Does Britain or The United States Have the Right Gasoline Tax?

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Abstract

This paper develops an analytical framework for assessing the second-best optimal level of gasoline taxation taking into account unpriced pollution, congestion, and accident externalities, and interactions with the broader fiscal system. We provide calculations of the optimal taxes for the US and the UK under a wide variety of parameter scenarios, with the gasoline tax substituting for a distorting tax on labor income.

Under our central parameter values, the second-best optimal gasoline tax is \$1.01/gal for the US and \$1.34/gal for the UK. These values are moderately sensitive to alternative parameter assumptions. The congestion externality is the largest component in both nations, and the higher optimal tax for the UK is due mainly to a higher assumed value for marginal congestion cost. Revenue-raising needs, incorporated in a "Ramsey" component, also play a significant role, as do accident externalities and local air pollution.

The current gasoline tax in the UK (\$2.80/gal) is more than twice this estimated optimal level. Potential welfare gains from reducing it are estimated at nearly one-fourth the production cost of gasoline used in the UK. Even larger gains in the UK can be achieved by switching to a tax on vehicle miles with equal revenue yield. For the US, the welfare gains from optimizing the gasoline tax are smaller, but those from switching to an optimal tax on vehicle miles are very large.

1. Introduction

Recent demonstrations in Europe against high fuel prices heightened interest in the appropriate level of gasoline taxation. Excise taxes on fuel vary dramatically across countries: Britain has the highest rate among industrial countries and the United States the lowest (see Figure 1). In Britain the excise tax on gasoline is about \$2.80 per US gallon (50 pence per liter), nearly three times the 2001 wholesale price, while in the United States federal and state taxes together amount to about \$0.40/gal.[1]

The British government has defended high gasoline taxes on three main grounds. First, by penalizing gasoline consumption, such taxes reduce the emissions of both carbon dioxide and local air pollutants. Second, gasoline taxes raise the cost of driving and therefore indirectly reduce traffic congestion and traffic-related accidents. Third, gasoline taxes provide a significant source of government revenue: in the UK, motor fuel revenue is nearly one-fourth as large as the entire revenue from personal

[1] Gasoline is also subject to sales taxation in the United States and value-added taxation in European countries. However these other taxes apply to (most) other goods, and therefore do not increase the price of gasoline relative to other goods.

income taxes (Chennells et al. 2000). This third argument finds an intellectual basis in Ramsey's (1927) insight that taxes for raising revenue should be higher on goods with smaller price elasticities. Gasoline taxes have also been defended on other grounds, such as a user fee for the road network (its primary role in the US) and as a means to reduce dependence on oil supplies from the Middle East.

As these arguments suggest, there are several important externalities associated with driving. Each potentially calls for a corrective Pigovian tax, although the ideal tax for each would be on something other than fuel. Only for carbon dioxide does a fuel tax closely approximate a direct Pigovian tax. For local air pollution, a direct tax on emissions would provide better incentives to improve pollution abatement technologies in vehicles. As for congestion, fuel taxes affect it through reducing total vehicle miles traveled (VMT), whereas peak-period congestion fees would also encourage people to consider avoiding peak hours and the most highly congested routes. An ideal tax to address accident externalities would charge according to miles driven rather than fuel consumed, and would vary across people with different risks of causing accidents.[2]

Nonetheless, ideal externality taxes have not been implemented for political, administrative, or other reasons. They raise objections on equity grounds, they require administrative sophistication, and they run counter to attempts to reduce geographical differences in taxes and insurance rates. The fuel tax, by contrast, is administratively simple and well accepted in principle, even at very high tax rates in some nations. Therefore it is entirely appropriate to consider how externalities that are not directly priced should be taken into account in an assessment of fuel taxes.

As for revenues, there is a well-developed public-finance literature providing a rigorous comparison of the efficiency of different tax instruments for raising revenues. Recently, this literature has been extended to compare externality taxes with labor-based taxes such as the income tax.[3] One of its key insights is that by raising the cost of living, externality taxes have a distorting effect on labor supply similar to that of labor-based taxes. It is now feasible to bring the insights of this literature to bear on a tax, such as the fuel tax, that is partially intended as an imperfect instrument for controlling externalities.

A number of previous studies attempt to quantify the external costs of transportation.[4] Typically these studies estimate external costs per distance traveled rather than per volume of fuel consumed. However the implications for the optimal fuel tax have not been rigorously spelled out; as our formulation

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[2] For further discussion of the efficiency of gasoline taxes at reducing externalities, see Walters (1961), UK Ministry of Transport (1964), De Borger and Proost (2000), Parry (2001) and Fullerton and West (2001).

[3] See for example Bovenberg and van der Ploeg (1994), Bovenberg and Goulder (1996), Parry and Oates (2000).

[4] For example, Lee (1993), US OTA (1994), Peirson et al. (1995), Mayeres et al. (1996), Quinet (1997), ECMT (1998, ch. 3), Porter (1999), Litman (1999), Rothengatter (2000), and various papers in Greene et al. (1997).

makes clear, the importance of distance-based externalities in the optimal fuel tax is substantially diminished to the extent that people respond to higher fuel taxes by purchasing more fuel-efficient vehicles rather than driving them less.[5] It is also important to update prior studies to take account of changes over time in vehicle emissions and safety, the value of travel time, the value of life, and so on.

This paper presents and implements a formula for the second-best optimal gasoline tax that accounts for both externalities and interactions with the tax system. This formula, extending that of Bovenberg and Goulder (1996), disaggregates the optimal fuel tax into components with economic interpretations. We furthermore consider the possibility that gasoline is a relatively weak substitute for leisure, thereby justifying a "Ramsey tax" component, and we incorporate feedback effects on labor supply from changes in congestion. We use our formula to estimate optimal gasoline taxes in the US and UK, focusing on externalities of congestion, air pollution (local and global), and traffic accidents.[6] In this way we illustrate why, and to what extent, the optimal tax may differ across countries, and under what circumstances, if any, the low US rates or the high UK rates can be justified.

We summarize the results as follows.

First, under our benchmark parameter assumptions the optimal gasoline tax in the US is $1.01/gal (more than twice the current rate) and in the UK is $1.34/gal (less than half the current rate). The higher optimal tax for the UK mainly reflects a higher assumed value for marginal congestion costs. Significantly different values are obtained under reasonable alternative parameter scenarios, but a Monte Carlo analysis suggests that it is highly unlikely for either the optimal US tax to be as low as its current value, or the optimal UK tax to be as high as its current value.

Second, the congestion externality is the largest component of the optimal fuel tax. Thus even though fuel taxes are a far from ideal instrument to control congestion, they still need to be significant in the absence of congestion pricing. The Ramsey component is the next most important, followed closely by accidents and local air pollution. Global warming plays a very minor role—ironically since it is the only component for which the fuel tax is (approximately) the right instrument.

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[5] De Borger et al. (1997) and Mayeres (2000) simulate fuel taxes for Belgium. However, both model fuel taxes essentially as taxes on vehicle-kilometers traveled, with limited scope for improvements in fuel efficiency. In contrast, we emphasize the importance of shifts in fuel efficiency for the second-best fuel tax. We also apply our model to two nations, the US and UK, which are more self-contained so we can ignore two phenomena important to Belgium, namely cross-border refueling and exporting of tax burdens.

[6] Virtually all quantitative estimates of external costs of motor vehicles have placed these three at the top of the list, in magnitude far above such other candidates as noise, water pollution, vehicle and tire disposal, policing needs, pavement damage, and security of national petroleum supplies. See Delucchi (1997), US FHWA (1997, pp. III-12 through III-23), and US FHWA (2000a, section entitled "Other Highway-Related Costs" and Table 10). For noise and pavement damage in comparison to other costs, see also De Borger et al. (1997, Table 1).

Third, the optimal gasoline tax is substantially diminished by the fact that only a portion of the tax-induced reduction in gasoline use—less than half in our base case—is due to reduced driving, the rest coming from changes in fuel efficiency. If we had made the mistake of assuming that vehicle miles are proportional to fuel consumption, we would have computed the optimal gasoline tax in both nations to be much higher, close to the current value in the case of the UK.

Fourth, when considered as part of the broader fiscal system, the optimal gasoline tax is only moderately higher than the marginal external cost of gasoline. While it is true that gasoline taxes should be set above marginal external costs because they raise revenue from a relatively price-inelastic good, the Ramsey component turns out to be only about $0.25 per gallon. Furthermore, there is a counteracting influence arising from the inefficiency of using a tax with a relatively narrow base.

Finally, we simulate a tax on vehicle miles, which more directly addresses the distance-related externalities of congestion, accidents, and local pollution (subject to regulations on emissions per mile). The potential welfare gains from this policy are much larger than those from optimizing gasoline-tax rates—nearly four times as large in the case of the US. Furthermore, the optimal tax rate is much higher, more than twice the optimal fuel tax when converted at the fuel efficiency that would obtain in that scenario. As a result, in the UK, most of the available welfare gains could be obtained simply by shifting the current tax from fuel to VMT, with a rate chosen to maintain equal revenues once people had adjusted their vehicle stocks in response. The Ramsey component is more important with a VMT tax because travel, being less elastic than fuel consumption, is a better target for raising revenue.

Our analysis abstracts from some other arguments that have been used to defend high gasoline taxes. These include alleged external costs in connection with road maintenance, parking subsidies, non-optimal urban form, and international political and military policy to secure petroleum supplies. For the most part, attempts to quantify these arguments have resulted in smaller costs than those considered here. For example, Small et al. (1989) show that the road damage from passenger vehicles is minuscule compared to that from heavy vehicles (which are mostly diesel), and that even for heavy vehicles the damage is not closely related to fuel consumption. Delucchi (1998a) has estimated the US external cost of petroleum due to the need for military expenditures to ensure a secure import supply, and gets numbers much smaller than those from congestion, accidents, and air pollution.[7] Nevertheless, there remains room

[7] Using the "military expenditures" line of his Table 7-23, which is $0.6-6.8 billion, and dividing by 1991 highway fuel consumption of 128.6×10^9 gallons, yields $0.005-$0.053 per gallon for 1991. He also considers the strategic petroleum reserve, yielding estimated costs an order of magnitude lower. An alternative higher estimate by Hall (1992), based largely on an autoregressive moving average relationship between oil imports and military expenditures, yields a total cost of US$18 billion in 1985; this amounts to $0.035 per gallon of crude oil consumed in the US in that year, or $0.057/gal in 2000 prices, about the same as our central estimate of global warming cost and well below the other externalities as estimated here.

for legitimate debate about the need for high fuel taxes for reasons that are hard to quantify. We hope that this article, by demonstrating what can and cannot be said based on externalities and revenue-raising needs, will discipline that debate.

The rest of the paper is organized as follows. Section 2 describes our analytical model and a formula for the optimal gasoline tax. Section 3 discusses parameter values. Section 4 presents calculations of the optimal gasoline tax for the US and UK, compares the welfare effects of taxes on gasoline and vehicle miles, and provides an extensive sensitivity analysis. Section 5 briefly comments on the politics of tax reform.

