The Simple Economics of Motor Vehicle Pollution: A Case for Fuel Tax

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The volume of pollution produced by an automobile is determined by driver's behavior along three margins: (i) vehicle selection, (ii) kilometers driven, and (iii) on-road fuel economy. The first two margins have been studied extensively, however the third has received scant attention. How significant is this 'intensive margin'? What would be the optimal policies when it is taken into account? The paper develops and analyzes a simple model of the technical and behavioral mechanisms that determine the volume emissions produced by a car. The results show that an optimal fuel tax would provide drivers with appropriate incentives along all three margins and that only public information is needed for a fuel tax to be set optimally. In contrast, an optimal distance tax would require private information. Lastly, relative to the optimal fuel tax, a simple uniform fuel tax is shown to be progressive. Thus, being already deployed worldwide, a uniform fuel tax is an attractive second-best policy. These findings should be accounted for when designing new mechanisms to alleviate motor vehicle pollution.

Key words: automobile externalities, car pollution, CO_2 emissions, fuel economy, driving behavior, distance tax, fuel tax.

JEL classification: H23, Q58, R41, R48.

1 Introduction

This article models the tailpipe emissions produced by motor vehicles and policies capable of adjusting drivers' marginal costs for these external costs. Air pollutants, including carbon monoxide (CO), nitrogen oxide (NO_x), hydrocarbons (HC), and particulate matter (PM), have been shown to have adverse effects on human health, especially for children (Arceo-Gomez et al., 2012; Chen et al., 2013; Gauderman et al., 2005). CO_2 emissions furthermore contribute significantly to climate change, although there is a debate about its effects and policy responses (Pindyck, 2013; Stern, 2013). The fuel burned in motor vehicles produces all of these emissions and can therefore be considered to result in social and ecological cost (Arceo-Gomez et al., 2012; Bin and Dowlatabadi, 2005; Dietz

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et al., 2009). The magnitude of these social costs is determined by drivers' behavior along three margins: (i) vehicle selection, (ii) kilometers driven, i.e. the extensive margin, and (iii) on-road fuel consumption per kilometer, henceforth the intensive margin. Drivers' decisions at the intensive margin include driving style, vehicle maintenance, and other choices affecting on-road fuel consumption.

External costs generate a mismatch between the private marginal costs of driving and the social marginal costs of driving. This means that the amount of driving likely exceeds the socially optimal amount because individual drivers face lower marginal costs relative to the marginal costs born by the society. An analogous argument applies to driving style. Driver behavior along the intensive margin determines the externality per kilometer and thus the total externality.

The existing economics literature concerned with motor vehicle externalities and policies mainly focuses on the extensive margin of motor vehicle use (kilometers driven); the intensive margin (fuel economy and emissions per kilometer) enters only via technical improvements in vehicle efficiency at the production level and subsequent changes in the vehicle stock composition (Austin and Dinan, 2005; Fischer et al., 2007; Frondel and Vance, 2009; Frondel et al., 2012; Fullerton and West, 2002; Greene, 2011; Harrington, 1997; Innes, 1996; Kleit, 2004; Parry and Small, 2005; Parry et al., 2007). This article differs from these studies in that it explicitly deals with the intensive margin of motor vehicle use, which is determined by the driver-vehicle interaction.[1] Intuitively, two identical cars may have different fuel consumption rates if one is driven in the countryside and the other one in urban areas or on highways, if one is more often driven in the summer and the other in the winter, if one is used for short distance commuting and shopping while the other is used for long distance travel, or if one is driven by a risk averse, anticipative, driver and the other by an adrenaline-loving youngster. As a result, these two cars will produce different amount of emissions per kilometer driven.

A number of recent studies have identified the intensive margin of motor vehicle use as an important source of potential energy savings and observe that this has received limited attention from researchers as well as policy makers (Barkenbus, 2010; Carrico et al., 2009; Dietz et al., 2009; Gardner and Stern, 2008; Ko et al., 2010; Onoda, 2009; Tong et al., 2000; Van Mierlo et al., 2004; Vandenbergh and Steinemann, 2007; Vandenbergh et al., 2008).[2] Drivers may directly influence the fuel efficiency of their vehicles not only by altering their speed and driving style, but also by trip planning, maintaining correct tire pressure, or regularly changing the air filter.

[1]Although some of the cited papers do mention the impact of driver-vehicle interaction on fuel economy, these effects are usually given only marginal attention and are assumed away in their models (Fullerton and West, 2002; Harrington, 1997; Innes, 1996).

[2]See also Goodwin et al. (2004) and Kobayashi et al. (2009).

By incorporating the intensive margin into the analysis of corrective tax instruments, this paper complements and connects these two literatures. The studies closest to the present one are Fullerton and West (2002) and Innes (1996), who study vehicle and fuel taxes in general equilibrium models. Similar to their results, optimal distance and fuel taxes derived in this paper are vehicle-specific. However, this paper shows that vehicle-specific distance taxes are optimal only if the intensive margin of driving is kept fixed; or if the tax rate depends on the driver behavior along the intensive margin, that is if it depends on the actual fuel consumption. Yet, a distance tax that depends on the actual fuel consumption essentially *is* a fuel tax. The explicit modeling of the intensive margin of the real-world driving in this paper thus yields new insights into the relative efficacy of fuel tax as an instrument for the control of pollution.

The intensive margin related to driver-vehicle interaction is a potentially attractive policy target, because it can lead to energy savings and reduced emissions with the existing stock of vehicles, without the costs of accelerated vehicle stock replacement. In addition to the environmental and economic perspectives, the intensive margin is also relevant for transportation safety, as lower speeds and a less aggressive style lead to fewer and less severe accidents (Aarts and van Schagen, 2006; van Benthem, 2015; Grabowski and Morrisey, 2006; Montag, 2014).[3]

The existence of the intensive margin has two main implications relevant to the pollution production 'technology': (i) Total fuel consumption, and therefore CO_2 emissions, are affected by kilometers driven, vehicle efficiency, and the on-road fuel economy. (ii) Deviations of the actual fuel economy from the standardized fuel economy generate variation in per-kilometer local pollutant emissions within vehicles over time as well as across vehicles. Both of these effects affect the efficacy of a given policy to control local as well as global pollution, yet they have not been adequately addressed in the economic literature on automobile externalities and policies. This paper aims to fill this gap.

2 Methods

In order to ascertain the effects of specific decision margins on pollution-related social costs, I develop a simple model capturing the main factors that determine tailpipe emissions

[3]A referee suggested that this effect may be absent if only a subset of drivers react, that is accidents may increase if the variability in speed and driving style increases. The evidence on speed variability and accidents is however inconclusive (Aarts and van Schagen, 2006). Additionally, composition effects may play and important role here: if occasional and young drivers respond with higher elasticity than daily commuters (see e.g. Bolderdijk et al., 2011; Frondel and Vance, 2010), crash and injury rates may decrease. In addition, if some drivers start driving more slowly, the others may need to slow down too (Barth and Boriboonsomsin, 2009). The relative importance of these effects is ultimately an empirical question. Note however, that these questions arise naturally once attention is given to the intensive margin.

at vehicle level. I then use this framework to study various possible policy instruments, to learn how these policies perform in matching the driver's private costs with the social costs he produces. Using the formulas for optimal distance and fuel taxes derived from the model, I calculate optimal distance tax and fuel tax for four vehicle examples.

The discussion is focused on externalities and policy instruments, hence only the mechanics behind motor vehicle externalities and the policy responses are modeled.[4] Drivers are assumed to behave rationally, and their behavioral reactions are assumed to be optimal, reflecting the structure of the marginal costs they face. Once the price reflects the social cost of an activity, individuals have incentives to undertake only those units of the activity for which the social benefits exceed the social cost, which is the social optimum. However, implications for the previous studies using general equilibrium models as well as implications of limited rationality for the results in this paper will be discussed.

