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Taxation of fuel and vehicles when emissions are constrained

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ABSTRACT

A tax on fuel combined with tax exemptions or subsidies for low- and zero emission vehicles is implemented in many countries to fulfill the Paris agreement and to curb mileage-related externalities from road traffic. The present study however shows that a tax on fuel should be combined with tax exemptions for high-emission vehicles to curb mileage-related externalities and to fulfill emission targets within the transport sector. The emission target is fulfilled by adjusting the CO_2-tax component on fuel. The road user charge on fuel is designed to curb mileage-related externalities. The heavier tax on low- and zero emission vehicles prevent motorists from avoiding the road user charge on fuel by purchasing low- and zero emission vehicles.

1. Introduction

Countries participating in the Paris agreement have adopted targets with respect to greenhouse gas emissions. A number of countries faced with such targets have introduced emission targets for their transport sector. The Biden administration recently announced ambitious targets for sales of zero-emission vehicles to among other things tackle the climate crisis. A CO_2 emission standard for passenger cars, Regulation (EU) 2019/631, applies in EU countries from 2020 as part of a strategy to fulfill emission targets for new passenger cars. Several European countries have introduced bonus-malus/ feebate schemes with taxes on purchase of high-emission vehicles and tax exemptions and subsidies for purchase of low- and zero emission vehicles, see Klier and Linn (2015). Domestic emission targets are implemented even though the Effort sharing regulation 2021–2030 incorporates flexibility for participating countries. But how should taxes on vehicles be designed to reach such targets? Several studies investigate how taxes on fuels and vehicles should be designed to curb traffic related externalities in the form of CO_2-emissions, local air pollution, accidents, congestion and noise (Innes, 1996; Fullerton and West, 2002, 2010); Parry and Small (2005); Bjertnæs (2019a). Empirical studies find that feebate schemes shift consumers towards lower-emission vehicles (Huse and Lucinda, 2013; Yan and Eskeland, 2018; Goldberg, 1998 for the US case with a corporate average fuel economy (CAFE) standard which resembles a firm-internal feebate scheme). Impacts of feebates on fuel consumption are modest however (Bansal and Dua, 2022; Kessler et al., 2023). Fuel consumption is also relatively unresponsive to changes in fuel price (Bento et al., 2009; Bansal and Dua, 2022). The marginal external benefits from higher gasoline taxes in the US are considerably higher than the marginal cost according to Bento et al. (2009), and the US CAFE standard is found to be a more costly fuel saving policy for the society compared to a fuel tax (Jacobsen, 2013; Karplus et al., 2013). An important explanation is that the CAFE standard lowers the per-mile driving cost which contributes to increase miles traveled, known as the rebound effect, while the tax on fuel increases the cost of driving. A revenue-neutral feebate policy could be more progressive than a gasoline price increase according to Sheldon and Dua (2021). The progressivity of the US CAFE-standard can be overturned by long-run effects in the used car market according to Jacobsen (2013), however. Feebate policies are on the other hand more cost-effective and less regressive when subsidies are targeted for low-income households which are found to be more myopic (Xing et al., 2021; Bansal et al., 2021; Sheldon and Dua, 2019). Second-best optimal taxation of road transport in the presence of emission targets are however an underexplored topic in the literature.

The present study contributes to the literature by analyzing second-best optimal combinations of taxes on fuels and vehicles designed to curb mileage-related externalities when emissions from road transport are restricted by an emission target. The target may deviate from the socially optimal amount of emissions. Mileage-related externalities are

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assumed to be identical for vehicles with different fuel economy. The tax on fuel, which is assumed to be uniform, is consequently unable to tax such mileage-related externalities with identical rates. The study shows that a tax on fuel should be combined with tax exemptions for high-emission vehicles to curb mileage-related externalities and to fulfill emission targets within the transport sector. The emission target should be fulfilled by adjusting the CO_2 component of the fuel tax. The road user charge on fuel should be set equal to the average reduction in mileage-related damage generated by the charge. The households' choice of vehicle is consequently distorted as the road user charge on fuel exceeds mileage-related externalities for fuel-intensive vehicles while the charge is below mileage-related externalities for fuel-efficient vehicles. The heavier tax on low- and zero emission vehicles is designed to neutralizes this distortion.

The rest of the paper is divided into three sections; Section 2 provides a literature review, Section 3 presents the model and results, and Section 4 concludes.

2. Literature review

Several European countries redesigned their vehicle tax system in the mid-2000s and implemented bonus-malus/ feebate schemes that favored fuel-efficient vehicles. Some countries imposed a CO_2-based tax on purchase of vehicles, while other countries imposed annual CO_2-based registration taxes; see Klier and Linn (2015). According to their study, CO_2-based tax on purchase of vehicles leads to larger reductions in the average emission rates of new vehicles. The emission reduction of such taxation is eroded as sales of new vehicles expand, however (Alberini and Bareit, 2017), and as the retirement of high-emitting vehicles is postponed (Alberini et al., 2018). The annual CO_2-based registration tax, levied on both new and existing vehicles, is not burdened by these undesirable impacts according to Alberini et al. (2018). The impact of these annual taxes on the average emission rates of new vehicles is modest, however, (Klier and Linn, 2015), and the cost per ton of reduced CO_2 emissions is substantial (Alberini and Bareit, 2017). Additional tax exemptions and subsidies for purchase of low- and zero emission vehicles were later introduced in many countries to fulfill emission targets within the Paris agreement. Sheldon et al. (2023) estimates the cost-effectiveness of electric vehicle subsidies in several countries. They find that subsidies in China have a short-run static cost of up to $1600 per ton, far exceeding the social cost of carbon, suggesting that such subsidies are part of China's industry policy, see also Sheldon and Dua (2020). Sheldon et al. (2023) also find relatively high costs in the Netherlands, Norway and Denmark due to subsidies and waivers for sales taxes for high-priced electric vehicles. This finding is consistent with findings in Bjertnæs (2013), which shows that generous tax exemptions for both purchase and use of electric vehicles in Norway are costly, and with findings in Holtsmark and Skonhoft (2014), which also identify unfortunate side-effects related to increased car use. Sheldon et al. (2023) find lower costs for the US economy as electric vehicles replaces high-emission cars, see also Sheldon and Dua (2018). Xing et al. (2021) on the other hand find that electric vehicles replaced relatively fuel-efficient vehicles in the US. Also, Xing et al. (2021) and Sheldon and Dua (2019) find that a substantial share of the electric vehicle owners would have chosen an electric vehicle even in the absence of tax credit. Cost-effectiveness of the US policy is hampered by these findings.