2. Analytical Framework

A. Model Assumptions

Consider a static, closed economy model with a large number of agents. The representative agent has the following utility function:

(2.1) $$U = u(\psi(C, M, T, G), N) - \varphi(P) - \delta(A)$$

All variables are expressed in per capita terms. C is the quantity of a numeraire consumption good, M is amount of travel measured in vehicle-miles, T is time spent driving, G is government spending, N is leisure or non-market time, P is the quantity of (local and global) pollution, and A is severity-adjusted traffic accidents. G, P, and A are characteristics of the individual's environment, perceived as exogenous. We include T in the utility function to allow the opportunity cost of travel time to differ from the opportunity cost of work time. The functions $u(.)$ and $\psi(.)$ are quasi-concave, whereas $\varphi(.)$ and $\delta(.)$ are weakly convex functions representing disutility from pollution and from accident risk.[8]

Vehicle travel (VMT) is "produced" according to the following homogeneous function:

(2.2) $$M = M(F, H)$$

where F is fuel consumption and H is money expenditure on driving. This allows for a tradeoff between vehicle cost and fuel efficiency, e.g. by using computer-controlled combustion or an improved drive train. It thereby allows for a non-proportional relation between gasoline consumption and VMT: in response to

[8] The separability of pollution and accidents in (2.1) rules out the possibility that they could have feedback effects on labor supply. Williams (2000) finds that the impacts on labor supply from pollution-induced health effects have ambiguous, and probably small, effects on the optimal pollution tax. The weak separability of leisure in (2.1) implies that consumption and VMT would increase in the same proportions following an income-compensated increase in the wage. Relaxing this assumption would have the same effect as using a different value for the expenditure elasticity of VMT in the optimal tax formula derived below, and we consider a wide range of values for this parameter in our simulations.

higher gasoline taxes people will buy more fuel-efficient cars (causing an increase in H) in addition to driving less.[9]

Driving time is determined as follows:

(2.3) $T = \pi M = \pi(\overline{M})M$

where π is the inverse of the average travel speed and $\overline{M}$ is aggregate miles driven per capita. We assume $\pi' > 0$, implying that an increase in VMT leads to more congested roads. The notation distinguishing between M and $\overline{M}$ is to remind us that agents take $\overline{M}$ and hence π as fixed—they do not take account of their own impact on congestion.

We distinguish two types of pollutants: those (denoted P_F) like carbon dioxide that depend directly on fuel consumption, and those (denoted P_M) that depend only on miles driven. The latter type includes nitrogen oxides, hydrocarbons, and carbon monoxide, for which regulations force emissions per mile to be uniform across most new vehicles.[10] P_F and P_M are both severity-weighted indices with units chosen so we can combine them as:

(2.4) $P = P_F(\overline{F}) + P_M(\overline{M})$

where $P_F', P_M' > 0$ and $\overline{F}$ is aggregate fuel consumption per capita. Agents ignore the costs of pollution from their own driving since these costs are born by other agents.

The term $\delta(A)$ in (2.1) represents the expected disutility from the *external* cost of traffic accidents. Some accident costs are internalized; for example people presumably consider the risk of injury or death to themselves when deciding how much to drive. These internal costs are implicitly included either in utility function $\psi(.)$ or money costs H. But other costs are external and are counted in $\delta(.)$. Many of these external costs are borne by people in their roles as pedestrians or cyclists,[11] and others are functions of the number of trips rather than their length; so we make the simplifying assumption that this disutility is independent of the amount of the individual's own driving (in contrast to the cost of congestion as specified in equation 2.3). The number of severity-adjusted accidents per capita is thus taken to be exogenous to the individual agent, but dependent on the amount of aggregate driving per capita:

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[9] We limit our analysis to gasoline-powered passenger vehicles and do not consider possible interactions between optimal tax rates for gasoline and diesel fuel. While there are interesting issues regarding relative taxes on these two fuels (Mayeres and Proost 2001a, De Borger 2001), we think they would have only minor affects on the quantitative results derived here.

[10] See ECMT (2000) for a review of current and anticipated emissions standards in Europe, the US, and Japan.

[11] In the US in 1994, 16 percent of fatalities from motor vehicle crashes were to non-motorists (US FHWA 1997, p. III-18).

(2.5) $A = A(\overline{M}) = a(\overline{M})\overline{M}$

where $a(\overline{M})$ is the severity-adjusted accident rate per mile. Note that we also ignore any indirect effects on accident externalities via changes in vehicle size, partly because the direction of such effects is uncertain.[12] The sign of a' is ambiguous: heavier traffic causes more frequent but less severe accidents as people drive closer together but more slowly.

On the production side, we assume that firms are competitive and produce all market goods using labor (and possibly intermediate goods) with constant returns to scale. Therefore all producer prices and the gross wage rate are fixed; since we do not explore policies that would change them, we normalize them all to unity, aside from the producer price of gasoline which we denote q_F.

Government expenditures are financed by taxes at rates t_F on gasoline consumption and t_L on labor income. Therefore the net wage rate is $1-t_L$ and the consumer price of gasoline is q_F+t_F. The government does not directly tax or regulate any of the three externalities, except as implicitly incorporated in the functions $\delta(.)$, $M(.)$, $\pi(.)$, $P_F(.)$, $P_M(.)$, and $a(.)$.[13]

The agent's budget constraint is therefore:

(2.6) $C + (q_F + t_F)F + H = I = (1-t_L)L$

where I is disposable income and L is labor supply. Agents are also subject to a time constraint on labor, leisure, and driving:

(2.7) $L + N + T = \overline{L}$

where $\overline{L}$ is the agent's time endowment. Finally, the government budget constraint is:

(2.8) $t_L L + t_F F = G$.

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[12] Small cars are more dangerous to their own occupants but less dangerous to occupants of other vehicles and to bicyclists and pedestrians. Current evidence seems to suggest partially offsetting effects of changes in composition of the aggregate fleet. A shift from very large passenger vehicles (especially light trucks, minivans, and sport utility vehicles) to moderate sized vehicles decreases the aggregate average severity of accidents, while a shift from moderate to very small vehicles increases it (Charles Lave, personal communication; see also Gayer, 2001).

[13] For example, requirements for reformulated gasoline and bumper effectiveness reduce pollution and accident costs, but also increase the money costs of driving and therefore affect $M(.)$ as well as $P_F(.)$, $P_M(.)$, and $a(.)$. We assume that fuel-efficiency standards are not binding rate; this is reasonable because even with regulated new-car technology, people may alter fuel efficiency through their choices of vehicle mix, driving habits, and maintenance practices. Rouwendal (1996, Table 3) finds that the fuel efficiency for using a specific given vehicle responds to fuel price with an elasticity of 0.15, not even counting for shifts among different vehicles. If such standards are binding at low tax rates, but not at optimal ones, our welfare calculations are affected but not the optimal tax calculations.

We take government spending as exogenous so that higher gasoline tax revenues reduce the need to raise revenues from other sources.[14]

B. Optimal Gasoline Tax

We now discuss the welfare effect of an incremental increase in the gasoline tax. This leads to our formula for the optimal gasoline tax, written in terms of concepts known from the optimal tax literature. We go straight to the key equations, but provide a rigorous derivation of these equations in the Appendix.

(i) Marginal Welfare Effects. In the Appendix we describe conditions for individual households to maximize utility. Differentiating household utility with respect to the gasoline tax, while taking into account changes in the labor tax required to keep the government budget balanced, we obtain:

$$\frac{1}{\lambda}\frac{dV}{dt_F} = \left(E^{P_F} - t_F\right)\left(-\frac{dF}{dt_F}\right) + \left(E^C + E^A + E^{P_M}\right)\left(-\frac{dM}{dt_F}\right) + t_L\frac{dL}{dt_F} \qquad (2.9)$$

where V is indirect utility, λ is the marginal utility of income and

$$E^{P_F} = \varphi' P_F' / \lambda\,; \quad E^{P_M} = \varphi' P_M' / \lambda\,; \quad E^C = v\pi' M\,; \quad E^A = \delta' A' / \lambda\,; \quad v \equiv 1 - t_L - u_T / \lambda\,. \qquad (2.10)$$

Equation (2.9) shows the marginal welfare change from increasing the fuel tax, decomposed into three effects. The first is the welfare change in the gasoline market. This equals the reduction in gasoline consumption times the difference between the direct marginal pollution damage from fuel combustion, denoted E^{P_F}, and the tax rate. The second is the welfare gain from the reduction in VMT. This equals the reduction in VMT times the sum of the (marginal) per-mile external costs of congestion (E^C), accidents (E^A), and mileage-related pollutants (E^{P_M}).[15] The third effect, i.e. the last term in (2.9), is the welfare effect in the labor market. It equals the change in labor supply (which is negative) times the wedge between the gross and net wage, that is, the wedge between the value of marginal product of labor and the marginal opportunity cost of forgone leisure time.

Another way to view (2.9) is by grouping the two terms containing tax rates. Then the welfare change from an incremental tax increase is seen as the effect of induced behavioral changes on total tax revenue less total externality cost.

[14] If instead gasoline-tax revenues financed additional public spending, the optimal gasoline tax would be higher (lower) than that calculated here to the extent that the social value of additional public spending were greater (less) than the social value of using extra revenue to cut distortionary income taxes.

[15] All external costs are in per capita terms. v denotes the opportunity cost of travel time.

(ii) Optimal Gasoline Tax. Setting (2.9) to zero yields, after some manipulation, the following formula (see Appendix):

$$(2.11)\quad t_F^* = \overbrace{\frac{MEC_F}{1+MEB_L}}^{\substack{\textit{Adjusted}\\ \textit{Pigovian tax}}} + \overbrace{\frac{(1-\eta_{MI})\varepsilon_{LL}^c}{\eta_{FF}}\frac{t_L(q_F+t_F)}{1-t_L}}^{\substack{\textit{Ramsey}\\ \textit{tax}}} + \overbrace{\frac{\beta}{\alpha_{FM}}E^C\left\{\varepsilon_{LL}-(1-\eta_{MI})\varepsilon_{LL}^c\right\}\frac{t_L}{1-t_L}}^{\substack{\textit{Congestion}\\ \textit{feedback}}}$$

where

$$(2.12a)\quad MEC_F \equiv E^{P_F} + (\beta/\alpha_{FM})(E^C + E^A + E^{P_M});$$

$$(2.12b)\quad \beta \equiv \frac{dM/dt_F}{dF/dt_F}\frac{F}{M} = \frac{\eta_{MF}}{\eta_{FF}}; \qquad \eta_{FF} = \eta_{MF} + \eta_{FF}^{\overline{M}}; \qquad \alpha_{FM} \equiv F/M;$$

$$MEB_L \equiv \frac{-t_L\dfrac{\partial L}{\partial t_L}}{L + t_L\dfrac{\partial L}{\partial t_L}} = \frac{\dfrac{t_L}{1-t_L}\varepsilon_{LL}}{1-\dfrac{t_L}{1-t_L}\varepsilon_{LL}}.$$

In these formulas, η_{MI} is the expenditure elasticity of demand for VMT (i.e. the elasticity with respect to disposable income), $1/\alpha_{FM}$ is fuel efficiency or miles per gallon, η_{FF} is the negative of the gasoline demand elasticity, η_{FM} is the negative of the elasticity of VMT with respect to the consumer fuel price, $\eta_{FF}^{\overline{M}}$ is the elasticity of fuel efficiency with respect to the price of fuel (i.e. the negative of the gasoline demand elasticity with VMT held constant), and ε_{LL} and ε_{LL}^c are the uncompensated and compensated labor supply elasticities. (We have defined all elasticities as positive numbers.)

