} & \underbrace{e_F\left\{-\frac{dF}{d\tau_{m_P}}\right\}}_{\text{energy related externalities}} \underbrace{e_m^c\left\{-\frac{dM}{d\tau_{m_P}}\right\}}_{\text{congestion externalities}} + \underbrace{e_{m_F}^{nc}\left\{-\frac{dM_F}{d\tau_{m_P}}\right\} + e_{m_P}^{nc}\left\{-\frac{dM_P}{d\tau_{m_P}}\right\}}_{\substack{\text{kilometrage related}\\ \text{non-congestion externalities}}} \\ & - \underbrace{\left[\tau_{m_P}\left\{-\frac{dM_P}{d\tau_{m_P}}\right\} + \tau_{m_F}\left\{-\frac{dM_F}{d\tau_{m_P}}\right\}\right]}_{\text{km-tax revenue}} - \underbrace{\left[\tau_F\left\{-\frac{dF}{d\tau_{m_P}}\right\} + \tau_P\left\{-\frac{dP}{d\tau_{m_P}}\right\}\right]}_{\text{energy tax revenue}} \\ & \underbrace{+ D_P\frac{dv_P}{d\tau_{m_P}} + D_F\frac{dv_F}{d\tau_{m_P}}}_{\substack{\text{direct/indirect tax revenue/cost from}\\ \text{vehicle stock}}} + \underbrace{\tau_L\frac{dW}{d\tau_{m_P}}}_{\text{labor tax revenue}}\end{aligned}$$

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

(79)
$$\frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = \left[\begin{array}{l}\left(e_{m_P}^{nc} - \tau_{m_P}\right) + \left(e_F - \tau_F\right)\left\{\dfrac{dF/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} - \tau_P\left\{\dfrac{dP/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} \\ + \left(e_{m_F}^{nc} - \tau_{m_F}\right)\left\{\dfrac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} + e_m^c\left\{\dfrac{dM/d\tau_{m_P}}{dM_P/d\tau_{m_P}}\right\} \\ + \left(D_P\dfrac{dv_P}{d\tau_{m_P}} + D_F\dfrac{dv_F}{d\tau_{m_P}} + \tau_L\dfrac{dW}{d\tau_{m_P}}\right)\dfrac{1}{-dM_P/d\tau_{m_P}}\end{array}\right]\left\{-\frac{dM_P}{d\tau_{m_P}}\right\}$$

Further rearranging gives:

$$(80)\qquad \frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = \begin{bmatrix} e_{m_P}^{nc} - \tau_{m_P} + \chi_F e_F - \chi_F e_F - \tau_P \left\{ \dfrac{dP/d\tau_{m_P}}{dM_P/d\tau_{m_P}} \right\} \\ +\eta_F (e_m^c + e_{m_F}^{nc}) + e_m^c - \tau_{m_F} \left\{ \dfrac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}} \right\} \\ + \left(D_P \dfrac{dv_P}{d\tau_{m_P}} + D_F \dfrac{dv_F}{d\tau_{m_P}} + \tau_L \dfrac{dW}{d\tau_{m_P}} \right) \dfrac{1}{-dM_P/d\tau_{m_P}} \end{bmatrix} \left\{ -\frac{dM_P}{d\tau_{m_P}} \right\}$$

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

(81)

$$\frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = \begin{bmatrix} \tau_{m_P}^C - \tau_{m_P} - \tau_F \left\{ \dfrac{dF/d\tau_{m_P}}{dM_P/d\tau_{m_P}} \right\} - \tau_P \left\{ \dfrac{dP/d\tau_{m_P}}{dM_P/d\tau_{m_P}} \right\} - \tau_{m_F} \left\{ \dfrac{dM_F/d\tau_{m_P}}{dM_P/d\tau_{m_P}} \right\} \\ + \left(D_P \dfrac{dv_P}{d\tau_{m_P}} + D_F \dfrac{dv_F}{d\tau_{m_P}} + \tau_L \dfrac{dW}{d\tau_{m_P}} \right) \dfrac{1}{-dM_P/d\tau_{m_P}} \end{bmatrix} \left\{ -\frac{dM_P}{d\tau_{m_P}} \right\}$$

Other parts can be converted into the interaction component (see eq.(47))

$$(82)\qquad \frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = \left[\tau_{m_P}^C - \tau_{m_P} + \tau_{m_P}^I \right] \left\{ -\frac{dM_P}{d\tau_{m_P}} \right\}$$

This gives us:

$$(83)\qquad \frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = \left[\tau_{m_P}^* - \tau_{m_P} \right] \left\{ -\frac{dM_P}{d\tau_{m_P}} \right\}$$

We can rewrite $\left\{ -\frac{dM_P}{d\tau_{m_P}} \right\}$ using eq. (60). This gives us:

$$(84)\qquad \frac{1}{\mu}\frac{\partial V}{\partial \tau_{m_P}} = \left[\tau_{m_P} - \tau_{m_P}^* \right] \frac{M_P \varepsilon_{M_P}}{\left(P_P\, p + c_P + \tau_{m_P} \right)}$$

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

A3 About the parameter values

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

Initial vehicle kilometrage per car (EV & ICEV): Statistics Norway provides data average kilometers driven annually per car on municipal level. We aggregate these numbers 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 also 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 car ownership on municipal level, and separates between ICEVs and EVs. We aggregate these numbers 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 personal cars to toll companies have been provided by the National Public Road Administration's toll statistics. Statistics Norway's StatBank provide statistics on passenger car traffic volumes (link). Users pay per passing of tolling station, but the numbers have been normalized to per km, by dividing passenger car toll revenue by passenger car traffic volumes on county level. The national average was 0.31 NOK per km. The average tolls per km 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 Road federation (OVF) provides disaggregate car sales data. From these data we can calculate the average price, purchase tax and VAT for the average ICEV in any given year.

Own-price elasticity of car kilometrage. The newest estimates of elasticity values for the National and Regional Transport Modelling system (NTM and RTM) in Norway gives an own price elasticity wrt. all kilometer costs and tolls together of -0.152.

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 the other car type 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.