Parry and Small (2005) show that the optimal uniform tax rate on gasoline consists of an adjusted Pigouvian tax component, which includes damage from carbon emissions and other driving-related externalities, a Ramsey tax component designed to raise tax revenue, and a congestion feedback component, which captures welfare gains as labor supply increases with lower congestion. The component of the tax related to externalities due to congestion and accidents as well as the Ramsey tax component are dominant, while the Pigouvian elements related to global warming and congestion feedback are modest. The tax-induced gain in terms of reduced externalities per liter of fuel is diminished as households avoid the mileage-related tax component by purchasing more fuel-efficient vehicles. Parry and Small's estimated optimal tax rates on gasoline are reduced accordingly. A range of other studies have adopted their method to calculate optimal tax rates on fuel (Anton-Sarabia and Hernandez-Trillo, 2014; Lin and Zeng, 2014; Anderson and Auffhammer, 2014). Differentiated taxes on purchase of vehicles are not considered in these studies even though restrictions on taxes on the use of vehicles imply that taxes on the purchase of vehicles are desirable[1] (Innes, 1996; Fullerton and West, 2002, 2010; De Borger, 2001). Indeed, Bjertnæs (2019a) shows that such avoidance should be neutralized by heavier taxation of fuel-efficient vehicles, and hence, that the gasoline tax rate should not be reduced due to such avoidance.

Innes (1996) shows that optimal vehicle taxes, or their regulatory equivalents, approximately equal the social cost of a vehicle's predicted emissions less the portion of costs that is internalized by a uniform gasoline tax. Fullerton and West (2002) extend his analysis and explore tax combinations that implement the social planner choices of mileage, engine size, pollution control equipment, and fuel type. They find that vehicles with bigger engines should be subsidized (taxed) if the tax rate on fuel, which equals the marginal damage per gallon of fuel, more (less) than completely internalizes the impact of engine size. According to their study, empirical investigations are required to determine whether to tax or subsidize vehicles with large engines. Fullerton and West (2010) extend the analysis in Fullerton and West (2002) with vehicle age and simulate different scenarios. They find that the three-part instrument involving a gas tax, a subsidy for engine size, and a subsidy for new cars maximize welfare. The subsidy for engine size does not increase welfare significantly, however. Bjertnæs (2019a) develops theories in Innes (1996) and Fullerton and West (2002) into operational tax formulas that are comparable with current taxation of fuel and vehicles. Scenarios with myopic behavior and electric vehicles (EVs) are included. Bjertnæs (2019a) shows that the tax on fuel-efficient vehicles should exceed the tax on fuel-intensive vehicles, and that the efficient tax on fuel equals the average marginal damage per liter fuel consumed. Hence, avoidance of road user charges on fuel by purchasing more fuel-efficient vehicles is neutralized by the heavier tax on low- and zero emission vehicles in this case. The Ramsey tax component on fuels is excluded in Bjertnæs (2019a) because Jacobs and de Mooij (2015) show that a Pigouvian tax on polluting goods without a Ramsey tax component is part of a welfare-maximizing tax system within a Mirrlees-economy framework.[2] The Pigouvian solution in Jacobs and de Mooij (2015) is not attainable, however, when policy instruments are restricted to a uniform tax on fuel and differentiated taxes on vehicles.

As mentioned, countries participating in the Paris agreement have adopted emission targets. Within some countries, such emission targets have given rise to ambitious emission targets for the transport sector. Many countries have implemented taxes on fuel combined with tax exemptions or subsidies for fuel-efficient vehicles to fulfill the Paris agreement and to curb mileage-related externalities. Second-best optimal taxation of road transport in the presence of emission targets are however an underexplored topic in the literature. The present study contributes to the literature by analyzing second-best optimal combinations of taxes on

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[1] Subsidizing substitutes for polluting goods might be desirable when governments are unable to tax emissions directly, see Sandmo (1978).

[2] A general set of assumptions excludes the Ramsey tax component from a welfare-maximizing tax system according to Atkinson and Stiglitz (1976). However, results in the literature differ on the issue of whether environmental taxes should deviate from the Pigouvian rate due to tax revenue requirements. The optimal tax rate in Parry and Small (2005) is lower due to tax revenue requirements. Jaeger (2011), however, finds that the need for tax revenue contributes to increasing the optimal environmental tax wedge to higher than the Pigouvian tax rate. The optimal CO_2 tax also exceeds the quota price when the government purchase quotas and the marginal cost of public funds exceed one, according to Bjertnæs et al. (2013).

fuel and vehicles when emissions is restricted by an emission target. The cost per emission unit within the model framework in Bjertnæs (2019a) is replaced with an emission target for road transport. The study shows that optimal tax formulas in Bjertnæs (2019a) are unchanged when this emission target is implemented. Hence, the emission target is fulfilled by adjusting the CO_2-tax component on fuel. The road user charge on fuel is designed to curb mileage-related externalities. The choice of vehicle is distorted by the tax on fuel, however, as the road user charge on fuel deviates from the mileage-related externality. The heavier tax on low- and zero emission vehicles is designed to neutralizes this distortion. Implementation of a road user charge based on driving might be an alternative, see Bjertnæs (2019a) and Bjertnæs (2019b).

3. The model framework

The model framework in Bjertnæs (2019a) is extended with an emission target for road transport. Other aspects of the model framework are identical. This section therefore draws heavily on the presentation of the model framework in Bjertnæs (2019a).

3.1. *Households*

All households, $\overline{N}$, have the same income. The income is spent on a vehicle, on fuel, and on a non-polluting good. There are two types of vehicles; fuel-efficient and fuel-intensive. Households' preferences are identical except that they consider the advantages and disadvantages of fuel-intensive cars differently. Each household chooses one car, which is either fuel efficient or fuel intensive. Household *i's* utility, u_i, excluding externalities, is given by the quasilinear utility function

$$u_i = u(m_i) + b_i + c_i \tag{1}$$

when a fuel-intensive vehicle is chosen. The utility, u_i, is determined by driving distance measured in kilometers, m_i, consumption of a non-polluting consumer good, c_i, and the utility associated with owning a fuel-intensive vehicle, b_i. The utility parameter, b_i, differs across households. Household *i's* utility when choosing a fuel-efficient vehicle equals the utility function in Eq. (1), but with b_i removed from the equation. The marginal utility of additional driving distance is positive, $u^{'} > 0$, but declines as the driving distance increases, $u^{''} < 0$. This feature of the utility function captures that some trips are more important/necessary to households than other trips. The vehicle-specific utility parameter, b_i, differs across households as transportation needs and requirements differ across households. The parameter is high for households which prefer high engine power due to e.g. heavy loads and frequent use of trailer. Differences in range anxiety associated with EVs might be another reason why the parameter differs across households when internal combustion engine vehicles (ICEVs) are compared with EVs. Note that some households may dislike the fuel-intensive vehicle, i.e., their utility parameter, b_i, is negative. Such vehicle specific preferences are implemented to study the allocation of vehicles. The specification of utility is chosen to be able to study the tradeoff faced by the government when taxes on fuel and vehicles are designed to satisfy a constraint on emissions, and to arrive at optimal tax formulas for fuel and vehicles in this setting. Transportation-policy aspects which are excluded from the model framework is discussed in later sections. Household *i's* budget constraint is given by the equation

