DISCUSSION PAPER

How Should Heavy-Duty Trucks Be Taxed?

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RESOURCES
FOR THE FUTURE

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Abstract

This paper develops and implements an analytical framework for estimating optimal taxes on the fuel use and mileage of heavy-duty trucks, accounting for external costs from congestion, accidents, pavement damage, noise, energy security, and local and global pollution. The analysis allows for endogenous fuel economy, increased auto travel (and externalities) in response to reduced truck congestion, and it distinguishes driving by truck type and region. We estimate the optimal (second-best) diesel fuel tax is $1.12 per gallon, and implementing it increases welfare by $1.34 billion per annum. However, optimizing over both fuel and mileage taxes, and differentiating mileage taxes by vehicle type and region, yields progressively higher welfare gains. The most efficient tax structure involves a diesel fuel tax of 69 cents per gallon and charges on trucks that vary between 7 and 20 cents per mile; implementing this tax structure yields welfare gains of $2.06 billion.

Keywords: truck tax; diesel tax; external costs; welfare gains.

JEL Classification Numbers: Q54; R48; H23

Discussion papers are research materials circulated by their authors for purposes of information and discussion. They have not necessarily undergone formal peer review.

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1. Introduction

Although heavy-duty commercial trucks account for only 7.5% of highway miles (BTS 2004), they contribute disproportionately to a wide array of highway externalities. Because they are heavier, larger, and burn more fuel than passenger vehicles, on a per mile basis they add more to pavement deterioration, traffic congestion, pollution, and nationwide dependence on a volatile world oil market. In principle, the optimal tax structure on trucks to address these externalities would involve a mix of fuel and mileage taxes, with the latter varying with vehicle characteristics as well as region (for example, congestion is more severe in urban areas).

To date, the main tax on heavy trucks has been the excise tax on diesel fuel, currently 24.4 cents per gallon at the federal level and (on average) 20.5 cents per gallon at the state level (FHWA 2003, Table MF-121T).[1] Traditionally, the level of this fuel tax has been governed by highway spending needs, rather than efficient (second-best) pricing of externalities. However, with developments in electronic metering technologies, there is growing interest in charging trucks on a per mile basis to reduce congestion and other highway externalities. Per-mile truck tolls were introduced in Germany in January 2005, with tolls varying according to weight, emissions classification, and other characteristics, and Switzerland has had a similar toll system since January 2001 (Comeau 2004). And per-mile truck tolling is being discussed in the United States, though sometimes as a means of financing new lanes that would be truck only (e.g., Poole and Samuel 2004, SCAG 2002).

This paper develops and implements an analytical framework for estimating the optimal level, and welfare gains from, taxes to address truck externalities, one that distinguishes between single-unit and (heavier) combination trucks, and driving in urban and rural areas. We account for three externalities that vary directly with fuel use, namely local pollution, greenhouse warming, and energy security, and four externalities that vary directly with vehicle miles, namely congestion, accidents, noise, and pavement damage. And we consider a hierarchy of policies increasing in precision at which they price externalities; these include optimizing over the diesel tax alone, optimizing over a uniform mileage tax on top of the current diesel tax, optimizing over both the diesel and uniform mileage taxes, and then allowing the mileage tax to differ according to truck type and region. As emphasized in Parry and Small (2005), a fuel

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[1] At the federal level, fuel taxes account for 63% of total revenues from truck taxes; other taxes include vehicle excises (24%), tire taxes (4%) and annual fees on heavier vehicles (9%) (FHWA 2003, Table MF-121T). These other taxes affect mileage to the extent they reduce the size of the truck fleet, though they do not affect miles per vehicle; they are ignored in our analysis.

tax is more efficient than a mileage tax at reducing fuel-related externalities, and less efficient at reducing mileage-related externalities, when (long-run) vehicle fuel economy responds to fuel price.

Our analysis builds on an earlier contribution by Calthrop et al. (2003). They employ a theoretical model, and a numerical simulation model of the UK transport system, to examine the efficiency properties of per-mile truck taxes. Their analysis demonstrates the significance of increased passenger vehicle travel that increases in response to lower congestion, and that partly offsets the externality gains from truck taxes (ideally, truck taxes should be implemented in conjunction with taxes on passenger vehicles, rather than piecemeal). Still, they find that higher truck taxes are welfare-improving overall for the United Kingdom, especially if revenues are used to reduce distortionary labor income taxes.[2] Our analysis differs from Calthrop et al. (2003) by disaggregating truck driving by vehicle type and region, considering a broader range of tax reforms including fuel taxes (with endogenous fuel economy) and differentiated mileage taxes, using explicit analytical formulas to compute optimal policies rather than a numerical transport network model, and by applying the analysis to the United States rather than the United Kingdom.[3] Unlike Calthrop et al. (2003), we do not consider interactions between truck taxes and the broader fiscal system, however we comment on how these interactions would affect our results at the end of the paper.

We estimate the optimal (second-best) tax on diesel fuel is $1.12 per gallon, or 2.5 times the current tax. This tax represents an average of fuel- and mileage-related truck externalities (net of the change in auto externalities), weighted by the elasticity of fuel use or mileage with respect to fuel price for each truck type/region, relative to the economy-wide fuel price elasticity. Raising the fuel tax from its current level to its second-best optimal level yields an (annualized) welfare gain of $1.34 billion.

However optimizing over both fuel and uniform mileage taxes, and differentiating mileage taxes by region and truck type, yields progressively higher welfare gains. The most efficient tax structure involves a diesel fuel tax of 69 cents per gallon and per mile charges on trucks that vary between 7 cents (for single-unit trucks in rural areas) to 20 cents (for combination trucks in urban areas). Here the fuel tax

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[2] Calthrop et al. (2003) also explore how higher auto taxes affect the optimal truck tax. In theory the effect is ambiguous; higher auto taxes reduce vehicle travel and thereby lower the marginal congestion cost from trucks, but they also reduce the welfare loss per unit increase in auto travel in response to truck taxes, which equals the marginal external cost of autos *net* of the auto tax. Their simulation results indicate that the optimal truck tax is initially rising, but eventually declining, with higher auto taxes.

[3] As noted below, our assumptions about external costs are in the same ballpark as those implicit in Calthrop et al. (2003), which in turn were based on estimation procedures described in Mayeres and van Dender (2001). However there is one critical exception to this: Calthrop et al. (2003) use a far greater value for marginal congestion costs due to the assumption of a near saturated road network in the (densely populated) United Kingdom. This is the main reason why they estimate a much greater optimal mileage tax (for the United Kingdom) than we do (for the United States).

equals fuel-related external costs per gallon averaged across truck types/regions and weighted by the fuel price elasticity for that truck type/region relative to the economy-wide fuel price elasticity; the mileage charge is simply the mileage-related external cost for that truck type/region, minus the increase in auto externalities (net of auto taxes). Implementing this tax structure (in place of the current fuel tax) results in an estimated (annualized) welfare gain of $2.06 billion.

There are a number of caveats to the analysis, discussed in more detail below. One is that optimum tax estimates are somewhat sensitive to parameter assumptions, which underscores the need for updating them as "best estimates" of external costs change over time; for example, local emissions will decline in future as environmental regulations on new trucks are phased in, while congestion will likely increase with continued growth in travel demand relative to highway capacity. Other caveats are that we ignore (a) interactions between truck taxes and the broader fiscal system (b) alternative freight modes to trucks and (c) diesel-powered passenger vehicles (the latter consideration is relevant for analyzing diesel taxes in Europe but not the United States at present).

The rest of the paper is organized as follows. Section 2 describes the analytical model and optimal tax and welfare formulas. Section 3 discusses parameter values. Section 4 presents the main results and sensitivity analysis. A final section offers concluding remarks.

2. Theoretical Framework

A. Assumptions

(i) Households. We consider a static model where a representative household (meant to reflect an average over households in different regions of the country) has utility function:

$$(1) \qquad u = u\{T_{SU}, T_{CU}, T_{SR}, T_{CR}, Y, A_U, A_R, \Pi, Z\}$$

All variables are expressed on a per capita basis.

T_{ij} denotes consumption of a market good whose production and/or distribution to consumers involves significant trucking costs; index i refers to the type of truck used to transport the good where $i = S$ (single-unit vehicle) or C (combination vehicle), while index j refers to the region where the transportation occurs, either $j = U$ (urban) or R (rural). Y denotes a general consumption good for which transportation costs are minimal (e.g., services, products with a high value to volume ratio). A_j denotes auto vehicle miles driven by households in region j and Π is total household travel time. Z is an index of negative externalities from all (auto and truck) vehicles, aside from congestion and pavement damage (which are incorporated below); Z includes local and global pollution, accidents, energy security, and noise. Function $u\{.\}$ is increasing and quasi-concave in T_{ij}, Y and A_j; it is decreasing in Z and Π with u_{ZZ}, $u_{\Pi\Pi} < 0$.