Both α_{FM} and t_L in these formulas are endogenous. Since α_{FM} is a function of t_F (see Appendix), we approximate this function by a constant-elasticity formula:

$$(2.12c)\quad \alpha_{FM} = \alpha_{FM}^0\left(\frac{q_F+t_F}{q_F+t_F^0}\right)^{-\eta_{FF}^{\overline{M}}}.$$

Finally, t_L is determined by budget constraint (2.8), which may be rewritten:

$$(2.12d)\quad t_L = \alpha_G - \frac{t_F}{q_F}\alpha_F$$

where $\alpha_G = G/L$ and $\alpha_F = q_F F/L$ are the shares of government spending and gasoline production in national output.

Equation (2.11) expresses the optimal fuel tax as a sum of three components. In interpreting it, let us start with the quasi-Pigovian tax represented by MEC_F. We may think of this as the marginal external cost of fuel use. It equals the marginal damage from pollution due directly to gasoline combustion, plus the marginal congestion, accident, and distance-related pollution costs; the latter are expressed per unit distance traveled and then multiplied first by fuel efficiency (*M/F*) and then by the portion of the gasoline demand elasticity due to reduced VMT (β). If fuel efficiency were fixed, i.e. if all the response to fuel price worked through the amount of driving, then we would have $\eta_{MF} = \eta_{FF}$ and $\beta = 1$. But in fact $\eta_{MF} < \eta_{FF}$, so $\beta < 1$. This point is important because, as we shall see, empirical studies suggest that probably $\beta<0.5$, i.e. less than half of the long-run price responsiveness of gasoline consumption is due to changes in the amount of driving. Therefore the common practice of multiplying estimates of the marginal distance-related external costs by fuel efficiency—i.e. setting $\beta=1$ in (2.12a)—substantially overestimates the appropriate contribution to the optimal fuel tax.[16]

This dilution of the externalities in calculating the optimal tax arises because the quasi-Pigovian tax MEC_F addresses mileage-related externalities only indirectly. The endogeneity of fuel efficiency intervenes between the external cost and the tax instrument. To put it differently: what matters for the optimal tax is not the external costs generated while consuming a gallon of fuel, but rather the external costs generated in the process of increasing fuel consumption by a gallon as a result of tax incentives. The former is simply *M/F* times the external cost per mile, whereas the latter is reduced by the ratio η_{MF}/η_{FF}.

Even with MEC_F correctly computed, the optimal gasoline tax in (2.11) differs from it due to three effects arising from interactions with the tax system. The first effect is that MEC_F is divided by $(1+MEB_L)$.[17] This adjustment reflects the fact that gasoline taxes have a narrow base relative to labor taxes, and in this respect are less efficient at raising revenues; it has been discussed elsewhere in the context of other externalities (e.g., Bovenberg and van der Ploeg 1994, Bovenberg and Goulder 1996).

The second effect is the Ramsey tax component in (2.11). It follows from Deaton (1981) that when leisure is weakly separable in utility, as it is here, travel is a relatively weak (strong) substitute for leisure if the expenditure elasticity for VMT is less (greater) than one. Thus, leaving aside the other two terms in (2.11), gasoline should be taxed or subsidized depending on whether travel is a relatively weak

[16] For example, Newbery (1995) says of mileage-related externalities in the UK: "If we allow *all* external road costs to be reflected in fuel taxes [by multiplying them by fuel efficiency], then [their size] suggests that doubling the tax would be justified" (p. 1267). He immediately qualifies this assertion by noting that "fuel taxes are a relatively blunt instrument to achieve efficiency in transport use." This qualification suggests correctly that raising the fuel tax may be inferior to a more comprehensive tax reform; but in fact our results show that the suggested tax is not even second-best efficient because it ignores the loss of desired impact via changes in the fuel efficiency of vehicles.

[17] MEB_L equals the welfare cost in the labor market from an incremental increase in t_L, divided by the marginal revenue. It is positive provided that $\varepsilon_{LL} > 0$ and that t_L and ε_{LL} are not so large as to make the marginal revenue negative.

or strong substitute for leisure—the more so the more inelastic is its demand relative to the compensated demand for leisure. This is a familiar result from the theory of optimal commodity taxes (Sandmo 1976).

The third effect, indicated by the last term in (2.11), is the positive feedback effect of reduced congestion on labor supply in a world where labor supply is distorted by the labor tax (cf. Parry and Bento 2000). Reduced congestion reduces the full price of travel relative to leisure (see Appendix); hence it leads to a substitution out of leisure into travel, which is welfare-improving because labor is taxed. This raises the optimal fuel tax, but only slightly according to our empirical results in Section 4.

Equation (2.11) is not yet a fully computational formula for the second-best optimal tax rate because t_F appears on both sides of the equation, being both explicitly in the Ramsey component and implicitly in the other components on the right-hand side via (2.12c-d). However, the system of equations (2.11)-(2.12) can be solved numerically for t_F, given values for the various parameters. A remaining issue is that the observed values for these parameters apply to the existing equilibrium (with non-optimal gasoline taxes) whereas (2.11) depends on the values of these parameters at the social optimum. To infer the appropriate values we simply assume that elasticities are constant, and use observed data directly in the formulas.

(iii) Total Welfare Effects and External Costs. We show in the Appendix that the per capita welfare benefits of an incremental tax change, as given in (2.9), can be rewritten as:

(2.13a) $$\frac{1}{\lambda}\frac{dV}{dt_F} = \left(1 + MEB_L\right)\left(-\frac{dF}{dt_F}\right)\left(t_F^* - t_F\right).$$

It is convenient to express the welfare change as a proportion of initial fuel production costs:

(2.13b) $$\frac{1}{q_F F^0}\left(\frac{1}{\lambda}\frac{dV}{dt_F}\right) = \left(1 + MEB_L\right)\left\{\frac{\eta_{FF}}{q_F(q_F + t_F)}\frac{F}{F^0}\right\}\left(t_F^* - t_F\right)$$

where F^0 is initial per capita fuel consumption. Starting with a current tax rate, we can numerically integrate (2.13b) to obtain the approximate welfare gain from moving to an optimal tax rate, as a fraction of production costs.[18]

As a matter of interest, we also compute the total external cost, which is just the sum of fuel- and mileage-related external cost. Since we will be interested only in how it changes over relatively small differences in consumption, we write it as though the marginal externality parameters (E^C, E^A, and so forth) were constant; this of course is highly implausible when fuel consumption and VMT are reduced all

[18] In doing so, we take F to depend on fuel price (q_F+t_F) with constant elasticity -η_{FF}. We do the same with α_F in (2.12d), ignoring any tiny difference between its elasticity and that of F.

the way to zero. Expressed as a faction of initial fuel production costs, total external cost calculated this way is:

$$\text{(2.14)} \qquad \frac{EC}{q_F F^0} = \frac{1}{q_F} \frac{F}{F^0} \left[E^{P_F} + \frac{1}{\alpha_{FM}} \left(E^C + E^A + E^{P_M} \right) \right]$$

(v) VMT Tax. With minor modification, our framework can be used to compute the welfare effects of a VMT tax, i.e. a tax on travel distance denominated in cents per vehicle-mile. This requires the observation that a VMT tax does not affect fuel efficiency; therefore travel and fuel change in the same proportions as the tax rate is varied. We show formally in the appendix that our equations can simulate a VMT tax simply by setting β=1 (so that $\eta_{FF} = \eta_{MF}$) and by holding η_{MF} at the same value as used in the fuel-tax calculations.[19]

The VMT tax has two advantages over the fuel tax. First, because most externalities are mileage-related, the Pigovian part of the tax gets at the externalities more directly. Second, the elasticity η_{FF} is smaller because of fewer substitution possibilities, so the revenue-raising function of the tax is more efficient. Both advantages result in a higher optimal tax rate per vehicle-mile than is the case for the fuel tax, as is easily seen by setting β=1 and decreasing the value of η_{FF} in (2.11).

3. Parameter Values

In this section we choose parameter values for simulations. Because we are more interested in obtaining plausible magnitudes than definitive results, we are free with approximations. For most parameters, we specify a central value and a plausible range, intended as roughly a 90% confidence interval. Table 1 summarizes the parameter assumptions.

We would like any parameter differences across nations to reflect differences in conditions rather than in assumptions. Therefore, where possible, we adjust US and UK studies for cross-national comparability and state them approximately in US$ at year-2000 price levels; we do this by updating each nation's figures as appropriate, then applying the end-2000 exchange rates of UK£1 =US$1.40 and ECU1= US$0.90.

[19] More specifically, here is how we simulate the effects of replacing the fuel tax by a VMT tax at some given rate, which we denote by $t_F^v \alpha_{FM}$. We first reduce the fuel-tax rate to zero, using (2.12c) to calculate the new value for fuel efficiency and integrating (2.13b) to calculate the welfare change. We then use (2.11) to calculate the optimal fuel-equivalent VMT tax rate, t_F^{v*} (i.e. the optimal VMT tax rate times fuel efficiency). In this calculation we set β=1, η_{MF} equal to its previous value, $\eta_{FF} = \eta_{MF}$, and α_{FM} to its zero-fuel-tax value. This value of t_F^{v*} is needed for the final step, which is to integrate (2.13b) while increasing the VMT tax to the desired given rate, again with the changes just mentioned. The total welfare change is the sum of the two integration steps.

Initial fuel efficiency: $1/\alpha^0_{FM}$ *(miles/gal).* Data for the late 1990s show average fuel efficiency at 20 miles/gal for US passenger cars and other 2-axle 4-tire vehicles. For the UK, the comparable figure is 30 miles/gal.[20]

Pollution damages, distance-related: E^{P_M} *(cents/mile).* Because most regulations specify maximum emissions per mile, we assume all costs of local (i.e. troposhperic) air pollution from motor vehicles are proportional to distance traveled. Quinet (1997) reviews the literature from Europe. McCubbin and Delucchi (1999) describe a comprehensive study for the United States, which for urban areas agrees reasonably well with Small and Kazimi's (1995) study of the Los Angeles region. Delucchi (2000) reviews evidence on a wider variety of environmental costs from motor vehicles, but finds air pollution to be by far the most important. The US studies suggest that costs of local pollution from motor vehicles are roughly 0.4-5.4 cents/mile for automobiles typical of the year-2000 fleet.[21] In reviewing these and other studies, the authors of US FHWA (2000a) choose a middle value that comes to 1.9 cents/mile at year-2000 prices, with low and high values of 1.4 and 16.2, respectively.[22] European studies give similar if slightly smaller results, and the differences are very likely due more to different assumptions than to different conditions.[23] We therefore use the same values for both countries, namely a central value of 2.0 cents/mile with range 0.4-10.0.

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[20] The US figure averages 1998 and 1999 data from US FHWA (2000b, table VM-1). The UK figure is for petrol-powered 4-wheeled cars, averaging 1997 and 1999 data from UK DOE (2000, table 2.4).

[21] The cost estimates are dominated by health costs, especially willingness to pay to reduce mortality risk. For US-wide estimates McCubbin and Delucchi (1999, Table 4, row 1) give a range 0.58–7.71 cents per vehicle-mile for light-duty vehicles in 1990; updating to 2000 prices gives 0.8–10.8 cents. For the mix of light-duty vehicles operating in the Los Angeles region in 1992, Small and Kazimi (1995) provide a central estimate of 3.3 cents per vehicle-mile at 1992 prices, or 4 cents per mile in year 2000; however meteorological conditions for pollution formation are much worse in Los Angeles than on average for the US. All these estimates are based on vehicles in use in the early 1990s. Small and Kazimi (Table 8) estimate costs from the California light-duty vehicle fleet projected for 2000 to be about half those from the 1992 fleet, due to improved controls, so we multiply the above estimates by one-half in quoting them in the text.

