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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.

Under our central parameter values, and with the gasoline tax substituting for a distorting tax on labor income, the second-best optimal gasoline tax is \$0.95/gal for the US and \$1.29/gal for the UK. These values are moderately sensitive to alternative plausible parameter assumptions. The congestion externality is the largest component in both nations, and the higher optimal tax for the UK is due almost entirely 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. However, we also find that a shift in taxation off gasoline and onto vehicle miles can produce much larger welfare gains than those from implementing second-best optimal gasoline taxes.

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 less than half the wholesale price.[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 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

[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.

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, unlike a fuel tax, would provide 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 externality taxes have a distorting effect on labor supply similar to that of labor-based taxes. This usually reduces their efficiency compared to the standard partial-equilibrium analysis of Pigou (1920). 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.

An extensive empirical literature attempts to quantify the external costs of transportation.[4] Typically these studies estimate external costs per distance traveled rather than per volume of fuel consumed. There are some important complications involved in using such estimates to obtain optimal gasoline taxes; in particular, as our formulation makes clear, the importance of distance-based

[2] For further discussion of the efficiency of gasoline taxes at reducing externalities, see Walters (1961), U.K. 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), Mauch and Rothengatter (1995), Mayeres et al. (1996), Quinet (1997), ECMT (1998, ch. 3), Porter (1999), and various papers in Greene et al. (1997).

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.

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 extends that of Bovenberg and Goulder (1996), who show how to adjust Pigovian taxes to take into account interactions with pre-existing taxes on labor income. We furthermore consider the possibility that gasoline is a relatively weak substitute for leisure compared with other goods, 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.[5] 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.

Two studies have estimated the effects of using fuel taxes as a second-best replacement for externality taxes, in both cases for Belgium. De Borger et al. (1997) use a partial equilibrium model with a highly disaggregated transport sector, whereas Mayeres (2000) uses a general equilibrium model with three passenger and three freight modes and two time periods. Both simulate fuel taxes essentially as taxes on vehicle-kilometers traveled, with fuel efficiency fixed except for changes arising from shifting among car sizes (large or small) and fuel types (gasoline or diesel). In contrast, we emphasize the importance of shifts in fuel efficiency and show how they weaken the link between distance-related externalities and the second-best fuel tax. We also provide a fully analytical model including an explicit formula disaggregating the optimal fuel tax into components with economic interpretations. Finally, we apply our model to two nations, the US and U.K., which are more self-contained so we can ignore two phenomena important to Belgium, namely cross-border refueling and exporting of tax burdens.

Our analysis abstracts from some other arguments that have been used in defense of gasoline taxes. However, to the extent that these arguments can be formulated as quantifiable external costs, there is no evidence that they are as large as costs 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 at all closely related to fuel consumption. Delucchi (1998a) has attempted an estimate of external cost of petroleum due to the need

[5] 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).

for military expenditures to ensure a secure import supply, and gets numbers much smaller than those from congestion, accidents, and air pollution.[6]

In analyzing tax policies, one must make assumptions about what other policies are to be held constant. We assume that emissions and safety regulations are not adjusted in response to any price-induced changes in vehicle usage.[7] We also assume that fuel efficiency standards are not binding at the optimal tax 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.[8] We include the costs of existing regulations on safety, emissions, and fuel in the private costs of driving and of purchasing fuel.

We summarize some of the results as follows. First, under our benchmark parameter assumptions the optimal gasoline tax in the US is \$0.95/gal and in the UK is \$1.29/gal, although significantly different values are obtained under alternative parameter scenarios. The higher optimal tax for the UK mainly reflects a higher assumed value for marginal congestion costs.

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 high 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.

Third, external cost estimates based on costs per mile cannot simply be multiplied by fuel efficiency in order to convert to an equivalent fuel tax. Even aside from the tax-interaction, congestion feedback, and other effects considered here, the second-best optimal Pigovian tax on fuel is substantially diminished by the fact that only a fraction of the tax-induced reduction in gasoline use is due to reduced driving, the rest coming from changes in fuel efficiency.

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, adjusted for endogenous fuel efficiency as just noted. It turns out that empirically the feedback effect of congestion on labor supply, the relatively weak substitution between travel and leisure, and the inefficiency due to the relatively narrow base of the fuel tax partially offset each other. While it is true that gasoline taxes should be set above marginal

[6] 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.

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

[8] Rouwendal (1996, Table 3) find 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.

external costs because they raise revenue from a relatively price-inelastic good that is a weak substitute for leisure, this "Ramsey component" turns out to be only about \$0.25 per gallon, roughly one-fourth or one-fifth of the optimal tax rate.

Finally we simulate a tax on vehicle miles, which more directly addresses the distance-related externalities of congestion, accidents, and local pollution. The potential welfare gains from this policy are much larger than those from optimizing gasoline tax rates. Simply shifting taxes off gasoline and onto vehicle miles, with no change in the burden of taxation on driving, produces much larger welfare gains than those from implementing the second-best optimal gasoline taxes; if the vehicle-mile rate is set optimally, the gains are substantially larger still.

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.

The rest of the paper is organized as follows. Section 2 describes our analytical model and derives a formula for the optimal gasoline tax. Section 3 discusses parameter values. Section 4 presents calculations of the optimal gasoline tax for the United States and United Kingdom. Section 5 concludes and discusses limitations to the analysis.

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:

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

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.[9]

[9] 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

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

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 $\pi'(\overline{M}) > 0$, 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 $\pi(\overline{M})$ as fixed—they do not take account of their own impact on congestion.

We distinguish two types of pollutants: those like carbon dioxide that depend directly on fuel consumption (denoted P_F), and those that depend only on miles driven (denoted P_M). The latter include nitrogen oxides, hydrocarbons, and carbon monoxide, for which regulations force emissions per mile to be uniform across new vehicles. 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 per capita 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,[10] and

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that consumption and VMT would increase in the same proportion 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.