$$c_i = y + k - (p_f + t_f) f_j m_i - t_{car,j} - p_{car,j} \tag{2}$$

where $j = high, low$ indicates fuel-intensive and fuel-efficient vehicle, respectively. Consumption of the non-polluting good, c_i, equals a fixed income, y, plus government transfers, k, minus costs of fuel, $\left(p_f + t_f\right) f_j m_i$, which is given by the price per liter of fuel, p_f, the tax per liter of fuel, t_f, and the fuel economy measured in liters per kilometer, f_j, minus the tax on the chosen vehicle, $t_{car,j}$, minus the price of the chosen vehicle, $p_{car,j}$. Utility maximization with respect to m_i implies that

$$u^{'}_{m_i}(m_i) = (p_f + t_f) f_j \tag{3}$$

which implicitly defines the following function:

$$m_i = m_j\left(t_f\right) \tag{4}$$

Eq. (3) shows that the marginal gain in utility of one additional kilometer, u'_{m_i}, equals the private cost of driving one additional kilometer, $\left(p_f + t_f\right) f_j$. Hence, driving is restricted to trips where the benefit exceeds the costs.[3] Eq. (3) also implies that total driving distance is longer for households with a fuel-efficient vehicle compared to households with a fuel-intensive vehicle. This rebound effect is one of the challenges connected with the transition towards fuel-efficient vehicles, and hence, a novel feature of the model framework.

As mentioned each household chooses one car, which is either fuel efficient or fuel intensive. The impact of a tax on purchase of fuel-intensive vehicles on the choice of vehicles is identical with the impact of a subsidy on purchase of fuel-efficient vehicles. The tax on purchase of fuel-intensive vehicles is also equivalent with a subsidy on fuel-efficient vehicles within the government optimization problem. The tax on purchase of fuel-intensive vehicles, $t_{car,high}$, is therefore labeled t_{car}, and the tax on purchase of fuel-efficient vehicles is set equal to zero. The indirect utility function net of externalities for each household, *i*, for each type of vehicle, is found by inserting Eq. (2) into Eq. (1), and then implementing Eq. (4).

$$\begin{aligned} v_{i,high} &= u\left(m_{high}\left(t_f\right)\right) + b_i + y + k - (p_f + t_f) f_{high} m_{high}\left(t_f\right) - t_{car} - p_{car,high}, \text{and} \\ v_{i,low} &= u\left(m_{low}\left(t_f\right)\right) + y + k - (p_f + t_f) f_{low} m_{low}\left(t_f\right) - p_{car,low}, \end{aligned} \tag{5}$$

Assume that households are ranked from high to low according to their utility parameter, b_i, and that the first *N* households have chosen the fuel-intensive vehicle. Assume that the accumulated utility from their b_i-utility parameter, *B*, is given by the expression

$$B = b_{max} N - a/2 N^2 \tag{6}$$

where parameter $a > 0$ and no restrictions are imposed on parameter b_{max}. Households choose the type of vehicle that maximizes utility. Households therefore choose the fuel-intensive vehicle up to the point where household number *N* is indifferent between types of vehicles. This equilibrium condition is given by the expression

$$\begin{aligned} & u\left(m_{high}\left(t_f\right)\right) + b_{max} - aN + y + k - (p_f + t_f) f_{high} m_{high}\left(t_f\right) - t_{car} - p_{car,high} \\ & \quad = u\left(m_{low}\left(t_f\right)\right) + y + k - (p_f + t_f) f_{low} m_{low}\left(t_f\right) - p_{car,low}. \end{aligned} \tag{7}$$

Households that derive higher utility from owning a fuel-intensive vehicle will choose a fuel-intensive vehicle. Households that derive lower utility from owning a fuel-intensive vehicle will choose a fuel-efficient vehicle. Eq. (7) determines the number of households which choose the fuel-intensive vehicle, as a function of fuel taxes, vehicle taxes, exogenous parameters and prices. Taxation of both fuel and vehicles is crucial for choice of vehicles, see Sallee et al. (2016) and Busse et al. (2013). Hence, such taxation is crucial for the transition towards a low-emission society, a novel feature incorporated into the model framework. Eq. (7) is written as Eq. (8) to simplify notations.

$$N = N\left(t_f, t_{car}\right) \tag{8}$$

The total number of households is $\overline{N}$. Hence, the number of

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[3] Vehicle maintenance and capital depreciation are excluded from the operating costs of vehicles to simplify the model framework. However, a tax designed to correct for negative externalities is not influenced by these operating costs when externalities are not influenced by them. Maintenance could be preserved by maintenance control, for example.

households that choose the fuel-efficient vehicle amounts to

$$N_{low} = \overline{N} - N \tag{9}$$

3.2. The emission target

Consumption of each liter of fuel generates a fixed amount of CO_2 emission. Hence, the CO_2 emission target translates into a fuel consumption target, S_{CO2}.

$$S_{CO2} = Nf_{high}m_{high}(t_f) + (\overline{N} - N)f_{low}m_{low}(t_f) \tag{10}$$

The fuel consumption target, S_{CO2}, equals the number of liters of fuel consumed by households with fuel-intensive vehicles, $Nf_{high}m_{high}(t_f)$, plus the number of liters of fuel consumed by households with fuel-efficient vehicles, $(\overline{N} - N)f_{low}m_{low}(t_f)$. A share of the current lifetime emissions from vehicles originates from production of vehicles and energy; see Hawkins et al. (2012). However, CO_2 emissions from production of energy and vehicles are excluded from the model framework. This assumption is appropriate when all polluters pay for their own emissions. The assumption is also relevant when these emissions are included in an emission trading system like that of the EU, and thus are neutralized by adjustments in other emission sources.

3.3. Social costs

The cost of mileage-related damage, S_d, is given by the expression

$$S_d = p_d N m_{high}(t_f) + p_d(\overline{N} - N)m_{low}(t_f) \tag{11}$$

S_d equals the damage per kilometer, p_d, multiplied by the number of kilometers driven by households with fuel-intensive vehicles, $Nm_{high}(t_f)$, plus the damage per kilometer, p_d, multiplied by the number of kilometers driven by households with fuel-efficient vehicles, $(\overline{N} - N)m_{low}(t_f)$. The costs of traffic congestion and damage due to accidents dominates, while the costs of local pollution are more modest. These costs are influenced by a range of factors like drinking and driving, reckless driving and speeding. It is assumed that the present level of drinking and driving, reckless driving and speeding is preserved by current traffic laws and regulations.

