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Trucking Fuel Taxes and Economic Efficiency in Primary Grain Transportation

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A tax on fuel is one of the primary mechanisms for reducing truck transport externalities such as greenhouse gas emissions, road damage, congestion, and accidents. The economic efficiency properties of a fuel tax are examined for the farm-to-elevator grain trucking sector—a sector for which the road damage externality is often severe. Because trucking volumes cumulate more rapidly near the delivery points, marginal external cost is generally not proportional to distance. Further, noncompetitive FOB pricing by grain buyers implies that road tax discounts to offset price markups should be independent of location. In both cases, a fuel tax is not capable of efficiently addressing the externality. With discriminatory pricing by buyers, "cross-hauling" emerges and the optimal fuel tax is unexpectedly high because the buyer passes on only a portion of the tax to the farmer. In a simple example with discriminatory pricing, the optimal fuel tax reduces excess average trucking distance by less than 50%.

Key words: fuel taxes, grain transportation, imperfect competition, spatial model

Introduction

There is a growing literature on truck transport fuel taxes as a mechanism for addressing environmental externalities such as emissions (Newberry 1992; Sterner, Dahl, and Franzen) and more direct externalities such as congestion, accidents, and road damage (e.g., Newberry 1988a, b; Vitaliano and Held; Gronau; Jansson; Hau; Verhoef, Nijkamp, and Rietveld; Calthrop and Proost).

Within this literature, it is well known that a fuel tax is usually less efficient than the more general optimal road charge, which must continually adjust to make up the difference between systemwide marginal cost and the portion of average variable cost borne by the trucker prior to the road charge (Small). More generally, it has been recognized that fuel taxes paid by truckers can have important distributional impacts and a variety of secondary impacts within the population as a whole due to income effects and interactions with existing transportation policies and taxation distortions (Gersovitz; Casler and Rafiqui; Mayeres).

Despite the shortcomings of a fuel tax and despite the fact that technologies now exist to implement explicit road pricing schemes at a reasonable cost, a fuel tax, in combination with trucking weight restrictions, remains the primary mechanism for dealing with truck transport externalities. At first glance, it would seem a fuel tax is a reasonable

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policy instrument to deal with external trucking costs because fuel consumption and external costs both tend to be roughly proportional to the volume and distance of transport.

The purpose of this analysis is to examine the economic efficiency properties of a fuel tax and to highlight the main disadvantages of this instrument for controlling truck transport externalities. The model constructed in this study to examine the fuel tax is specifically designed for farm-to-elevator grain trucking, but there are many other scenarios. For example, firms which utilize just-in-time inventory systems where retail outlets are served by local warehouse hubs (e.g., WalMart) will create externalities and face fuel tax incentives similar in many respects to those in grain transportation.

Each year over 100 million tons of grain are transported on rural roads, secondary highways, and freeways in the United States and Canada as grain moves from farms to primary delivery points. In many cases, road damage from grain transport is considerable, and there is growing concern about other aspects of grain transportation such as greenhouse gas emissions and accidents.[1]

What level of fuel tax does a typical grain trucker face? In Canada, a \$0.02/liter federal excise tax on diesel fuel was introduced in 1985, and this tax was later raised to \$0.04/liter (about 7% of the total price for diesel). In the grain-producing province of Saskatchewan, the provincial excise tax for diesel has remained constant at \$0.15 per liter (about 25% of the total selling price) since 1993. Saskatchewan farmers are allowed to purchase specially marked, tax-exempt diesel fuel for exclusive use on their farms. However, many farmers are contracting with commercial trucking firms or making arrangements with grain companies to supply the trucking service, implying a diminished importance for this tax exemption.

A number of unexpected theoretical results emerge from the current analysis of a fuel tax, primarily because the grain trucking sector has several unique characteristics. First, farm-level grain supply is distributed throughout a region and is trucked to one or two delivery points located within the region. This configuration implies grain volumes cumulate more rapidly near delivery points, and thus marginal external road cost is highest at locations nearest to a delivery point. Because of this spatial variation in marginal external cost, the optimal road tax is generally not strictly proportional to distance. The fuel tax is strictly proportional to distance and as a result is not efficient.