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

others are functions 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:

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

where $a(\overline{M})$ is the severity-adjusted accident rate per mile.[11] The sign of $a'(.)$ is ambiguous: the accident rate may increase with more traffic, but accidents can be less severe because heavier traffic causes people to drive slower.

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 $a(.)$.[12]

The agent's budget constraint is therefore:

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

where L is labor supply and I is disposable income, equal to spending on consumption, gasoline, and the other costs of driving. Agents are also subject to the time constraint:

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

where $\overline{L}$ is the agent's time endowment. This equation says that the sum of labor time, leisure time and driving time exhausts the time endowment.

Finally, the government budget constraint is:

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[11] We do not account for the fact the severity of accidents depends in part on the size of vehicles, which may be affected by fuel taxes. Inducing people to buy smaller cars may increase the severity of injuries to themselves, and/or reduce the severity of injuries to other drivers, bicycles, and pedestrians. Current evidence seems to suggest partially offsetting effects of changes in composition of the aggregate fleet: a shift into very small passenger vehicles increases the severity of accidents, while a shift out of very large passenger vehicles (minivans and sport utility vehicles) decreases it (Charles Lave, personal communication).

[12] 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 $a(.)$.

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

That is, revenues from the labor and gasoline taxes equal government spending. We take government spending as exogenous so that higher gasoline tax revenues reduce the need to raise revenues from other sources. This is appropriate for considering the argument that some level of fuel taxation is justified on the grounds that it raises revenue, thereby reducing the need to raise revenue from other sources. More generally, if instead gasoline tax revenues financed additional public spending the optimal gasoline tax would be higher (lower) than that calculated below if the social value of additional public spending is greater (less) than the social value of using extra revenue to cut distortionary income taxes.

B. Optimal Gasoline Tax

We derive the analytical results in three stages. First we describe the conditions for individual households to maximize utility. Then we derive the change in indirect utility from a marginal change in the fuel-tax rate, taking all constraints into account. Finally, we set the latter to zero and solve for the fuel-tax rate that maximizes utility, which we write in a manner that facilitates interpretation in terms of concepts known from the optimal tax literature.

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

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

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 ($M = M_F F + M_H H$):

(2.10a) $$\frac{u_C}{\lambda} = 1; \qquad \frac{u_N}{\lambda} = 1 - t_L; \quad \frac{u_M}{\lambda} = p_M$$

where

(2.10b) $$p_M \equiv (q_F + t_F)\alpha_{FM} + \alpha_{HM} + \nu\pi; \qquad \alpha_{FM} \equiv F/M; \qquad \alpha_{HM} \equiv H/M; \quad \nu \equiv 1 - t_L - u_T/\lambda$$

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, ν, is less than the net wage

$(1-t_L)$ if the marginal utility of travel time, u_T, is positive.[13] The equality of marginal utility u_M/λ and full price p_M holds due to the envelope theorem, even though the latter 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 normalized except for the fuel tax rate. Therefore we can write them 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 (2.10a) and (2.7), we can then obtain the demand functions in a conventional manner, writing them as[14]

$$(2.11a)\quad C = C(p_M, t_L); \qquad M = M(p_M, t_L); \qquad L = L(p_M, t_L);$$

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

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

$$(2.11b)\quad p_M = p_M(t_F, \pi, t_L).$$

(ii) Welfare Effect of the Gasoline Tax. Partially differentiating (2.9), we can eliminate terms using (2.10), the first-order conditions for F and H, and the Euler equation for $M(\bullet)$; we then obtain:

$$(2.12)\quad \frac{\partial V}{\partial t_F} = -\lambda F; \quad \frac{\partial V}{\partial t_L} = -\lambda L; \quad \frac{\partial V}{\partial P} = -\varphi'(P); \quad \frac{\partial V}{\partial A} = -\delta'(A); \quad \frac{\partial V}{\partial \pi} = -\lambda v M$$

This equation would tell us the welfare effects if we could make arbitrary changes in the parameters affecting individuals' decisions. However, those changes are constrained by the government budget constraint (2.8). To incorporate this constraint, we totally differentiate it while holding G constant, obtaining:

$$(2.13)\quad \frac{dt_L}{dt_F} = -\frac{F + t_F \dfrac{dF}{dt_F} + t_L \dfrac{dL}{dt_F}}{L}$$

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 (2.12) to write the total derivative dV/dt_F, while taking into account the budget constraint via (2.13) and the externalities

[13] What really matters is the marginal utility of travel time relative to that of work, as shown by Johnson (1966) in a model in which time spent at work also enters the utility function. See also Small (1992), eq. (2.42). Here the marginal utility of time spent at work is zero by assumption.

[14] The functions in (2.11a) and (2.11b) are independent of A and P because of the separability assumptions in (2.1), and we exclude G as an argument because G is fixed.

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:

$$(2.14)\quad \frac{1}{\lambda}\frac{dV}{dt_F} = \left(E^{P_F} - t_F\right)\left(-\frac{dF}{dt_F}\right) + \left(E^C + E^A + E^{P_M}\right)\left(-\frac{dM}{dt_F}\right) + t_L\frac{dL}{dt_F}$$

where

$$(2.15)\quad E^{P_F} = \varphi' P_F' / \lambda; \qquad E^{P_M} = \varphi' P_M' / \lambda; \qquad E^C = v\pi' M; \qquad E^A = \delta' A' / \lambda .$$

Equation (2.14) decomposes the marginal welfare change from increasing the fuel tax 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}). (Recall that all external costs are in per capita terms.) The last term in (2.14) is the welfare effect in the labor market. It equals the change in labor supply 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 (2.14) is by grouping the two terms containing tax rates, in which case the welfare change is the net change in tax revenue less externality cost resulting from behavioral changes induced by the tax increase.