[22] This is calculated by separating out all gasoline vehicles from US FHWA (2000a, Table 12), for whom the central estimate for year 2000 costs in 1990 prices is 1.42 cents/mile (the VMT-weighted average of the three classes of vehicles shown); multiplying by 1.31, the 2000-to-1990 ratio of the consumer price index for all urban consumers (obtained from US Bureau of Labor Statistics at http://stats.bls.gov/cpihome.htm); and applying the ratios of low-to-middle and high-to-middle total air-pollution costs from US FHWA (2000a, Table 10). The FHWA estimates are drawn from a study by the US Environmental Protection Agency (EPA), except they are adjusted downward to reflect the FHWA's preferred 1990 "value of statistical life" of $2.7 million, which is lower than the value of $4.8 million used by EPA.

[23] For the European estimates, we obtain a range of 0.37-2.7 cents/mile from Quinet's Table A.1, after deleting extreme high and low estimates and multiplying the results from the early 1990s by 1.35 to adjust for UK inflation.

Pollution damages, fuel-related: E^{P_F} *(cents/gallon)*. Global warming costs are much more speculative due to the long time period involved, uncertainties about atmospheric dynamics, and inability to forecast adaptive technologies that may be in place a half-century or more from now. Tol et al. (2000) review the estimates and conclude that (p. 199): "it is questionable to assume that the marginal damage costs exceed $50 /tC" (metric ton carbon). In fact, nearly all the evidence reviewed by Tol et al. suggests values considerably lower than this upper bound. Fankhauser (1994), using a Monte Carlo technique to capture uncertainty, suggests an expected damage in the early 1990s of $20/tC, or as high as $33/tC if catastrophic events are given positive probability. The review by ECMT (1998, p. 70) cites estimates ranging from $2-$10/tC. Nordhaus (1994) and Cline (1990) give mid-range values that average to $4.2/tC in year-2000 prices, while Nordhaus's low estimate is $0.7/tC. Azar and Sterner (1996) arrive at much higher estimates, $260-590/tC, but using less conventional methods.[24] A European Union research project known as QUITS suggests an intermediate range of US$66-170/tC (Rothengatter, 2000, p. 108).

Given this evidence and the great uncertainty, we take the central value to be $25/tC with range $0.7-100. This is equivalent to a central value for E^{P_F} of 6 cents/gal, with range 0.2-24.[25] These values are small in comparison to local pollution. They do not account for the possibility that for political or institutional reasons it may be desirable to adopt measures early in order to provide flexibility in responding to future scientific findings.

External congestion cost: E^C *(cents/mile).* Congestion is a sharply nonlinear phenomenon, and highly variable across times and locations. Therefore the marginal congestion cost averaged over an entire nation depends crucially on the proportion of its traffic that occurs in high-density areas at peak times.

A number of studies estimate congestion costs for individual cities, but few attempt an average over a nation. One good one is Newbery (1990) for the UK. He estimates the marginal external cost of congestion averaged across 11 road classes at 3.4pence/km, or around 10-12 US cents/mile after updating

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A study by ECMT (1998, Table 78) estimates this cost at ECU 0.0084/km, or 1.2 US cents/mile, for the UK. As for emissions per mile standards, a definitive comparison is impossible because they are constantly changing and in the US they vary by state; but a review of Appendices A and B of ECMT (2000) shows that they are similar in magnitude.

[24] For example, they assume the subjective rate of time preference is zero. They also apply distributional weights to income losses in rich and poor nations which are equal to one for rich nations and more than one for poor nations, thereby effectively capturing a pure transfer benefit from spending today in rich nations in order to help poor nations in the future.

[25] The conversion rate of 413 gal/tC is based on US National Research Council (2001), p. 5-5.

to 2000.[26] By way of comparison, Mayeres (2000, Table 5) and Mayeres and Proost (2001a) obtain marginal congestion costs for Belgium equivalent to around 12 cents per mile.

For the US, Delucchi (1997) estimates 1990 external congestion costs from private vehicles at 1.3-5.6 cents per vehicle-mile (in 2000 prices), with a geometric mean of 2.5 cents.[27] The US Federal Highway Administration (FHWA), in its Highway Cost Allocation Study, estimates marginal external congestion costs for autos, pickups, and vans at 5.0 cents/mile, with range 1.2-14.8.[28]

These VMT-weighted averages need to be adjusted for our purposes because the congestion cost enters our formula multiplied by the sensitivity to gasoline price (see equation 2.14), but that sensitivity is greater under congested conditions.[29] This is because more work trips occur during peak periods and also because, through self-selection, more trips taking place under congested conditions are of high value to the user. What we require is an average weighted not only by VMT but by fuel-price elasticity.[30] Adjusting the estimates just described for this would lower the marginal cost in both countries, but more so in the UK than the US; so it also reduces the gap between their marginal congestion costs. Another factor that argues for a smaller gap is that some of the differences among studies of the two nations are probably due to different assumptions. Still, it is entirely reasonable that marginal external congestion costs are somewhat higher in the UK than the US, because the UK has a much higher overall population density and a higher proportion of its population lives in cities.[31]

[26] Scaling up Newbery's estimate by wage inflation (about 64% in UK manufacturing between 2000 and 1990, per International Labour Organization 2000, table 5A, p. 894) gives about 12.5 cents/mile. Wardman (2001) suggests that the opportunity cost of travel time increases by wage growth to the power 0.5, which instead would yield 9.6 cents per mile. We do not adjust for increased congestion over time, because some or all of that increase is offset by people moving to less-congested regions (Gordon and Richardson, 1994).

[27] This calculation is from Delucchi's Table 1-A4 (p. 57), and assumes that travel is two-thirds "daily travel" and one-third "long trips", with average vehicle occupancy 1.3. This yields a range of 0.75 to 3.26 cents per passenger-mile in 1990. We update by the factor 1.32 for inflation between 1990 and 2000.

[28] Calculated from US FHWA 1997, Table V-23, using VMT weights 0.73 for automobiles and 0.27 for pickups and vans (from US FHWA 1997, Table ES-1) and updating from 1994 to 2000 prices by the consumer price index for all urban consumers (factor of 1.16). The low, middle, and high FHWA estimates assume values of congested travel time of \$7.18, \$14.36, and \$21.54 per vehicle-hour in 2000 prices (FHWA 1997, Table III-11, updated by inflation factor 1.16), and also differ in that the amount of delay caused by an average vehicle is halved in the low estimate, and doubled in the high estimate, compared to the middle estimate.

[29] For example, Mayeres and Proost (2001b, table 4) report that trips on uncongested roads are three times as price-sensitive as peak-period trips.

[30] In a richer model distinguishing among many classes of roads and times of day, each class would contribute a term like $E^C \cdot (-dM/dt_F)$ in (2.9). Adding these terms together would be equivalent to creating a weighted average value for the external cost, E^C, weighting each class of traffic by its fuel-price-sensitivity.

[31] For example, one-sixth of the UK population lives in London, where street congestion is notoriously bad. Mohring (1999) estimates that the average peak-period marginal external cost for roads in the Minneapolis area is 18

With these factors in mind, we adopt central values of 3.5 cents/mile and 7 cents/mile for the marginal congestion cost averaged across the US and UK respectively. We consider ranges of 1.5-9.0 cents/mile for the US and 3-15 cents/mile for the UK.

External accident cost: E^A *(cents/mile).* Several researchers have found that the total costs of motor vehicle accidents are quite large, comparable to time costs (Newbery 1988, Small 1992). However, accident rates have declined significantly since the studies of the 1980s. Furthermore, the majority of these costs are not external. Drivers presumably take into account the risks to themselves and probably to other family members in the car. Traffic laws provide for penalties, which drivers may perceive as costs that they incur on an expected basis. And some studies have suggested that the sign of a' in equation (2.15), relating severity-adjusted accident rates to total travel, and some studies have suggested that a' is negative because accidents are so much less severe with slower traffic.[32] All these factors tend to make the accident externalities much smaller than the average accident costs estimated a decade ago.

Taking these considerations into account, Delucchi (1997) estimates the marginal external cost E^A for all motor vehicles for the US in 1991 at 1.4-9.8 cents/mile in 2000 prices.[33] The US Federal Highway Administration estimates E^A for autos, pickups, and vans, which we again update to 2000 prices to get 2.3 cents/mile with range 1.3-7.2 cents/mile.[34] For the UK, Newbery (1988) estimates E^A for cars and taxis at values that convert to 7.8-11.4 cents/mile in US currency at 2000 prices.[35] While the US and UK

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cents/mile in 1990 while Newbery's estimate for urban peak-period travel is 51 cents/mile for 1990, suggesting that urban congestion is more severe in the UK than in the US. Moreover, Newbery's table suggests that about two-thirds of UK travel was urban, whereas it is about 60% for the US (US FHWA 1991, Table VM-2).

[32] Fridstrøm and Ingebrigtsen (1991) and Fridstrøm (1999) provide such evidence. For more discussion of these issues, see Newbery (1990), Delucchi (1998b), and Small and Gomez-Ibanez (1999). Note that even if insurance were charged on a per mile basis, the social costs of driving would still exceed the private costs. In particular, insurance companies do not pay the full value of a statistical life for fatalities.

[33] We have added the low and high totals in Delucchi's Table 1-8 (monetary externalities) to those in his Table 1-9A (non-monetary externalities), and divided by VMT from his Table 1-A5, obtaining 1.1-7.8 cents/mile in 1991. The US inflation factor from 1991 to 2000 is 1.26.

[34] US FHWA (1997). We have taken the VMT-weighted average of "automobiles" and "pickups and vans" for all highways, from Table V-24, and inflated by the factor 1.16 to put in year-2000 prices. The FHWA estimates are derived from calculations in Urban Institute (1991). The middle and high estimates include uncompensated costs of pain and suffering, but only the high estimate includes costs paid by insurance companies; see US FHWA (1997), p. III-18.

[35] Newbery's range, corrected for a transcription error, is 2.0-2.9 pence/km (1984 costs at 1986 prices). The stated upper range in Newbery's article is 4.9 rather than 2.9, but this is due to an error in copying a column of figures for "externality costs" from one table to another in his working paper, Newbery (1987). We have updated by the factor 1.74 for inflation, an approximation for the UK consumer price index as given by International Monetary Fund (2000). We then multiply by conversion factors 1.4 cents/pence and 1.61 miles/km. From Newbery's Table 3 it is

estimates might seem rather far apart, they are really not when two adjustments are made: for value of life and for changes in accident rates since the studies were performed.

Our preferred values for a statistical life are derived from a meta-analysis by Miller (2000) and are \$4.8 and \$3.2 million for the US and UK, respectively.[36] For a range, we multiply by 0.5 for the low end and 1.5 for the high end. We adjust the corresponding values of statistical life assumed by the above three studies (stated in US\$ at 2000 prices) to these preferred values. When we do this, we find that the two US estimates are adjusted only modestly. However, the UK estimate is reduced very substantially at the low end and slightly at the high end; this is because Newbery used a single value of life that was US\$5.5 million in 2000 prices, substantially higher than our preferred value for the UK and slightly higher even than our high estimate for the UK.[37]

Next, we adjust for the fact that fatality and injury rates have fallen dramatically in both nations. We assume half of E^A is directly proportional to the fatality rate and half to the injury rate. In the US, these two rates fell on average by 21 percent since 1991 and by 6 percent just since 1994; in the UK they fell by 52 percent since 1986. Adjusting the studies by these factors gives the following ranges, all in year-2000 US cents per vehicle-mile: Delucchi 1.0-8.3; FHWA 1.9-6.4 (middle 2.7) Newbery 1.1-4.7. (By way of comparison, Mayeres 2000 and Mayeres and Proost 2001a use estimates of around 3.0-4.5 cents/mile for Belgium.)