A second important characteristic of grain trucking is that the grain procurement sector is generally noncompetitive as a result of spatially differentiated grain buyers who market grain with considerable economies of scale. Noncompetitive pricing results in inefficiently low grain volumes, and thus the efficient fuel tax should be reduced below the level corresponding to the competitive case. With FOB pricing, this reduction should be the same for all farmers. A reduction which is independent of location is not possible with a fuel tax, and consequently the outcome is inefficient. In some situations, it will not be feasible for the taxing authority to reduce the fuel tax to completely

[1] Most of Canada's grain is produced in the province of Saskatchewan. An extensive network of rural roads and highways connect the approximately 60,000 Saskatchewan farmers with several hundred country elevators (the average distance is about 30 kilometers). Many of these roads are thinly paved or graveled, and thus are not designed to handle heavy truck traffic, especially during the spring thaw. The average cost of road maintenance and upgrading in Saskatchewan is between 16 and 17 cents per ton kilometer for heavy truck traffic (Richards). This expenditure compares with a private truck operating cost of about 6 cents per ton kilometer. Vercammen estimated total Saskatchewan grain shipments by truck could rise from about 0.4 billion ton kilometers to as much as 2 billion ton kilometers because of elevator closures.

eliminate the effects of noncompetitive pricing because the tax revenue is needed to finance the external costs. The so-called Ramsey pricing solution is formally considered in the analysis.

Another aspect of the noncompetitive pricing problem concerns the nature of competition between grain buyers. In the standard environment, buyers are assumed to set FOB prices (perhaps in a Bertrand fashion) such that farmers who deliver grain receive the same gross price for their product but pay an amount for trucking (including fuel taxes) which depends on location. In this case, the farmer's choice of where to deliver is efficient, but the volume of grain produced is inefficiently low. Rather than setting FOB prices, buyers may be able to spatially price discriminate. For example, buyers may compete for grain on a farm-by-farm basis by signing ex ante production contracts.[2] In this case, the price is set at the farm gate and the buyer absorbs the trucking expense. It is also established in this analysis that the optimal fuel tax is comparatively high in the discriminatory pricing case, and can even exceed the marginal external road cost. The main reason for this result is that only a portion of the fuel tax is passed on to farmers when buyers price discriminate.

Discriminatory pricing also results in "cross-hauling" (i.e., grain from a particular location moving in multiple directions). A tax on trucking fuel reduces, but does not eliminate, cross-hauling. The failure of the fuel tax to eliminate cross-hauling is compounded by an additional inefficiency: with discriminatory pricing, grain volumes do not necessarily decrease as the distance to market increases, regardless of the size of the fuel tax. A simple example demonstrates that the optimal fuel tax reduces excess average travel distances by less than 50% when buyers price discriminate. In the long run, when the location of the elevators is endogenous, fuel taxes have additional efficiency considerations. A second example shows a higher tax is generally needed to reduce the spacing between elevators toward the efficient level.

The remainder of the article proceeds as follows. First, the model is developed and the socially efficient road tax is derived and analyzed under the assumption the FOB procurement price set by a single buyer is exogenous and constant, possibly at a noncompetitive level. The next section details the analysis, which focuses on a fuel tax. Specifically, the optimal fuel tax is derived and its general properties are compared to the optimal road tax derived in the previous section. Only in special circumstances are the two tax mechanisms equivalent. The case of a fuel tax with discriminatory pricing and cross-hauling is then considered. Concluding comments are offered in the final section.

Optimal Road Tax with Fixed Procurement Price

Consider a straight road of unit length with a grain buyer located at the left end.[3] Identical farmers are uniformly distributed along the road and use a truck to deliver their grain to the buyer. The buyer pays a fixed FOB price per unit of grain, θ, for all deliveries (i.e., there is no spatial price discrimination). The resale price of each unit of

[2] In the absence of production contracts, buyers may choose to set FOB prices but will offer trucking subsidies that differ according to farm location. In the extreme case, setting FOB prices and offering trucking subsidies is identical to pure discriminatory pricing. Trucking subsidies are common in the province of Saskatchewan.