(iii) Optimal Gasoline Tax. We now derive the (second-best) optimal gasoline tax in terms of elasticities and other parameters familiar from the optimal tax literature. Setting (2.14) to zero yields, after some manipulation, the following formula (see Appendix A):

$$(2.16)\quad t_F^* = \overbrace{\frac{MEC_F}{1+MEB_L}}^{\substack{\text{Adjusted}\\ \text{Pigouvian tax}}} + \overbrace{\frac{(1-\eta_{MI})\varepsilon_{LL}^c}{\eta_{FF}}\frac{t_L(q_F+t_F)}{1-t_L}}^{\substack{\text{Ramsey}\\ \text{tax}}} + \overbrace{\frac{\beta}{\alpha_{FM}}E^C\left\{\varepsilon_{LL} - (1-\eta_{MI})\varepsilon_{LL}^c\right\}\frac{t_L}{1-t_L}}^{\substack{\text{Congestion}\\ \text{feedback}}}$$

where

$$(2.17a)\quad MEC_F \equiv E^{P_F} + (\beta / \alpha_{FM})(E^C + E^A + E^{P_M})$$

$$(2.17b)\quad \beta \equiv \frac{dM/dt_F}{dF/dt_F}\frac{F}{M} = \frac{\eta_{MF}}{\eta_{FF}}; \qquad \eta_{FF} = \eta_{MF} + \eta_{FF}^{\overline{M}}; \qquad MEB_L \equiv \frac{t_L\dfrac{\partial L}{\partial t_L}}{L - t_L\dfrac{\partial L}{\partial t_L}} = \frac{\dfrac{t_L}{1-t_L}\varepsilon_{LL}}{1-\dfrac{t_L}{1-t_L}\varepsilon_{LL}}$$

and where η_{MI} is the expenditure elasticity of demand for VMT (i.e. the elasticity with respect to income net of labor tax), $M/F \equiv 1/\alpha_{FM}$ is fuel efficiency or miles per gallon, η_{FF} is the gasoline demand elasticity, η_{MF} is 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 gasoline demand elasticity with VMT held constant), and ε_{LL} and ε_{LL}^{c} are uncompensated and compensated labor supply elasticities. All elasticities are expressed as positive numbers.

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

$$(2.17c)\quad \alpha_{FM} = \alpha_{FM}^{0}\left(\frac{q_F + t_F}{q_F + t_F^{0}}\right)^{-\eta_{FF}^{\overline{M}}}$$

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

$$(2.17d)\quad t_L = \alpha_G - \frac{t_F}{q_F}\alpha_F$$

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 (2.16) 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 general $\eta_{MF} < \eta_{FF}$, so $\beta < 1$. This point is important because, as we shall see, empirical studies suggest that probably half or more of the long-run price responsiveness of gasoline is due to changes in fuel efficiency rather than amount of driving. Therefore the common practice of multiplying estimates of the marginal distance-related external costs by fuel efficiency – i.e. setting β=1 in (2.17b) – substantially overestimates the appropriate contribution to the optimal fuel tax.[15]

This dilution of the externality arises because the partial-equilibrium Pigovian tax represented by MEC_F is an indirect one. The externality is proportional to distance traveled, so the endogeneity of fuel

[15] 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.

efficiency intervenes between the external cost and the tax instrument. 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 (2.16) differs from the Pigovian tax due to three effects arising from interactions with the tax system. The first effect is that the Pigovian tax in the first term in (2.16) is divided by one plus the marginal excess burden of labor taxation, MEB_L.[16] This term adjusts for the fact that gasoline taxes have a narrow base relative to labor taxes, and in this respect are less efficient at raising revenues. This adjustment to the optimal tax 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 (2.16). 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 (2.16), gasoline should be taxed or subsidized depending on whether travel is a relatively weak 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 (2.16), 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, as shown by (2.10); hence it leads to a substitution out of leisure into travel, which is welfare-improving because labor is taxed.

A special case is when congestion accounts for all external costs and VMT is an average leisure substitute (E^P=E^A=0, η_{MI}=1). Then from (2.16) and (2.17), the optimal gasoline tax equals the marginal congestion cost, $\beta E^C M / F$, because the second effect just described is zero and the first and third effects exactly cancel.[17] Thus, in this case the fact that the fuel tax raises revenue would not justify setting the tax rate above that called for on externality grounds.

[16] 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 ε_{LL} >0 and that t_L and ε_{LL} are not so large as to make the marginal revenue negative.

[17] The first effect causes t_F to differ from βE^C by a factor $[1/(1+MEB_L)-1]$, whereas the third causes it to differ by a fraction $\varepsilon_{LL}t_L/(1-t_L)$. The formula for MEB_L shows that these fractions are equal in magnitude and opposite in sign.

Equation (2.16) 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 o the right-hand side via (2.17c) and (2.18). However, the system of equations (2.16)-(2.18) 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 the above formulas depend on the values of these parameters at the social optimum. To infer the appropriate values we need to make some functional form assumptions. We simply assume that elasticities are constant, and use observed data directly in the formulas.

(iv.) Welfare Effects. Using the same steps that led to (2.16), we show in Appendix A that the per capita welfare benefits of an incremental tax change in (2.14) can be rewritten as:

(2.18a) $$\frac{1}{\lambda}\frac{dV}{dt_F} = (1 + MEB_L)\left(-\frac{dF}{dt_F}\right)(t_F^* - t_F)$$

or, as a proportion of initial fuel production costs,

(2.18b) $$\frac{1}{q_F F^0}\left(\frac{1}{\lambda}\frac{dV}{dt_F}\right) = (1 + MEB_L)\left(\frac{\eta_{FF}}{q_F(q_F + t_F)}\frac{F}{F^0}\right)(t_F^* - t_F)$$

where F^0 is initial fuel consumption. Starting with a current tax rate, we can numerically integrate (2.18b) to obtain an approximate welfare gain from moving to an optimal tax rate, as a fraction of production costs. 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 (2.17d), ignoring any tiny difference between its elasticity and that of F.