2.1 The mechanics behind automobile emissions

As long as a car remains parked with its engine off, it produces zero emissions. Once it starts moving, the marginal externalities are determined by two types of law: the laws of nature, and government regulations. Carbon dioxide (CO_2) emissions are purely determined by the former because there are no available technologies that would mitigate the amount of CO_2 emissions per liter of fuel (Parry et al., 2007), and so the amount of CO_2 increases linearly with the amount of combusted fuel.[5] Hence, a reduction in CO_2 emissions is only possible if fuel economy is improved or fewer kilometers are traveled, or both.

With regard to air pollutants, however, abatement technologies enable car manufacturers to limit the amount of tailpipe pollutant emissions per liter of fuel. As a result, regulation of these emissions was introduced both in the US and in the EU, by the Clean Air Act Amendments of 1990 and Council Directive 91/441/EEC of 1991, respectively. Both norms work in a similar way: starting with the model year 1994, they define categories of vehicles that are subject to uniform emission limits. All passenger cars (including SUVs and light duty trucks) are treated as a single category; separate categories are defined for

[4]That is, only the external component of the social cost ($SMC - MC$) and specific tax instruments are modeled.

[5]In fact, there is a trade-off between the amount of carbon dioxide and toxic waste. This is because the latter consists of fuel not oxidized into CO_2. Specifically when hydrocarbon burns in oxygen the result is energy, water, CO_2, and toxic waste, which becomes pollution when emitted into the air. Generally, about 99 percent of carbon in fuel gets oxidized (U.S. Environmental Protection Agency, 2005). Thus, the better an engine burns the fuel, the fewer air pollutants are produced and the more kilometers driven per liter of fuel, but the more CO_2 is produced. This margin is ignored here, as it is rather small.

commercial vehicles, buses, and trucks.[6] For the passenger car category both norms set upper limits for toxic pollutants on a per mile or per kilometer basis. Over the last two decades, these limits have gradually been tightened.[7] The available evidence shows that these regulations have been effective, and that vehicle pollution has decreased rapidly since the 1990s (Huo et al., 2012; Parry et al., 2007).

Because these per-kilometer limits apply to all new passenger cars, car manufacturers have been forced to produce cars with lower air pollutants emissions, by improving their fuel economy and introducing new abatement technologies. As this is costly, new cars tend to be produced to just meet the regulation emissions levels (Fischer et al., 2007; Harrington, 1997; Khazzoom, 1995; Parry and Small, 2005; Parry et al., 2007; World Health Organization, 2014). Furthermore, vehicles must satisfy these emission norms throughout their lifetime and this requirement is regularly tested during vehicle inspections, which are mandatory in the EU as well as in most US states. As a result, all cars produced under a specific norm should emit a similar quantity of air pollutants per kilometer driven, regardless of their fuel efficiency and age (Fischer et al., 2007; Parry et al., 2007).

The independence between fuel economy and emissions, however, holds only for emissions measured during the manufacturer's testing cycle, since cars are seldom driven in laboratories. Real-life deviations from the testing cycle conditions are likely to affect actual fuel economy when the vehicles are operated. As an extreme, yet highly relevant example, consider that an idling car travels zero kilometers, yet it consumes fuel and produces a nonzero quantity of CO_2 emissions and local pollutants (Carrico et al., 2009; Chan and Ning, 2005; Frey et al., 2008a,b; Ning et al., 2005; Tong et al., 2000). The extent to which a motor is left idling is influenced by the surrounding conditions, such as weather, traffic, and road infrastructure (roundabouts, traffic lights, etc.) but is also a result of the driver's decisions (Carrico et al., 2009; Tong et al., 2000). Thus, notwithstanding that pollutant emissions per kilometer may be independent of cars' technical fuel efficiency,

[6]Until 2003, the US norm treated light trucks and SUVs more leniently from other passenger vehicles. Since 2004, however, SUVs and light trucks have been subject to the same emission limits as passenger vehicles (see World Health Organization, 2014).

[7]The first directive, called Euro 1, was enacted in 1992 and introduced per kilometer limits of 2.72 grams of carbon monoxide (CO), 0.97 grams of hydrocarbon and nitrogen oxide ($HC + NO_x$), and for diesel vehicles 0.14 grams of particulate matter (PM). Since September 2014, the limits have been set by the Euro 6, which was introduced together with Euro 5 by the Regulation (EC) No 715/2007. The main change from Euro 5 to Euro 6 was a reduction in the NO_x limit for diesel cars from 0.18 to 0.08 grams. The largest changes in limits over time pertain to NO_x, which was initially set at 0.50 grams under Euro 3 (2000-2005) and particulates, for which the initial limit of 0.14 grams under Euro 1 was reduced to 0.005 grams per kilometer since Euro 5 became effective in 2005. In the US the limits are managed by the Environmental Protection Agency. The same emission limits expressed in grams per mile apply to all vehicles regardless of the fuel used. The current, Tier 2, limits are of similar magnitude to the EU limits, except for CO, where the US norm is more lenient (3.4 grams per mile in the US versus 0.5 and 1.0 grams per kilometer for petrol and diesel cars in the EU, respectively). For further comparisons and details of the EU and US emission standards and regulations in other countries, see World Health Organization (2014, p. 469–486).

they are a function of the actual fuel consumption per kilometer with which a particular vehicle is operated.[8] As a result, emissions of local pollutants, are partly affected by the driver's decisions along the intensive margin.

2.2 How significant is the intensive margin?

As discussed in the Introduction, two margins influence fuel consumption and emissions per kilometer: (i) The between-vehicle fuel economy, which is determined by the technological properties of a vehicle (engine displacement, fuel type, aerodynamics, weight, etc.). (ii) The within-vehicle fuel economy, which is determined by driver-vehicle interaction and surrounding conditions.

2.2.1 Technical efficiency

The between-vehicle fuel economy has long been the object of policies (the Corporate Average Fuel Economy, or CAFE, standards introduced in the US by the Energy Policy and Conservation Act of 1975, and more recently in the EU, Regulation (EC) No. 443/2009).[9] Some European countries have also introduced vehicle taxes based on fuel consumption or CO_2 emissions (Giblin and McNabola, 2009; Kunert and Kuhfeld, 2007). However, improvements in technical fuel economy do not translate directly into fuel savings: First, the average fleet economy changes over time as new vehicles replace older ones (Austin and Dinan, 2005; Crandall, 1992; Frondel and Vance, 2009; Karplus et al., 2013; Kleit, 2004). Second, improved fuel economy lowers the marginal costs of driving, giving drivers incentives to drive more; this has been termed the 'rebound effect' (see e.g. Frondel and Vance, 2013; Greene, 2012). In addition, resources released by lower marginal costs of driving due to better fuel economy may allow drivers to drive faster or more aggressively (these points will be revisited formally in Section 3.3.4). Simultaneously, it has been argued that these policies are costly.[10]

[8] Harrington (1997) also studied the relationship between fuel economy and pollutant emissions, however his study analyzed in the effect of deterioration of abatement equipment over time; rather than the effect of on-road fuel efficiency, which is the focus of this paper. Note that recent research suggests that modern abatement technologies are durable so that emissions are stable throughout vehicles' lifetimes (see Fischer et al., 2007, and Section 2.1 below).

[9] See Kobayashi et al. (2009) for an overview of efficiency-enhancing technologies for motor vehicles.

[10] See also N. Gregory Mankiw, Carbon tax that America could live with, Online, August 31, 2013, at http://www.nytimes.com/2013/09/01/business/a-carbon-tax-that-america-could-live-with.html?_r=0 (last accessed on April 17, 2015).

2.2.2 Driver behavior and fuel efficiency

The intensive margin related to driver-vehicle interaction is a potentially attractive policy target, because it can lead to energy savings and reduced emissions with the existing stock of vehicles. However, the existence of this decision margin does not automatically guarantee its relevance: After all, the extent of its effect may be negligible, or people may not have an adequate control over their driving style because is dictated by factors such as weather, traffic, speed limits, and road infrastructure.