[3] Of course, the assumption the road is of unit length does not result in any loss of generality because the length of the road can be implicitly varied by scaling the other parameters of the model.

grain procured by the buyer is constant at p. The buyer incurs variable cost m per unit of deliveries and has no fixed costs.[4]

Let $x(r)$ denote the volume of grain produced by a farmer a distance r to the right of the buyer, where $r \in [0, 1]$. To simplify the analysis, assume one unit of production is equal to one truckload of grain (all farmers have the same truck size), such that x units of production give rise to x truck trips between the farm and the buyer. The conceptual problem associated with fractional truckloads is ignored. Let $c(x)$ denote the farmer's cost of producing x units of grain (the same for all farmers). This cost function is assumed increasing and convex [i.e., $c'(x) > 0$ and $c''(x) > 0$]. Let $h(r)$ denote the per trip trucking cost for a farmer located at r.[5] Specifically, $h(r) = f\phi r + z(r)$, where f is the amount of fuel used by the truck per unit distance, ϕ is the unit cost of fuel, and $z(r)$ is a general function that measures the nonfuel truck costs.[6] This latter function is assumed increasing and possibly convex such that $z'(r) > 0$ and $z''(r) \geq 0$. The per truckload road tax imposed by the policy maker for a farmer at location r is given by the general function $t(r)$.

External Road Cost Function

For each load of grain delivered to the buyer, the road deteriorates and additional external costs arise due to factors such as increased congestion, emissions, accidents, stone chips, and so forth. For simplicity, assume the total external cost at location s depends only on the cumulative number of truckloads of grain transported over point s. Let $X(s)$ denote the cumulative truck volume passing over point s, and let $\omega(X(s))$ denote the external cost function. It is natural to assume $\omega'(\cdot) > 0$ and $\omega''(\cdot) \geq 0$, implying external costs increase (possibly at an increasing rate) as more trucks pass over point s.

The external cost at point s attributable to the farmer located at r ($s < r$) can be expressed as follows:

$$(1) \qquad \omega\big(X(s)\big) - \omega\big(X(s) - x(r)\big) \approx \omega'\big(X(s)\big)x(r).$$

To simplify the analysis, it is assumed that marginal external cost, $\omega'(X)$, is a linear function of cumulative volume; that is, $\omega'(X) = \alpha + \beta X(r)$. Given this assumption, an expression for the total external costs attributable to the farmer at point r, denoted $\Omega(r)$, can be written as

$$(2) \qquad \Omega(r) = x(r)\int_0^r \left(\alpha + \beta\int_s^1 x(t)\,dt\right) ds.$$

This expression can be integrated by parts and rewritten as

$$(3) \qquad \Omega(r) = x(r)\left[\alpha r + \beta\left(r\int_r^1 x(s)\,ds + \int_0^r x(s)s\,ds\right)\right].$$

[4] The assumption that fixed costs equal zero is made only for convenience, and it does not affect the main results of the analysis.

[5] The relationship between trucking cost and location will generally depend on whether the truck is owned and operated by the farmer or the trucking function is contracted out. This distinction is ignored in this analysis.

[6] To account for the return trip, f should be defined as the amount of fuel used to travel a distance $2r$, where the truck is loaded for distance r and empty for distance r.

The total external cost from all farmers delivering to the buyer, denoted D, can be specified as

$$D = \int_0^1 \Omega(r)\,dr. \tag{4}$$

Substituting in equation (3) and integrating by parts allows equation (4) to be rewritten as

$$\begin{aligned} D = {} & \alpha \int_0^1 rx(r)\,dr + \beta \int_0^1 \bar{x}_0(r)x(r)r\,dr - 0.5\beta \int_0^1 \bar{x}_1(r)x(r)r^2\,dr \\ & - \beta \int_0^1 \left[\bar{x}_0(r) - \bar{x}(r_1)\right]x(r)r^2\,dr, \end{aligned} \tag{5}$$

where

$$\bar{x}_0(r) = \frac{1}{r}\int_0^r x(m)\,dm \quad \text{and} \quad \bar{x}_1(r) = \frac{2}{r^2}\int_0^r mx(m)\,dm.$$