(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 because the consumer is optimizing over both M and F, the elasticity of travel with respect to per-mile cost from the demand function for miles, $(p_M/M)\partial M/\partial p_M$, is equal to $\eta_{MF.}$ (We ignore the small feedback effects through the government budget constraint, which are included in η_{MF} in theory though not in practice in its measurement). In order to use our equations to simulate a VMT tax, then we set β=1 while keeping η_{MF} unchanged, which implies that η_{FF} is reduced to the original value of η_{MF}. Equation (2.18b) still applies, but now (F/F^0)=1 and $\eta_{FF} = \eta_{MF}$.

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.

Initial fuel efficiency: 1/ α^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.[18]

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 is 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.[19] 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.[20] European studies give similar if

[18] 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 U.K. DOE (2000, table 2.4).

[19] 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, so we multiply the above estimates by one-half.

[20] 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

slightly smaller results, and the differences are very likely due more to different assumptions than to different conditions.[21] We therefore use the same values for both countries, namely a central value of 2.0 cents/mile with range 0.4-10.0.

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: "it is questionable to assume that the marginal damage costs exceed \$50 /tC" (metric ton carbon).[22] In fact, nearly all the evidence reviewed by Tol et al. suggests values considerably lower than this upper bound. The review by ECMT (1998, p. 70) cites estimates ranging from \$2-\$10/tC. Nordhaus (1994) and Cline (1990) give mid-range values which average to \$4.2/tC in year-2000 prices, while Nordhaus's low estimate is \$0.7/tC.

Given this evidence and the great uncertainty, we take the central value to be \$5/tC with range \$0.7-40. This is equivalent to a central value for E^{P_F} of 1.2 cents/gallon, with range 0.2-9.7.[23] These values are small in comparison to local pollution, and suggest that our current knowledge of global warming does not support much change in gasoline taxes. They do not account for remote risks of catastrophic climate shifts due to unforeseen changes in ocean currents or other factors. An additional consideration in public policy, not accounted for here, is the desirability of undertaking capital investments that provide greater flexibility to respond 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.

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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.

[21] 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. 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.

[22] Tol et al. (2000, p. 199). A metric ton is 1000 kg. "Carbon" here means the mass of carbon atoms in carbon dioxide gas.

[23] The conversion rate of 413 gal/tC is based on US National Research Council (2001), p. 5-5, note 3.

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 to 2000.[24] 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.[25] 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.[26] 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;[27] in addition 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.

These VMT-weighted averages need to be adjusted for our purposes because the elasticity of VMT on congested and uncongested roads with respect to gasoline prices are not identical. Traffic volumes at highly congested times and locations are less sensitive to gasoline prices than other traffic volumes because the former contain a higher proportion of work trips and, through self-selection, of other trips that cannot easily be shifted. For example, Mayeres and Proost (2001b, table 4) report that trips on uncongested roads are three times as price-sensitive as peak-period trips. Trips on uncongested roads should receive a correspondingly higher weight in estimating marginal congestion cost, as can be seen by the fact that E^C is multiplied by $(-dM/dt_F)$ in (2.14). To put it differently, 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

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[24] Scaling up Newbery's estimate by wage inflation (about 64% in UK manufacturing between 2000 and 1990, ILO 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).

[25] This calculation is from Delucchi's Table 1-A4 (p. 57), and assumes that travel is 2/3 "daily travel" and 1/3 "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.

[26] 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).

[27] FHWA (1997), Table III-11, updated by inflation factor 1.16.

(2.14). 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.[28]

The adjustment just described lowers the marginal cost in both countries, but more so in the UK than the US; so it also lowers the gap between their marginal congestion costs. Furthermore, we suspect that some of the differences among studies of the two nations are due to different assumptions. Still, it is entirely reasonable that marginal external congestion costs are higher in the UK than the US, because the UK has a much higher overall population density than the US and a higher proportion of its population lives in cities.[29] For example, one-sixth of the UK population lives in London, where street congestion is notoriously bad.

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). From equations (2.5) and (2.15), we know that $E^A = \delta' A' / \lambda = (\delta' / \lambda)(a + a'\overline{M})$. 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, and 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. Moreover, as noted above, the sign of a' is unclear: some studies have suggested that more traffic *decreases* the severity-adjusted accident rate ($a' < 0$) because accidents are less deadly with slower traffic.[30] All these factors tend to make the accident externalities much smaller than the average accident costs estimated a decade ago.

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[28] We do not make a similar adjustment for pollution cost because there the relevant distinction is between urban and rural travel rather than between congestion and uncongested travel.

[29] Mohring (1999) estimates that the average peak-period marginal external cost for roads in the Minneapolis area is 18 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)

[30] 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.

A number of studies have estimated the marginal external cost E^A from accidents, taking these considerations into account. We choose three as starting points for our own estimates, adjusting each to a common set of assumptions.

For the US, Delucchi (1997) estimates E^A for all motor vehicles in 1991 at 1.4-9.8 cents/mile in 2000 prices.[31] 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.[32] 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.[33]

While the US and UK 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.

First, we adjust to more consistent values for statistical life (defined as willingness to pay for a small reduction in probability of a fatality, divided by the amount of that reduction). Our preferred values are derived from a meta-analysis by Miller (2000), who 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. These predictions, after inflating to 2000 price levels and adjusting for changes in real GNP per capita (with 0.96 elasticity), are approximately \$4.8 and \$3.2 million for the US and UK,

[31] 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.

[32] 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.

[33] 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). The result is that the numbers for "other" in Newbery (1988, table 3) are out of order and one is missing: they should be 3.05, 1.08, 3.89, 1.28, and 1.87, from top to bottom. The second row, "cars and taxis," is thus 1.08, not 3.05 as printed, and adding the columns together then yields 2.9, not 4.9, for "Total: Max". This error affects the high estimate only. 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 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.

respectively.[34] (These figures are somewhat closer to each other than are the raw means of the reviewed studies in the two nations.) For a range, we multiply by 0.5 for the low end and 1.5 for the high end. This gives a preferred value of statistical life for each nation and for each part of the range (low, central, high). We then adjust the corresponding values of statistical life assumed by each study (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.[35]

Finally, 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.)