Let's look at the numbers. Keeping tires properly inflated may improve fuel economy by up to 3 percent and save about 1.2 percent of the household's energy consumption (Gardner and Stern, 2008; Onoda, 2009). However, a number of studies found that most savings can be achieved via changes in driving behavior, such as less aggressive acceleration, anticipative driving, lower and more stable speeds, and reduced idling (Carrico et al., 2009; Dietz et al., 2009; Gonder et al., 2012; Wang et al., 2008). Driving behavior may lead to improvements in fuel economy by 12 to 47 percent.[11] Other channels through which drivers' decisions and behavior may affect the on-road fuel economy of their vehicle are: trip planning, tire selection, maintenance (air filters), and the use of air conditioning (Ko et al., 2010). In addition, a number of studies have found that drivers are capable of altering their behavior (Barkenbus, 2010; Beusen et al., 2009; Barth and Boriboonsomsin, 2009; Gonder et al., 2012; Onoda, 2009; Takada et al., 2007; Thijssen et al., 2014; Van Mierlo et al., 2004).[12]

Table 1 provides an overview of estimates of the potential fuel-economy related savings available to households, according to the information available at the www.fueleconomy.gov website maintained by the US Department of Energy.[13] The table is complemented by earlier estimates of total household energy savings related to fuel efficiency by Gardner and Stern (2008). Taking the numbers in the last column of Table 1 at face value, improvements in driving behavior and keeping tires properly inflated may yield fuel savings of about one half of the magnitude of the savings that are available when buying a more fuel efficient vehicle. The overall magnitude of the available savings is comparable to those that may

[11]See also Ford Motor Company, Ford tests show eco-driving can improve fuel economy by an average of 24 percent, Online, August 27, 2008, at http://www.at.ford.com/news/cn/ArticleArchives/27527.aspx (last accessed on April 21, 2015).

[12]For instance Beusen et al. (2009, p. 516) test the effect of these fuel-efficient driving rules in relation to a four-hour driving course: "1. Shift up as soon as possible (shift up between 2000 and 2500 revolutions/min). 2. At steady speeds use the highest gear possible and drive with low engine RPM. 3. Try to maintain a steady speed by anticipating traffic flow. 4. Decelerate smoothly by releasing the accelerator in time while leaving the car in gear (this is called "coasting"). Further, some additional driving style instructions were provided at the course: 5. Shut down the engine for longer stops, e.g. before a level crossing or when you pick somebody up. 6. Do not drive faster than 120 km/h." The average fuel consumption fell by 5.8 percent four months after the course.

[13]See http://www.fueleconomy.gov/feg/drive.shtml and references therein. See also the UK Department of Transport's site http://www.dft.gov.uk/vca/fcb/smarter-driving-tips.asp or http://www.ecodrive.org.

Table 1: Overview of fuel economy improvements available to drivers

Action	Fuel economy improvements (in %)[a]	Savings per gallon in cents[a]	Household energy potentially saved (in %)[b]
Driving behavior[c]	12–47	29–114	Up to 5.6
Avoiding roof cargo	2–17	5–41	-
Avoiding excess weight	1 per 50 kg	2	-
Auto maintenance[d]	5–6	12-15	3.9
Proper tire pressure	Up to 3	Up to 7	1.2
Low resistance tires	-	-	1.5
Fuel efficient vehicle	-	-	13.5

[a] Source: U.S. Department of Energy: Keeping Your Vehicle in Shape, Online at http://www.fueleconomy.gov/feg/drive.shtml (last accessed on April 17, 2015). Cost savings are calculated for fuel price $2.41/gallon.
[b] Source: Gardner and Stern (2008), data for US households.
[c] Includes slower acceleration, observing speed limits, use of cruise control, and reduced idling.
[d] Includes regular tune ups, air filter changes, and using the recommended grade of motor oil.

be achieved by buying a more efficient vehicle if the driver, additionally, has her vehicle properly maintained, avoids excess weight and roof cargo, and uses low resistance tires. Furthermore, the costs related to these measures are a fraction of the cost of a new car. As a result, exploiting these opportunities makes sense both from an economic perspective and from an environmental point of view, as substantial efficiency gains may be achieved with the current stock of vehicles, resulting in faster gains as well as smaller environmental costs relative to new vehicle production.

To put these potential savings from more efficient vehicle use into a broader perspective, consider that households account for about 28 percent of US energy consumption (38 percent of US CO_2 emissions), and that individual road transport represents about 40 percent of household energy consumption (Bin and Dowlatabadi, 2005; Dietz et al., 2009; Gardner and Stern, 2008; Vandenbergh and Steinemann, 2007). Globally, the road transportation sector was responsible for 16.9 percent of CO_2 emissions from fuel combustion in 2012 (International Energy Agency, 2014). The US contributed 4.5 of those percentage points, and the EU 2.6 (which is more than China and India together). Thus the, intensive margin is not necessarily marginal from either the individual or from the global perspective.

2.3 The model setup

Car pollution, at the individual car level, can be described as a function of three variables: activity, i.e. number of kilometers driven, denoted a; fuel consumption per unit of activity, denoted c; and the monetary value of emissions per combusted unit of fuel measured in euro, denoted e.[14] Denote the car's standardized fuel consumption per kilometer as $\bar{c}$; this is the fuel consumption measured by manufacturers during the testing cycle and is fixed for each car. Then the factor $c/\bar{c}$ is the ratio of that car's actual fuel consumption to its standardized fuel consumption and captures the driver's behavior at the intensive margin; I term it car's relative fuel consumption.

We have already seen in Section 2.1 that e can be decomposed into two parts: (i) The marginal social cost of CO_2 emissions per liter of fuel, denoted e_f, which is fuel-specific, where the fuel type is indexed by f. (ii) The marginal social cost of air pollutants per liter of fuel $e_n/\bar{c}$, where e_n is the marginal social cost of air pollutants per kilometer and is the same for all vehicles produced under a specific norm n. Because $\bar{c}$ varies across cars, the marginal social cost of air pollutants per liter of fuel, $e_n/\bar{c}$, is vehicle-specific.[15]

Since e_f and e_n are defined in monetary units, the value of the total externality, denoted v, produced by a car is

$$v = ace = a\left(ce_f + \frac{c}{\bar{c}}e_n\right) \tag{1}$$

euro. The two terms in parentheses represent the car's emissions per kilometer driven: the first term is the value of CO_2 emissions per kilometer. The second term captures the value of air pollutants per kilometer driven as a function of a car's relative fuel consumption, $c/\bar{c}$. The relative fuel consumption captures individual-level variation in fuel consumption due to variation in driving style, load, number of passengers, etc., which, as a consequence, generates individual-car-level variation in the volume of air pollutants emitted per kilometer. In the special case when the car is driven in a way that matches the testing cycle conditions, the relative consumption is equal to one, and the car's air pollutant emissions per kilometer will match the regulatory limits. But whenever the actual consumption differs from the standardized consumption, the actual air pollutant emissions per kilometer will also differ from those given by emission standards.

2.4 Decision margins

A driver's behavior may affect v through multiple channels, mainly in terms of kilometers driven, driving choices and style, and vehicle choice. The sum of those effects is

[14] That is, e can be thought of as encapsulating the monetary value of all external social costs resulting from burning a liter of fuel in a specific car, this would include health-related and environmental costs born by the current as well as future generations.