The analysis is greatly simplified if an approximation is made within equation (5). Specifically, substitute the constant $\bar{x}$ for $\bar{x}_0(r)$ and $\bar{x}_1(r)$, where $\bar{x}$ can be interpreted as the average volume delivered by farmers within the system. The approximation is exact if the farmers' supply schedule is perfectly inelastic, and diminishes in accuracy the greater the supply differential between farmers at different locations. After making this substitution, an expression for approximate total external cost, $\tilde{D}$, can be rewritten as

$$\tilde{D} = (\alpha + \beta\bar{x})\int_0^1 rx(r)\,dr - 0.5\beta\bar{x}\int_0^1 r^2x(r)\,dr. \tag{6}$$

Incentive Compatibility Constraint

The problem facing the policy maker is to choose the schedule of road taxes that maximizes social welfare. The solution procedure entails the policy maker choosing the welfare-maximizing level of output for each farmer along the road. Once the optimal level of output has been determined, the level of tax required to ensure each farmer will voluntarily produce the optimal level of output is then determined. The function specifying the correct amount of road tax for a farmer at location r is referred to as the incentive compatibility constraint.

The incentive compatibility constraint is derived from an individual farmer's first-order condition for profit maximization. The problem facing a farmer at location r is to choose x to maximize profits given by $[\theta - h(r) - t(r)]x - c(x)$. The first-order condition can be written as

$$t(r) = \theta - c'(x) - h(r). \tag{7}$$

The incentive compatibility constraint given by equation (7) holds globally as well as locally because $c''(x) > 0$ and $h''(r) \geq 0$ by assumption.

Objective Function and Solution

It is now necessary to specify the objective function for the policy maker in order to derive the optimal road tax. The policy maker sets the road tax to maximize social welfare, denoted S, which is comprised of the sum of producer surplus, tax revenues, and buyer profits minus the external road cost. The policy maker is assumed to face a budget constraint. Specifically, total external costs minus aggregate fuel tax revenues must be less than Z. The parameter Z represents both the fraction of external costs absorbed by the taxing authority and the extent of external subsidies to the system.

The objective function can be expressed as

$$(8)\qquad \begin{aligned} S &= \int_0^1 [(\theta - h(r) - t(r))x(r) - c(x(r))]\,dr + \int_0^1 t(r)x(r)\,dr \\ &\quad + \int_0^1 [p - m - \theta]x(r)\,dr - \tilde{D}, \\ &\text{s.t.: } \tilde{D} - \int_0^1 t(r)x(r)\,dr \le Z. \end{aligned}$$

After canceling and rearranging terms, the Lagrange function associated with equation (8) can be denoted by

$$(9)\qquad L = \int_0^1 \{(p - h(r) - m)x(r) - c(x(r)) + \lambda t(r)x(r)\}\,dr + \lambda(Z - \tilde{D}).$$

To derive the optimal level of production for each farmer, it is necessary to first substitute the incentive compatibility constraint given by equation (7) into equation (9). The resulting expression does not involve $\partial x(r)/\partial r$ or higher order derivatives, and thus differentiation with respect to x (i.e., pointwise differentiation) is appropriate to obtain the set of first-order conditions. After some rearranging, the schedule showing the optimal level of production at each location r can be represented by

$$(10)\qquad p - m - h(r) - c'(x) - \frac{\partial \tilde{D}}{\partial x} - \frac{\lambda}{1+\lambda}(p - m - \theta + x(r)c''(x)) = 0.$$

Equation (10) can be interpreted as follows. The first five terms represent the marginal benefits and costs from additional grain production at location r, thus defining the efficient level of production in the absence of a budget constraint. The set of terms in parentheses reflects the extent to which production deviates from the efficient outcome because of the budget constraint. For example, if $p - m > \theta$, implying a positive price markup by the grain buyer, then a binding budget constraint (i.e., $\lambda > 0$) implies production at location r is less than the unconstrained efficient level.