government budget constraint, Eq. (12), and the condition determining the allocation of vehicles, Eq. (8), are incorporated in the welfare function. The production side is omitted as the study assume fixed producer prices and zero pure profit. The government chooses the uniform tax rate on fuel, t_f, and the tax on purchase of fuel-intensive vehicles, t_{car}, to maximize welfare given the emission target, Eq. (10). The problem is

$$\begin{aligned}
&\underset{t_f,t_{car}}{Max}\,\overline{N}y + N(t_f,t_{car})u(m_{high}(t_f)) + b_{max}N(t_f,t_{car}) - \frac{1}{2}aN(t_f,t_{car})^2 \\
&+(\overline{N} - N(t_f,t_{car}))u(m_{low}(t_f)) - N(t_f,t_{car})\left[p_{car,high} + p_f f_{high}m_{high}(t_f)\right] \\
&-(\overline{N} - N(t_f,t_{car}))\left[p_{car,low} + p_f f_{low}m_{low}(t_f)\right] - p_d N(t_f,t_{car})m_{high}(t_f) \\
&\qquad -p_d(\overline{N} - N(t_f,t_{car}))m_{low}(t_f),
\end{aligned} \tag{13}$$

subject to the emission target

$$S_{CO2} = Nf_{high}m_{high}(t_f) + (\overline{N} - N)f_{low}m_{low}(t_f)$$

The Lagrangian of the government's maximization problem is

$$\begin{aligned}
&L = \overline{N}y + N(t_f,t_{car})u(m_{high}(t_f)) + b_{max}N(t_f,t_{car}) - \frac{1}{2}aN(t_f,t_{car})^2 \\
&+(\overline{N} - N(t_f,t_{car}))u(m_{low}(t_f)) - N(t_f,t_{car})\left[p_{car,high} + p_f f_{high}m_{high}(t_f)\right] \\
&-(\overline{N} - N(t_f,t_{car}))\left[p_{car,low} + p_f f_{low}m_{low}(t_f)\right] - p_d N(t_f,t_{car})m_{high}(t_f) \\
&\qquad -p_d(\overline{N} - N(t_f,t_{car}))m_{low}(t_f) \\
&-p_{CO2}\left[N(t_f,t_{car})f_{high}m_{high}(t_f) + (\overline{N} - N(t_f,t_{car}))f_{low}m_{low}(t_f) - S_{CO2}\right],
\end{aligned} \tag{14}$$

where p_{CO2} equals the shadow price of the fuel consumption target. The tax on fuel affects the number of fuel-intensive vehicles, $N(t_f, t_{car})$, the driving distance of fuel-intensive vehicles, $m_{high}(t_f)$, and the driving distance of fuel-efficient vehicles, $m_{low}(t_f)$. The tax on purchase of fuel-intensive vehicles affects the number of fuel-intensive vehicles, $N(t_f, t_{car})$. Note that choice of transfers, k, is excluded from the optimization problem as the government budget constraint is incorporated in the welfare function. First order conditions and tax formulas become identical with first order conditions and tax formulas in Bjertnæs (2019a). Hence, interpretation of results is therefore closely related to interpretations in Bjertnæs (2019a). The first order conditions imply that

$$\begin{aligned}
&u(m_{high}(t_f)) + b_{max} - aN - p_{car,high} - p_f f_{high}m_{high}(t_f) - p_{CO2}f_{high}m_{high}(t_f) - p_d m_{high}(t_f) \\
&\quad = u(m_{low}(t_f)) - p_{car,low} - p_f f_{low}m_{low}(t_f) - p_{CO2}f_{low}m_{low}(t_f) - p_d m_{low}(t_f).
\end{aligned} \tag{15}$$

3.4. Taxation of fuel and vehicles

Tax revenue collected is transferred to households. Each household receives a lump-sum transfer, k. The transfer is chosen to conform to the constraint of a balanced government budget. The government budget constraint is given by the following equation

$$\overline{N}k = Nt_f f_{high}m_{high}(t_f) + Nt_{car} + (\overline{N} - N)t_f f_{low}m_{low}(t_f) \tag{12}$$

Total transfers, $\overline{N}k$, equal tax revenue from taxation of fuel for fuel-intensive vehicles, $Nt_f f_{high}m_{high}(t_f)$, plus tax revenue from taxation of fuel-intensive vehicles, Nt_{car}, plus tax revenue from taxation of fuel for fuel-efficient vehicles, $(\overline{N} - N)t_f f_{low}m_{low}(t_f)$.

The welfare function is given by the indirect utility function minus driving related social costs. The sum of indirect utility functions net of externalities, Eq. (5), is found by accumulating over the number of individuals choosing fuel-efficient and fuel-intensive vehicles. The accumulated utility associated with owning a fuel-intensive vehicle is given by Eq. (6). The driving related social costs is given by Eqs. (11). The

See appendix A. Second order conditions are presented in Appendix B. Eq. (15) shows that benefits minus the private and social costs of one additional fuel-intensive vehicle equal the benefits minus private and social costs of one additional fuel-efficient vehicle.[4]

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[4] A detailed inspection of equation (15) shows that the driving-related utility of one additional fuel-intensive vehicle, $u(m_{high}(t_f))$, plus the additional utility of owing a fuel-intensive vehicle, $b_{max} - aN$, minus the producer price of a fuel-intensive vehicle, $p_{car,high}$, minus the production cost of fuel for one additional fuel-intensive vehicle, $p_f f_{high}m_{high}(t_f)$, minus shadow costs related to CO_2 emissions of one additional fuel-intensive vehicle, $p_{CO2}f_{high}m_{high}(t_f)$, minus mileage-related damage attributable to one additional fuel-intensive vehicle, $p_d m_{high}(t_f)$, equal the driving-related utility of one additional fuel-efficient vehicle, $u(m_{low}(t_f))$, minus the producer price of a fuel-efficient vehicle, $p_{car,low}$, minus the production cost of fuel for one additional fuel-efficient vehicle, $p_f f_{low}m_{low}(t_f)$, minus shadow costs related to CO_2 emissions from one additional fuel-efficient vehicle, $p_{CO2}f_{low}m_{low}(t_f)$, minus mileage-related damage related to one additional fuel-efficient vehicle, $p_d m_{low}(t_f)$.

Tax theory is unable to produce a unique optimal tax rate on polluting goods due to the choice of normalization, see Fullerton (1997). The explanation is that the allocation of resources is unchanged when a uniform tax increase on consumer goods is combined with a proportional, revenue-neutral reduction in taxation of income. The optimal tax rate on fuel is therefore labeled the optimal additional tax rate on fuel. This tax rate equals

$$t_f^* = p_{CO2} + \frac{\left(Nm_{high}{}'_{t_f} + (\overline{N} - N)m_{low}{}'_{t_f}\right)p_d}{Nm_{high}{}'_{t_f}f_{high} + (\overline{N} - N)m_{low}{}'_{t_f}f_{low}} \tag{16}$$

The optimal additional tax rate on fuel, t_f^*, equals the shadow price per liter of fuel, p_{CO2}, plus the road user charge on fuel, labeled t_d, given by the second term on the right-hand side of Eq. (16). This road user charge equals the reduction in mileage-related damage due to a marginal tax increase on fuel (the numerator), divided by the reduction in fuel consumption due to a marginal tax increase on fuel (the denominator). Thus, the road user charge on fuel equals the reduction in mileage-related damage per liter of reduced fuel consumption due to a marginal tax increase on fuel. The road user charge on fuel exceeds mileage-related externalities, p_d, for fuel-intensive vehicles. The road user charge on fuel is lower than mileage-related externalities, p_d, for fuel-efficient vehicles.[5] This outcome shows that the approach in Fullerton and West (2002), where the tax system is designed to implement the social planner solution, is inconsistent with the optimal tax solutions in the present study.