Based on these ranges, we take 3.0 and 2.4 cents/mile as the central estimates for the US and UK, respectively.[38] In each case, we divide the central estimate by 2.5 to get the low estimate, and multiply by 2.5 for the high estimate.

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apparent that virtually all the costs in the low estimate are deaths and injuries to pedestrians, whereas those in the high estimate also include one-fourth of the costs of fatalities and injuries incurred by motorists.

[36] Miller compiles 68 credible studies from 13 developed nations and uses regression analysis to relate their results to real gross national product (GNP) per capita and to several control variables. The resulting values are found to be nearly proportional to GNP per capita, having an elasticity of 0.96. Furthermore, the regression results permit an adjustment for various differences in study methodologies, and therefore a set of consistent predictions of value of statistical life for any developed nation. In 1995 US\$, Miller's predicted values of statistical life are \$3.67 million for the US and \$2.75 million for the UK. Inflating to 2000 price levels and adjusting for changes in real GNP per capita (with 0.96 elasticity), yields the values stated in the text.

[37] In making the adjustments, we assume the US estimates apply to half the costs, but the UK estimates apply to all the costs. This procedure is based on the assumption that the value of injury prevention is proportional to value of statistical life, and on the fact that half the US but all the UK estimate reflects deaths and injuries (the rest being mainly property damage). The resulting adjustment factors are: Delucchi low estimate 0.975, high 1.07; FHWA low 1.54, middle 1.26, high 0.95; Newbery low 0.29, high 0.87.

[38] We have deliberately chosen the ratio of these estimates to be 0.8 from the following consideration. The two main differences between the US and UK affecting E^A are: (a) the UK has about two-thirds as high a willingness to pay for reduction in injury and death, based on Miller's study; and (b) the fatality rate in the UK is about 79 percent of that in the US, whereas injury rates are about the same. (This latter statement is based on 1998 rates, which are 1.58 and 1.25 per 10^8 vehicle-miles in US and UK, respectively, for fatalities, and 117 and 122 for injuries. Source:

Gasoline price elasticities, η_{FF} *and* η_{MF} . Reviews of the many time-series and cross-sectional studies of demand for gasoline conducted before 1990 generally find price elasticities between 0.5 and 1.1.[39] However, more recent studies often find values about half as large, with a best estimate proposed by US DOE (1996) of 0.38.[40] We adopt a compromise value for η_{FF} that is somewhat closer to the recent estimates, namely 0.55, with a range 0.3 to 0.9.

Studies of the response of total vehicle travel to fuel prices typically get much lower long-run elasticities, mostly ranging from 0.1 to 0.3 but sometimes larger.[41] These numbers would suggest a ratio $\beta \equiv \eta_{MF} / \eta_{FF}$ around 0.25 to 0.5. When the same study is used to measure both elasticities, the ratio tends to vary between 0.2 and 0.6.[42] Based on this information, we choose a central value for β of 0.4, and a range of 0.2 to 0.6. This central value is close to the recommendations of Johansson and Schipper (1997) and by US DOE (1996).[43]

Our central values for η_{FF} and β imply that the elasticity of VMT with respect to fuel price, η_{MF}, is 0.22. This quantity is crucial for the analysis of the VMT tax.

Expenditure elasticity of demand for VMT, η_{MI} . This is for practical purposes the same thing as an income elasticity. It is important in calculating the Ramsey component of the optimal tax rate in (2.16).

Economic Commission for Europe 2000, pp. 18, 122, and US FHWA 2000b, Table VM-1.) Assuming that fatalities account for one-fourth of the external costs, and injuries another one-fourth, and that other external costs are proportional to injury rates, this suggests that E^A in the UK and the US have the ratio 0.25x(2/3)x0.79 + 0.25x(2/3)x1.0 + 0.5x1.0 = 0.80.

[39] Dahl and Sterner 1991, Table 2; Goodwin 1992, Table 1.

[40] The differences occur mainly because the more recent studies better control for some or all of three confounding factors: (a) corporate fuel economy standards that were binding on some but not all manufacturers, (b) correlation among vehicle use, vehicle age, and fuel economy, and (c) geographical correlation between fuel price and other variable costs of driving such as parking fees. See the discussion in US DOE (1996), pp. 5-13 through 5-15 and 5-82 through 5-87. The "best estimate" quoted is that in the first row of numbers in Table 5-2. One recent study producing a higher estimate, albeit on Canadian rather than US or British data, is Yatchew and No (2001), who suggest the long-run elasticity is 0.9.

[41] Goodwin (1992), Table 2; Greene et al. (1999), pp. 6-10; US DOE (1996), pp. 5-83 to 5-87.

[42] The VMT-portion of the gasoline demand elasticity in four studies reviewed by Schimek (1996), including his own, was 59%, 57%, 24%, and 19%, for an average of 40%.

[43] The Johansson-Schipper best value is [1-(0.4/0.7)]=0.43, from their pp. 289-290. The US DOE best value is 0.46, calculated from the top row in US DOE (1996), Table 5-2; that row decomposes a long-run price elasticity of 0.376 into a fuel efficiency component (0.200) and a vehicle-travel component (0.176).

Estimates are typically between about 0.35 and 0.8, although a few estimates exceed unity.[44] We might expect the income elasticity to be a little higher in the UK because there is more room for vehicle ownership to grow, and more room for mode shifts to and from public transport. We set the central value for income elasticity at 0.6 for the US and 0.8 for the UK. For a range, we choose plus or minus half the central value.

Labor market and other parameters. The remaining parameters are less important. There is a large literature on labor supply elasticities for the US.[45] Based on this literature, we adopt the same values for supply elasticities in both countries: for the uncompensated elasticity ε_{LL} a central value of 0.2 with range 0.1-0.3, and for the compensated elasticity ε^{c}_{LL} a central value of 0.35 and a range 0.25-0.50. These elasticities reflect both participation and hours worked decisions, averaged across males and females. (Since most of the labor supply-response is in fact due to changes in participation, the relevant labor-tax rate t_L is primarily the average rather than the marginal rate, which provides some justification for our assumption of a proportional labor tax.)

We assume that the ratio of total government spending to GDP (α_G) is 0.35 for the US and 0.45 for the UK, based on summing average labor and consumption tax rates in Mendoza et al. (1994). For the range we add plus or minus 0.05.

For the producer price of gasoline (q_F) we use \$0.94/gal and \$1.01/gal for the US and UK respectively.[46] For the range, we add plus or minus \$0.50/gal, which is 2.7 standard deviations of the weekly retail prices for the US (keeping in mind that some of that variation is due to tax changes). Initial gasoline tax rates are taken from Figure 1 (rounding off slightly) at \$0.40/gal for the US and \$2.80/gal for the UK. Finally, we assume production shares α_F of 0.012 for the US and 0.009 for the UK, based on shares of gross domestic product spent on motor gasoline.[47]

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[44] Based on Pickrell and Schimek (1997), and Pickrell (personal communication).

[45] See, for example, Blundell and MacCurdy (1999) for a review of both US and UK studies, and also Fuchs et al. (1998).

[46] Both UK and US prices are provided by the US Energy Information Administration weekly from 1996 through early June of 2001 (see www.eia.doe.gov/emeu/international/gas1.html). The retail price for premium gasoline, including tax, averaged over this period was US\$1.42/gal in US and US\$3.93/gal in UK. We subtract \$0.10/gallon, which is about half the difference between premium and regular prices in the US, and we subtract the taxes shown in Figure 1 to obtain the producer prices.

[47] For the US, the share is based on 1999 consumption of motor gasoline of $3.06\text{x}10^9$ barrels (US Energy Information Administration 2000, Table 5.11), net-of-tax gasoline price of \$(1.25-0.38) per gallon (average of premium unleaded 95RON and 91RON), and gross domestic product of $\$9.30\text{x}10^{12}$. For UK, it is based on 1998 consumption of 511,000 barrels per day (source: US Energy Information Agency (2001), Table 3.5) at net price

4. Empirical Results

A. Benchmark Calculations

(i) Optimal Tax Rates. Table 2 gives the components of the second-best optimal gasoline tax t_F^* under our central parameters. The total is $1.01/gal for the US, more than twice the current rate, and $1.34/gal for the UK, less half the current rate. Thus, according to these estimates, there is justification for the tax rate being higher in the UK than in the US but the current size of the difference is unjustified. The difference between the two countries in the optimal tax rate is due primarily to the higher assumed congestion costs for the UK.

These results are 9-22 percent above the marginal external cost MEC_F shown in the second row, which would be the optimal tax rate in the absence of labor-market distortions. The three interactions with the tax system that causes the optimal tax rate to differ from this amount are relatively modest in size and partially offsetting. For the UK, where the marginal excess burden of labor taxation is higher due to the higher average income-tax rate,[48] the narrow base of the gasoline tax relative to the labor tax shaves $0.19 from MEC_F in reaching the "adjusted Pigovian tax;" but the Ramsey component adds back $0.23 and the congestion-feedback effect another $0.07. For the US, the narrow base subtracts only $0.09, but the Ramsey component adds $0.26.

These results for t_F^* are far below the "naïve" computation typically proposed in the literature. That value, here denoted MEC_F^1, is MEC_F as computed from (2.12a) but with β=1 and with fuel economy held at its initial value. Our calculation of MEC_F^1 is shown in the last row of the table. It is especially high in the UK because the mileage-related externalities in MEC_F^1 are multiplied by initial rather than optimal fuel economy, and in the UK they are substantially different (30 versus 25.6 miles per gallon).

Of the three externalities included in MEC_F, congestion is easily the largest component in the UK but only slightly larger than accidents and air pollution in the US. The global warming component is small, and is the smallest of the four externalities even if we were to triple our central estimate of global warming costs.

(2.57-1.73) pounds per gallon (average of premium leaded and premium unleaded gasoline) and gross domestic product of $747\text{x}10^9$ pounds. Source for prices: International Energy Agency (2000), pp. 286, 277.

[48] In our case the marginal excess burden depends only on uncompensated labor supply elasticities, which are fairly small. For other purposes, for example when the extra revenue is used to finance transfer spending, the marginal excess burden would be much larger because it would depend in part on the compensated labor supply elasticity. See Snow and Warren (1996) for more discussion.

(ii) Welfare Effects. Table 3 shows the welfare effects, relative to the current situation, of several tax rates including the second-best optimum t_F^* and the "naïve" value just described. Raising the US tax from its current rate ($0.40/gal) to t_F^* ($1.01/gal) would induce a welfare gain equal to 7.4 percent of pre-tax fuel expenditures. Raising it to the "naïve" rate ($1.76/gal), by contrast, would overshoot the optimal rate so much as to yield very little net benefit. For the UK, the welfare gain from reducing the current tax ($2.80/gal) to the optimal ($1.34/gal) would produce substantial gains, nearly one-fourth of pretax gasoline expenditures, while increasing the tax to the "naïve" rate of $3.43 would create a welfare *loss* of nearly 18 percent of pretax expenditures.