Household travel time is:

(2) $\Pi = \Sigma_j \pi_j A_j$

where π_j is the (average) time to drive a mile in region j (the inverse of the driving speed). Households are also subject to the following budget constraint equating disposable income with spending on consumption goods and auto fuel (gasoline):

(3) $I + LST = \Sigma_{ij} p_{ij} T_{ij} + Y + (t_G + p_G) \Sigma_j (1 + \psi_j^A) f_G A_j$

I is exogenous household income, implicitly equal to a fixed wage times a fixed labor supply, while LST denotes a lump-sum transfer from the government to households, which captures recycling of tax revenues (Section 5 comments on endogenous labor supply and alternatives for revenue recycling). p_{ij} is the market price of good T_{ij}, which incorporates transport costs (see below); the price of Y is normalized to unity. The final term in (3) is auto fuel costs; t_G and p_G denote the per gallon gasoline tax and the pre-tax gasoline price respectively. f_G is gasoline consumption per mile for rural driving and $\psi_U^A > 0$ is the excess gasoline consumption rate per mile for urban driving over rural driving ($\psi_R^A = 0$). Thus $\Sigma_j (1 + \psi_j^A) f_G A_j$ is gasoline consumption aggregated across urban and rural driving.

Households choose goods and travel to maximize utility subject to the constraints in (2) and (3). This yields:

(4a) $u_{A_j} / \lambda = (t_G + p_G)(1 + \psi_j^A) f_G - \pi_j u_\Pi / \lambda ; \quad u_{T_{ij}} = \lambda p_{ij} ; \quad u_Y = \lambda$

(4b) $h = h(p_{SU}, p_{CU}, p_{SR}, p_{CR}, LST, \pi_U, \pi_R) ; \quad h = T_{ij}, Y, A_j$

where λ is the marginal utility of income and $-u_\Pi / \lambda$ is the marginal value of travel time for households (in dollars). In (4a) households equate the marginal private benefit from driving in region j with the per-mile fuel cost, and (monetized) time cost, $-\pi_j u_\Pi / \lambda$. In (4b) the demand for goods and travel are expressed as functions of economy-wide variables, namely good prices, the government transfer, and travel time, each of which are perceived as exogenous by individual agents when making their own travel and consumption choices. I, f_G, ψ_j^A, p_G and t_G are fixed in the analysis and therefore excluded from the demand functions, as are non-congestion externalities, which are assumed to have no feedback effects on goods and travel demand.[4] To the extent that truck taxes reduce road congestion in region j this will cause an increase in auto mileage ($-\partial A_j / \partial \pi_j > 0$) (Calthrop et al. 2003); we assume that any such travel increase comes from latent travel demand rather than substitution between rural and urban driving ($\partial A_R / \partial \pi_U =$

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[4] We suspect that these feedback effects are relatively minor though there is a lack of solid empirical evidence on this.

$\partial A_U / \partial \pi_R = 0$). We further assume that $\partial A_j / \partial p_U = \partial A_j / \partial p_R = 0$; that is, higher product prices for freight-intensive consumption goods do not directly affect auto mileage (instead they cause a substitution effect into the non-freight intensive good Y).

(ii) Production of goods. Competitive firms employ labor to produce the five final goods, gasoline, and diesel fuels (used by trucks). There are no freight costs associated with producing and selling Y and gasoline to households, and diesel fuel to trucking companies; for these goods production costs per unit (implicitly equal to the fixed labor requirement per unit times the fixed wage) equal pre-tax prices in competitive equilibrium. For goods T_{ij} the equilibrium market price is:

$$(5) \qquad p_{ij} = p_{ij}^T + p_{ij}^0$$

where p_{ij}^0 is the fixed production cost per unit and p_{ij}^T is the per unit freight cost, paid to trucking companies. We define a unit of consumption good T_{ij} by the quantity delivered per mile of freight; thus, in equilibrium, consumer demand T_{ij} is equivalent to truck mileage incurred in transporting that product.[5]

(iii) Freight. Homogeneous and competitive trucking companies ship goods T_{ij} to consumers at a given cost per mile; in equilibrium this cost equals the freight price p_{ij}^T, given by

$$(6) \qquad p_{ij}^T = \tau_{ij} + (t_D + p_D)(1 + \psi_j^T) f_{iD} + w \pi_j + k_i \{1 / f_{iD}\}$$

The first component of p_{ij}^T is a per mile tax τ_{ij} that may vary across region and truck type. The second is diesel fuel costs $(t_D + p_D)(1 + \psi_j^T) f_{iD}$, where t_D is the tax on diesel fuel, p_D is the producer price of diesel, f_{iD} is fuel used per mile of rural driving by truck i, and ψ_U^T is the excess fuel consumption rate in urban areas over rural driving, assumed the same for both types of trucks ($\psi_R^T = 0$). Third is the cost of truck driver travel time, equal to the wage rate w multiplied by the time per mile π_j. The final term in (6) is vehicle capital/maintenance costs expressed on a per mile basis, $k_i\{1/f_{iD}\}$. These costs are the same for urban and rural driving and are a convex function of truck fuel economy, as represented by $1/f_{iD}$; in other

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[5] We assume that tons delivered per vehicle mile of freight are fixed. To the extent that tonnage per vehicle mile increase in response to higher fuel or mileage taxes this might increase certain external costs through increasing truck weight, though the effect would likely be moderate. Empirical estimates of fuel and mileage elasticities that are used to implement our analytical formulas below do, implicitly, account for changes in tons per mile.

words, maintaining a truck fleet with higher fuel economy requires the incorporation of fuel saving technologies, the cost of which (net of fuel savings) is passed forward into higher freight prices.[6]

Trucking companies (in aggregate) supply whatever mileage is required to meet consumer demand for T_{SU}, T_{CU}, T_{SR} and T_{CR} at prevailing market prices. They also choose fuel economy to minimize total shipping costs $\Sigma_{ij} p_{ij}^T T_{ij}$ (taking T_{ij} as given); this yields

(7) $\qquad \dfrac{(t_D + p_D)(T_{iR} + (1+\psi_U^T)T_{iU})}{T_{iR} + T_{iU}} = \dfrac{k_i'}{f_{iD}^2}$

This equation implies that fuel economy of truck type i is improved until the incremental savings in fuel costs per mile, averaged over urban and rural driving, equals the added vehicle cost (per mile). Higher diesel taxes raise the marginal savings in fuel costs (the left-hand side of (7)) and therefore lead to higher fuel economy; in contrast, mileage taxes do not affect fuel economy.

(iv) External costs. Time per mile or traffic congestion is summarized by:

(8a) $\qquad \pi_j = \pi_j(T_{Sj}, T_{Cj}, A_j)$

(8b) $\qquad e_{ij} = \dfrac{\partial \pi_j / \partial T_{ij}}{\partial \pi_j / \partial A_j}$

In (8a) π_j is increasing and quasi-convex in its arguments, namely truck and auto mileage in region j. In (8b) e_{ij} is the "passenger-car equivalent" for truck type i in region j, that is, the increase in congestion from one extra truck mile relative to the increase in congestion from one extra auto mile; $e_{ij} > 1$ as trucks take up more road space and travel at slower speeds than autos.[7] Individual drivers do not take account of their impact on (incrementally) increasing π_j and thereby imposing an external cost on other road users.

External costs, aside from congestion and pavement damage, are:

(9) $\qquad Z = \Sigma_j z_j^A A_j + \Sigma_{ij}(z_j^{TF} F_{ij} + z_{ij}^{TM} T_{ij})$

where $F_{ij} = (1+\psi_j^T)f_{iD}T_{ij}$ is total (per capita) diesel fuel consumption by truck type i in region j. z_j^A is the external cost per mile of auto travel in region j; it combines local and global pollution, oil dependency, accident, and noise externalities. Since auto fuel economy is fixed, and only auto miles vary, all these

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[6] We assume that vehicle capital costs are proportional to (long run) total freight miles, which is reasonable if vehicles are replaced after a given mileage. This assumption ensures the supply curve for freight is perfectly elastic.

[7] The contribution of a vehicle to congestion, averaged across time of day, also depends on the share of its mileage that occurs at peak versus off-peak period. A larger share of truck mileage occurs at off-peak period than for auto as, in the latter case, individuals have little flexibility in their choice of travel time when commuting to work. This complication is taken into account in the choice of parameter values below.

external costs change in proportion to auto miles driven. In contrast, proportionate changes in diesel fuel may differ from proportionate changes in truck mileage when policies—namely diesel taxes—affect fuel economy; for trucks we therefore distinguish externalities that vary with fuel use as opposed to mileage. z_j^{TF} is fuel-related external costs per gallon of fuel used by truck type i in region j; it reflects local and global emissions, and oil dependency, and may vary across region (though not truck type) with, for example, regional population exposure to local emissions.[8] z_{ij}^{TM} is mileage-related external costs per mile from accidents and noise; these vary both across space and with truck type.

The remaining externality is pavement damage. We assume that the government pays whatever repair and maintenance costs are needed to keep average road quality at a given standard. Required spending (P) is:

(10) $\qquad P = \Sigma_{ij} z_{ij}^{P} T_{ij}$

where z_{ij}^{P} is pavement costs per mile by truck i in region j. Road damage costs, which are a rapidly increasing function of axle weight, are relatively small for light vehicles (e.g., FHWA 2000, Table 13); we therefore ignore them for autos.

(v) Government. The government is subject to the following budget constraint equating spending on the household transfer and road maintenance with revenues from truck and auto taxes:

(11) $\qquad LST + P = t_d F + \Sigma_j \tau_j^A A_j + \Sigma_{ij} \tau_{ij} T_{ij}$

where $F = \Sigma_{ij} F_{ij}$ is total fuel use and $\tau_j^A = t_G \Sigma_j (1 + \psi_j^A) f_G$ is the gasoline tax in region j expressed per mile of auto travel in region j. The revenue effects of tax changes (net of any change in spending on road maintenance or revenues from other taxes) are therefore neutralized by adjusting the transfer payment to households (alternative assumptions are discussed in Section 5).