The welfare-maximizing tax on fuel-intensive vehicles equals

$$t_{car}^* = \frac{\frac{\overline{N}-N}{\overline{N}}\left(f_{low} - f_{high}\right)}{\frac{N}{\overline{N}}\frac{m_{high}{}'_{t_f}}{m_{low}{}'_{t_f}}f_{high} + \frac{\overline{N}-N}{\overline{N}}f_{low}}p_d m_{high}\left(t_f^*\right) + \frac{\frac{N}{\overline{N}}\frac{m_{high}{}'_{t_f}}{m_{low}{}'_{t_f}}\left(f_{low} - f_{high}\right)}{\frac{N}{\overline{N}}\frac{m_{high}{}'_{t_f}}{m_{low}{}'_{t_f}}f_{high} + \frac{\overline{N}-N}{\overline{N}}f_{low}}p_d m_{low}\left(t_f^*\right) \tag{17}$$

Both terms on the right side are negative. Hence, there should be a subsidy for fuel-intensive vehicles when fuel-efficient vehicles are untaxed. Or equivalently, there should be heavier taxes on fuel-efficient vehicles than on fuel-intensive vehicles. Inserting the expression for the road user charge on fuel, t_d, from Eq. (16) into Eq. (17) implies that

$$t_{car}^* = (p_d - t_d f_{high})m_{high}(t_f) - (p_d - t_d f_{low})m_{low}(t_f) \tag{18}$$

Eq. (18) shows that the optimal tax on fuel-intensive vehicles, t_{car}^*, equals mileage-related damage minus road user charges for fuel-intensive vehicles, $\left(p_d - t_d f_{high}\right)m_{high}(t_f)$, minus the difference between mileage-related damage and road user charges for fuel-efficient vehicles, $(p_d - t_d f_{low})m_{low}(t_f)$. Future taxes on fuel are fully accounted for by households with rational expectations. Therefore, the CO_2 tax on fuel provides a correct incentive for the choice of vehicle in this case. The choice of vehicle is distorted, however, as the mileage-related tax on fuel deviates from the mileage-related externality. The heavier tax on fuel-efficient vehicles neutralizes this distortion. Hence, household's choice of vehicles implements the socially desirable allocation of vehicles given by Eq. (15).

The model framework is unable to distinguish between a tax on fuel-efficient vehicles and a subsidy on fuel-intensive vehicles. However, a welfare maximizing tax system consists of a Pigouvian tax on polluting goods designed to correct for externalities according to Jacobs and de Mooij (2015). Adopting this insight implies that tax formulas within the present study should be interpreted as environmental taxes designed to correct for externalities. Hence, purchase of fuel-intensive vehicles should be subsidized with an amount which equals the difference between road user charges on fuel and the mileage-related damage associated with each fuel-intensive vehicle, i.e. the first expression on the right-hand side of Eq. (18). Purchase of fuel-efficient vehicles should be taxed with the difference between mileage-related damage and road user charges on fuel associated with each fuel-efficient vehicle, i.e. the second expression on the right-hand side of Eq. (18). Fullerton (1997) shows that the optimal commodity tax on clean and polluting goods is uniform when combined with an optimal environmental tax on polluting goods. Hence, tax formulas within the present study should be combined with a uniform commodity tax on fuel, both types of vehicles, and on the non-polluting good according to this insight.

Some limitations should be considered when results are interpreted. The simple one-period model framework adopted, with specific externalities and preferences with respect to driving and type of vehicle, suggests that results are limited to specific settings. A share of the mileage-related damage might e.g. be related to the weight of vehicles, and hence, to the fuel consumption of vehicles, see Anderson and Auffhammer (2014). Hence, a mileage-related tax on fuel might be desirable to correct for this share of the mileage-related externalities. The model framework excludes choices, such as economical driving (Bjertnæs, 2019b), and other externalities, like the race for status. Other policy tools designed to reduce traffic-related externalities, like parking fees, toll roads and CAFE standards, are omitted from the model framework. Heterogeneity along dimensions like demand for driving, income and environmental awareness are also excluded. The simple model framework is, however, able to arrive at optimal tax formulas that are mainly determined by the damage fuel and vehicles inflict upon society. Such damage is determined by empirical estimates, so tax formulas are mainly determined by these estimates.

3.5. *Electric vehicles*

A user charge on EVs is desirable to correct for mileage-related externalities. The aim of this section is however to analyzes optimal taxation of fuel and purchases of EVs when the use of EVs is not taxed. The problem is analyzed within the present model framework by replacing low-emission vehicles with EVs, and by assuming that the private cost of using an EV is zero. CO_2 emissions from production of electricity and EVs are excluded. Thus, the driving distance for EVs is determined by the condition, $u'_{m_{low}} = 0$. Private operating costs of EVs is excluded from the model framework in this case. However, a tax designed to correct for negative externalities is not influenced by such operating costs when externalities are not influenced by such operating cost. Driving distance, and hence, mileage-related externalities are magnified when private operating costs equals zero. This problem is solved by implementing appropriate driving distance for EVs within optimal tax formulas.

The maximization problem of the government is found by inserting $f_{low} = 0$, and by assuming that $m_{low}(t_f)$ is fixed in problem (13). First order conditions imply that

$$u'_{m_{high}} = p_f f_{high} + p_{CO2} f_{high} + p_d \tag{19}$$

Inserting Eq. (19) into Eq. (3) gives

$$t_f^{**} = p_{CO2} + \frac{p_d}{f_{high}} \tag{20}$$

Thus, the optimal tax difference between fuel and non-polluting consumer goods equals the shadow price of CO_2 emissions plus the mileage-related marginal damage of road transport. The first order condition with respect to t_{car} combined with Eqs. (20) and (7) implies that

$$t_{car}^{**} = -p_d m_{low} \tag{21}$$

Eq. (21) shows that the optimal additional tax on purchase of EVs equals mileage-related damage associated with EVs. The shadow price of CO_2 emissions and mileage-related damage due to ICEVs with an average fuel efficiency is incorporated into the price of fuel. The cost of mileage-related damage associated with EVs is incorporated into the price of the vehicle. Thus, rational households face costs attributable to

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[5] This result is consistent with the result in Diamond (1973).

externalities when choosing between a ICEV with average fuel consumption and an EV. Note that greater damage from CO_2 emissions, preferences for vehicles due to factors such as range anxiety, and price differences between vehicles do not alter the optimal additional tax on EVs expressed by Eq. (21).