It is now time to apply our judgment. The two main differences between the US and UK affecting E^A are (1) the UK has about two-thirds as high a willingness to pay for reduction in injury and death, based on Miller's study; and (2) the fatality rate in the UK is about 79 percent of that in the US, whereas injury rates are about the same.[36] Assuming fatalities account for one-fourth of the external costs, and injuries another one-fourth, and that other costs are proportional to injury rates, this suggests that E^A in Britain is about four-fifths that in the US.[37] Taking 3 cents/mile as the central estimate for the US, this gives 2.4 cents/mile for the UK. In each case, we divide the central estimate by 2.5 to get the low

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[34] In 1995 US$, Miller's predicted values of statistical life are $3.67 million for the US and $2.75 million for the UK.

[35] 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 proportion of the US and UK estimates that reflect deaths and injuries. 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.

[36] This statement is based on 1998 rates, which we have assumed are unchanged in 2000. Those rates, expressed in number per 100 million vehicle-miles, are 1.58 and 1.25 (US and UK, respectively) for fatalities and 117 and 122 for injuries. Source: Economic Commission for Europe (2000, pp. 18, 122) and US FHWA (2000b, Table VM-1).

[37] Calculated as 0.25x(2/3)x0.79 + 0.25x(2/3) + 0.5 = 0.80.

estimate, and multiply by 2.5 for the high estimate. This matches quite nicely the ranges calculated in the previous paragraph, and produces the numbers shown in Table 1.

Gasoline price elasticities, η_{FF} and η_{MF}. Reviews of the many time series and cross-section studies of demand for gasoline generally find price elasticities between 0.5 and 1.1 for studies conducted before 1990 (Dahl and Sterner 1991, Table 2; Goodwin 1992, Table 1). However, more recent studies find values about half as large, with a best estimate proposed of 0.38.[38] 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. Thus for η_{FF}, we adopt a compromise value but one 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.[39] These numbers would suggest a ratio β around 0.25 to 0.5. When the same study is used to measure both η_{FF} and η_{MF}, the ratio $\beta \equiv \eta_{MF} / \eta_{FF}$ tends to vary between 0.2 and 0.6.[40] In summarizing their own extensive empirical estimations, Johansson and Schipper (1997, pp. 289-290) suggest a best value of β=[1-(0.4/0.7)]=0.43, whereas US DOE (1996) suggests a best value of 0.46 from the more recent studies.[41] Based on this information, we chose a central value for β of 0.4, and a range of 0.2 to 0.6.

[38] 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.

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

[40] 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%. These studies include Wheaton (1982), who characterizes the results by saying that "the price effect through reduced driving is much greater than the price effect on fleet composition or fuel efficiency"; but in fact his main results (Table 2) imply VMT-elasticity -0.42 and fuel-efficiency elasticity 0.32, for a ratio β=0.57. Wheaton uses a recursive system where auto ownership A and fuel efficiency E are chosen in response to exogenous variables, whereas distance traveled per auto D depends also on A and E. The VMT-elasticity is calculated as $\varepsilon_{AP} + \varepsilon_{DP} + \varepsilon_{DA}\varepsilon_{AP} + \varepsilon_{DE}\varepsilon_{EP}$, where ε_{AP}, ε_{DP}, and ε_{EP} are elasticities of auto ownership, distance traveled per auto, and fuel efficiency (miles/gallon) with respect to fuel price, and where ε_{DA} and ε_{DE} are elasticities of distance traveled per auto with respect to auto ownership and fuel efficiency, respectively. Equivalently, β=[1-(-$\varepsilon_{EP} / \eta_{FF}$)], which is easily calculated from Schimek (1996, Table 5) for all four studies.

[41] Calculated from the top row in Table 5-2, which decomposes the long-run price elasticity of 0.376 into a fuel efficiency component (0.200) and a vehicle-travel component (0.176).

These central values for η_{FF} and β imply that the elasticity of VMT with respect to fuel price, η_{MF}, is 0.22.

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). Estimates are typically between about 0.35 and 0.8, although a few estimates exceed unity.[42] 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 for the optimal gasoline tax. There is a large literature on labor supply elasticities for the US.[43] 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_{LL}^{c} a central value of 0.35 and a range 0.25-0.5. 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.[44] 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 to the nearest 10 cents) at \$0.40/gal for the US

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

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

[44] 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.

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.[45]

4. Optimal Tax Calculations

A. Benchmark Calculations

Table 2 gives the components of the second-best optimal gasoline tax t_F^* for both countries, under our central parameters. The total is \$0.95/gal for the US, more than twice the current rate, and \$1.29/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 size of the difference is unjustified: the rate should be much lower in the UK and much higher in the US than is currently the case. 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 10-22 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,[46] the narrow base of the gasoline tax relative to the labor tax shaves \$0.18 from MEC_F, but the Ramsey component adds back \$0.23 and the congestion-feedback effect another \$0.07 in deriving the optimal tax rate. For the US, the narrow base subtracts only \$0.08, but the Ramsey component adds \$0.25. Thus the revenue-raising argument makes a notable difference in both nations, due to the assumed income-inelasticity of gasoline consumption and the consequent low substitution of leisure for gasoline when the gasoline tax is raised.

However, the results are far below the "naïve" computation typically proposed in the literature, which is MEC_F computed from (2.17a) with β=1 and with fuel economy at its initial value. That value is shown in the last row of the table, and is especially high in the UK because not only are the mileage

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[45] For the US, the share is based on 1999 consumption of motor gasoline of 3.06×10^9 barrels (US Energy Information Administration 2000, Table 5.11), net-of-tax gasoline price of \$(1.252-0.383) per gallon (average of premium unleaded 95RON and 91RON), and gross domestic product of $\$9.30 \times 10^{12}$. 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 (2.572-1.728) pounds per gallon (average of premium leaded and premium unleaded gasoline) and gross domestic product of 747×10^9 pounds. Source for prices: International Energy Agency 2000, pp. 286, 277.