B. Optimal Tax and Welfare Formulas

(i) Diesel tax. We now derive a formula for the optimal (second-best) diesel tax; this formula incorporates fixed taxes on truck mileage, though these are set to zero in our benchmark estimates of the optimal fuel tax.

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[8] As discussed below, it is appropriate to count local pollution as a fuel-related externality for heavy trucks because (future) emissions regulations are defined in terms of grams per gallon (in contrast, auto emissions are regulated on a grams per mile basis).

We start by obtaining the indirect utility function $\tilde{u}\{.\}$ from the individual household optimization over goods and travel taking externalities, travel time, prices, and policy parameters as given. We then totally differentiate the indirect utility function with respect to t_D, accounting for economy-wide behavioral responses that affect prices, externalities, and congestion, as well as government revenues that affect the transfer payment. This yields the following decomposition for the welfare effect (in dollars) from an incremental increase in the diesel tax (see Appendix):

$$(12a) \quad \frac{1}{\lambda}\frac{d\tilde{u}}{dt_D} = \Sigma_{ij}(MEC_j^{TF} - t_D)\left(-\frac{dF_{ij}}{dt_D}\right) + \Sigma_{ij}(MEC_{ij}^{TM} - \tau_{ij})\left(-\frac{dT_{ij}}{dt_D}\right) - \Sigma_j(MEC_j^A - \tau_j^A)\frac{dA_j}{dt_D}$$

$$(12b) \quad MEC_j^{TF} = z_j^{TF}(-u_Z/\lambda), \qquad MEC_j^A = z_j^A(-u_Z/\lambda) + v_j(\partial\pi_j/\partial A_j)$$

$$MEC_{ij}^{TM} = z_{ij}^{TM}(-u_Z/\lambda) + z_{ij}^P + (w(T_{Sj} + T_{Cj}) - (u_\Pi/\lambda)A_j)\,\partial\pi_j/\partial T_{ij}$$

In (12b) MEC_j^{TF} summarizes the marginal external cost of local and global emissions and oil dependency per gallon of diesel fuel consumed in region j by either truck type (all marginal external costs are expressed in monetary equivalents). MEC_{ij}^{TM} is the marginal external cost per mile by truck i in region j from accidents, noise, road damage and congestion; road damage is simply the dollar repair cost per mile (financed by lowering the household transfer), while congestion is the vehicle's incremental contribution to raising travel time for all road users in region j, $\partial\pi_j/\partial T_{ij}$, times the sum of truck and auto miles in that region, where mileage is weighted by the value of time (w for truck drivers and $-u_\Pi/\lambda$ for auto mileage, respectively). MEC_j^A summarizes the marginal external cost from all auto externalities for region j (local and global pollution, oil dependence, accidents, noise and congestion) expressed on a per mile basis.

The first component of the welfare change in (12a) equals the induced reduction in diesel fuel for truck type i in region j, $-dF_{ij}/dt_D$, times the marginal external cost of fuel-related externalities, MEC_j^{TF}, net of the amount already internalized by the current diesel tax, and summed over truck types and regions. The second component is the reduction in mileage for truck type i in region j, $-dT_{ij}/dt_D$, times the marginal cost of mileage-related externalities net of any existing tax, $MEC_{ij}^{TM} - \tau_{ij}$, and summed over truck types and regions. The third component equals the increase in auto travel in response to reduced congestion, dA_j/dt_D, times the difference between the marginal external cost of auto travel and the gasoline tax, all expressed on a per mile basis and aggregated over regions. We define:

$$(13) \quad \beta_j = -\frac{(\partial \pi_j / \partial A_j)(dA_j / dt_D)}{\Sigma_i (\partial \pi_j / \partial T_{ij})(dT_{ij} / dt_D)} = -\frac{dA_j / dt_D}{\Sigma_i e_{ij} \cdot dT_{ij} / dt_D}$$

β_j is the "congestion offset", or the fraction of the reduction in congestion in region j due to reduced truck mileage that is offset by increased congestion from auto travel. This effect is probably minimal in rural areas and for simplicity we set $\beta_R = 0$. We assume that $\beta_U > 0$ and is constant over the relevant range, which is reasonable so long as truck mileage (weighted by passenger equivalents) is small relative to auto mileage.

Equating (12a) to zero, we can obtain the following expression for the optimal (second-best) diesel tax per gallon (see Appendix):

$$(14a) \quad \hat{t}_D = \overbrace{\Sigma_{ij} MEC_j^{TF} s_{ij}^F \frac{\eta_{ij}^{FF}}{\eta^{FF}}}^{fuel-related\ externalities} + \overbrace{\Sigma_{ij}(MEC_{ij}^{TM} - \tau_{ij})\frac{T_{ij}}{F_{ij}} s_{ij}^F \frac{\eta_{ij}^{MF}}{\eta^{FF}}}^{mileage-related\ externalities}$$

$$\overbrace{-(MEC_U^A - \tau_A)\beta_U \Sigma_i e_i \frac{T_{iU}}{F_{iU}} s_{iU}^F \frac{\eta_{iU}^{MF}}{\eta^{FF}}}^{auto\ offset}$$

$$(14b) \quad s_{ij}^F = \frac{F_{ij}}{F} \ ; \qquad \eta^{FF} = \Sigma_{ij} \frac{dF_{ij}}{dt_D} \frac{p_D + t_D}{\Sigma_{ij} F_{ij}} \ ; \qquad \eta_{ij}^{FF} = \frac{dF_{ij}}{dt_D}\frac{p_D + t_D}{F_{ij}} \ ; \quad \eta_{ij}^{MF} = \frac{dT_{ij}}{dt_D}\frac{p_D + t_D}{T_{ij}}$$

In (14b) s_{ij}^F is the share of total diesel fuel consumed by trucks of type i in region j, η^{FF} is the overall own-price elasticity of demand for diesel fuel, η_{ij}^{FF} is the diesel fuel price elasticity for truck type i in region j, and η_{ij}^{MF} is the elasticity of mileage for truck type i in region j with respect to the price of diesel.

In (14a) the first component of the optimal diesel tax, termed "fuel-related externalities", is the marginal external cost of diesel fuel consumption, averaged across truck types regions, and weighted by the responsiveness of F_{ij} to diesel prices relative to the responsiveness of total fuel use. Thus, for example, if a disproportionately large fuel reduction occurs in rural areas (where fuel costs per mile are larger relative to time costs) then MEC_{iR}^{TF} would receive a correspondingly higher weight (and MEC_{iU}^{TF} a correspondingly lower weight) in the optimal fuel tax. The second component of the optimal tax, termed "mileage-related externalities", is the marginal external cost of mileage-related truck externalities, net of any per mile tax, multiplied by the conversion factor T_{ij} / F_{ij} (miles per gallon) to convert costs per mile into costs per gallon, averaged across regions, and weighted by $\eta_{ij}^{MF} / \eta^{FF}$. To the extent that the reduction in fuel consumption by truck type i in region j is due to (long run) improvements in truck fuel

economy rather than reduced truck mileage, η_{ij}^{MF}/η^{FF} is smaller than η_{ij}^{FF}/η^{FF}, and the contribution of net mileage-related externalities to the optimal fuel tax is scaled back (Parry and Small 2005).[9] The third component of the optimal tax, applying in the urban area, is termed the "auto offset" and is a downward adjustment. It is greater in magnitude the greater is (a) the marginal external cost per urban auto mile net of the auto tax $MEC_U^A - \tau_A$ (b) the congestion offset β_U (c) the passenger-car equivalent e_i as this implies more extra auto mileage for a given congestion offset (d) the conversion factors T_{iU}/F_{iU} (e) fuel use shares for urban truck driving s_{iU} and (f) the responsiveness of urban truck driving to fuel prices relative to the responsiveness of overall diesel fuel consumption η_{iU}^{MF}/η^{FF}.

(ii) Uniform mileage tax. We now equate mileage taxes across truck types and regions $\tau_{ij} = \tau$ and optimize household welfare with respect to τ, given the existing diesel tax denoted t_D^0. In deriving the optimal tax we make use of the identity $dT_{ij}/d\tau \equiv (dT_{ij}/dt_D)T_{ij}/F_{ij}$; that is, a unit increase in per mile driving costs has the same effect on mileage for truck type i in region j as increasing the fuel tax by T_{ij}/F_{ij}. Using this enables us to express the optimal tax in terms of the mileage elasticity with respect to fuel prices rather than with respect to per mile driving costs, which facilitates calibration to empirical literature. The second-best optimal uniform per mile tax is (see Appendix):

$$
(15a) \quad \hat{\tau} = \overbrace{\sum_{ij} MEC_{ij}^{TM} s_{ij}^M \frac{\tilde{\eta}_{ij}^{MF}}{\tilde{\eta}^{MF}}}^{\text{mileage-related externalities}} + \overbrace{\sum_{ij}(MEC_j^{TF} - t_D^0)(F_{ij}^0/T_{ij}^0)s_{ij}^M \frac{\tilde{\eta}_{ij}^{MF}}{\tilde{\eta}^{MF}}}^{\text{fuel-related externalities}}
$$

$$
\overbrace{-(MEC_U^A - \tau_A)\beta_U \sum_i e_{iU} s_{iU}^M \frac{\tilde{\eta}_{iU}^{MF}}{\tilde{\eta}^{MF}}}^{\text{auto offset}}
$$

$$
(15b) \quad s_{ij}^M = \frac{T_{ij}}{T}; \qquad T = \sum_{ij} T_{ij}
$$

$$
\tilde{\eta}_{ij}^{TM} = \eta_{ij}^{TM} \frac{T_{ij}^0}{F_{ij}^0}; \qquad \tilde{\eta}^{TM} = \sum_{ij} s_{ij}^M \tilde{\eta}_{ij}^{TM}
$$

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[9] In the extreme case when all of the fuel reduction comes from improved fuel economy and none from reduced mileage, then $\eta_j^{MF} = 0$ and mileage-related external costs would play no role in the optimal diesel tax.

where s_{ij}^{M} is a mileage, as opposed to a fuel, share and superscript 0 denotes an initial value. $\tilde{\eta}_{ij}^{TM}$ is the elasticity of mileage for truck type i in region j expressed as the mileage elasticity with respect to the equivalent increase in fuel prices; it equals η_{ij}^{TM} times initial fuel economy T_{ij}^{0}/F_{ij}^{0}. The average of this elasticity across all truck mileage is $\tilde{\eta}^{TM}$.