4. Caveats

The present study shows that a tax on fuel should be combined with tax exemptions for high-emission vehicles to curb mileage-related externalities and to fulfill emission reduction targets within the transport sector. This finding is based on assumptions which calls for a clarifying discussion. First, second-best optimal taxes on fuel and vehicles within the present study is designed to correct for externalities and to fulfill an emission reduction target. This approach is consistent with the result in Jacobs and de Mooij (2015). Hence, these second-best optimal taxes are not affected by reduced cost-effectiveness as electric vehicle owners would have chosen an electric vehicle even in the absence of tax credits (Xing et al., 2021; Sheldon and Dua, 2019), or by distributional impacts of vehicle policies (Sheldon and Dua, 2021). Second, empirical studies indicate that consumer sensitivity to fuel taxes is relatively low. The second-best optimal tax on fuel required to satisfy an ambitious emission reduction target is consequently substantial. Such tax increases on fuel may face political resistance in countries where the present tax on fuel is low and fuel consumption per capita is high, see Hammar et al. (2004). Opposing voters and lobby groups are likely to benefit from the suggested optimal and lenient taxation of fuel-intensive vehicles, however. Third, Holland et al. (2016) find substantial geographic variation in the environmental benefits/costs from driving electric vehicles in US states. They find that the second-best electric vehicle purchase subsidy ranges from $2785 in California to -$4964 in North Dakota, and that 90 % of local environmental externalities from driving electric vehicles in one state are exported to others. One may also argue that driving distance is likely to differ among heterogeneous households, and hence, that a tax on EVs consequently deviates from mileage-related damage for some households. The present study is unable to illuminate on these issues. Diamond (1973) however argue that a uniform price which corrects for externalities which differ among households should be set equal to a weighted average of externalities.[6] Fourth, several empirical studies find that households have rational expectations when purchasing vehicles (Sallee et al., 2016; Busse et al., 2013). The analyzes above have adopted this assumption. Some studies find support for myopic behavior, however (Grigolon et al., 2018; Allcott and Wozny, 2014; Gillingham et al., 2021). Bjertnæs (2019a) shows that myopic behavior calls for tax rebates for zero- and low emission vehicles. The optimal additional tax on zero emission vehicles designed to neutralize distortions due to a mileage tax on fuel exceeds tax rebates designed to correct for myopic behavior, however. Bansal et al. (2021) on the other hand uncover a substantial degree of heterogeneity in the valuation of future operating costs both within and across specific income groups, with lower income buyers being far more myopic than higher income buyers. The average Indian two-wheeler buyer is not myopic according to their study. Hence, their result lend support to a progressive feebate policy, involving higher rebates and lower fees for lower income consumers, see also (Xing et al., 2021; Sheldon and Dua, 2019). Fifth, several car manufacturers have recently been caught manipulating tests to classify their vehicles as fuel efficient. Taxes are avoided and customers are cheated. Customers may however benefit as prices are reduced, see Reynaert and Sallee (2021). The heavier tax on zero and low emission vehicles lower incentives for such avoidance, and hence contributes to solving this problem. Improved testing is of course an alternative solution. Sixth, countries have implemented tax exemptions and subsidies for EVs to promote the development of clean-transport technology, and possibly to prepare their car industry for an electric future. It is challenging to quantify such externalities, but additional adverse impacts, such as increased car use and less public transport, should be expected (Holtsmark and Skonhoft, 2014; Aasness and Odeck, 2015). Seventh, externalities associated with a network of charging stations could also justify tax exemptions for the purchase of EVs; see Greaker and Midttømme (2016). Shanjun et al. (2017), on the other hand, show that direct subsidies for investing in charging stations are more efficient than subsidies for EVs.

5. Conclusion

Second-best optimal taxation of road transport in the presence of emission targets are an underexplored topic in the literature. The present study contributes to the literature by analyzing second-best optimal combination of taxes on fuel and vehicles when emissions from road transport is restricted by an emission target. The study shows that a tax on fuel should be combined with tax exemptions for high-emission vehicles to curb mileage-related externalities and to fulfill emission targets within the transport sector. The emission target is fulfilled by adjusting the CO_2-tax component on fuel. The road user charge on fuel is designed to curb mileage-related externalities. The choice of vehicle is distorted by the tax on fuel, however, as the road-user charge on fuel exceeds mileage-related externalities for fuel-intensive vehicles while the charge is below mileage-related externalities for fuel-efficient vehicles. The heavier tax on low- and zero emission vehicles is designed to neutralize this distortion.

The expansion of EVs create a need for road user charges based on driving. A few countries have introduced GPS-based road user charges on heavy duty vehicles, but systems for light-duty passenger vehicles are lagging. Bjertnæs (2019a) shows that the optimal tax on EVs equals the tax on ICEVs when the road user charge is based on GPS tracking, the tax on fuel equals the marginal damage of CO_2 emissions, and other market imperfections are absent.[7] This solution leads to a more socially desirable allocation of vehicles and driving than the solution with a uniform tax on fuel combined with heavier taxation of fuel-efficient vehicles (Ashley et al., 2017; Montag, 2015). However, a GPS-based system is more costly to administer and is likely to impose information-processing costs and undesirable surveillance according to Parry et al. (2007). One may argue that a road-user charge based on odometer readings or pay-as-you-drive insurance combined with congestion charges and toll roads resembles GPS-based road user charges. However, such charges are also costly to administer, are susceptible to evasion, and leads to undesirable traffic planning designed to avoid toll stations, see Parry (2002). Technological advances within information technology may on the other hand overcome some of these hurdles.

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Declaration of Competing Interest

None.

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[6] Differences in mileage-related costs across geographic regions call for geographic tax differentiation across regions. Implementation of geographic tax differentiation favors an annual vehicle tax, as differentiated taxes on purchases are more likely to be subject to evasion.

[7] Myopic behavior calls for tax differentiation according to Jansen and Denis (1999).

Linda Nøstbakken and from attendees at the 76th Annual Congress of the International Institute of Public Finance. The author declares no known interests related to this manuscript.

Appendix A

First order equations w.r.t

$$t_{car}: -\frac{1}{a}u\left(m_{high}\left(t_f\right)\right) - \frac{1}{a}b_{max} + N + \frac{1}{a}u\left(m_{low}\left(t_f\right)\right) + \frac{1}{a}\left(p_{car,high} + p_f f_{high} m_{high}\left(t_f\right)\right)$$
$$-\frac{1}{a}\left(p_{car,low} + p_f f_{low} m_{low}\left(t_f\right)\right) + \frac{1}{a}p_{CO2} f_{high} m_{high}\left(t_f\right) - \frac{1}{a}p_{CO2} f_{low} m_{low}\left(t_f\right) + \frac{1}{a}p_d m_{high}\left(t_f\right)$$
$$-\frac{1}{a}p_d m_{low}\left(t_f\right) = 0 \tag{A.1}$$

Note that $\frac{\partial N}{\partial t_{car}} = \frac{1}{-a}$ according to Eq. (7). If we multiply (A.1) by $-a$, (then)

$$u\left(m_{high}\left(t_f\right)\right) + b_{max} - aN - p_{car,high} - p_f f_{high} m_{high}\left(t_f\right) - p_{CO2} f_{high} m_{high}\left(t_f\right) - p_d m_{high}\left(t_f\right)$$
$$= u\left(m_{low}\left(t_f\right)\right) - p_{car,low} - p_f f_{low} m_{low}\left(t_f\right) - p_{CO2} f_{low} m_{low}\left(t_f\right) - p_d m_{low}\left(t_f\right). \tag{A.2}$$