Of primary interest is the form of the optimal tax schedule across the set of farmers. This schedule is obtained by solving equation (10) for $c'(x)$ and substituting the resulting expression into the incentive compatibility constraint given by equation (7). After substituting in the expression for $\partial\tilde{D}/\partial x$ obtained from equation (6), the resulting optimal tax schedule, denoted $t^*(r)$, can be expressed as

$$(11)\qquad t^*(r) = (\alpha + \beta\bar{x}(1 - 0.5r))r - (p - m - \theta - \lambda x(r)c''(x))\frac{1}{1+\lambda}.$$

Equation (11) shows the optimal tax schedule has two distinct components. The first component, expressed on a per unit volume and per unit distance basis, is $\alpha + \beta\bar{x}(1 - 0.5r)$. Notice that all farmers pay a unit tax of $\alpha + \beta\bar{x}$ less a discount which is proportional to the distance from the chosen delivery point. Only if $\beta = 0$ (i.e., the external road cost is constant) do all farmers pay the same unit tax. Equation (11) emerges because, in the absence of pricing distortions or budget constraints, the optimal tax for each farmer equals the sum of the marginal external cost over all points between the farmer and his/her chosen delivery point. The reason the unit tax rate (i.e., the tax per unit volume per unit distance) falls for more distant farmers when $\beta > 0$ is because the average unit external cost at a particular point is lower for more distant points due to lower cumulative grain volumes.[7]

The second component of the optimal tax schedule in equation (11) corrects for pricing distortions and accounts for the budget constraint. Suppose there is no budget constraint, such that $\lambda = 0$. If the buyer earns unit revenues in excess of marginal cost equal to $p - m - \theta$, then it is optimal for the social planner to offset this price distortion with a road tax reduction equal to $p - m - \theta$ per unit volume for all farmers. For farmers located near the grain buyer, the optimal tax might therefore be negative. If the budget constraint is binding (i.e., $\lambda > 0$), then the road tax reduction to account for noncompetitive pricing by the grain buyer is smaller. These budget constraint outcomes correspond to the well-known Ramsey pricing solution in the public economics literature (e.g., Atkinson and Stiglitz, pp. 370–75).

Optimal Fuel Tax

Suppose the optimal road tax given by equation (11) cannot be implemented. Furthermore, suppose the only feasible instrument for dealing with the road cost externality is a fuel tax of γ per unit of fuel. With this scenario, the trucking cost function can be expressed as $h(r, \gamma) = f(\phi + \gamma)r + z(r)$, and the total per trip fuel tax paid by the farmer at location r, denoted $\tau(r)$, can be expressed as $\tau(r) = f\gamma r$. To simplify matters, assume the budget constraint of the taxing authority is not binding (i.e., $\lambda = 0$), such that the optimal tax can fully address the noncompetitive pricing externality. It may be the case that farmers are required to pay a lump-sum tax (e.g., a property tax) to make up any shortfall in revenue for the taxing authority.

The objective function given by equation (8) can now be rewritten as

$$(12) \qquad S = \int_0^1 [(p - m - f\phi r - z(r))x(r) - c(x(r))]\, dr - \tilde{D}.$$

The first-order condition for choosing the value of the fuel tax, γ, to maximize equation (12) can be expressed as

$$(13) \qquad \frac{dS}{d\gamma} = \int_0^1 [(p - m - f\phi r - z(r)) - c(x(r))]\, \frac{dx(r)}{d\gamma}\, dr - \frac{d\tilde{D}}{d\gamma} = 0.$$

As before, the incentive compatibility restriction can be written as $\theta - f(\phi + \gamma)r - z(r) - c'(x(r)) = 0$, and used to show that $dx(r)/d\gamma = -fr/c''(x(r))$. If these expressions are substituted into equation (13), then an expression for the optimal unit fuel tax can be specified as

[7] With $\beta = 0$, the unit tax is the same for all farmers and is set equal to marginal external cost, α, in which case aggregate tax revenue just equals aggregate external cost. If $\beta > 0$, then the marginal external cost is increasing as the total volume of grain increases, in which case the marginal tax rate will exceed the marginal external cost attributable to that farmer. Now, aggregate tax revenue will exceed aggregate external cost. This type of result is common in the public economics literature (Oum and Tretheway).

$$\gamma^* = \frac{-d\tilde{D}/d\gamma - (p - m - \theta) f \int_0^1 r/c''(x(r))\, dr}{f^2 \int_0^1 r^2/c''(x(r))\, dr}. \tag{14}$$