The formula in (15a) resembles that in (14a), though there are some differences. Most notable, for a given truck type and region, both mileage and fuel-related truck externalities now change in the same proportion, since there is no change in truck fuel economy (i.e., elasticities with respect to mileage enter both the numerator and denominator in each component of the optimal tax). Thus, unlike under the diesel tax, there is no scaling back of mileage-related externalities in the optimal tax (see also Parry and Small 2005). Other differences are that the current diesel tax is netted out of the fuel-related external costs, mileage elasticities are expressed with respect to the equivalent change in fuel prices, and that external costs, and the optimal tax, are expressed per mile rather than per gallon (hence external costs are not multiplied by the conversion factor T_{ij}/F_{ij}).

(iii) Quasi-optimal diesel and uniform mileage taxes. We also consider the following tax structure:

(16a) $\quad \hat{t}_D = \quad \overbrace{\Sigma_{ij} MEC_{ij}^{TF} s_{ij}^{F} \frac{\eta_{ij}^{FF}}{\eta^{FF}}}^{fuel-related\ externalities}$

(16b) $\quad \hat{\tau} = \quad \overbrace{\Sigma_{ij} MEC_{ij}^{TM} s_{ij}^{M} \frac{\tilde{\eta}_{ij}^{MF}}{\tilde{\eta}^{MF}}}^{milage-related\ externalities} \quad \overbrace{-(MEC_{U}^{A}-\tau_{A})\beta_{U}\Sigma_{i} e_{iU} s_{iU}^{M} \frac{\tilde{\eta}_{iU}^{MF}}{\tilde{\eta}^{MF}}}^{auto\ offset}$

In (16a), the diesel tax (per gallon) is now equal to the sum of fuel-related external costs weighted by fuel shares and relative responsiveness of fuel use. And in (16b) the per mile tax equals the sum of marginal costs from mileage-related externalities, weighted by mileage shares and relative responsiveness of mileage, minus the net increase in external costs from the auto offset. We call the tax structure in (16) quasi-optimal, as it is not quite the fully optimized one.[10] However, the empirical difference between optimized tax structure and that in (16) is relatively minor (see below), and therefore we focus on the simpler system.

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[10] To see this substitute (16a) in (15a) and the fuel-related externalities term does not exactly cancel out since marginal external costs are weighted by mileage shares and relative mileage elasticities in (15a) while marginal external costs are weighted by fuel use shares and relative fuel elasticities in (16a). For analogous reasons, the last two components of the optimal fuel tax in (14a) do not exactly cancel when we substitute (16b).

(iv) Quasi-optimal diesel and differentiated mileage taxes. The final tax structure we examine is:

$$\text{(17a)} \quad \hat{t}_D = \Sigma_{ij} MEC_{ij}^{TF} s_{ij}^M \frac{\eta_{ij}^{FF}}{\eta^{FF}}$$

$$\text{(17b)} \quad \hat{\tau}_{iU} = MEC_{iU}^{TM} - (MEC_U^A - \tau^A)e_{iU}\beta_U, \qquad \hat{\tau}_{iR} = MEC_{iR}^{TM}$$

The diesel tax is the same as previously, while the individual mileage tax for truck type *i* in region *j* is now simply equal to the respective marginal external cost, net of the auto offset in urban areas. For this case the fuel tax is fully optimal, while the mileage taxes are an approximation to their optimal levels.[11]

(v) Computational Considerations. We assume that all fuel and mileage elasticities are constant, which implies the following demand relations

$$\text{(18a)} \quad \frac{F_{ij}}{F_{ij}^0} = \left(\frac{p_D + t_D}{p_D + t_D^0}\right)^{\eta_{ij}^{FF}} \left(1 + \frac{(\tau_{ij} - \tau_{ij}^0)T_{ij}/F_{ij}}{p_D + t_D^0}\right)^{\eta_{ij}^{MF}}$$

$$\text{(18b)} \quad \frac{T_{ij}}{T_{ij}^0} = \left(\frac{p_D + t_D + (\tau_{ij} - \tau_{ij}^0)T_{ij}/F_{ij}}{p_D + t_D^0}\right)^{\eta_{ij}^{MF}}$$

In addition we assume that marginal external costs MEC_{ij}^{TF}, MEC_{ij}^{TM}, and MEC_U^A are constant; this is a reasonable approximation as the truck taxes discussed below have only a moderate effect on total mileage and hence the marginal external costs from all highway vehicles.

We solve for optimal (or quasi-optimal) taxes in a spreadsheet by increasing tax rates above their initial levels by successive increments, computing fuel use and mileage shares, and miles per gallon, according to (18), and hence the optimal taxes as determined by (14)-(17); this is repeated until we converge on the optimal tax.

(vi) Welfare Effects. The marginal welfare effects from increasing the diesel fuel tax above its current level, and introducing a uniform mileage tax on top of the existing diesel tax, are given by (see Appendix):

$$\text{(19a)} \quad \frac{1}{\lambda}\frac{d\tilde{u}}{dt_D} = \left(\hat{t}_D - t_D\right)\left(-\Sigma_{ij}\frac{dF_{ij}}{dt_D}\right) = \left(t_D - \hat{t}_D\right)\eta^{FF}\frac{F}{p_D + t_D}$$

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[11] Substituting (17b) in (14a) causes the last two components of the optimum fuel tax to cancel. However, substituting (17a) in (15a), the fuel-related externalities component does not cancel. This implies that fully optimal mileage taxes would differ, albeit slightly, from those in (17b).

$$\text{(19b)} \quad \frac{1}{\lambda}\frac{d\tilde{u}}{d\tau} = (\hat{\tau} - \tau)\left(-\Sigma_{ij}\frac{dT_{ij}}{d\tau}\right) = (\tau - \hat{\tau})\frac{\Sigma_{ij}\tilde{\eta}_{ij}^{MF}T_{ij}}{p_D + \tau\Sigma_{ij}s_{ij}^{F}T_{ij}/F_{ij}}$$

In these equations the marginal welfare gain is the product of the difference between the optimized tax and the current tax and the marginal reduction in either total fuel use or total mileage; the latter can be expressed in terms of quantities, prices and elasticities. Total welfare gains are obtained by summing over marginal welfare gains as taxes are increased in successive increments over the range between the initial and the optimal level. For the fuel tax/uniform mileage tax combination we use (19a) to compute the welfare gain from raising the fuel tax and then (19b) to compute the additional welfare gain from raising the mileage tax (using as initial quantities those at the ex post fuel tax). Welfare gains from the fuel tax/differentiated mileage tax combination are more complicated and are explained in the Appendix.

3. Parameter Values

Parameter values for single-unit and combination trucks and autos used in our benchmark simulations are summarized in Table 1, for year 2000.[12] Data on mileage and fuel use are from FHWA (1997) and BTS (2004), while most of the external costs are from a detailed and widely cited assessment for year 2000 by FHWA (1997, 2000). Evidence on truck mileage and fuel elasticities, particularly disaggregated across region and truck type, is sparse; we therefore make plausible assumptions for our benchmark simulations and consider alternative assumptions in the sensitivity analysis. Below we comment on parameter values and measurement issues.

Mileage and fuel use. Total truck mileage was 205 billion in 2000 with 56% of this mileage in rural areas, and 66% of the mileage by combination trucks.[13] 61% of driving by combinations occurs in rural areas while only 45% of mileage by single-unit trucks is in rural areas. On-road fuel economy (mileage divided by fuel consumption) averages 7.4 miles per gallon over all regions for single-unit trucks and 5.3 miles per gallon for combinations; we disaggregate fuel economy and fuel use across regions by assuming fuel

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[12] Data on single-unit trucks represents a mileage-weighted aggregation over vehicles with 2, 3, 4 or more axles and at least 6 tires. Data on combinations represents an aggregation over semi-trailers with 3, 4, 5, 6, 7 or more axles, truck trailers with 3, 4, 5, 6 or more axles, tractor double semi-trailers with 5, 6, 7, 8 or more axles, and tractor triple semi-trailers. See FHWA (1997), Table I-1 and Figure I-1, for more discussion on vehicle classifications.