First order equations w.r.t. t_f:

$$\frac{f_{low} m_{low}\left(t_f\right) - f_{high} m_{high}\left(t_f\right)}{a}\left[u\left(m_{high}\left(t_f\right)\right) + b_{max} - aN() - u\left(m_{low}\left(t_f\right)\right) - p_{car,high}\right.$$
$$-p_f f_{high} m_{high}\left(t_f\right) + p_{car,low} + p_f f_{low} m_{low}\left(t_f\right) - p_{CO2} f_{high} m_{high}\left(t_f\right) + p_{CO2} f_{low} m_{low}\left(t_f\right)$$
$$\left.-p_d m_{high}\left(t_f\right) + p_d m_{low}\left(t_f\right)\right] + N()u'_m m_{high}{}'_{t_f} - N()p_f f_{high} m_{high}{}'_{t_f}$$
$$-N()p_{CO2} f_{high} m_{high}{}'_{t_f} - N()p_d m_{high}{}'_{t_f} + (\overline{N} - N())u'_m m_{low}{}'_{t_f} - (\overline{N} - N())p_f f_{low} m_{low}{}'_{t_f}$$
$$-(\overline{N} - N())p_{CO2} f_{low} m_{low}{}'_{t_f} - (\overline{N} - N())p_d m_{low}{}'_{t_f} = 0. \tag{A.3}$$

Note that Eq. (7) implies that $\frac{\partial N}{\partial t_f} = \frac{f_{low} m_{low}\left(t_f\right) - f_{high} m_{high}\left(t_f\right)}{a}$. The first order equation w.r.t t_{car}, (A.1), implies that the parameters in the first bracket equal zero. Hence, these conditions imply that

$$\frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}u'\left(m_{high}\right) + \frac{\overline{N} - N}{\overline{N}}u'\left(m_{low}\right) = \frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}p_f f_{high} + \frac{\overline{N} - N}{\overline{N}}p_f f_{low}$$
$$+\frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}p_{CO2} f_{high} + \frac{\overline{N} - N}{\overline{N}}p_{CO2} f_{low} + \frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}p_d + \frac{\overline{N} - N}{\overline{N}}p_d \tag{A.4}$$

Multiplying Eq. (3) by $\frac{N}{\overline{N}}$ and $\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}$ (gives)

$$\frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}u'\left(m_{high}\right) = \frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}p_f f_{high} + \frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}t_f f_{high} \tag{A.5}$$

Multiplying Eq. (3) by $\frac{\overline{N} - N}{\overline{N}}$ (gives)

$$\frac{\overline{N} - N}{\overline{N}}u'\left(m_{low}\right) = \frac{\overline{N} - N}{\overline{N}}p_f f_{low} + \frac{\overline{N} - N}{\overline{N}}t_f f_{low} \tag{A.6}$$

Summing Eqs. (A.5) and (A.6) gives:

$$\frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}u'\left(m_{high}\right) + \frac{\overline{N} - N}{\overline{N}}u'\left(m_{low}\right) = \frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}p_f f_{high} + \frac{\overline{N} - N}{\overline{N}}p_f f_{low}$$
$$+\frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}t_f f_{high} + \frac{\overline{N} - N}{\overline{N}}t_f f_{low} \tag{A.7}$$

The first order conditions w.r.t. t_f and t_{car}, (A.1) and (A.2), and Eq. (A.7) imply that

$$\frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}t_f f_{high} + \frac{\overline{N} - N}{\overline{N}}t_f f_{low} = \frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}\mathrm{p}_{CO2} f_{high} + \frac{\overline{N} - N}{\overline{N}}p_{CO2} f_{low}$$
$$+\frac{N}{\overline{N}}\frac{m_{high}{}^{‘}{}_{t_f}}{m_{low}{}^{‘}{}_{t_f}}p_d + \frac{\overline{N} - N}{\overline{N}}p_d \tag{A.8}$$

Hence,

$$t_f^* = p_{CO2} + \frac{\left(Nm_{high}{}^{‘}{}_{t_f} + (\overline{N} - N)m_{low}{}^{‘}{}_{t_f}\right)p_d}{Nm_{high}{}^{‘}{}_{t_f} f_{high} + (\overline{N} - N)m_{low}{}^{‘}{}_{t_f} f_{low}} \tag{A.9}$$

Substituting t_f^* in Eq. (7) gives

$$\begin{aligned} & u\left(m_{high}\left(t_f^*\right)\right) + b_{max} - aN - p_{car,high} - t_{car} - p_f f_{high} m_{high}\left(t_f^*\right) \\ & -p_{CO2} f_{high} m_{high}\left(t_f^*\right) - \frac{\left(\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}} + \frac{\overline{N}-N}{\overline{N}}\right) p_d f_{high}}{\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}} f_{high} + \frac{\overline{N}-N}{\overline{N}} f_{low}} m_{high}\left(t_f^*\right) \\ & = u\left(m_{low}\left(t_f^*\right)\right) - p_{car,low} - p_f f_{low} m_{low}\left(t_f^*\right) \\ & -p_{CO2} f_{low} m_{low}\left(t_f^*\right) - \frac{\left(\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}} + \frac{\overline{N}-N}{\overline{N}}\right) p_d f_{low}}{\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}} f_{high} + \frac{\overline{N}-N}{\overline{N}} f_{low}} m_{low}\left(t_f^*\right) \end{aligned} \tag{A.10}$$

Hence,

$$\begin{aligned} & u\left(m_{high}\left(t_f^*\right)\right) + b_{max} - aN - p_{car,high} - t_{car} - p_f f_{high} m_{high}\left(t_f^*\right) \\ & -p_{CO2} f_{high} m_{high}\left(t_f^*\right) - p_d m_{high}\left(t_f^*\right) - \frac{\left(\frac{\overline{N}-N}{\overline{N}}\right)\left[f_{high} - f_{low}\right]}{\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}} f_{high} + \frac{\overline{N}-N}{\overline{N}} f_{low}} p_d m_{high}\left(t_f^*\right) \\ & = u\left(m_{low}\left(t_f^*\right)\right) - p_{car,low} - p_f f_{low} m_{low}\left(t_f^*\right) \\ & -p_{CO2} f_{low} m_{low}\left(t_f^*\right) - p_d m_{low}\left(t_f^*\right) - \frac{\left(\frac{N}{\overline{N}}\right)\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}}\left[f_{low} - f_{high}\right]}{\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}} f_{high} + \frac{\overline{N}-N}{\overline{N}} f_{low}} p_d m_{low}\left(t_f^*\right) \end{aligned} \tag{A.11}$$

Implementing first order conditions v.r.t. t_{car}, (A.1) gives

$$t_{car}^* = \frac{\frac{\overline{N}-N}{\overline{N}}\left(f_{low} - f_{high}\right)}{\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}} f_{high} + \frac{\overline{N}-N}{\overline{N}} f_{low}} p_d m_{high}\left(t_f^*\right) + \frac{\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}}\left(f_{low} - f_{high}\right)}{\frac{N}{\overline{N}}\frac{m_{high}{}^{\text{‘}}{}_{t_f}}{m_{low}{}^{\text{‘}}{}_{t_f}} f_{high} + \frac{\overline{N}-N}{\overline{N}} f_{low}} p_d m_{low}\left(t_f^*\right) \tag{A.12}$$

Both expressions on the right-hand side are negative. This proves that t_{car}^* is negative.