Table 4 shows results for a VMT tax. Results are computed at four different tax rates: (a) the initial fuel-tax rate converted to a per-mile basis using initial fuel efficiency; (b) the VMT rate that raises the same revenue as did the original fuel tax;[49] (c) a pure Pigovian tax equal to the "naïve" fuel-tax rate described above, converted similarly to a per-mile basis using initial fuel efficiency; and (d) the optimal VMT tax rate. The welfare change is the net gain from reducing the gas tax from t_F^0 to zero then increasing the VMT tax from zero to the rate shown.

Comparing these welfare changes with those in Table 3, we see that the VMT tax can achieve much greater gains than a fuel tax in the US, and moderately greater gains in the UK. Furthermore, the optimal VMT tax is very high, around 15 cents per vehicle-mile; it brings in 150 percent more revenue than the optimal fuel tax in the US and 70 percent more in the UK (not shown in the table).

Several other observations about VMT taxes are noteworthy. First, in the UK, just converting the current fuel tax to an equal-revenue VMT tax achieves substantial benefits—more than one-fifth of current fuel expenditures and more than the welfare gain from cutting the fuel tax from $2.80/gal to its optimal rate of $1.34/gal. Second, it happens that the current tax burden on driving in the UK is only seven percent lower than the amount that would be optimal if it were levied on VMT instead of fuel. Third, the pure Pigovian ("naïve") VMT tax achieves most of the benefits of the optimal VMT tax. Fourth, a breakdown of the optimal VMT tax into the three components listed in equation (2.11) reveals that the Ramsey component is quite large: 42 percent of the optimal rate in the US and 31 percent in the UK. This is because the VMT elasticity with respect to fuel cost is quite small, 0.22 in our base calculations, making VMT a more attractive target than fuel for a Ramsey tax.

[49] That rate is $t_F^0 \alpha_{FM}$. The revenue from either the fuel tax or the VMT tax is $t_F F$ in our notation. Since fuel use under either tax is given by $F = F^0[(q_F + t_F)/(q_F + t_F^0)]^{-\varepsilon_{FF}}$, where F^0 is initial fuel use, F is identical to F^0 under either the fuel tax at rate t_F^0 or the VMT tax at rate $t_F^0 \alpha_{FM}$.

Finally, Table 5 shows how the optimal gasoline tax and the resulting total external costs vary with government revenue requirements, which effectively means how they vary with the labor-tax distortion. In each country, as government revenue requirement α_G is increased, the adjusted Pigovian tax decreases but so does the total externality damage, calculated from (2.14). This confirms for our model a finding of Metcalf (2000) for a simpler model, [50] and reinforces Metcalf's point that increasing the labor-tax distortion does not necessarily make it optimal to put up with greater externality damage.

B. Sensitivity Analysis

How sensitive are the results in Table 2 to variations in parameters within the ranges we have suggested are plausible? We explore this question in several ways.

(i) Varying Parameters Individually. First, we vary each of the six most important parameters one at a time, holding all others at their central values. The results are shown in Figure 2. The upper and lower curves in each panel show the calculated UK and US optimal tax rates, and 'X' denotes the optimal tax in the benchmark case (that in Table 2). The range covered by each curve is that shown in Table 1 for that parameter and nation.

In most cases, optimal tax rates vary by around US$0.50-$1.00/gal as we cover the reasonable range of each parameter. Results are more sensitive to congestion costs, due to their dominance in the optimal tax calculation. Results in the UK are also especially sensitive to the VMT portion of the price-elasticity of gasoline consumption, β, because it multiplies all the mileage-related externalities.

Results are not very sensitive to the labor tax rate, labor supply elasticity, fuel-related pollution damage, or producer price of gasoline, which when varied individually across their ranges change the result by up to only about plus or minus 5 cents/gal (these results are not shown in the figure).

[50] In Metcalf's model, this occurs because as the labor tax is increased in response to greater revenue requirements, the substitution of dirty for clean goods caused by lowering the adjusted Pigovian tax (due to the term $1+MEB_L$ in its denominator) is more than offset by substitution of leisure for consumption of the dirty good.

(ii) High and Low Scenarios for the Optimal Tax. Table 6 shows what magnitude of external costs might justify given low or high values for the optimal gasoline tax, assuming particular values for the VMT portion of the gasoline demand elasticity β. In constructing these scenarios, all four external cost components of MEC_F in equation (2.12) are scaled up or down by the same proportion relative to their central case values. Each entry in the table is the required value of these external cost components as a fraction of their corresponding benchmark values in Table 2.

Table 6 shows, for example, that in order for the current US tax rate of \$0.40/gal to be optimal, we would have to assume values for all external costs that are only 33% of those in our central case when $\beta = 0.4$, or between 23% and 61% of the central case values when β lies between 0.2 and 0.6. For the UK, with $\beta = 0.4$ the current tax of \$2.80/gal would be optimal if all external costs were 1.88 times their benchmark values, while a tax of only \$1.00/gal would be optimal if all external costs were 24% below their benchmark values.

(iii) Monte Carlo Analysis. Clearly, a wide range of outcomes is possible under alternative parameter scenarios. To give a sense of how likely different outcomes might be, given our parameter ranges, we perform some simple Monte Carlo simulations. We focus on an approximation for the optimal tax rate (which does not require solving simultaneous equations) when external costs and the VMT portion of the gasoline demand elasticity are uncertain. For each country we draw those parameters randomly and independently 1000 times from selected distributions and for each draw we calculate the optimal gasoline tax t_F^*. This calculation uses (2.11)-(2.12), but in (2.12) and on the right-hand side of (2.11) it uses the values for α_{FM}, t_L, and t_F from our benchmark case in Table 2. We then compute the distribution of t_F^* across the 1000 draws.[51]

Table 7 shows the resulting frequencies with which the (approximate) optimal tax is less than a given value. Here we see that for the US, the probability that the optimal tax is less than the current tax of \$0.40/gal is only 0.01, and the probability that it is below \$1.00 is 0.58. For the UK, marginal external costs are below the current tax of \$2.80/gal with probability .98, and below \$1.50 with probability 0.68.

[51] For all external costs we fit gamma distributions with means equal to our central values and with 5% and 95% percentiles roughly equal to the minimum and maximum values for these parameters specified in Table 1. For the VMT fraction of the gasoline price-elasticity, we assume a uniform distribution over the parameter range. We experimented with other distributions but the results were only modestly affected. As discussed above, the optimal gasoline tax is far more sensitive to these parameters than the other parameters in the optimal tax formula. Therefore, the results would probably be similar if we had done a much more complex Monte Carlo analysis with all the uncertain parameters in Table 1 drawn from distributions and with the optimal tax computed numerically for each draw.

5. Conclusion

Policy toward gasoline taxation can be assessed most effectively within a framework that explicitly incorporates revenue needs and the existence of other distorting taxes. Such a framework makes clear, among other things, how far from optimal would be a tax calculated simply by multiplying per-mile external costs by average fuel efficiency. A primary reason is that people can partially evade such an externality tax by increasing fuel efficiency.

Our best assessment is that the optimal gasoline tax for the US is more than double its current rate, while that for the UK is less than half its current rate. Paradoxically, the prospects are remote for substantial change in the direction of optimality in either nation, given current political factors. In the US, the Clinton Administration achieved an increase in the federal gasoline tax rate of only 4 cents/gal in 1993, despite a major effort. In the UK, the Conservative Party's 2001 election pledge to cut gasoline taxes by 6 pence/liter (32 US cents/gal) failed to resonate with an electorate concerned about global warming and the funding of public services.

Both countries could do a lot better by addressing the external costs of driving, which are substantial, with other instruments. On that score there are some limited grounds for optimism, for example the experiments with "value pricing" in California and Texas and the plans for cordon pricing in London. But it will be a long time before these types of policies could become widespread.

However, our results also reveal the attractiveness of a less drastic change, namely a tax on vehicle-miles. Such a tax is considerably more efficient than a tax on fuel, even though it falls short of a true externality tax. For the US, achieving benefits from such a shift would still require greatly increasing the tax burden on motorists, which may be politically untenable. But for the UK, more could be gained in welfare simply from swapping gasoline taxes for mileage taxes, *even with no change in the overall burden of taxation on driving*, than from reducing the gasoline tax to its optimal level. The analytical framework described here enhances our ability both to analyze such a shift and to explain its advantages.

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Appendix: Analytical Derivations for Section 2

A. Definitions

For the analytical derivations we define the following terms:

(A1) $I = (1-t_L)L$; $\eta_{MI} = \dfrac{\partial M}{\partial I}\dfrac{I}{M}$; $\varepsilon_{LL} = -\dfrac{\partial L}{\partial t_L}\dfrac{(1-t_L)}{L}$; $\varepsilon^{c}_{LL} = -\dfrac{\partial L^c}{\partial t_L}\dfrac{(1-t_L)}{L}$;

$$\eta_{LI} = \frac{\partial L}{\partial I}\frac{I}{L}; \quad \eta_{FF} = -\frac{dF}{dt_F}\frac{p_F}{F}; \quad \eta_{MF} = -\frac{dM}{dt_F}\frac{p_F}{M}; \quad \eta^{\overline{M}}_{FF} = -\left.\frac{dF}{dt_F}\right|_{M=\overline{M}}\frac{p_F}{F};$$

$$\theta_{FI} = \frac{(p_F)F}{I}; \; p_F = q_F + t_F$$

B. Deriving (2.9)

Using (2.1)-(2.3), (2.6) and (2.7), the household's utility maximization problem can be expressed as:

(B1) $$V(t_F, t_L, P, A, \pi) = \underset{C,M,N,F,H}{Max} \quad u(\psi(C, M, \pi M, G), N) - \varphi(P) - \delta(A) + \mu\{M(F,H) - M\}$$
$$+\lambda\{(1-t_L)(\overline{L} - N - \pi M) - C - (q_F + t_F)F - H\}$$

where λ and μ are Lagrange multipliers and V(.) is the indirect utility function. (We have suppressed as arguments of V those parameters that are held constant throughout our simulation, namely q_F and G.) The first-order conditions can be expressed, after using Euler's theorem ($M = M_F F + M_H H$):

(B2a) $$\frac{u_C}{\lambda} = 1; \qquad \frac{u_N}{\lambda} = 1 - t_L; \qquad \frac{u_M}{\lambda} = p_M$$

where

(B2b) $$p_M \equiv (q_F + t_F)\alpha_{FM} + \alpha_{HM} + \nu\pi; \quad \alpha_{FM} \equiv F/M; \quad \alpha_{HM} \equiv H/M; \quad \nu \equiv 1 - t_L - u_T/\lambda$$

Households equate the marginal benefit of driving (in dollars), u_M/λ, with p_M, the "full" price of driving. The latter includes fuel used per mile (α_{FM}), other market inputs per mile (α_{HM}), and time per mile (π), all multiplied by their respective prices. Note that the "price" of time, v, is less than the net wage ($1-t_L$) if the marginal utility of travel time, u_T, is positive. The equality of marginal utility u_M/λ and full price p_M holds due to the envelope theorem, even though p_M is endogenous to the individual consumer.