Using equation (6), it can be shown that

$$\frac{d\tilde{D}}{d\gamma} = -f(\alpha + \beta\bar{x}) \int_0^1 r^2/c''(x(r))\, dr + 0.5 f\beta\bar{x} \int_0^1 r^3/c''(x(r))\, dr. \tag{15}$$

To further simplify the analysis, consider the special case of a quadratic cost function where $c''(x(r))$ is a constant. An expression for the optimal fuel tax paid by the farmer at location r can be derived by substituting equations (14) and (15) into the fuel tax expression, $\tau(r) = f\gamma r$, canceling the c'' expressions and then integrating:

$$\tau^*(r) = \left[\alpha + (5/8)\beta\bar{x} - (3/2)(p - m - \theta)\right] r. \tag{16}$$

It is now possible to compare the optimal fuel tax given by equation (16) and the optimal road tax given by equation (11) for the special case where the taxing authority's budget constraint does not bind (i.e., $\lambda = 0$) and the farmers' cost function is quadratic. The optimal fuel tax is a linear approximation of the optimal road tax, which is nonlinear because of the nonlinear relationship between road volume and external cost. The parameter β provides a measure of the degree of nonlinearity and is thus central to the analysis. The multiplier on β for the optimal fuel tax in equation (16) is $(5/8)r\bar{x}$, whereas the multiplier on β for the optimal road tax in equation (11) is $(1 - 0.5r)r\bar{x}$ (recall r ranges from 0 to 1). The larger the value of β, the greater the approximation error and the less effective is the fuel tax relative to the first-best outcome. Further, it can be shown the deadweight loss from using the less efficient taxation scheme increases at an increasing rate as β takes on larger values.

It can be shown the two tax functions are equal at $r = r^*$, where r^* satisfies

$$r^* = \frac{3}{8} + \frac{3(p - m - \theta)}{2\beta\bar{x}} + 0.5\left[\left(\frac{3}{4} + \frac{3}{\beta\bar{x}}(p - m - \theta)\right)^2 - \frac{8}{\beta\bar{x}}(p - m - \theta)\right]^{1/2}. \tag{17}$$

If pricing is competitive (i.e., $\theta = p - m$), then equation (17) reduces to $r^* = 3/4$ for $\beta > 0$. With $\theta = p - m$ and $\beta = 0$, the two tax functions are identical, and thus there is no unique point of intersection. Equation (17) also shows that r^* is increasing in θ, implying a greater degree of noncompetitive pricing results in a smaller value of r^*.

The optimal road tax function and optimal fuel tax function are compared in figure 1. Note, for the competitive pricing case (the top set of graphs), all farmers located between the delivery point and $r = 3/4$ prefer the fuel tax to the road tax, while the opposite is true for farmers located beyond $r = 3/4$. The intuition of this result is that the fuel tax is excessive for distant farmers because the average tax per unit distance is constant but the average external cost per unit distance declines as distance to the market increases. As observed from figure 1, the greater the degree of nonlinearity of road damage (as measured by β), the greater the distortionary and distributional impacts of the fuel tax. In the noncompetitive pricing case, the farmer located at $r^* = r^0 < 3/4$ is indifferent between the two tax schemes. Contrary to the previous case, farmers to the left of this indifferent farmer prefer the optimal road tax to the optimal fuel tax, and farmers to the right prefer the opposite.