[15] The assumption of constant amount of emissions per liter of fuel, for a given vehicle, is consistent with results obtained by Frey et al. (2008b), see their Tables 1 and 2. See also Harrington (1997), Unal et al. (2004), and Van Mierlo et al. (2004).

obtained by differentiating equation (1), which yields

$$
\begin{aligned}
dv = &\left(ce_f + \frac{c}{\bar{c}} e_n\right) da \\
&+ a\left[\left(e_f + \frac{e_n}{\bar{c}}\right) dc + cde_f + \frac{c}{\bar{c}} de_n - \frac{c}{\bar{c}^2} e_n d\bar{c}\right].
\end{aligned} \tag{2}
$$

Note that $d\bar{c}$ as well as de_f and de_n vary only when the driver selects her vehicle; once the driver has chosen her car, both es and $\bar{c}$ are fixed (i.e. $d\bar{c}$ as well as de_f and de_n are equal to zero). To simplify the exposition, we now focus on driving behavior; the problem of vehicle choice will be revisited later. Thus, for a specific vehicle equation (2) simplifies to

$$
dv = \left(e_f + \frac{e_n}{\bar{c}}\right)(cda + adc). \tag{3}
$$

In other words, the amount of CO_2 and air pollutants a car produces is affected by the choice of distance traveled as well as choices that influence the actual fuel consumption per kilometer. Note also that the multiplicative structure of (1) implies that elasticity of v with respect to a is equal to one, which is the same as the elasticity of v with respect to c. This means that the importance of the intensive margin of driving behavior is technically comparable to the importance of the extensive margin.[16]

3 Results

External costs generate a mismatch between the private marginal costs of driving and the social marginal costs of driving. This means that the amount of driving, a, likely exceeds the socially optimal amount and the driving style, $c/\bar{c}$, may be suboptimal, because individual drivers face lower marginal costs of these choices relative to the marginal costs born by the society. An appropriate policy response may be called for to fix this by adjusting drivers' private marginal costs for these external costs born by the society. Although the universe of potential policy interventions may be broader, economists have traditionally focused on correcting the price mechanism by taxing the externalities.[17] The model of tailpipe externalities produced by cars allows us to study and evaluate alternative policies. Here I consider two major alternatives: making drivers pay a tax per kilometer

[16]To see this, take the natural logarithm of equation (1) $\ln(v) = \ln(a) + \ln(c) + \ln(e)$, which after differentiating gives $dv/v = da/a + dc/c$. In other words, the effect of a one-percent change in the distance driven on the total externality produced by a car, keeping all else constant, is the same as a one-percent change in fuel consumption per kilometer. It is puzzling that the two margins have attracted rather different levels of attention both from researchers and in the policy debate.

[17]For an overview see Parry et al. (2007).

traveled, and making drivers pay a tax per liter of fuel; CAFE standards will be briefly revisited later.

3.1 Distance tax

Let p_f be the price of fuel f. Then the private marginal costs of driving an additional kilometer are cp_f, however the social marginal costs are $cp_f + \partial v/\partial a$.[18] We are looking for a kilometer tax, t_k, that equates the private marginal costs of driving and social marginal costs of driving, so formally we have

$$cp_f + t_k = cp_f + c\left(e_f + \frac{e_n}{\bar{c}}\right),$$

which after solving for t_k, of course, yields

$$t_k = c\left(e_f + \frac{e_n}{\bar{c}}\right). \tag{4}$$

Thus, an optimal per-kilometer tax on automobile emissions is a vehicle-specific rate based on each car's actual fuel consumption. More specifically, the optimal distance tax requires five pieces of information: (i) the fuel type f, (ii) the emissions standard n, (iii) standardized fuel consumption $\bar{c}$, (iv) the distance traveled a, and (v) the actual fuel consumption c. A known disadvantage of a distance-based tax is that drivers can roll back their odometers (Fullerton and West, 2002). However, eliciting information about actual fuel consumption may constitute an even greater challenge.

3.2 Fuel tax

An alternative response may be to impose a tax associated with purchasing a unit of fuel. Thus, we are looking for a fuel tax, t_f, which equates the private marginal costs of driving with the social marginal costs of driving, and formally we have

$$c\left(p_f + t_f\right) = cp_f + c\left(e_f + \frac{e_n}{\bar{c}}\right),$$

which after solving for t_f yields

$$t_f = e_f + \frac{e_n}{\bar{c}}. \tag{5}$$

[18] I assume a competitive market for fuel where p_f equals the marginal cost of producing a unit of fuel. This assumption is reasonable for refineries and distributors, but probably not for producers of crude oil, which is the main input in fuel production. Thus, the difference between the prices faced by consumers and the competitive prices serve as a *de facto* tax on fuel consumption; albeit collected by crude oil producers rather than any state. Models of optimal tax on fuel that do not take this into account, which includes the present paper, overestimate the optimal tax.

The result is a vehicle-specific fuel tax, which depends on three parameters: (i) the type of fuel f, (ii) the emissions standard n, and (iii) the standardized fuel consumption c; all of which are public information.

In a more general framework, one may argue that decisions about distance traveled and fuel consumption are made simultaneously. A sensible driving style, for instance, results in lower fuel consumption. This lowers emissions per kilometer, however it also frees up resources that may be used to make an additional trip. It is straightforward to show that t_f from (5) remains an optimal policy response. Dividing equation (3) by dc yields the derivative

$$\frac{dv}{dc} = \left(e_f + \frac{e_n}{\bar{c}}\right)\left(a + c\frac{da}{dc}\right). \tag{6}$$

The private marginal costs of increasing fuel consumption by one liter can be expressed as $[a + c(da/dc)]p_f$, whereas the social marginal costs are $[a + c(da/dc)]p_f + dv/dc$, which after substituting from (6) and rearranging gives $[a + c(da/dc)](p_f + e_f + e_n/\bar{c})$. We are now looking for a fuel consumption tax, t'_f, which would make the private marginal costs equal to the social marginal costs. Formally

$$\left(p_f + t'_f\right)\left(a + c\frac{da}{dc}\right) = \left(p_f + e_f + \frac{e_n}{\bar{c}}\right)\left(a + c\frac{da}{dc}\right),$$

which after solving for t'_f yields again

$$\begin{aligned} t'_f &= e_f + \frac{e_n}{\bar{c}} \\ &= t_f. \end{aligned}$$

Two important properties of this fuel tax need to be highlighted: (i) Newer cars should have a lower tax. (ii) Less intuitively, larger vehicles, that is less fuel efficient ones, should have lower fuel tax, for vehicles produced under the same norm. This can be seen formally when we take partial derivatives of t_f with respect to e_n and $\bar{c}$, which yields

$$\frac{\partial t_f}{\partial e_n} = \frac{1}{\bar{c}}, \qquad \text{and} \tag{7}$$

$$\frac{\partial t_f}{\partial \bar{c}} = -\frac{e_n}{\bar{c}^2}, \tag{8}$$

noting that e_n decreases with the car's manufacturing year. Equation (7) implies that newer cars, that is cars produced under more stringent emission standards, should have a lower optimal fuel tax. Equation (8) implies, that the optimal fuel tax decreases with increases in technical fuel consumption. The reason for both effects is better abatement equipment, resulting in lower pollutant emissions per liter of fuel.[19]

To summarize, the optimal fuel tax given in equation (5) provides drivers the right incentives across both relevant decision margins. It looks relatively simple in design, and requires only public information that is available in each car's documentation (as well as on the Internet). In comparison, the optimal distance based tax given in equation (4) requires additional information about fuel consumption and distance traveled, which is essentially private. As a result, an optimal fuel tax seems much more feasible to implement than an optimal distance tax. Finally, note that the optimal distance tax (4) can be expressed as

$$t_k = ct_f,$$

which suggests that the optimal distance tax is *de facto* a fuel tax.

3.3 Can we persuade people to choose cars efficiently?

This section focuses on the effect of fuel efficiency, $\bar{c}$, on the social costs (and benefits) of buying a car. Let's begin by separately analyzing the effects of change in $\bar{c}$ on CO_2-related costs and on air pollutants-related costs. Later, I discuss the possibility of a tax scheme that would yield incentives to make car choices efficient.

3.3.1 Vehicle choice and CO_2 emissions

Let v_f denote the social costs of driving due to CO_2 emissions, then the effect of vehicle choice on CO_2 emissions can be written as

$$\begin{aligned}\frac{dv_f}{d\bar{c}} &= ce_f\frac{da}{d\bar{c}} + ae_f\frac{dc}{d\bar{c}} + ac\frac{de_f}{d\bar{c}} \\ &= e_f\left(c\frac{da}{d\bar{c}} + a\frac{dc}{d\bar{c}}\right), \qquad (9)\end{aligned}$$

[19]This result will be demonstrated numerically in Section 3.4 below. Note that the effect of a change in $\bar{c}$ on the optimal distance tax, t_k, is ambiguous, as can be seen when differentiating equation (4) with respect to the technical fuel consumption $dt_k/d\bar{c} = (e_f + e_n/\bar{c})(dc/d\bar{c}) - c(e_n/\bar{c}^2)$, and noting that the actual fuel consumption is likely to change in the same direction as $\bar{c}$ (see also Section 3.3.1 below). The numerical results in Section 3.4 suggest that the fuel consumption effect in the derivative dominates the effect of better abatement equipment, so the optimal distance tax should increase with higher fuel consumption.

assuming, for simplicity, ${de_f}/{d\bar{c}} = 0$.[20] The two terms in parentheses represent a total change in fuel consumption associated with a change in standardized fuel consumption.