[46] 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 is much larger because it depends in part on the compensated labor supply elasticity. See Snow and Warren (1996) for more discussion.

components of MEC_F not reduced by β but they are also multiplied by the current fuel economy, which is significantly lower than that under the optimal tax.

Of the three externalities included in MEC_F, congestion is easily the largest component in Britain but only slightly larger than accidents and air pollution in the US. Furthermore, the accident and air pollution components are both substantial and together are larger than the Ramsey (revenue-raising) component. The global warming component is virtually negligible, and would be the smallest of the four externalities even if we increased our estimate of global warming costs by a factor of 10.

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^* (\$0.95/gal) would induce a welfare gain equal to 6% of pre-tax fuel expenditures; but increasing it to the "naïve" rate (\$1.71/gal) would overshoot the optimal rate and yield virtually zero net benefits. For the UK, the welfare gain from reducing the current tax (\$2.80/gal) to the optimal (\$1.29/gal) would produce substantial gains, nearly one-fourth of pretax gasoline expenditures, while increasing the tax to the "naïve" rate would create a welfare *loss* of 17.4 percent of pretax expenditures.

Table 4 shows results for a true VMT tax at three different rates: (a) the initial fuel-tax rate converted to a per-mile basis using initial fuel efficiency; (b) a pure Pigovian tax equal to the "naïve" fuel-tax rate described above, converted similarly to a per-mile basis; and (c) 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. These results show how dramatically better a VMT tax is than a fuel tax. Even charging the same per-mile rate as the current gasoline tax provides great benefits – more than one-fifth of pretax gasoline expenditures in the US and more than half of those expenditures in the UK. *These welfare gains are substantially larger than those from implementing the optimal gasoline tax* (see Table 3). Charging a straight Pigovian tax yields benefits that are much greater still. The optimal VMT tax is very high, close to 14 cents per vehicle-mile, and the benefits are roughly one-third of pretax gasoline expenditures in the US and 94 percent of them in the UK.

Two other observations about VMT taxes are noteworthy. First, the pure Pigovian tax is substantially lower than the optimal tax but achieves nearly all the benefits. Thus the "naïve" calculations are highly relevant to public policy, but need to be recognized as relevant to a VMT tax rather than a fuel tax. Second, a breakdown of the optimal VMT tax into the three components listed in equation (2.16) (not shown in the table) reveals that the Ramsey component is quite large: 41 percent of the optimal rate in the US and 28 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.

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.

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 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).

High and Low Scenarios for the Optimal Tax. Table 5 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 (2.17) 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 5 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 35% of those in our central case when $\beta = 0.4$, or between 24% and 70% 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 1.94 times their benchmark values, while a tax of only \$1.00/gal would be optimal if all external costs were 21% below their benchmark values.

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 just on the marginal external cost at the initial gasoline tax rate, denoted MEC_F^0. For each country we draw the five uncertain parameters that determine MEC_F^0 1000 times randomly and independently from selected distributions, and we calculate the marginal external cost for each draw according to equation (2.17a).[47]

Table 6 shows the resulting frequencies with which the marginal external cost MEC_F is less than a given value. Here we see that for the US, the probability that the marginal external cost is less than the current tax of \$0.40/gal is 0.15, and the probability that it is below \$1.00 is 0.82. For the UK, marginal external costs are below the current tax of \$2.80/gal with probability .98, and below \$1.50 with probability 0.60.

5. Conclusion

Although there is considerable uncertainty over parameter values, our best assessment is that the optimal gasoline tax for the US is more than double its current rate, and for the UK is less than half its current rate. Paradoxically, the prospects for either a substantial increase in gasoline taxes for the US, or for a substantial cut in gasoline taxes for the UK, appear extremely remote in the current political climate. Despite a considerable push, the Clinton Administration achieved an increase in the federal gasoline tax rate of only 4 cents in 1993, and the Conservative Party's pledge in the 2001 British election to cut gasoline taxes by 6 pence/litre (33 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. There are some grounds for optimism, for example there have been limited experiments with congestion pricing in California and Texas and cordon pricing is planned for London, but it will be a long time before these types of policies might become more widespread.

However our results also reveal the attractiveness of a tax on vehicle miles which, although less efficient than closely targeted externality taxes, is still much more effective than a tax on fuel. For both countries, we find that a lot more could be gained in economic efficiency simply from swapping gasoline taxes for mileage taxes, *with no change in the overall burden of taxation on driving*, than from implementing (politically untenable) second-best optimal gasoline taxes.

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[47] For congestion and accident 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. Using gamma distributions is not possible for the pollution related costs since the upper values are much larger relative to the central values; for these cases we use log-normal distributions with median values equal to our central values and geometric standard deviations equal to 1.5. 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.

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Appendix A: Analytical Derivations for Section 2

For the analytical derivations we define the following terms:

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

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

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

Deriving (2.16) and (2.17).