[13] The fleet size is far greater for single trucks than combinations but the latter are driven more intensively as they are more likely to be used for long distance, inter-city freight.

economy is 30% greater for rural driving than urban driving. Urban auto fuel economy is taken to be 15 miles per gallon.[14]

Prior diesel tax and price. The current tax on diesel fuel is 45 cents per gallon (24.4 cents at the federal level and on average 20.5 cents per gallon at the state level) and the gasoline tax is 39 cents per gallon (18.4 at the federal level) (FHWA 2003, Table MF-121T). The pre-tax diesel fuel price is taken to be $1.55 per gallon.[15]

Congestion and passenger-car equivalents. Marginal congestion costs are taken from FHWA (1997), Table V-23. They primarily reflect the impact of an extra truck mile on adding to recurrent congestion and raising travel costs for other road users; they are obtained from observed traffic flow data, assumptions about speed-flow relations and passenger car equivalents for representative urban and rural roads, and assumptions about the value of time. The estimates weight marginal costs across time of day based on mileage shares for truck types at peak and off-peak period. They also incorporate non-recurrent congestion costs from traffic accidents and other highway incidents, as well as extra fuel consumption costs.

   Marginal congestion costs in urban areas are 16.8 cents per mile for combination trucks and 14.5 cents per mile for single-unit trucks (Table 1); marginal costs for urban auto travel are 7.7 cents per mile. Although combinations have a higher passenger car equivalent than single-unit trucks they also have a smaller share of mileage at peak period, hence the difference in marginal costs or passenger-car equivalents, between truck types is modest, when averaged across time of day. Similarly, autos have a larger share of mileage at peak period than trucks and this reduces the difference in marginal costs between autos and trucks, averaged over all times of day. Marginal costs for trucks are roughly five times larger in urban areas than rural areas.

Accidents. Marginal external accident costs have been quantified by using (a) accident data to allocate observed fatalities and injuries to vehicles involved in crashes (b) comprehensive measures of economic costs per injury type (including quality of life costs, medical costs, property damage, emergency services,

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[14] Mileage and fuel use by truck type (but not disaggregated across region) is from BTS (2004), Appendix A. Mileage shares disaggregated by region are inferred from FHWA (1997), Table II-6. Average on-road auto fuel economy across all (urban and rural) regions was 21.9 miles per gallon in 2000 (BTS 2004, Table 4-23).

[15] The post-tax price is therefore $2.00 per gallon, which represents an average over the January price for the last three years (from www.eia.doe.gov).

etc.) and (c) assumptions about what injury risks are internal to drivers versus external.[16] We use FHWA (1997) Table V-24 to obtain relative external accident costs per mile across truck types and autos, and across urban and rural areas; we then increase all these costs by the same proportion so that the external accident costs for all auto travel would be consistent with a recent assessment in Parry and Small (2005). Marginal costs vary between 1.1 and 3.4 cents per mile for trucks and are 2.0 for autos (in urban areas); costs are lower in urban areas due to slower driving speeds (note that congestion costs from accidents in urban areas are incorporated in the marginal cost of congestion).

Noise. Marginal external costs of noise are taken from FHWA (1997), Table V-22. They were obtained by examining the effect of proximity to roads, and traffic flow on those roads, on local property values, controlling for other factors and using assumptions about how noise varies with weight and other vehicle characteristics. Noise costs vary from 0.1 cents per mile for urban autos and single-unit trucks in rural areas to 3.7 cents per mile for combinations in urban areas.

Pavement damage. Our estimates of the costs of repairing road damage are inferred from FHWA (2000, Table 13).[17] They are a sharply increasing function of (axle) weight and vary from 1.0 cents per mile for single-unit trucks in rural areas to 10.5 cents per mile for combinations in urban areas. Urban damage costs are about three times those in rural areas in part due to higher urban labor costs.

Local pollution. FHWA (2000), Table 13, provides estimates of local air pollution costs averaged over all trucks for urban and rural driving. These were based on a comprehensive EPA assessment of air pollution costs (primarily mortality effects) and emissions attributable to trucks (as a group) and other motor vehicles. Based on these estimates we assume pollution costs are 36 cents per gallon in rural areas and 42 cents per gallon in urban areas.[18]

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[16] Own-driver injury risks in single vehicle crashes are assumed internal while pedestrian injuries are external. Whether one driver raises the injury risk for other drivers remains unclear; more vehicles on the road raise the likelihood that other drivers will collide, however to the extent motorists are more careful or drive slower in heavier traffic a given accident will be less severe. Our values for accident costs in the sensitivity analysis below roughly spans the range of FHWA (1997) estimates under alternative assumptions.

[17] FHWA (2000) provides road damage estimates for a subset of vehicle types rather than aggregates of all single-unit and combination trucks. Our estimates correspond to those for 40 kip 4-axle single-unit trucks and 60 kip 5-axle combination trucks.

[18] Regulations limiting local emissions per unit of truck fuel will be phased in starting in 2007, and this will progressively reduce emissions per gallon of the in-use truck fleet as the fleet is turned over. These emissions standards will be defined in terms of grams per gallon of fuel and therefore emissions will still be proportional to total fuel use; this is not the case for passenger vehicles for which emissions are regulated on a grams per mile basis (Fischer et al. 2005).

Global pollution. Most economic assessments of the damages to future world agriculture, forestry, coastal activities, etc. from carbon emissions put damages at below $50 per ton of carbon (Tol et al. 2000, Pearce 2005, Nordhaus and Boyer 2000), though a few studies obtain much higher values by attaching differing distributional weights to rich and poor nations and assuming zero rates of time preference. These estimates are highly speculative given so little is known about the possibility of abrupt, non-linear climate change (e.g., Schneider 2004). We follow NRC (2002) in adopting a benchmark value of $50 per metric ton of carbon; this is equivalent to 14 cents per gallon of diesel fuel and 12 cents per gallon of gasoline.[19]

Energy security. Most estimates of the marginal external costs of US oil dependence focus on two main components. First is the "optimum tariff" due to US monopsony power in the world oil market. It is given by the "inverse elasticity" rule familiar from trade theory, that is, the world oil price divided by the long run import supply elasticity. Second is the expected cost of economic disruptions during price shocks that the private sector may not fully anticipate or be insured against. These might include added payments for imports and various adjustment costs (e.g., temporarily idled capital and labor); they are estimated using postulated probability distributions for price shocks or supply disruptions, estimated oil price-GDP elasticities, and assumptions about how markets internalize oil price risks. Estimates for these two components combined vary between $0 and $14 per barrel, or 0 to 33 cents per gallon (CEC 2003, Table 3.12, Leiby et al. 1997). NRC (2002) assumed a value of 12 cents per gallon; we use a benchmark value of 16 cents, to make some adjustment for recent oil price increases on affecting the optimum tariff. Again, we emphasize that these estimates are also speculative as they exclude political costs of US oil dependence, such as constraints imposed on foreign policy.[20]

Summary of external costs. In sum, fuel-related external costs are 66−72 cents per gallon across truck types and regions, significantly higher than the current diesel tax. And combined mileage related external costs are higher still; they vary from 6.7 cents per mile for single-unit trucks in rural areas to 32.8 cents per mile for combinations in urban areas or, multiplying by initial fuel economy, from 63−138 cents per gallon (Table 1). Mileage related costs (on a cents per mile basis) are about three times as large in urban

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[19] A gallon of diesel and a gallon of gasoline contain 0.0028 and 0.0024 tons of carbon respectively. See http://bioenergy.ornl.gov/papers/misc/energy_conv.html.

[20] Middle East military expenditures have been quantified at around $50 billion per year, or 17 cents per gallon of fuel consumption (www-cta.ornl.gov/data/Download23.html, Table 1.9). Although these costs might apply to an estimate of *total* external costs, they are usually excluded from marginal costs because they are regarded as a fixed cost that would not fall following a moderate reduction in US oil consumption.

areas as in rural areas, and about 50% larger for combination trucks than for single-unit trucks. In urban areas mileage-related external costs are dominated by congestion, while local emissions account for more than half of fuel-related externalities across both regions.[21] Fuel-related urban auto externalities are much lower than for urban trucks; mileage-related externalities are also smaller on a per mile basis, though on a per gallon basis they are slightly larger as we are multiplying by a fuel economy value that is almost three times that for urban truck driving.[22]

Elasticities. The absolute welfare gains from tax reforms are sensitive to the chosen values for fuel and mileage elasticities, though not so much the welfare gains from one policy reform relative to that for another. Moreover, optimal tax rates depend on relative rather than absolute values for elasticities (e.g., the fuel price or mileage elasticity for truck i in region j relative to the economy-wide fuel price elasticity). This means that the lack of solid evidence on the absolute value of fuel and mileage elasticities across truck types and regions is less of a handicap for our purposes than it may first appear.

We begin by assuming an economy-wide diesel fuel price elasticity η^{FF} of −0.4 with 60% of the response due to reduced mileage, that is $\eta^{MF} = -0.24$, and the other 40% due to long run improvements in vehicle fuel economy.[23]

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[21] When external costs are aggregated across all trucks weighting by mileage shares and relative mileage elasticities, and by fuel use shares and relative fuel use elasticities, the results are only moderately different. In the first case, mileage-related and fuel-related external costs sum to 16.3 cents per mile and 68.2 cents per gallon respectively; in the second case they sum to 18.9 cents per mile and 68.6 cents per gallon. Given that the discrepancies between the two measures are relatively minor, the difference between the optimized taxes and the simpler quasi-optimal taxes in (16) and (17) will be relatively minor.