The first term is the part related to a change in distance driven, $c({da}/{d\bar{c}})$, that is the rebound effect. To the extent that standardized fuel consumption is positively correlated with car size and engine power, it will be positively related to car price. In addition, standardized consumption is probably positively related to actual fuel consumption. Thus the income effect from the higher costs of driving cars with higher standardized consumption will result in fewer kilometers driven and *vice versa*. As a result the sign of the first term in the parentheses should be negative.[21]

The second term in parentheses relates to the change in the actual fuel consumption per kilometer related to a change in standardized consumption, $a({dc}/{d\bar{c}})$, which I call the fuel economy effect. This effect is a counterpart of the rebound effect working through the intensive margin. It should be positive as it is safe to assume that cars with higher standardized consumption are normally driven with higher actual consumption as well and *vice versa*. In addition, driving a vehicle with a high fuel consumption implies high marginal costs of driving and this may induce the driver to drive more carefully, *ceteris paribus*, suggesting ${dc}/{d\bar{c}}$ is generally less than one.[22]

3.3.2 Vehicle choice and air pollutants

The properties of air pollutant-related social costs are slightly more complex. Let v_d denote these costs, then we can write

$$\begin{aligned} \frac{dv_d}{d\bar{c}} &= e_n \frac{c}{\bar{c}} \frac{da}{d\bar{c}} + a \frac{e_n}{\bar{c}} \frac{dc}{d\bar{c}} + a \frac{c}{\bar{c}} \frac{de_n}{d\bar{c}} - a e_n \frac{c}{\bar{c}^2} \frac{d\bar{c}}{d\bar{c}} \\ &= \frac{e_n}{\bar{c}} \left(c \frac{da}{d\bar{c}} + a \frac{dc}{d\bar{c}} \right) - a \frac{c}{\bar{c}} \frac{e_n}{\bar{c}}, \end{aligned} \tag{10}$$

assuming, for simplicity again, ${de_n}/{d\bar{c}} = 0$. The two terms in parentheses have the same interpretation as above, that is the overall change in fuel consumption due to a change in $\bar{c}$. The first term of (10) predicts the change in the value of air pollutant emissions due to a change in the overall consumption. The second, negative, term represents the social benefit

[20]My attention is focused on fuel efficiency, and I abstract from the choice of fuel type as well as the interaction between the two. This affects only the simplicity of the exposition and not the substance or generality of the results. It is straightforward to show that the optimal fuel tax would give individuals incentives to select their fuel type efficiently as well.

[21]The rebound effect is the key parameter disputed in the literature on the efficiency of CAFE standards (Frondel and Vance, 2013; Greene, 2012).

[22]Note, the notion of this fuel economy effect is missing in the standard literature, possibly because it only emerges when the actual fuel consumption is allowed to be a choice variable; essentially ${dc}/{d\bar{c}}$ is implicitly assumed to be equal to one although it is not straightforward that this assumption is justified.

of selecting a car with higher standardized fuel consumption due to its better emission abatement technology. That is, driving a car with higher standardized fuel consumption will, *ceteris paribus*, decrease the quantity of air pollutants emitted per liter of fuel (recall the result 8 in Section 3.2).[23]

3.3.3 Optimal policy

The overall effect of a change in standardized fuel consumption is the sum of the two specific effects given in (9) and (10), so we can write

$$\begin{aligned}\frac{dv}{d\bar{c}} &= \frac{dv_f}{d\bar{c}} + \frac{dv_d}{d\bar{c}} \\ &= e_f\left(c\frac{da}{d\bar{c}} + a\frac{dc}{d\bar{c}}\right) + \frac{e_n}{\bar{c}}\left[c\frac{da}{d\bar{c}} + a\left(\frac{dc}{d\bar{c}} - \frac{c}{\bar{c}}\right)\right] \\ &= \left(e_f + \frac{e_n}{\bar{c}}\right)\left(c\frac{da}{d\bar{c}} + a\frac{dc}{d\bar{c}}\right) - a\frac{c}{\bar{c}}\frac{e_n}{\bar{c}}. \qquad (11)\end{aligned}$$

The product of the two terms in parentheses is the value of change in the overall fuel consumption and the product of the two fractions is the social benefit stemming from more effective air pollutant emissions abatement technology.

Is there a tax policy that would equate the marginal private costs of driving with the social costs of driving and, at the same time, give people incentives to select a vehicle with socially optimal emissions and fuel consumption? Let the total private costs of driving be $ac\left(p_f + t\right)$, where t is a tax policy, then the private marginal costs of choosing a car with higher standardized fuel consumption are

$$\begin{aligned}d\frac{ac\left(p_f + t\right)}{d\bar{c}} &= c\left(p_f + t\right)\frac{da}{d\bar{c}} + a\left(p_f + t\right)\frac{dc}{d\bar{c}} + ac\frac{dt}{d\bar{c}} \\ &= \left(p_f + t\right)\left(c\frac{da}{d\bar{c}} + a\frac{dc}{d\bar{c}}\right) + ac\frac{dt}{d\bar{c}}. \qquad (12)\end{aligned}$$

[23] Observe that this social benefit increases in the actual fuel consumption c.

Substituting t_f from (5) for t in (12) we get

$$
\begin{aligned}
d\frac{ac\left(p_f+t_f\right)}{d\bar{c}} &= \left(p_f+e_f+\frac{e_n}{\bar{c}}\right)\left(c\frac{da}{d\bar{c}}+a\frac{dc}{d\bar{c}}\right)-ac\frac{e_n}{\bar{c}^2} \\
&= \left(e_f+\frac{e_n}{\bar{c}}\right)\left(c\frac{da}{d\bar{c}}+a\frac{dc}{d\bar{c}}\right)-a\frac{c}{\bar{c}}\frac{e_n}{\bar{c}}+p_f\left(c\frac{da}{d\bar{c}}+a\frac{dc}{d\bar{c}}\right) \\
&= \frac{dv}{d\bar{c}}+\left(c\frac{da}{d\bar{c}}+a\frac{dc}{d\bar{c}}\right)p_f, \qquad \text{by equation (11),}
\end{aligned}
$$

which is the social marginal cost of driving a car with higher standardized consumption. In summary, a fuel tax gives appropriate price incentives across all relevant decision margins: distance traveled, driving style, and vehicle selection.

3.3.4 Vehicle choice and CAFE standards

Some analysts have also expressed concerns that policies targeting the between-car intensive margin, $\bar{c}$ in our notation, such as the CAFE standards, may have perverse effects with respect to local air pollution (Khazzoom, 1995; Kleit, 2004). This can be seen in equation (11) where the term in the second parentheses is the change in total fuel consumption induced by a change in technical fuel consumption. The change in total fuel consumption is the sum of the rebound effect, $c\left({}^{da}/_{d\bar{c}}\right)$, and the fuel economy effect, $a\left({}^{dc}/_{d\bar{c}}\right)$. The sign is indeterminate as the expected sign of the rebound effect is negative, while the fuel efficiency effect is positive. The last, negative, term gives the change in pollutant emissions evaluated at the initial level of total fuel consumption. When standards force manufacturers to produce cars with lower technical fuel consumption $\bar{c}$, less effective abatement equipment is needed in those vehicles in order to satisfy the pollution standards.

The prediction of the sign of the overall effect of tightening fuel economy standards is thus not clear. One implication is that to prevent deterioration in the pollution abatement efficiency of new vehicle fleets, tighter CAFE standards need to be accompanied with a tightening of emission standards. Another implication is that those who criticize CAFE policies as ineffective in reducing CO_2 emissions on the grounds of the rebound effect may actually have a strong case, on environmental grounds, as CAFE standards seem to undermine the effectiveness of local pollution limits.