From (2.11):

(B1) $$\frac{dL}{dt_F}=\frac{\partial L}{\partial t_F}+\frac{\partial L}{\partial \pi}\frac{d\pi}{dt_F}+\frac{\partial L}{\partial t_L}\frac{dt_L}{dt_F}$$

Differentiating (2.8), and using (2.11), an alternative expression for the change in labor tax is:

(B2) $$\frac{dt_L}{dt_F}=-\frac{F+t_F\dfrac{dF}{dt_F}+t_L\left(\dfrac{\partial L}{\partial t_F}+\dfrac{\partial L}{\partial \pi}\dfrac{d\pi}{dt_F}\right)}{L+t_L\dfrac{\partial L}{\partial t_L}}$$

From (B1) and (B2):

(B3) $$t_L\frac{dL}{dt_F}=MEB_L\cdot t_F\frac{dF}{dt_F}+\frac{MEB_L}{\partial L/\partial t_L}\left\{\frac{\partial L}{\partial t_F}L-\frac{\partial L}{\partial t_L}F+L\frac{\partial L}{\partial \pi}\frac{d\pi}{dt_F}\right\}$$

where, using the definition of ε_{LL} from (A1),

(B4) $$MEB_L=\frac{-t_L\dfrac{\partial L}{\partial t_L}}{L+t_L\dfrac{\partial L}{\partial t_L}}=\frac{\dfrac{t_L}{1-t_L}\varepsilon_{LL}}{1-\dfrac{t_L}{1-t_L}\varepsilon_{LL}}$$

Using (2.10) and (2.11):

(B5) $$\frac{\partial L}{\partial t_F}=\frac{\partial L}{\partial p_M}\alpha_{FM};\qquad \frac{\partial L}{\partial \pi}=\frac{\partial L}{\partial p_M}q;\qquad \frac{d\pi}{dt_F}=\pi'\frac{dM}{dt_F}$$

From the Slutsky equations:

(B6) $$\frac{\partial L}{\partial p_M}=\frac{\partial L^c}{\partial p_M}-\frac{\partial L}{\partial I}M;\ \frac{\partial L}{\partial t_L}=\frac{\partial L^c}{\partial t_L}-\frac{\partial L}{\partial I}L$$

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

(B7) $$\frac{\partial L^c}{\partial p_M} = \frac{\partial M^c}{\partial t_L}$$

Because leisure is weakly separable in the utility function, changes in the demands for consumption and for travel occur only through a change in disposable income, which is caused by the change in the labor-tax rate (Layard and Walters 1978, p. 166). Therefore:

(B8) $$\frac{\partial M^c}{\partial t_L} = \frac{\partial M}{\partial I}(1-t_L)\frac{\partial L^c}{\partial t_L}$$

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 (B5)-(B8), and the definitions of I, η_{MI} and E^C from (A1) and (2.15):

(B9) $$\frac{\partial L}{\partial t_F}L - \frac{\partial L}{\partial t_L}F = F\frac{\partial L^c}{\partial t_L}(\eta_{MI}-1); \qquad L\frac{\partial L}{\partial \pi}\frac{d\pi}{dt_F} = \left\{\eta_{MI}\frac{\partial L^c}{\partial t_L} - \frac{\partial L}{\partial I}L\right\}E^C\frac{dM}{dt_F}$$

Substituting (B9) in (B3), using the definitions of ε_{LL}, ε_{LL}^c and η_{LI} in (B3), and using the Slutsky equation $\varepsilon_{LL} = \varepsilon_{LL}^c + \eta_{LI}$ gives:

(B10) $$t_L\frac{dL}{dt_F} = MEB_L \cdot t_F\frac{dF}{dt_F} - \frac{MEB_L}{\varepsilon_{LL}}\left\{\varepsilon_{LL}^c F(\eta_{MI}-1) + E^C\frac{dM}{dt_F}\left\{\varepsilon_{LL} - (1-\eta_{MI})\varepsilon_{LL}^c\right\}\right\}$$

From (B4), (B10), equating (2.14) to zero, dividing through by dF / dt_F, and using the definition of η_{FF} in (A1), we can obtain (2.16). Finally, using (2.9):

(B11) $$\frac{dF}{dt_F} = \frac{F}{M}\frac{dM}{dt_F} + M\alpha'_{FM}$$

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 (2.17).

Deriving (2.18).

First, use the definitions of η_{FF}, η_{MF}, and MEC_F to write (2.14) as:

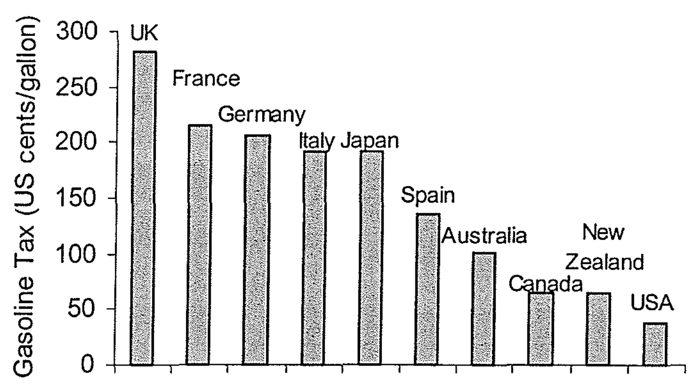
$$\frac{1}{\lambda}\frac{dV}{dt_F} = \left[MEC_F - t_F(1+MEB_L)\right]\left(\frac{F\eta_{FF}}{p_F}\right) + t_L\frac{dL}{dt_F}$$

where $p_F \equiv q_F + t_F$. Next, substitute (B10) for the last term, regroup terms, and factor out $(F\eta_{FF}/p_F)$ to get

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

where $\tau_L \equiv t_L/(1-t_L)$. From (B4) 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 (2.16) yields (2.18b).