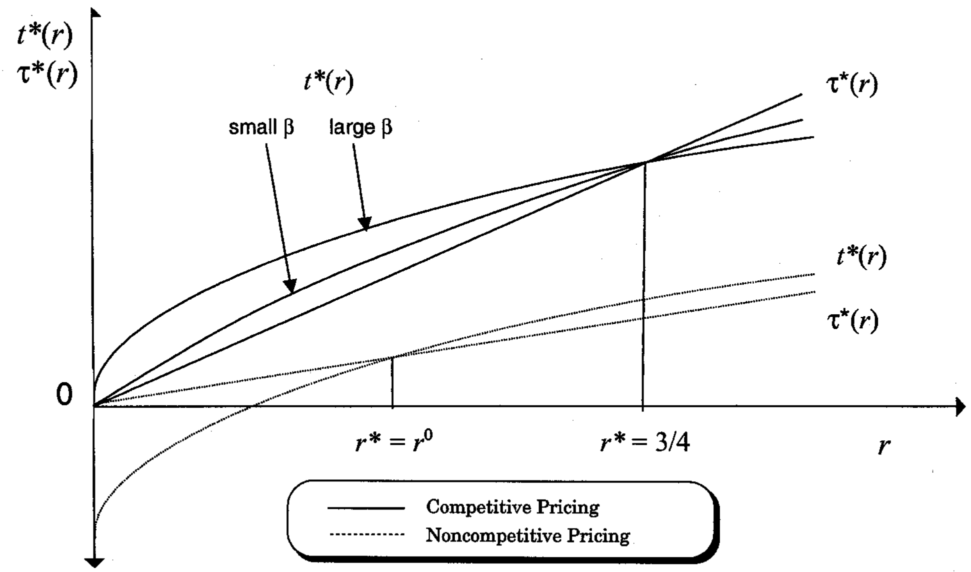

Figure 1. Comparison of optimal fuel tax and unconstrained optimal road tax

Finally, it is useful to compare the average optimal road tax and average optimal fuel tax across all farmers. Integrating equation (11) with $\lambda = 0$ and equation (16) from 0 to 1, subtracting the latter from the former, and simplifying yields the following:

$$\int_0^1 t^*(r)\,dr - \int_0^1 \tau^*(r)\,dr = (1/48)\beta\bar{x} - 0.5(p - m - \theta). \tag{18}$$

Equation (18) shows that with competitive pricing (i.e., $\theta = p - m$), the average optimal road tax exceeds the average optimal fuel tax, although the difference is relatively small.

Fuel Tax with Strategic Discriminatory Pricing

In the previous section for the case of competitive pricing, excessive grain production was the sole cause of the excessive road cost. In other words, the farmers' equilibrium choice of where to deliver was efficient, but the amount of grain each farmer produced was inefficiently high. In reality, external road costs are often due to both excessive grain volumes and excessive trucking distances. Indeed, farmers commonly choose to deliver to distant delivery points because, as compared to a closer point, they are offered a better grade or price or are offered a trucking cost subsidy.

In this section, a model is developed wherein "cross-hauling" occurs, and thus trucking distances are excessive. The basic structure of this cross-hauling model is derived from chapter 8 of Greenhut, Norman, and Hung, where it is assumed strategic competition takes an extreme form: perfect spatial price discrimination. With perfect discrimination, the standard quantity-setting Cournot duopoly result emerges at each farm location.[8]

[8] In a related literature on intra-industry trade with identical products (e.g., Brander; Brander and Krugman; Greenhut, Norman, and Hung, chapter 9), similar models are used and the results are similar to the basic price discrimination case considered here.

Suppose competing grain buyers are located on each end of a line segment of length L (A on the left and B on the right). As before, distance is measured with respect to the left side of the line, and thus r denotes the distance between the customer and Buyer A, and $L - r$ measures the distance between the customer and Buyer B. In reality, the two firms will generally have different resale prices for the grain they procure. Indeed, if p is equal to the port price minus the rail rate from the country elevator position to the port position, then p will generally be different for the two firms simply because the two firms are different distances to the port. Moreover, p may be endogenous to the problem because the railway's choice of rail rate may depend on the size of the fuel tax. These considerations are ignored in the analysis (i.e., equal p values are assumed) because the qualitative nature of the results is largely unaffected by this assumption, and the modeling becomes significantly more complicated when this assumption is relaxed.

To further simplify the analysis, the following restrictions are imposed:

(*a*) $\lambda = 0$ (i.e., there is no budget constraint for the taxing authority);
(*b*) $c'(x) = a + x$ (i.e., the supply schedule of each farmer is linear);
(*c*) $\beta = 0$ (i.e., marginal external road cost is constant); and
(*d*) $z(r) = 0$ (i.e., all trucking costs are proportional to fuel use).