[22] With one critical exception, our values for marginal external costs for US truck mileage are broadly consistent with those (for all trucks) estimated for Belgium by Mayeres and van Dender (2001) (see their Table 7.14), which in turn are comparable with those for the United Kingdom assumed by Calthrop et al. (2003) (these other studies ignore energy security). The critical exception is urban marginal congestion costs, which are substantially higher than we assume; this reflects higher traffic densities per lane-mile of capacity in Europe than in the United States.

[23] Recent studies suggest a demand elasticity for gasoline use in passenger vehicles of around 0.5 in magnitude or less with 50% or more of the response from improved fuel economy (Small and van Dender 2005, Parry and Small 2005). The very limited evidence available on diesel fuel elasticities suggests they are roughly comparable in magnitude (Dahl 1993, pp. 122-123).

As regards the relative contribution of mileage and fuel economy to the diesel fuel elasticity, EIA (1998) suggest that technological opportunities for improving fuel economy are more limited for trucks than for cars because of the high power requirements necessary to move freight; we therefore assume the mileage component of the elasticity is somewhat larger for diesel than for gasoline. Our assumption is broadly consistent with empirical literature on own-price elasticities for truck freight. Small and Winston (1999), Table 2.2, report estimates for this elasticity from studies varying from −0.04 to −2.97; however some of the estimated responses are "too large" in magnitude for our purposes as they apply to narrowly defined types of freight (and therefore include inter-product substitution) rather than all freight. Calthrop et al. (2003), Table A2, assume a truck freight elasticity of −0.42; given

We might expect urban truck driving to be somewhat less responsive to fuel or mileage taxes than rural driving, since travel time costs are larger relative to the tax for (slower moving) urban driving; we assume $\eta_{iU}^{MF} = 0.7\eta_{iR}^{MF}$. And, since a given fuel tax (or fuel tax equivalent) will raise per mile costs by a smaller amount for the more fuel-efficient single-unit truck than the combination, we assume $\eta_{Sj}^{MF} = 0.7\eta_{Cj}^{MF}$ (i.e. relative elasticities are approximately equal to relative fuel consumption rates). Using these equations, along with $\eta^{MF} = \Sigma_{ij} s_{ij}^M \eta_{ij}^{MF}$, allows us to compute η_{ij}^{MF}, and in turn $\tilde{\eta}_{ij}^{MF}$. We assume the same proportionate reduction in fuel per mile in response to higher fuel taxes for both truck types; adding $(\eta^{FF} - \eta^{MF})$ to η_{ij}^{MF} gives the diesel fuel elasticities η_{ij}^{FF} across trucks and regions in Table 1.

Finally, we assume $\beta_U = 0.6$ based on empirical results by Cervero and Hansen (2002) implying that (for given income and population density) nearly 60% of the reduction in congestion from new urban road capacity is offset by new congestion due to latent demand for travel. For comparison, assumptions for the United Kingdom in Calthrop et al. (2003), where vehicle travel is more likely to be capacity constrained, are equivalent to assuming $\beta_U = 0.8$.

4. Results

A. Benchmark Estimates

Table 2 shows our estimates of optimal taxes using (14)-(17) and parameter values in Table 1. We discuss each tax structure in turn.

First, in the absence of mileage taxes, the optimal (second-best) diesel fuel tax is $1.12 per gallon, or 2.5 times the current tax. Fuel-related externalities account for 68 cents per gallon of this tax and mileage related externalities 60 cents per gallon, after scaling them back by the ratio of the mileage elasticities to the overall fuel price elasticity; the auto offset lowers the optimal tax by 16 cents per gallon. Welfare gains from raising the tax from its current rate of 45 cents per gallon to its optimal level are $1.34 billion per annum.[24]

Second, keeping the diesel fuel tax at its current level, the optimum (second-best) uniform mileage tax is 14.6 cents per mile, which is equivalent to 85 cents per gallon (given current fuel

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that fuel costs are roughly half of operating costs per mile in their analysis, this is approximately consistent with our value for η^{MF}.

[24] If the pre-existing fuel tax were zero, welfare gains from implementing the optimal tax would be a much larger $4.65 billion, as we are integrating over a larger range of fuel reduction with a larger initial difference between the optimum and the initial tax.

economies and mileage shares at the optimum tax). Thus, compared with the previous case, the overall level of taxation is somewhat larger, equivalent to $1.30 per gallon when the current fuel tax is included. Welfare gains from implementing this mileage tax are $1.59 billion, or $0.25 billion higher than under the optimized fuel tax alone. The mileage tax reduces mileage-related externalities more directly than the fuel tax as all, rather than just a portion, of the behavioral response to the tax comes from reduced mileage; this advantage is partly offset however, because the mileage tax forgoes improvements in fuel economy for which (up to a point) there would be net efficiency gains.

The advantage of mileage-related taxes over fuel taxes is less pronounced for heavy-duty trucks than for light-duty passenger vehicles, as analyzed by Parry and Small (2005). The main reason is that mileage-related externalities are much larger in magnitude than fuel-related externalities for passenger vehicles than for heavy trucks; in fact, improvements in passenger vehicle fuel economy in Parry and Small (2005) are actually efficiency reducing, given that the current gasoline tax exceeds their assumed value for marginal fuel-related external costs.[25]

The third tax system involves an optimized diesel tax of 69 cents per gallon, and a mileage tax of 10.9 cents per mile; it represents an improvement over the previous system as it exploits improvements in fuel economy up to the point where the diesel tax equals the marginal cost of fuel-related externalities. However, overall welfare gains are $1.71 billion, which is only $0.12 billion higher than in the previous case.

Finally, the most efficient tax system involves a fuel tax of 69 cents per gallon and mileage taxes that vary from 7 cents per mile for single-unit trucks in rural areas to 20 cents per mile for combinations in urban areas. Welfare gains from this policy are $2.06 billion, a further improvement of $0.35 billion.

B. Sensitivity Analysis

Table 3 illustrates the sensitivity of optimal taxes to alternative parameter assumptions focusing, for simplicity, on the independently optimized diesel fuel tax, and the optimized uniform mileage tax (given the current diesel tax). The upper part of the table varies marginal external costs where, in most

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[25] Local pollution is counted as a mileage-related external cost in their analysis, given that passenger vehicle emissions are regulated on a per-mile basis; they also use a more conservative value for the climate externality and exclude energy security. Fuel economy is also greater for passenger vehicles, which implies that mileage costs convert to a larger figure on a per gallon basis. Finally, Parry and Small assume that the mileage response accounts for 40% of the overall gasoline price elasticity, which weakens the impact of fuel taxes on mileage.

cases, these ranges approximately span high and low values reported in various tables in FHWA (1997, 2000) listed above, while the lower half of the table varies elasticities.[26]

The optimized fuel tax is somewhat sensitive to alternative assumptions about external costs; it varies from 93 cents to $1.50 per gallon across these perturbations, or 83−134% of the benchmark value. The optimized uniform mileage tax is somewhat more sensitive to alternative congestion cost scenarios; it varies between 78 and 159% of its benchmark value across these parameter ranges. Optimal tax rates are not very sensitive to varying the fuel price elasticity, or the mileage elasticity ratios across urban/rural driving and single-unit/combination trucks. However the optimal fuel tax is more sensitive to varying the ratio of the (economy-wide) mileage/fuel price elasticity to the (economy-wide) fuel price elasticity between 0.2 and 0.8 as this significantly affects the relative importance of mileage-related externalities in the optimal tax.

5. Conclusion

This paper develops and implements an analytical framework for estimating optimal fuel and mileage-related taxes to address externalities from heavy-duty trucks in the United States. In our benchmark case, the most efficient tax structure involves a diesel tax of 69 cents per gallon and mileage taxes that vary between 7 and 20 cents per mile across urban and rural areas and single-unit and combination trucks. However, failing to differentiate the mileage tax, or optimizing over a diesel tax alone, yields welfare gains that are 63−83% of those from the most efficient tax structure. In the latter case, the second-best diesel fuel tax is $1.12 per gallon, or 2.5 times the current tax.

As usual in this type of analysis we emphasize the uncertainty over particular parameter values such as the (marginal) damages from greenhouse warming and energy security. In addition, truck emissions of fine particulates and oxides of nitrogen per gallon of fuel for new vehicles will be reduced by up to 90% as new regulations are phased in beginning with the 2007 model year; furthermore, new fuel regulations will drastically lower the sulfur content of diesel fuel. Thus, as the truck fleet turns over during the next couple of decades, local pollution damages should fall substantially. On the other hand, this may be offset (in the absence of widespread implementation of congestion pricing) by higher marginal congestion costs as the growth in demand for highway travel continues to outpace capacity additions. These considerations underscore the need to update the analysis in light of new evidence on parameter values.

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[26] For the most part it seems reasonable to vary external costs one at a time given that most of their underlying determinants are unrelated; the main exception to this is willingness to pay to avoid external harm, which could exhibit some correlation across accidents, noise and local pollution.

Another caveat is that we ignore interactions between truck taxes and distortions in the labor market from income and payroll taxes. As discussed in other literature (e.g., Goulder et al. 1999, Calthrop et al. 2003) these interactions take two forms; first is the efficiency gain from using extra revenues to reduce distortionary labor taxes and second is the efficiency loss from the reduction in labor supply as (freight) taxes are passed forward into higher product prices, thereby diminishing the real returns to work effort. Assuming freight-intensive products have the same degree of substitution with leisure as consumption goods in general, then the net effect is a welfare loss, and optimal taxes are equal to Pigouvian taxes divided by the marginal cost of public funds (Bovenberg and Goulder 1996); for the United States, this adjustment might reduce the optimal tax by around 15%.[27] This critically assumes that extra revenues are used efficiently; if revenues lead to extra public spending that has a lower social benefit than cutting distortionary taxes the optimal truck tax can be considerably reduced (Calthrop et al. 2003, Parry and Bento 2001).