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)

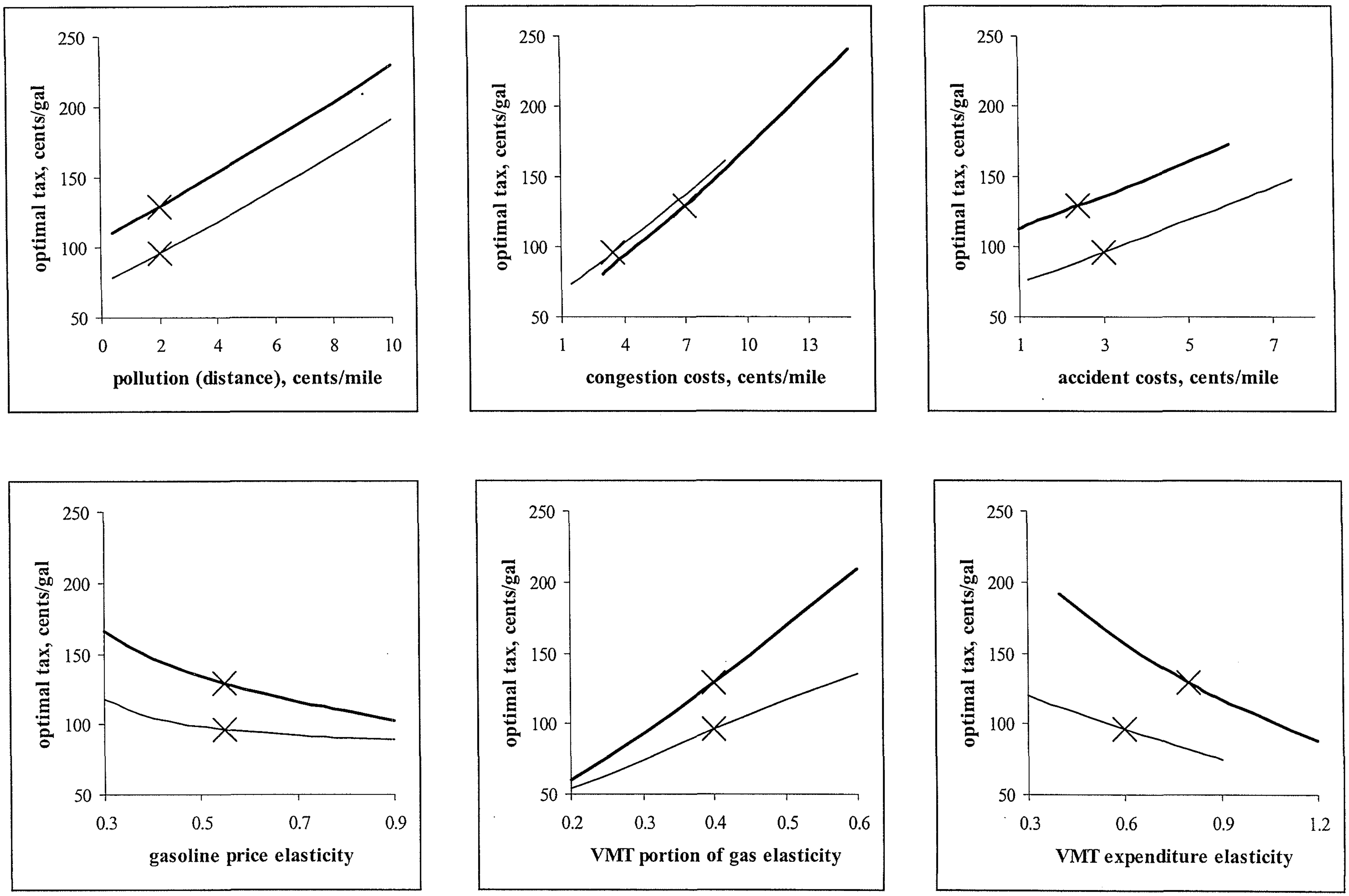


Table 1. Parameter Assumptions

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)	1.4	0.2-10	1.4	0.2-10
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 ($/gal)	0.94	0.44-1.44	1.01	0.51-1.51
Initial tax rate on gasoline: t_F^{0} ($/gal)	0.40	-	2.80	-

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 (2.16):		
Fuel efficiency, M/F (miles/gal)	22.4	25.4
Marginal external cost, MEC_F	78	117
Pollution--fuel component, E^{P_F}	1	1
Pollution--distance component, $(M/F)\beta E^{P_M}$	18	20
Congestion component, $(M/F)\beta E^C$	31	71
Accident component, $(M/F)\beta E^A$	27	24
Marginal excess burden, MEB_L	0.11	0.18
Adjustment to MEC_F for excess burden, $MEC_F \bullet [(1+MEB_L)^{-1}-1]$	-8	-18
Components of optimal gasoline tax rate:		
Adjusted Pigovian tax:		
Pollution, fuel-related	1	1
Pollution, distance-related	16	17
Congestion	28	60
Accidents	24	20
Ramsey component	25	23
Congestion feedback	1	7
Optimal gasoline tax rate (t_F^*)	**95**	**129**
Naïve gasoline tax rate[a]	171	343

[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 pretax fuel expenditures)

Fuel tax rate	US	UK
0	-19.7	-45.0
$0.50\,t_F^*$	1.8	13.7
$0.75\,t_F^*$	5.2	22.2
t_F^*	6.1	24.5
$1.25\,t_F^*$	5.4	22.8
$1.50\,t_F^*$	3.5	18.6
Naïve rate	0.4	-17.4

Table 4. VMT Tax: Benchmark Parameters

VMT tax rate	US		UK	
	Rate (cents/mile)	Welfare change[a] (% of pretax expen.)	Rate (cents/mile)	Welfare change[a] (% of pretax expen.)
(a) $t_F^0 \alpha_F^0$	4.75	21.5	4.3	54.6
(b) $MEC_F^0 \alpha_{FM}^0$	8.55	32.2	11.4	92.1
(c) Optimal VMT tax	13.3	35.5	14.5	94.3

[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 $\eta_{MF} = \eta_{MF}^0$.

Table 5. 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	.70	2.80	1.668	3.84
0.4	.35	1.55	.79	1.94
0.6	.24	1.11	.49	1.30

Table 6. Monte Carlo Results for Marginal External Costs

	Probability that MEC_F^0 is less than				
	\$0.25	\$0.40	\$0.75	\$1.00	\$1.50
US	.03	.15	.63	.82	.98
	Probability that MEC_F^0 is less than				
	\$0.50	\$1.00	\$1.50	\$2.00	\$2.80
UK	.03	.30	.60	.83	.98