3.4 Calculating optimal distance and fuel taxes on car pollution

Having derived formulas for optimal distance and fuel taxes in Sections 3.1 and 3.2, we can now ask what the tax rates would be. This section presents numerical estimates of optimal rates of distance and fuel taxes, as alternative policies to adjust the private marginal costs of driving to reflect social marginal costs. The optimal rates are estimated using examples of four alternative vehicles ranging from a small Renault Clio with a 1.2 liter engine, through a Volkswagen Golf (1.6 liter), and a Toyota Camry (2.4 liter), to a Ford F-150 with a 4.6 liter engine. The VW Golf and Renault Clio ranked as the first and third bestselling cars in Europe in 2014, respectively. Similarly, the Ford F-150 and Toyota Camry ranked first and third in the US, respectively. Mid-range petrol-engine models from 2007 were selected to approximate typical vehicles on the road in Europe and the US today.

The results are presented in Table 2. The topmost block reports technical fuel consumption figures given by the manufacturers for the three standard modes of driving: highway, city, and combined. The variation in fuel consumption within as well as across cars is substantial. A Renault Clio driven on the highway consumes slightly less than 5 liters per 100 km, whereas a Ford F-150 needs over 18 liters to drive 100 km within the city. For all four cars, fuel consumption in the city is approximately 50 percent higher compared to fuel consumption on the highway.[24] These numbers should provide a picture of the possible variation in on-road fuel economy for these four vehicles.

Block A of Table 2 then reports the quantities of emissions produced by each vehicle at each fuel consumption level. CO_2 emissions are calculated from fuel consumption (one liter of gasoline contains 2.321 kg of CO_2).[25] Emissions of local pollutants are calculated using the per kilometer limits on CO, NO_x, and THC given by the Euro 4 norm, which was valid from 2005 to 2009. These per kilometer limits are used as estimates of pollutant emissions per kilometer when a vehicle's on-road fuel consumption equals its theoretical combined fuel consumption. The quantities of these local pollutant emissions for highway and city were then calculated assuming constant emission rates per liter as in the model.[26] As a result, there is substantial variation in per kilometer pollution emissions across the three driving locations. However, the values of emissions per kilometer are very similar across cars, when comparing highway and city fuel consumption levels, respectively.

Blocks B and C report estimates of optimal distance taxes on vehicle pollution for these vehicles in euros and US dollars (in 2014 prices). The marginal cost of CO_2 is computed using Nordhaus's (2014) estimate of the marginal costs of a ton of CO_2 to be 18.6 US dollars (in 2005 prices), which implies a social cost of 4.76 euro cents per liter (21.84

[24]You may also notice that there are overlaps in the fuel consumption rates at which these cars can be driven. A Clio can be driven with higher consumption than a Golf and perhaps even a Camry. A Golf can be driven with similar consumption to a Camry, which in turn can be driven with a fuel consumption rate comparable to an F-150.

[25]See U.S. Environmental Protection Agency (2005).

[26]See footnote 15 on page 9.

Table 2: Calculating pollution components of distance tax and fuel tax rates for 2007 vehicles with gasoline engines (2014 prices[a])

	Renault Clio 1.2 liter, 65 hp, manual.			Volkswagen Golf 1.6 liter, 102 hp, manual.			Toyota Camry 2.4 liter, 159 hp, automatic.			Ford F-150 4.6 liter, 235 hp, automatic.		
	Highway	Combined	City	Highway	Combined	City	Highway	Combined	City	Highway	Combined	City
Fuel consumption liters per 100 km	4.90	5.90	7.60	5.60	7.20	9.90	7.80	9.90	13.60	13.80	15.70	18.10
	A. Emissions in grams per km[b]											
CO_2	113.76	136.97	176.44	130.01	167.15	229.83	181.08	229.83	315.73	320.37	364.48	420.20
CO	0.83	1.00	1.29	0.78	1.00	1.38	0.79	1.00	1.37	0.88	1.00	1.15
THC	0.08	0.10	0.13	0.08	0.10	0.14	0.08	0.10	0.14	0.09	0.10	0.12
NO_x	0.07	0.08	0.10	0.06	0.08	0.11	0.06	0.08	0.11	0.07	0.08	0.09
	B. Social costs in euro cents per 100 km and the implied optimal distance tax											
CO_2[c]	21.28	25.62	33.01	24.32	31.27	43.00	33.88	43.00	59.07	59.93	68.19	78.61
Local pollution[d]	94.17	113.39	146.06	88.19	113.39	155.91	89.34	113.39	155.77	99.67	113.39	130.73
Distance tax	115.45	139.02	179.07	112.51	144.66	198.91	123.21	156.39	214.84	159.60	181.58	209.33
	C. Social costs in US dollar cents per 100 miles and the implied optimal fuel tax											
CO_2[c]	45.50	54.78	70.57	52.00	66.86	91.93	72.43	91.93	126.28	128.14	145.78	168.07
Local pollution[d]	201.34	242.43	312.29	188.56	242.43	333.35	191.01	242.43	333.04	213.09	242.43	279.49
Distance tax	246.84	297.22	382.86	240.56	309.29	425.27	263.43	334.36	459.32	341.23	388.22	447.56
	D. Social costs in euro cents per liter and the implied optimal distance tax											
CO_2[c]	–	4.34	–	–	4.34	–	–	4.34	–	–	4.34	–
Local pollution[d]	–	19.22	–	–	15.75	–	–	11.45	–	–	7.22	–
Fuel tax	–	23.56	–	–	20.09	–	–	15.80	–	–	11.57	–
	E. Social costs in US dollar cents per gallon and the implied optimal fuel tax											
CO_2[c]	–	21.84	–	–	21.84	–	–	21.84	–	–	21.84	–
Local pollution[d]	–	96.65	–	–	79.20	–	–	57.60	–	–	36.32	–
Fuel tax	–	118.49	–	–	101.04	–	–	79.44	–	–	58.16	–

[a] The 2014 dollars were calculated using the 2014/2005 Consumer Price Index of 1.212 (Bureau of Labor Statistics, CPI Inflation Calculator, Online, at http://www.bls.gov/data/inflation_calculator.htm, last accessed on April 24, 2015). Prices in 2014 euros were obtained using the exchange rage of 1.3285 USD/EUR, the average for 2014 (European Central Bank, Online at https://www.ecb.europa.eu/stats/exchange/eurofxref/html/eurofxref-graph-usd.en.html, last accessed on April 24, 2015).

[b] Emissions of CO, THC, and NO_x are set to be equal to the limits of Euro 4 (valid from 2005 to 2009) when the car fuel consumption is equal to the combined technical fuel consumption. Quantities of these emissions for highway and city were then calculated assuming constant emission rates per liter (which is consistent with per liter emissions at different fuel consumption levels measured by Frey et al., 2008b, see also Harrington, 1997, Unal et al., 2004, and Van Mierlo et al., 2004).

[c] The social costs of CO_2 emissions were estimated using Nordhaus's (2014) estimate of $18.6 as the marginal cost of one ton (= 907.185 kg) of CO_2. One liter of gasoline contains 2.321 kg of CO_2, so the social cost of CO_2 produced by burning one liter of gasoline is estimated at $0.0476 (= 18.6 / 907.185 × 2.321) in 2005 U.S. dollars, see U.S. Environmental Protection Agency (2005).

[d] Local pollution costs were estimated using the estimate of the social cost of local pollution by Parry et al. (2007, p. 384) of 2 cents per mile in 2005 US dollars.

US dollar cents per gallon) of gasoline burned in 2014 prices.[27] The social costs of local pollution were estimated using the estimate of 2 US dollar cents (2005) per vehicle-mile reported in (Parry et al., 2007).[28] Pollution externalities per kilometer are set equal across cars for combined fuel consumption and externalities produced on highway and in a city are calculated assuming constant emission rates per liter. The distance tax capturing the marginal cost of pollution reported in blocks B and C is then the sum of the social costs of CO_2 and local pollution.