Another limitation is that we ignore the effect of truck taxes on causing substitution into other freight modes, including rail, air and barge; to the extent that marginal external costs for these other modes exceed freight taxes, these supply shifts will induce welfare losses and lower the optimal level of truck taxes. However, estimates of external costs for other modes are currently less well developed than those for trucks so it is difficult to gauge the empirical significance of these effects.

Finally, we assume that the only diesel vehicles are heavy trucks; this is currently reasonable for the United States where diesel vehicles account for only 4% of new passenger vehicle sales (EIA 2005, Table 45), though not for European countries where diesel passenger vehicles are far more common. In the latter case, auto externalities would play a larger role in determining optimal diesel taxes.

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[27] The reduction in congestion from truck taxes will produce an offsetting efficiency gain to the extent it lowers the costs to people from commuting to work, hence stimulating labor supply (e.g., Parry and Bento 2001). However, this efficiency gain is quantitatively important only if the tax is confined to urban mileage at peak period.

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Appendix

Deriving equation (12)

Using (1)-(3) and (5), the household indirect utility function is given by:

$$(A1) \quad \tilde{u} = \tilde{u}(p_{SU}, p_{CU}, p_{SR}, p_{CR}, LST, \pi_U, \pi_R, Z)$$

$$= MAX \quad u\{T_{SU}, T_{CU}, T_{SR}, T_{CR}, Y, A_U, A_R, \Sigma_j \pi_j A_j, Z\}$$

$$+ \lambda[I + LST - \Sigma_{ij}(p_{ij}^T + p_{ij}^0)T_{ij} - Y - (t_G + p_G)\,\Sigma_j(1 + \psi_j^A)f_G A_j]$$

From partially differentiating we obtain:

$$(A2) \quad \frac{\partial \tilde{u}}{\partial \pi_j} = u_\Pi A_j; \quad \frac{\partial \tilde{u}}{\partial Z} = u_Z; \quad \frac{\partial \tilde{u}}{\partial LST} = \lambda; \quad \frac{\partial \tilde{u}}{\partial p_{ij}^T} = -\lambda T_{ij}$$

Totally differentiating the indirect utility function with respect to t_D and using (A2) gives

$$(A3) \quad \frac{1}{\lambda}\frac{d\tilde{u}}{dt_D} = -\Sigma_{ij}T_{ij}\frac{dp_{ij}^T}{dt_D} + \frac{u_Z}{\lambda}\frac{dZ}{dt_D} + \frac{u_\Pi}{\lambda}\Sigma_j A_j\frac{d\pi_j}{dt_D} + \frac{dLST}{dt_D}$$

From differentiating (6), using the envelope condition in (7) and the definition of F_{ij}:

(A4) $\Sigma_{ij} T_{ij} \dfrac{dp_{ij}^T}{dt_D} = \Sigma_{ij} F_{ij} + \Sigma_{ij} T_{ij} w \dfrac{d\pi_j}{dt_D}$

From differentiating (9):

(A5) $\dfrac{dZ}{dt_D} = \Sigma_j z_j^A \dfrac{dA_j}{dt_D} + \Sigma_{ij} \left(z_j^{TF} \dfrac{dF_{ij}}{dt_D} + z_{ij}^{TM} \dfrac{dT_{ij}}{dt_D} \right)$

From differentiating (8):

(A6) $\dfrac{d\pi_j}{dt_D} = \dfrac{\partial \pi_j}{\partial T_{Sj}} \dfrac{dT_{Sj}}{dt_D} + \dfrac{\partial \pi_j}{\partial T_{Cj}} \dfrac{dT_{Cj}}{dt_D} + \dfrac{\partial \pi_j}{\partial A_j} \dfrac{dA_j}{dt_D}$

And from differentiating (10) and (11):

(A7) $\dfrac{dLST}{dt_D} = \Sigma_{ij} F_{ij} + t_D \Sigma_{ij} \dfrac{dF_{ij}}{dt_D} + \Sigma_j \tau_j^A \dfrac{dA_j}{dt_D} + \Sigma_{ij} (\tau_{ij} - z_{ij}^P) \dfrac{dT_{ij}}{dt_D}$

Substituting (A4)-(A7) into (A3) and collecting terms gives (12a-b).

Deriving equation (14)

Equating (12a) to 0, multiplying through by $(p_D + t_D)/F$, substituting η_{FF} as defined in (14b), and substituting dA_j / dt_D using (13) with $\beta_R = 0$, gives:

(A8) $\eta_{FF} \hat{t}_D = \Sigma_{ij} MEC_j^{TF} \dfrac{dF_{ij}}{dt_D} \dfrac{p_D + t_D}{F_{ij}} \dfrac{F_{ij}}{F} + \Sigma_{ij} (MEC_{ij}^{TM} - \tau_{ij}) \dfrac{dT_{ij}}{dt_D} \dfrac{p_D + t_D}{T_{ij}} \dfrac{T_{ij}}{F_{ij}} \dfrac{F_{ij}}{F}$

$$- (MEC_U^A - \tau_U^A) \beta_U \Sigma_i e_{iU} \dfrac{dT_{ij}}{dt_D} \dfrac{p_D + t_D}{T_{ij}} \dfrac{T_{ij}}{F_{ij}} \dfrac{F_{ij}}{F}$$

Substituting the definitions of η_{ij}^{FF}, η_{ij}^{MF} and s_{ij}^F in (14b) in (A8), and dividing by η_{FF}, gives (14a).

Deriving equation (15)

Totally differentiating the indirect utility function in (A1) with respect to τ yields an analogous expression to that in (A3) (i.e., the same equation with $d\tau$ rather than dt_D in the price coefficients); analogous expressions to (A5) and (A6) can also be obtained. Differentiating (6) and (11) with respect to τ yields:

(A9) $\Sigma_{ij} T_{ij} \dfrac{dp_{ij}^T}{d\tau} = \Sigma_{ij} T_{ij} \left(1 + w \dfrac{d\pi_j}{dt_D} \right)$

(A10) $\dfrac{dLST}{d\tau} = t_D \Sigma_{ij} \dfrac{dF_{ij}}{d\tau} + \Sigma_j \tau_j^A \dfrac{dA_j}{d\tau} + \Sigma_{ij} T_{ij} + \Sigma_{ij} (\tau_{ij} - z_{ij}^P) \dfrac{dT_{ij}}{d\tau}$

Using the analogous equations, along with (A9) and (A10), we can obtain the following equation, analogous to (12):

$$(A11) \quad \frac{1}{\lambda}\frac{d\tilde{u}}{d\tau} = \Sigma_{ij}(MEC_j^{TF} - t_D)\left(-\frac{dF_{ij}}{d\tau}\right) + \Sigma_{ij}(MEC_{ij}^{TM} - \tau)\left(-\frac{dT_{ij}}{d\tau}\right) - \Sigma_j(MEC_j^A - \tau_j^A)\frac{dA_j}{d\tau}$$

We now equate (A11) to zero, using $dT_{ij}/d\tau \equiv (dT_{ij}/dt_D)T_{ij}/F_{ij}$ and noting that $dF_{ij}/d\tau \equiv (dT_{ij}/d\tau)F_{ij}/T_{ij}$. In addition, from (13) β_j is the same regardless of whether the denominator of the price coefficient is t_D or τ, since it measures the change in auto mileage in response to a given change in truck mileage. Thus we obtain, after multiplying through by $(p_D + t_D)/T$, and setting $\beta_R = 0$:

$$(A12) \quad \hat{\tau}\Sigma_{ij}\frac{dT_{ij}}{dt_D}\frac{p_D + t_D}{T_{ij}}\frac{T_{ij}}{T}\frac{T_{ij}}{F_{ij}} = \Sigma_{ij}(MEC_j^{TF} - t_D)\frac{dT_{ij}}{dt_D}\frac{p_D + t_D}{T_{ij}}\frac{T_{ij}}{T}$$

$$+ \Sigma_{ij}MEC_{ij}^{TM}\frac{dT_{ij}}{dt_D}\frac{p_D + t_D}{T_{ij}}\frac{T_{ij}}{T}\frac{T_{ij}}{F_{ij}} - (MEC_U^A - \tau_U^A)\beta_U\Sigma_i e_{iU}\frac{dT_{iU}}{dt_D}\frac{p_D + t_D}{T_{iU}}\frac{T_{iU}}{T}\frac{T_{iU}}{F_{iU}}$$

Substituting expressions s_{ij}^M, $\tilde{\eta}_{ij}^{TM}$, η_{ij}^{TM} and $\tilde{\eta}^{TM}$ from (14b) and (15b) in (A12) gives (15a); since fuel economy is unaffected by the mileage tax it is constant at its initial value T_{ij}^0/F_{ij}^0.