Because of the homogeneity property of M(.), the input ratios for producing travel are functions only of prices, which are all constant except for the fuel tax rate. Therefore we can write the input ratios as $\alpha_{FM}(t_F)$ and $\alpha_{HM}(t_F)$. In practice, we simplify by specifying $\alpha_{FM}(t_F)$ as a simple empirical function rather than deriving it from the full model. Using (B2a) and (2.6)-(2.7), we can then obtain the demand functions in a conventional manner, writing them as

(B3 a) $C = C(p_M, t_L)$; $M = M(p_M, t_L)$; $L = L(p_M, t_L)$;

$F = F(t_F, \pi, t_L) = \alpha_{FM}(t_F)M(p_M, t_L)$; $H = H(t_F, \pi, t_L) = \alpha_{HM}(t_F)M(p_M, t_L)$

The full price of driving depends on all the exogenous variables:

(B3b) $p_M = p_M(t_F, \pi, t_L)$.

Partially differentiating (B1), we can eliminate terms using (B2), the first-order conditions for *F* and *H*, and the Euler equation for *M*(.); we then obtain:

(B4) $\frac{\partial V}{\partial t_F} = -\lambda F$; $\frac{\partial V}{\partial t_L} = -\lambda L$; $\frac{\partial V}{\partial P} = -\varphi'(P)$; $\frac{\partial V}{\partial A} = -\delta'(A)$; $\frac{\partial V}{\partial \pi} = -\lambda v M$

Totally differentiating (2.8) while holding *G* constant gives:

(B5) $$\frac{dt_L}{dt_F} = -\frac{F + t_F \frac{dF}{dt_F} + t_L \frac{dL}{dt_F}}{L}$$

This is the balanced budget reduction in the labor tax from an incremental increase in the gasoline tax. The welfare effect of an incremental increase in the gasoline tax is found by using (B4) to write the total derivative dV/dt_F, while taking into account the budget constraint via (B5) and the externalities via (2.3)-(2.5). Because this is a normative analysis, the aggregates $\overline{F}$ and $\overline{M}$ are variables in this calculation, and are set equal to *F* and *M*. The result is (2.9).

C. Deriving (2.11) and (2.12)

To determine the optimal tax t_F^*, we will set (2.9) to zero. But before that, we write its components in terms of empirically measurable elasticities.

First, consider the last term in (2.9). Substituting (B3b) into (B3a), we can write *L* as a function of t_F, π, and t_L. Differentiating totally as t_F changes:

(C1) $$\frac{dL}{dt_F} = \frac{\partial L}{\partial t_F} + \frac{\partial L}{\partial \pi}\frac{d\pi}{dt_F} + \frac{\partial L}{\partial t_L}\frac{dt_L}{dt_F}$$

Substituting (C1) into (B5) and solving for dt_L/dt_F yields an alternative expression for the balanced-budget change in labor tax rate:

(C2) $$\frac{dt_L}{dt_F} = -\frac{F + t_F \frac{dF}{dt_F} + t_L\left(\frac{\partial L}{\partial t_F} + \frac{\partial L}{\partial \pi}\frac{d\pi}{dt_F}\right)}{L + t_L \frac{\partial L}{\partial t_L}}$$

Substituting (C2) into (C1) and multiplying by t_L yields:

(C3) $$t_L \frac{dL}{dt_F} = MEB_L \cdot t_F \frac{dF}{dt_F} - \frac{MEB_L}{\partial L / \partial t_L} \left\{ \frac{\partial L}{\partial t_F} L - \frac{\partial L}{\partial t_L} F + L \frac{\partial L}{\partial \pi} \frac{d\pi}{dt_F} \right\}$$

where MEB_L is defined in (2.12b).

We now consider the term in brackets in (C3). Using (B2b) and (B3a), and the chain rule for differentiating $\pi(M)$:

(C4) $$\frac{\partial L}{\partial t_F} = \frac{\partial L}{\partial p_M} \alpha_{FM}\,; \qquad \frac{\partial L}{\partial \pi} = \frac{\partial L}{\partial p_M} q\,; \qquad \frac{d\pi}{dt_F} = \pi' \frac{dM}{dt_F}$$

From the Slutsky equations applied to the demand functions in (B3a):

(C5) $$\frac{\partial L}{\partial p_M} = \frac{\partial L^c}{\partial p_M} - \frac{\partial L}{\partial I} M\,; \; \frac{\partial L}{\partial t_L} = \frac{\partial L^c}{\partial t_L} - \frac{\partial L}{\partial I} L$$

where superscript c denotes a compensated coefficient. From the Slutsky symmetry property for goods in the utility function:

(C6) $$\frac{\partial L^c}{\partial p_M} = \frac{\partial M^c}{\partial t_L}$$

Leisure is weakly separable in our utility function. Therefore when its price changes due to a change in t_L, the resulting changes in the demands for consumption and for travel occur only through a change in disposable income (Layard and Walters 1978, p. 166). Therefore:

(C7) $$\frac{\partial M^c}{\partial t_L} = \frac{\partial M}{\partial I} (1 - t_L) \frac{\partial L^c}{\partial t_L}$$

where $(1 - t_L)\partial L^c / \partial t_L$ is the change in disposable income following a compensated increase in the labor tax. Using (C4)-(C7) and the definitions of I, η_{MI} and E^C from (A1) and (2.10):

(C8) $$\frac{\partial L}{\partial t_F} L - \frac{\partial L}{\partial t_L} F = F \frac{\partial L^c}{\partial t_L} (\eta_{MI} - 1)\,; \qquad L \frac{\partial L}{\partial \pi} \frac{d\pi}{dt_F} = \left\{ \eta_{MI} \frac{\partial L^c}{\partial t_L} - \frac{\partial L}{\partial I} L \right\} E^C \frac{dM}{dt_F}$$

Substituting (C8) in (C3), using the definitions of ε_{LL}, ε^c_{LL} and η_{LI} in (A1), and using the Slutsky equation $\varepsilon_{LL} = \varepsilon^c_{LL} + \eta_{LI}$ gives:

(C9) $$t_L \frac{dL}{dt_F} = MEB_L \cdot t_F \frac{dF}{dt_F} - \frac{MEB_L}{\varepsilon_{LL}} \left\{ \varepsilon^c_{LL} F (\eta_{MI} - 1) + E^C \frac{dM}{dt_F} \left\{ \varepsilon_{LL} - (1 - \eta_{MI}) \varepsilon^c_{LL} \right\} \right\}$$

Using (C9) we can now equate (2.9) to zero. Dividing through by dF / dt_F, and using the definition of η_{FF} in (A1) and MEB_L in (2.12b), we obtain (2.11).

Finally, using (B1):

(C10) $$\frac{dF}{dt_F} = \frac{F}{M}\frac{dM}{dt_F} + M\alpha'_{FM}$$

Multiplying through by $(q_F + t_F)/F$, and using $\alpha'_{FM} = (dF/dt_F|_{\overline{M}})/\overline{M}$, we obtain the decomposition for η_{FF} in (2.12b).

D. Deriving (2.13)

First, use the definitions of η_{FF}, η_{MF}, and MEC_F to write (2.9) as:

(D1) $$\frac{1}{\lambda}\frac{dV}{dt_F} = \left(MEC_F - t_F\right)\left(\frac{F\eta_{FF}}{p_F}\right) + t_L\frac{dL}{dt_F}$$

where $p_F \equiv q_F + t_F$. Next, substitute (C9) for the last term, regroup terms, and factor out $(F\eta_{FF}/p_F)$ to get

(D2) $$\frac{1}{\lambda}\frac{dV}{dt_F} = \left(\frac{F\eta_{FF}}{p_F}\right)\left[MEC_F - t_F(1 + MEB_L)\right]$$
$$+\left(\frac{F\eta_{FF}}{p_F}\right)\frac{\tau_L}{1-\tau_L\varepsilon_{LL}}\left[\frac{(1-\eta_{MI})\varepsilon^C_{LL}\tau_L p_F}{\eta_{FF}} - \frac{\beta}{\alpha_{FM}}E^C\left\{\varepsilon_{LL} - (1-\eta_{MI})\varepsilon^C_{LL}\right\}\tau_L\right]$$

where $\tau_L \equiv t_L/(1-t_L)$. From (2.12b) we can see that $(1+MEB_L) = 1/(1-\tau_L\varepsilon_{LL})$. Substituting this in the second term, factoring out $(1+MEB_L)(F\eta_{FF}/p_F)$ from both terms, and using (2.11) yields (2.13b).

E. VMT Tax

Suppose we replace the fuel tax by a VMT tax, i.e. a tax on M. To keep notation as similar as possible, denote the tax rate by $t_F^v\alpha_{FM}^v$, where α_{FM}^v is the inverse of fuel economy with no fuel tax, determined from (2.12c) with t_F=0. Because the production function $M(F,H)$ is homogeneous and we no longer vary the price of either F or H, the input ratio α_{FM} is now constant at α_{FM}^v. Therefore the tax payments can be written as $t_F^v\alpha_{FM}M = t_F^v F$, in analogy to the tax payments $t_F F$ in the case of the fuel tax.

As a result, the above derivations all apply with t_F replaced by t_F^v. This includes replacing any derivative with respect to t_F by the corresponding derivative with respect to t_F^v. As already noted, α_{FM} is constant with respect to t_F^v. Equivalently, $\eta_{FF}^{\overline{M}} = 0$, so we see from (2.12b) that $\eta_{FF}^v = \eta_M^v$ and β=1, where

(E1) $$\eta_{MF}^v \equiv \frac{q_F + t_F^v}{M}\frac{dM}{dt_F^v};\quad \eta_{FF}^v \equiv \frac{q_F + t_F^v}{F}\frac{dF}{dt_F^v}.$$

The fact that β=1 is the most important difference between the fuel tax and the VMT tax, because it means that the mileage-related externalities in (2.12a) are much more important in the latter.

The question remains: What is the empirical counterpart of η_{MF}^{v}? Recall that the traveler is optimizing inputs F and H to produce M at least money cost. Therefore the price of travel p_M changes in either case by F times the change in tax rate (dt_F or dt_F^v). To show this more formally, we decompose the changes in M both in the VMT-tax case and the fuel-tax case. Recall that M=$M(p_M,t_L)$ from (B3a), with p_M given by (B2b). Ignoring the small feedback from changes in t_L via balanced-budget considerations (which is also ignored in our empirical measurement of the elasticities), we can use the chain rule as follows:

(E2) $$\frac{dM}{dt_F^v}=\frac{\partial M}{\partial p_M}\alpha_{FM}$$

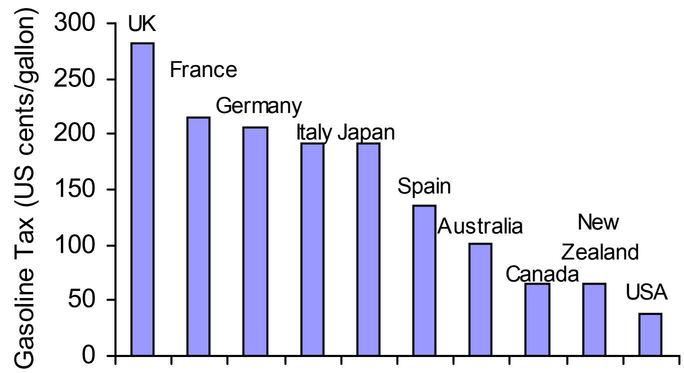
(E3) $$\frac{dM}{dt_F}=\frac{\partial M}{\partial p_M}\frac{dp_M}{dt_F}.$$

The cost function for producing M is just $C(M;t_F)=(p_M-\nu\pi)M$. Applying Shephard's Lemma yields

(E5) $$\frac{dp_M}{dt_F}M=F$$

which implies that the right-hand sides of (E2) and (E3) are equal. Equivalently, $\eta_{MF}^{v}=\eta_{MF}$. This means that for purposes of calculating the VMT tax, η_{MF} is held at the same value as in the fuel-tax calculation, while $\eta_{FF}\equiv\eta_{MF}/\beta$ is reduced to the value η_{MF} as β is changed to one.