The variation in optimal distance tax is substantial. The optimal tax rate for a Ford F-150 driven in a city is estimated at 209 euro cents per 100 km (448 US dollar cents per 100 miles), which is 30 percent more than the tax for the same vehicle when mostly driven on highways. For a Renault Clio, the difference between city and highway optimal distance taxes is over 55 percent, whereas for the Toyota Camry and VW Golf it is 73 and 77 percent, respectively. These numbers illustrate that even though there is no variation in local pollutants per kilometer across cars, the variation within cars is substantial and explains most of the variation in per kilometer optimal fuel tax within cars.

Blocks D and E report estimates of per liter externalities and implied optimal fuel taxes. As predicted by the model, the optimal tax is negatively related to technical fuel consumption per kilometer. Thus the estimated fuel tax for an F-150 is 11.6 euro cents per liter (58.2 US dollar cents per gallon) of petrol, whereas the optimal tax for a Clio is 23.6 euro cents per liter (118.5 US dollar cents per gallon), almost exactly the double. Owners of Camrys and Golfs should be charged 15.8 and 20.9 euro cents per liter (79.4 and 101.4 US dollar cents per gallon), respectively. Of course, an F-150 owner would eventually pay more fuel tax than a Clio owner, because the effect of F-150's lower social costs per liter of fuel, due to better abatement equipment, will be dominated by three times as much fuel consumption, as apparent from panels B and C.

4 Discussion

4.1 Caveats and limitations

Three main criticisms may be made of the approach and results in this paper: (i) Fuel taxes are already too high and an additional tax would harm the economy, especially if unilaterally increased. (ii) A car-specific tax may be too costly to implement. (iii) People may not be fully rational, in particular with respect to the proper valuation of future fuel

[27] See Table 2 for details. Nordhaus's (2014) estimates are higher than his earlier estimate of $12 per ton of CO_2 in Nordhaus (2011) as well as Tol's (2005) recommended upper bound of $13.6 per ton of CO_2 (both in 2005 US dollars).

[28] These values are consistent with the range of estimates recently reported by Litman (2013) and Palma et al. (2013).

savings. (iv) Individuals may not be properly informed or may be unable to change their driving behavior in an economically meaningful way. I now briefly address these concerns.

The analysis does not imply that an additional fuel tax should be imposed on top of existing taxes. Indeed, I suggest that the existing fuel taxes are *de facto* emission taxes, to the extent that they alter the relative prices of driving and put a price on the production of emissions. What the analysis implies is that fuel taxes should be explicitly linked to the social costs of emissions and possibly should be named as such. At the same time, there is substantial variation in fuel taxes across the EU, as apparent from Figure 1; similar variation exists in the US (also see Parry et al., 2007; Sterner, 2007). The analysis in this paper suggests that tax competition in the realm of fuel taxes is unwanted. Thus I believe that the existing EU-wide minimum rates are a good starting point for designing fuel taxes that would price in the emissions. Figure 1 also enables us to compare the optimal tax rates estimated in Table 2 to the existing tax rates. Note, however, that optimal fuel taxes would need to account for other vehicle externalities apart from the pollution components (oil dependence, congestion, and accidents). According to the estimates by (Parry et al., 2007, p. 384), these externalities carry social costs of \$1.80 per gallon (in 2005 USD), which gives 43.4 euro cents per liter of fuel in 2014 prices (229.2 US dollar cents per gallon), hence the implied optimal fuel taxes for Ford F-150 and Renault Clio would be 55.0 and 67.0 euro cents per liter (276.4 and 336.7 US dollar cents per gallon) of petrol, respectively. These estimates must be taken with a pinch of salt; however, the comparison with existing rates in Figure 1 suggests that optimal tax policies are well within the current range of fuel tax rates across the EU. In the US, the current fuel tax on petrol is 42.52 US dollar cents per gallon, which is much less than our estimates of optimal fuel tax, for all four vehicles.

The approach presented here is heavily price-theory oriented and I acknowledge that deficiencies in rationality may bear on the relevance of the results. For instance, short-sighted consumers may inappropriately discount fuel consumption in the long term and thus purchase less efficient cars (Gerard and Lave, 2003; Greene, 2011; Greene et al., 2013). By a similar reasoning, people may undervalue the present value of future savings from more careful driving, which may result in suboptimal driving decisions and irresponsiveness to price incentives. I note that fuel taxes represent shocks to the relative prices of travel, and as such they work not only through substitution effects, but also via income effects. Rationality is not required for the latter to take place (Becker, 1962). Thus, the suggestion that fuel taxes are ineffective due to a lack of consumer rationality, as some have claimed (Fischer et al., 2007; Greene, 2011; Greene et al., 2013), may be incorrect. First, fuel taxes work in the right direction and complement other policies and economic incentives aimed at improving driving behavior, such as driver training, social norms activation, speed limits, on-board driver support systems, and pay-as-you-drive insurance (see e.g. Barkenbus, 2010;

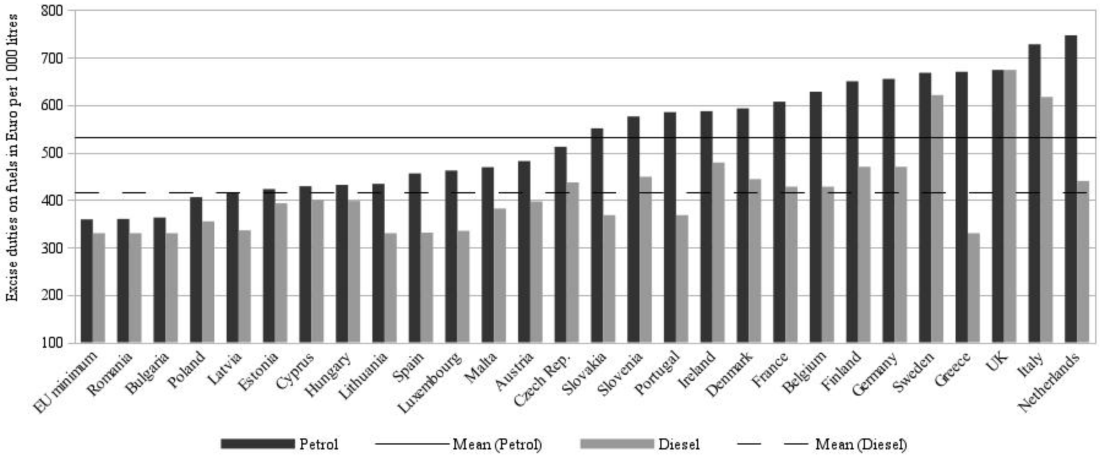

Figure 1: Excise duties of fuels in the EU as of 1 January 2013 (calculations are based on exchange rates from 18 March 2013). Data source: European Comission (2013).

Bolderdijk et al., 2011; Dietz et al., 2009; Onoda, 2009; Thijssen et al., 2014; Vandenbergh and Steinemann, 2007; Wåhlberg, 2007). Second, the lack of responsiveness may not be present in all individuals, and if there is a subpopulation that behaves in accordance with the rational model, fuel taxes would give these people appropriate incentives. Finally, a number of studies shown that people do react to fuel price shocks (e.g. Frondel and Vance, 2009; Frondel et al., 2012; Frondel and Vance, 2013; Goodwin et al., 2004; Grabowski and Morrisey, 2006).