First order equations w.r.t. p_{CO2}:

$$S_{CO2} = N f_{high} m_{high}\left(t_f\right) + \left(\overline{N} - N\right) f_{low} m_{low}\left(t_f\right) \tag{A.13}$$

Appendix B

Second order conditions for the government maximization problem, Eq. (13). First order conditions solve the maximization problem if the Lagrangian is concave. Hence

$$\begin{aligned} \frac{\partial^2 L}{\partial t_f \partial t_f} = & \frac{f_{low} m_{low}\left(t_f\right) - f_{high} m_{high}\left(t_f\right)}{a}\left[-a\left[\frac{f_{low} m_{low}\left(t_f\right) - f_{high} m_{high}\left(t_f\right)}{a}\right]\right. \\ & + u'_m m_{high}{}'_{t_f} - p_f f_{high} m_{high}{}'_{t_f} - p_{CO2} f_{high} m_{high}{}'_{t_f} - p_d m_{high}{}'_{t_f} \\ & \left. - u'_m m_{low}{}'_{t_f} + p_f f_{low} m_{low}{}'_{t_f} + p_{CO2} f_{low} m_{low}{}'_{t_f} + p_d m_{low}{}'_{t_f}\right] \\ & + \frac{f_{low} m_{low}\left(t_f\right) - f_{high} m_{high}\left(t_f\right)}{a}\left[u'_m m_{high}{}'_{t_f} - p_f f_{high} m_{high}{}'_{t_f} - p_{CO2} f_{high} m_{high}{}'_{t_f}\right. \\ & \left. - p_d m_{high}{}'_{t_f} - u'_m m_{low}{}'_{t_f} + p_f f_{low} m_{low}{}'_{t_f} + p_{CO2} f_{low} m_{low}{}'_{t_f} + p_d m_{low}{}'_{t_f}\right] \\ & + N\left(t_f, t_{car}\right)\left[u'_m{}'_m m_{high}{}'_{t_f} m_{high}{}'_{t_f} + u'_m m_{high}{}'_{t_f}{}'_{t_f} - p_f f_{high} m_{high}{}'_{t_f}{}'_{t_f} - p_{CO2} f_{high} m_{high}{}'_{t_f}{}'_{t_f}\right. \\ & - p_d m_{high}{}'_{t_f}{}'_{t_f} - u'_m{}'_m m_{low}{}'_{t_f} m_{low}{}'_{t_f} - u'_m m_{low}{}'_{t_f}{}'_{t_f} + p_f f_{low} m_{low}{}'_{t_f}{}'_{t_f} + p_{CO2} f_{low} m_{low}{}'_{t_f}{}'_{t_f} \\ & \left. + p_d m_{low}{}'_{t_f}{}'_{t_f}\right] + \overline{N}\left[u'_m{}'_m m_{low}{}'_{t_f} m_{low}{}'_{t_f} + u'_m m_{low}{}'_{t_f}{}'_{t_f} - p_f f_{low} m_{low}{}'_{t_f}{}'_{t_f} - p_{CO2} f_{low} m_{low}{}'_{t_f}{}'_{t_f}\right. \\ & \left. - p_d m_{low}{}'_{t_f}{}'_{t_f}\right] < 0 \end{aligned} \tag{B.1}$$

$$\frac{\partial^2 W}{\partial t_{car} \partial t_{car}} = \frac{1}{-a} < 0 \tag{B.2}$$

$$\frac{\partial^2 L}{\partial t_f \partial t_{car}} = \frac{f_{low} m_{low}\left(t_f\right) - f_{high} m_{high}\left(t_f\right)}{a} - \frac{1}{a}\left[u'_m {m_{high}}'_{t_f} - p_f f_{high} {m_{high}}'_{t_f} - p_{CO2} f_{high} {m_{high}}'_{t_f} \right.$$
$$\left. - p_d {m_{high}}'_{t_f} - u'_m {m_{low}}'_{t_f} + p_f f_{low} {m_{low}}'_{t_f} + p_{CO2} f_{low} {m_{low}}'_{t_f} + p_d {m_{low}}'_{t_f}\right] \tag{B.3}$$

The second order condition is satisfied if.

$$\frac{\partial^2 L}{\partial t_{car} \partial t_{car}} < 0 \text{ and } \frac{\partial^2 L}{\partial t_{car} \partial t_{car}} \frac{\partial^2 L}{\partial t_f \partial t_f} - \left(\frac{\partial^2 L}{\partial t_f \partial t_{car}}\right)^2 > 0.$$

The first inequality condition, $\frac{\partial^2 L}{\partial t_{car} \partial t_{car}} < 0$, is satisfied if $a > 0$.

The second inequality condition, $\frac{\partial^2 L}{\partial t_{car} \partial t_{car}} \frac{\partial^2 L}{\partial t_f \partial t_f} - \left(\frac{\partial^2 L}{\partial t_f \partial t_{car}}\right)^2 > 0$, is satisfied when

$$-\frac{1}{a} N\left(t_f, t_{car}\right)\left[u'_m{}'_m {m_{high}}'_{t_f} {m_{high}}'_{t_f} + u'_m {m_{high}}'_{t_f}{}'_{t_f} - p_f f_{high} {m_{high}}'_{t_f}{}'_{t_f} \right.$$
$$- p_{CO2} f_{high} {m_{high}}'_{t_f}{}'_{t_f} - p_d {m_{high}}'_{t_f}{}'_{t_f} - u'_m{}'_m {m_{low}}'_{t_f} {m_{low}}'_{t_f} - u'_m {m_{low}}'_{t_f}{}'_{t_f} + p_f f_{low} {m_{low}}'_{t_f}{}'_{t_f}$$
$$\left. + p_{CO2} f_{low} {m_{low}}'_{t_f}{}'_{t_f} + p_d {m_{low}}'_{t_f}{}'_{t_f}\right] - \frac{1}{a^2}\left[u'_m {m_{high}}'_{t_f} - p_f f_{high} {m_{high}}'_{t_f} - p_{CO2} f_{high} {m_{high}}'_{t_f} \right.$$
$$\left. - p_d {m_{high}}'_{t_f} - u'_m {m_{low}}'_{t_f} + p_f f_{low} {m_{low}}'_{t_f} + p_{CO2} f_{low} {m_{low}}'_{t_f} + p_d {m_{low}}'_{t_f}\right]^2 > 0 \tag{B.4}$$

Parameter values and functional forms are restricted to those that satisfy this condition.

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