Figure 1. Gasoline Excise Taxes in Different Countries



Source: International Energy Association, Energy Prices and Taxes, First Quarter 2000.

Figure 2. Sensitivity of Optimal Gasoline Tax to Parameter Variation
(— US ▬ UK)

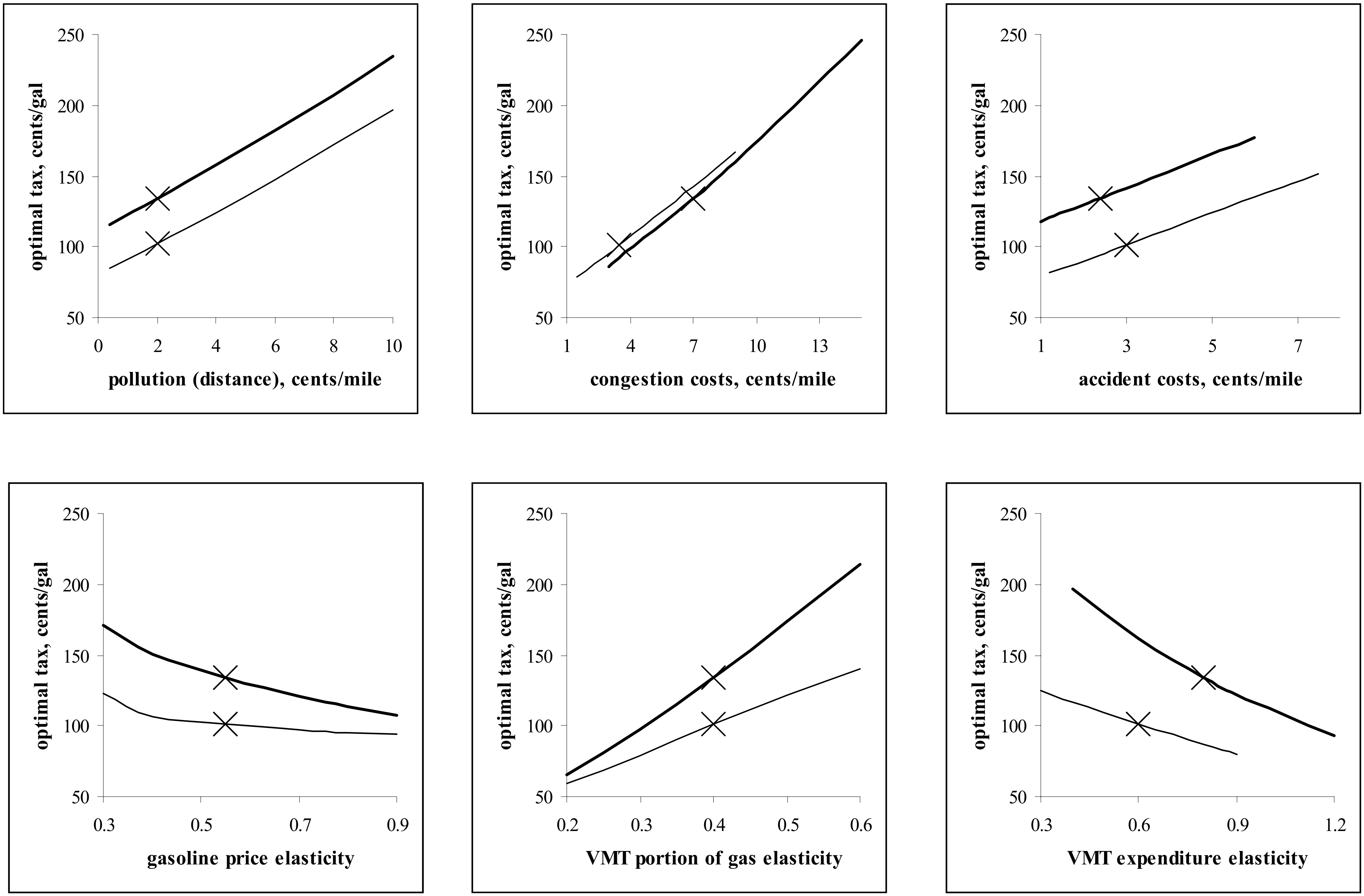


Table 1. Parameter Assumptions
(US units)

Parameter	US		UK	
	Central value	range	Central value	range
Initial fuel efficiency: $1/\alpha_{FM}^{0}$ (miles/gal)	20	-	30	-
Pollution damages, distance-related: E^{P_M} (cents/mile)	2.0	0.4-10	2.0	0.4-10
Pollution damages, fuel-related: E^{P_M} (cents/gal)	6	0.2-24	6	0.2-24
External congestion costs: E^C (cents/mile)	3.5	1.5-9.0	7	3-15
External accident cost: E^A (cents/mile)	3	1.2-7.5	2.4	0.96-6.0
Gasoline price elasticity: η_{FF}	0.55	0.3-0.9	0.55	0.3-0.9
VMT portion of gas price elasticity, β	0.4	0.2-0.6	0.4	0.2-0.6
VMT expenditure elasticity: η_{MI}	0.6	0.3-0.9	0.8	0.4-1.2
Uncompensated labor supply elasticity: ε_{LL}	0.2	0.1-0.3	0.2	0.1-0.3
Compensated labor supply elasticity: ε_{LL}^{c}	0.35	0.25-0.5	0.35	0.25-0.5
Government spending/GDP: α_G	0.35	0.3-0.4	0.45	0.4-0.5
Gasoline production share: α_F	0.012	-	0.009	-
Producer price of gasoline: q_F (cents/gal)	94	44-144	101	51-151
Initial tax rate on gasoline: t_F^0 (cents/gal)	40	-	280	-

Table 2. Benchmark Calculations of the Optimal Gasoline Tax Rate
(All monetary figures in cents/gal at US 2000 prices)

	US		UK	
Elements in Equation (2.11):				
Fuel efficiency, M/F (miles/gal)	22.6		25.6	
Marginal external cost, MEC_F	83		123	
Pollution--fuel component, E^{P_F}		6		6
Pollution--distance component, $(\beta/\alpha_{FM})E^{P_M}$		18		20
Congestion component, $(\beta/\alpha_{FM})E^{C}$		32		72
Accident component, $(\beta/\alpha_{FM})E^{A}$		27		25
Marginal excess burden, MEB_L	0.11		0.18	
Adjustment to MEC_F for excess burden, $MEC_F \cdot [(1+MEB_L)^{-1}-1]$	-9		-19	
Components of optimal gasoline tax rate:				
Adjusted Pigovian tax:	74		104	
Pollution, fuel-related		5		5
Pollution, distance-related		16		17
Congestion		29		61
Accidents		24		21
Ramsey tax	26		23	
Congestion feedback	1		7	
Optimal gasoline tax rate (t_F^*)	**101**		**134**	
Naïve gasoline tax rate,[a] MEC_F^1	176		348	

[a] The "naïve" rate is MEC_F computed from (2.17a) with $\alpha_{FM} = \alpha_{FM}^0$ and β=1.

Table 3. Welfare Effects of Gasoline Tax Rates Using Benchmark Parameters
(Relative to current rate, expressed as percent of initial pretax fuel expenditures)

Fuel tax rate	US		UK	
	Rate (cents/gal)	Welfare change[a] (% of pretax expen.)	Rate (cents/gal)	Welfare change (% of pretax expen.)
0	0	-21.2	0	-51.2
$0.50\,t_F^*$	50	2.7	67	11.4
$0.75\,t_F^*$	76	6.4	100	20.3
Optimal rate (t_F^*)	101	7.4	134	22.7
$1.25\,t_F^*$	126	6.6	167	21.0
$1.50\,t_F^*$	151	4.7	201	16.5
Naïve rate (MEC_F^1)	176	1.9	348	-17.9

Table 4. VMT Tax: Benchmark Parameters

VMT tax rate ($t_F^v \alpha_{FM}$)	US			UK		
	VMT tax rate (cents/mile)	Equiv. fuel tax rate (cents/gal) (t_F^v)	Welfare change[a] (% of pretax expen.)	VMT tax rate (cents/mile) ($t_F^v \alpha_{FM}$)	Equiv. fuel tax rate (cents/gal) (t_F^v)	Welfare change[a] (% of pretax expen.)
(a) Equiv. initial rate ($t_F^0 \alpha_{FM}^0$)	2.0	36	-0.9	9.3	181	21.6
(b) Equal-revenue ($t_F^0 \alpha_{FM}$)	2.25	40	1.0	14.5	280	27.4
(c) Naïve ($MEC_F^1 \alpha_{FM}^0$)	9.9	176	26.4	18.0	348	26.8
(d) Optimal ($t_F^{v*} \alpha_{FM}$)	14.0	248	28.4	15.5	300	27.5
Components[b] of t_F^{v*}:						
Adjusted. Pigov. tax		142			193	
Ramsey tax		104			94	
Congestion feedback		2			13	

[a] Welfare effect of replacing the initial fuel tax by a VMT tax at the rate shown. Calculated using (2.16)-(2.18) with β=1 and $\eta_{MF} = \eta_{MF}^0$.

[b] The components of t_F^{v*} are the three identified terms in equation (2.16), with t_F replaced by t_F^v.and with $\beta=1$, α_{FM} held at its value when t_F=0, and η_{FF} set equal to η_{MF}.

Table 5. Effects of Government Revenue Requirement on Optimal Tax Rate and Total External Cost

(External cost is relative to zero revenue requirement, as percent of initial pretax fuel expenditures)

α_G	US				UK			
	t_L^*	t_F^*	Adj. Pigov. Tax	Total Extern. Cost	t_L^*	t_F^*	Adj. Pigov. Tax	Total Extern. Cost
0	-0.01	80	80	0	-0.01	120	121	0
0.25	0.24	92	77	-2.7				
0.35	**0.34**	**101**	**74**	**-4.6**	0.33	129	110	-3.5
0.45	0.44	114	71	-7.2	**0.43**	**134**	**104**	**-5.4**
0.55					0.53	142	96	-8.3

Table 6. Values for External Costs that Yield High and Low Values for the Optimal Gasoline Tax
(expressed relative to the external costs for the benchmark case)

VMT portion of gasoline demand elasticity, β	US		UK	
	low value: t_F=\$0.40/gal	high value: t_F=\$1.50/gal	low value: t_F=\$1.00/gal	high value: t_F=\$2.80/gal
0.2	.61	2.60	1.54	3.62
0.4	.33	1.47	.76	1.88
0.6	.23	1.07	.48	1.27

Table 7. Monte Carlo Results for Approximate Optimal Gasoline Tax

US		UK	
Amount in US cents/gal (X)	Probability that $t_F^* < X$	Amount in US cents/gal (X)	Probability that $t_F^* < X$
25	0	50	0
40	0.01	100	0.30
75	0.29	150	0.68
100	0.58	200	0.90
150	0.89	280	0.98