My results suggest that an optimal automobile emissions tax would vary according to fuel type, the emissions standard under which a car was produced, and its technical fuel efficiency, all of which are public-domain information. It is possible to imagine that a fuel tax could be computed at the counter based on this information, which is readily available in each car's technical documentation, and, with today's technology, could be recorded on a credit card, or similar. Even if such a tax was not feasible, a uniform fuel tax would still be a good, even if not optimal, policy. Recall that the optimal fuel tax would, among other things, result in newer and bigger (that is less fuel efficient) cars paying lower tax, as they have more efficient abatement technology (results 7 and 8 in Section 3.2, as well as Table 2 in Section 3.4). If income is negatively correlated with car age and positively correlated with car size, imposing a uniform tax, possibly based on the average characteristics of a vehicle fleet, would result in a redistribution from owners of big cars to owners of small cars and from owners of new cars to owners of old cars. This is because a uniform fuel tax, if set to match the externalities per liter of fuel produced by an average vehicle, would be smaller than the optimal fuel tax for small vehicles and higher than the optimal tax for large cars. In other words, a uniform fuel tax, relative to the optimal fuel tax, redistributes wealth from the rich to the poor. Finally, there are other externalities that may be positively correlated with car size or income, such as oil dependency and congestion (Parry et al., 2007). Taking these externalities into account would then tilt the optimal fuel tax towards a simple uniform fuel tax. [29]

Various authors have noted that fuel efficiency is one of the most saliently communicated parameters of new cars (Crandall, 1992; Kleit, 2004). Analogously, each active driver is probably aware, that the way she drives somehow affects the costs and benefits from getting from A to B, including safety, travel time, and fuel economy. A number of studies have investigated whether individuals' driving habits are amenable to change (Beusen et al., 2009; Barth and Boriboonsomsin, 2009; Gonder et al., 2012; Sato et al., 2010; Takada et al., 2007; Thijssen et al., 2014; Van Mierlo et al., 2004; Wåhlberg, 2007). All of these studies find substantial potential for fuel savings, while those that evaluate long term effects generally find that changes in driving habits can realistically lead to fuel economy savings in the region of 5 to 20 percent (Beusen et al., 2009; Onoda, 2009; Wåhlberg, 2007). True, drivers may not be fully aware about these opportunities, and may even hold wrong beliefs, as argued by Carrico et al. (2009), with respect to the economic benefits and environmental impacts of cold engine idling and restarting the engine. Therefore there is scope for policies aimed at providing drivers with appropriate information and incorporating the principles of efficient driving into driver training (Barkenbus, 2010; Beusen et al., 2009; Onoda, 2009). At the same time, price incentives make this information as well as the implied behavioral changes economically meaningful and should therefore stimulate demand for them.

4.2 Some implications for existing policies

The results presented above lend strong support to a fuel tax as an adequate first-choice policy response to address tailpipe externalities. Fuel taxes are widely used, however, they are not explicitly linked to air pollutants or CO_2 emissions, nor labeled as such.[30] I suggest

[29]Note that, based on the results in Table 2, the opposite argument can be made with respect to a uniform distance tax. Because the optimal distance tax is higher for vehicles with high fuel consumption, a uniform distance tax would be too low for big vehicles and too high for small vehicles, redistributing in the less convenient direction.

Note also, that the vehicle-specificity of the optimal fuel tax is dictated by the fact that pollutant emissions limits are defined on per-kilometer basis. If emissions were regulated on per-liter basis, a simple fuel tax would be optimal in our framework.

[30]For instance, fuel taxes in the EU are harmonized together with excise duties on alcohol and tobacco. The harmonization is implemented through EU-wide minimum rates (European Comission, 2013). Although this tax would be ideal, or close to ideal, for pricing in air pollutants and CO_2-related externalities, the directive only mentions that taxation of energy products is one of the instruments for achieving the Kyoto Protocol objective (European Comission, 2003, par. 7).

a revision of the existing taxes, which would use fuel taxes as a primary tool for addressing car-produced pollution.

At the same time, many countries in Europe impose car registration taxes and annual car taxes based on hypothetical CO_2 emissions, calculated based on the standardized fuel consumption. For instance, out of 27 EU countries, 13 have a one-time car registration tax and 15 have an annual car tax; nine countries have both (European Automobile Manufacturers Association, 2013). These taxes are independent of the actual amount of externalities a car produces, as they depend neither on the distance traveled nor on the actual fuel consumption. As a result, they affect the marginal costs of car ownership, rather than the marginal costs of emitting CO_2 or pollution—once paid, they become a sunk cost and are irrelevant in decisions whether to drive an additional journey, or whether to save on fuel consumption. In addition, while these taxes give people incentives to buy fuel efficient cars, the related savings on fuel, as well as savings on the car tax itself, represent a positive income shock. This may increase the number of kilometers driven and weaken incentives to save on fuel consumption. As a result, at least part of the potential positive effect of these taxes on CO_2 emissions is likely to be lost. These taxes are thus hardly optimal as incentives to curb CO_2 emissions or air pollution.

Finally, some analysts have expressed concerns that the current system of fuel taxes might be abandoned and replaced by alternative instruments (Frondel et al., 2011; Sterner, 2007). The results in this paper indeed call into question some proposed changes in policies aimed at decreasing car pollution, especially CO_2 emissions, through distance-based fees or taxes (Greene, 2011; Proost et al., 2009). This includes the European Commission's goal of replacing car registration taxes with annual vehicle taxes based on hypothetical CO_2 emissions (Kunert and Kuhfeld, 2007). Car registration taxes may make sense if they compensate for consumers' inability to appreciate improvements in fuel economy. However, the existing CO_2-related annual car taxes should be reconsidered and perhaps dropped in exchange for a more intensive use of fuel taxes that are better instruments for producing appropriate incentives for using a socially optimal amount of fuel.

4.3 Implications for existing models and future research

The results in this paper bear implications for previous as well as future research evaluating automobile externalities and policies. In particular, future studies should explicitly consider accounting for the intensive margin of motor vehicle use. Without aspiring to reevaluate the existing literature, the following implications with regard to the relevance of the intensive margin for the interpretation of the results of previous research may be noted: (i) Studies that propose policies not directly linked to fuel use, most prominently distance taxes and CAFE standards, may be overestimating the benefits of these policies if the intensive margin is unaccounted for (Greene, 2011; Proost et al., 2009). More specifically, as discussed in Section 3.3.4, the rebound effect may understate the driver's reaction to price incentives and the reaction to improvements in technical fuel economy, because these may also affect the intensive margin. (ii) Omission of the intensive margin in studies that evaluate the efficacy of fuel taxes may lead to conservative bias in their estimated effect and may result in overestimation of the optimal fuel tax (Austin and Dinan, 2005; Frondel and Vance, 2013; Parry and Small, 2005; Sterner, 2007). (iii) As the intensive margin appears to be significant, assuming it away in models of driver behavior and general equilibrium models may imply that the specification of the optimization problem is incomplete (Fischer et al., 2007; Fullerton and West, 2002; Parry and Small, 2005). The magnitude of the introduced bias is unknown but the implications for policies are likely to be in the directions suggested by the previous two points.

Future research to investigate the implications of the intensive margin in models of individual driver behavior as well as in general equilibrium settings is needed. The model also shows that apart from the rebound effect, the fuel economy effect is an important parameter, which has been overlooked in the previous research and its importance needs to be further ascertained (see Sections 3.3.1 and 3.3.4). Another opportunity for future research is to study automobile externalities and policies when drivers' behavior produces spillovers to other drivers.[31] Note, that these questions arise naturally once attention is given to the intensive margin. These spillover effects have been abstracted from in this study as well as in the cited literature on automobile externalities and policies. Yet, they may interact with alternative policies and carry implications for their relative efficacy.

5 Conclusion and policy implications

This paper revisits the problem of automobile emission-related externalities. It contributes to the existing literature by distinguishing actual fuel consumption from the standardized fuel consumption measured in manufacturer's laboratories, and incorporating the actual fuel consumption as a choice variable that affects the size of externalities produced by individual cars. The actual fuel consumption clearly depends on factors under the driver's control and in turn affects the actual amount of air pollutants emitted per kilometer relative to the limits set by the emissions standards. I show that the economic and environmental importance of this often omitted margin is comparable to the importance of the distance driven. Existing research of driver effects on on-road fuel efficiency also points to substantial savings being available through alterations in driver behavior.

[31] See footnote 3 on page 3.

The primary implication of this paper is that fuel taxes should remain the core instrument for car pollution control. Other policies, such as a car tax, may complement fuel taxes but are not substitutes. In addition, to the extent that fuel consumption is related to driving style, a higher fuel tax gives people incentives to drive more carefully, which carries potential safety and health benefits. That should, in turn, allow the traffic to flow more smoothly, improving the overall efficiency of road travel. Finally, the intensive margin is an attractive policy target, as it may lead to increased fuel efficiency of the currently operated stock of vehicles; that is faster and cheaper than policies forcing technical improvements in fuel economy, such as CAFE standards and vehicle taxes. I conclude that fuel taxes should be more intensively employed as policies dealing with automobile externalities.

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