Deriving (19)

From using (14b) we can obtain

$$(A13) \quad \hat{t}_D\Sigma_{ij}\frac{dF_{ij}}{dt_D} = \hat{t}_D\frac{F}{p_D + t_D}\eta_{FF}$$

Substituting (14a) in (A13), after substituting for s_{ij}^F and η_{ij}^{FF} from (14b) gives:

$$(A14) \quad \hat{t}_D\Sigma_{ij}\frac{dF_{ij}}{dt_D} = \Sigma_{ij}MEC_j^{TF}\frac{dF_{ij}}{dt_D} + \Sigma_{ij}(MEC_{ij}^{TM} - \tau_{ij})\frac{dT_{ij}}{dt_D} - (MEC_U^A - \tau_U^A)\beta_U\Sigma_i e_i\frac{dT_{iU}}{dt_D}$$

Adding and subtracting $\hat{t}_D\Sigma_{ij}dF_{ij}/dt_D$ to (12a), using (A13), (A14), and (13) yields (19a). Equation (19b) is obtained in an analogous fashion from adding and subtracting $\hat{\tau}\Sigma_{ij}dT_{ij}/d\tau$ to (A11). Note that the fuel tax equivalent of the mileage tax, averaged across mileage, is $\hat{\tau}\Sigma_{ij}s_{ij}^F(T_{ij}/F_{ij})$.

Computing Welfare Effects for Differentiated Mileage Taxes

Welfare gains under the fuel tax/differentiated mileage policy equal those under the optimized fuel tax/uniform mileage tax plus the gains from changing individual mileage taxes by $\hat{\tau}_{ij} - \hat{\tau}$. We first compute the welfare change from changing the tax on single-unit trucks in rural areas using the following expression:

$$(A15) \quad \left(\tau_{SR} - \hat{\tau}_{SR} - \mu_{SU}^{SR}(\hat{\tau} - \hat{\tau}_{SU}) - \mu_{CR}^{SR}(\hat{\tau} - \hat{\tau}_{CR})\right) \frac{T_{SR}\tilde{\eta}_{SR}^{MF}(1 - \mu_{SU}^{SR} - \mu_{CR}^{SR})}{p_D + \tau \Sigma_{ij} s_{ij}^F T_{ij} / F_{ij} + (\tau_{SR} - \hat{\tau})T_{SR} / F_{SR}}$$

Here μ_{SU}^{SR} and μ_{CR}^{SR} are the fractions (assumed constant) of the reduction in single-unit/rural truck driving that is diverted into single/urban and combination/rural driving respectively (we assume no diversion into combination/urban driving). Thus $\mu_{SU}(\hat{\tau} - \hat{\tau}_{SU})$ and $\mu_{CR}(\hat{\tau} - \hat{\tau}_{CR})$ are the welfare effect from the substitution into these other truck modes per mile reduction in single/rural truck driving. The other notable difference between (A15) and the analogous expression in (19b) is that the elasticity $\tilde{\eta}_{SR}^{MF}$ is divided by $1 - \mu_{SU}^{SR} - \mu_{CR}^{SR}$. The reduction in single/rural driving in response to an increase in the mileage tax on that mode compared with the response when the tax on all modes is increased; the former tax increase causes inter-modal substitution effects (in addition to reduced overall truck driving an increased tonnage carried per mile) while the latter tax increase does not. We integrate over (A15) to compute the total welfare gain from increasing the single/rural tax from $\hat{\tau}$ to $\hat{\tau}_{SR}$.

Next, we compute the welfare gain from changing the single/urban mileage tax from $\hat{\tau}$ to $\hat{\tau}_{SU}$ using:

$$(A16) \quad \left(\tau_{SU} - \hat{\tau}_{SU} - \mu_{CU}^{SU}(\hat{\tau} - \hat{\tau}_{CU})\right) \frac{T_{SU}\tilde{\eta}_{SU}^{MF}(1 - \mu_{SR}^{SU} - \mu_{CU}^{SU})}{p_D + \tau \Sigma_{ij} s_{ij}^F T_{ij} / F_{ij} + (\tau_{SU} - \hat{\tau})T_{SU} / F_{SU}}$$

Here μ_{SR}^{SU} and μ_{CU}^{SU} are the fraction of the reduction in single/combination truck driving that is diverted into single/rural and combination/urban driving respectively. This expression is analogous to that in (A15) except that there is no welfare effect from the substitution into single/rural driving, given that the tax has previously been set equal to the marginal cost of mileage-externalities. Again, (A16) is integrated to compute the total welfare gain from the tax change.

Next we use an analogous expression to (A16) to compute the welfare change from changing the combination/rural truck mileage tax from $\hat{\tau}$ to $\hat{\tau}_{CR}$, accounting for substitution into combination/urban and single/rural truck driving. Finally, we change the combination/urban tax from $\hat{\tau}$ to $\hat{\tau}_{CU}$; in this case, neither the substitution into combination/rural or single/urban affects welfare, given that taxes for these modes have already been optimized. Summing the welfare changes from the four individual tax changes

gives the additional welfare gain from the differentiated mileage tax system over the quasi-optimal fuel and uniform mileage tax system.

There is no econometric evidence on which to base values for the μs; we make the assumption that all the μs are equal to 0.25, therefore half of the reduction in mileage on a mode in response to a higher tax on that mode is due to substitution into other modes and half comes from reduced overall mileage due to reduced product demand or higher tonnage per mile. If instead, 25% or 75% of the reduction in mileage came from inter-modal substitution, the additional welfare gains from differentiated mileage taxes would be (approximately) 67% smaller, or 100% larger, respectively.

Table 1. Benchmark Parameter Values

| | Single-unit trucks | | Combination trucks | | All trucks | | | Auto |
	Rural	Urban	Rural	Urban	Rural	Urban	All regions	urban
Vehicle miles, billion	32	39	82	53	114	91	206	1,664
Mileage shares	0.15	0.19	0.40	0.26	0.56	0.44	1	
Fuel economy, miles/gal.	9.4	6.3	6.3	4.2	6.9	4.9	5.8	15.0
Fuel use, billion gals	3.4	6.2	13.2	12.5	16.5	18.7	35	
Fuel use shares	0.10	0.18	0.37	0.36	0.47	0.53	1	
Prior fuel tax, cents/gal.	45	45	45	45	45	45	45	40
Marginal external costs								
Milage-related (cents/mile)								
Congestion	2.5	14.5	3.7	16.8	3.4	15.8	8.9	7.7
Accidents	3.1	1.1	3.4	1.8	3.3	1.5	2.5	2.0
Noise	0.1	1.2	0.3	3.7	0.2	2.7	1.3	0.1
Road damage	1	3.1	3.3	10.5	2.7	7.4	4.7	0
Sum	**6.7**	**19.9**	**10.7**	**32.8**	**9.6**	**27.3**	**17.5**	**9.9**
Sum (cents/gallon)	**63**	**125**	**67**	**138**	**66**	**132**	**95**	**148**
Fuel-related (cents/gal.)								
Local pollution	36	42	36	42	36	42	39	20
Global pollution	14	14	14	14	14	14	14	12
Oil dependency	16	16	16	16	16	16	16	16
Sum	**66**	**72**	**66**	**72**	**66**	**72**	**69**	**48**
Sum (cents/mile)	**7.1**	**11.5**	**10.5**	**17.2**	**9.8**	**15.3**	**12.7**	**3.2**
Fuel price elasticity	-0.38	-0.31	-0.47	-0.38	-0.44	-0.35	-0.40	
Mileage/fuel price elasticity	-0.22	-0.15	-0.31	-0.22	-0.28	-0.19	-0.24	
Congestion offset								0.6
Passenger-car equivalent		1.9		2.2				

Sources: See discussion in text.

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Table 2. Benchmark Estimates of Optimal Taxes and Welfare Gains

Tax reforms	units	optimized taxes Fuel-related externalities	Mileage-related externalities	auto offset	sum	welfare gain from optimal tax, $billion
Diesel tax only	cents/gal.	68	60	-16	112	1.34
Uniform mileage tax only	cents/mile	3.7	14.4	-3.5	14.6	1.59
	cents/gal.	22	84	-20	85	
Optimized diesel and uniform mileage taxes						
diesel tax	cents/gal.	69			69	1.71
mileage tax	cents/mile		14.4	-3.5	10.9	
	cents/gal.		85	-21	65	
Diesel and differentiated mileage taxes						
diesel tax	cents/gal.	69			69	2.06
single-unit/rural			7		7	
single-unit/urban			20	-11	9	
combination/rural			11		11	
combination/urban			33	-13	20	

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Table 3. Sensitivity of Optimal Taxes to Alternative Parameters
(for the diesel tax and diesel tax/uniform mileage tax combination)

		Optimized diesel tax, cents/gal.	Optimized mileage tax given initial diesel tax, cents/mile
Benchmark values		112	14.6
Marginal external costs			
Congestion	increased 200%	148	23.2
	reduced 75%	99	11.4
Accidents	increased 200%	128	19.0
	reduced 50%	109	13.4
Noise	increased 125%	117	15.5
	reduced 70%	110	14.1
Road damage	increased 100%	130	18.6
	reduced 50%	104	12.6
Local pollution	increased 100%	150	20.3
	reduced 50%	93	11.8
Global pollution	increased 200%	139	18.6
	reduced 75%	102	13.1
Oil dependence	increased 200%	142	19.0
	reduced 75%	101	13.0
Magnitude of elasticities			
Fuel price elasticity	increased to 0.8	115	14.7
	reduced to 0.2	111	14.6
Mileage to fuel price elasticity	increased to 0.8	125	14.6
	reduced to 0.2	84	14.6
Urban to rural mileage elasticity	increased to 0.9	115	15.0
	reduced to 0.5	109	14.1
Single to combination mileage elasticity	increased to 0.9	111	14.2
	reduced to 0.5	114	15.0