The profits for Buyer A when purchasing from a farm located at r can be expressed as

$$\pi_A(r) = x_A(r)\big[p - m - \big(a + \big(x_A(r) + x_B(r)\big)\big) - f(\phi + \gamma)r\big]. \tag{19}$$

A similar equation can be written for the profits of Buyer B when purchasing from the farm located at r. The simultaneous solution to the set of first-order conditions associated with maximizing the two profit equations yields the following equilibrium quantities supplied by the farmer located at r:

$$\begin{aligned} x_A^*(r) &= \frac{1}{3}\big[(p - m - a) - (3r - L)f(\phi + \gamma)\big], \\ x_B^*(r) &= \frac{1}{3}\big[(p - m - a) - (2L - 3r)f(\phi + \gamma)\big]. \end{aligned} \tag{20}$$

The parameters of the model are assumed to be such that $x_A^*(r)$ and $x_B^*(r)$ both take on nonnegative values for $r \in [0, 1]$.

The two expressions in equation (20) can be added together to obtain total equilibrium production at location r: $x_A^*(r) + x_B^*(r) = 2(p - m - a)/3 - f(\phi + \gamma)L/3$. Substituting this expression into the farmer's marginal cost equation, $a + x$, results in an expression for the equilibrium procurement price at location r:

$$w^* = a + \frac{2}{3}(p - m - a) - \frac{1}{3}f(\phi + \gamma)L. \tag{21}$$

Equation (21) reveals the size of the equilibrium procurement price is independent of location. With discriminatory pricing, the two buyers compete more aggressively for farmers located toward the center of the line segment, and thus the procurement price does not decrease as the distance to the buyer increases, as in the previous section.[9]

[9] The result that the equilibrium procurement price is the same for all farmers is unique to this simple linear model.

Equation (21) also shows that only a fraction of the fuel tax is passed on to farmers in the form of a lower procurement price. Although not formally derived here, it can be established that if the two competing firms were to set FOB prices in a Betrand fashion (rather than discriminatory prices using Cournot quantity competition), then more than 100% of the fuel tax is passed on to farmers. In other words, the fuel tax exacerbates noncompetitive pricing with Betrand pricing, whereas this is not the case with discriminatory pricing.

Substituting equation (20) into equation (19) and integrating over r results in an expression for aggregate profits for Buyer A. If the resulting expression is multiplied by 2 (because the profits for buyers A and B are identical in equilibrium), then an expression for aggregate profits for both buyers can be written as

$$\pi_A^* + \pi_B^* = \frac{2}{9}\big[(p - m - a + f(\phi + \gamma)L)^2 \\ - 3(p - m - a + f(\phi + \gamma)L)f(\phi + \gamma)L + 3f^2(\phi + \gamma)^2L^2\big]. \tag{22}$$

Similarly, if equations (20) and (21) are substituted into the farmer's profit equation, $w(r)[x_A(r) + x_B(r)] - a[x_A(r) + x_B(r)] - 0.5[x_A(r) + x_B(r)]^2$, and if the resulting expression is integrated over r, then an expression for aggregate profit for all farmers, denoted W, can be represented by

$$W = \frac{1}{2}\left[\frac{2(p - m - a)}{3} - \frac{f(\phi + \gamma)L}{3}\right]^2 L. \tag{23}$$

An expression for the fuel tax on grain from location r delivered to Buyer A can be written as $f\gamma x_A r$. Making the appropriate substitutions, integrating over r, and multiplying by 2 (because the fuel tax on grain deliveries to Buyer A and Buyer B are identical in equilibrium) allows an expression for aggregate fuel tax, τ_Σ, to be written as

$$\tau_\Sigma = \frac{f\gamma L^2}{3}[p - m - a - f(\phi + \gamma)L]. \tag{24}$$

Similarly, using equation (6) with $\beta = 0$, an expression for the equilibrium level of external cost can be designated by

$$\tilde{D} = \frac{\alpha L^2}{3}(p - m - a - f(\phi + \gamma)L). \tag{25}$$

The sum of equations (22) through (24) minus equation (25) provides a measure of net welfare for the system. The optimal fuel tax is found by maximizing that expression with respect to γ. The resulting first-order condition can be rearranged and written as

$$f\gamma^* = \frac{3\alpha L + 2f\phi - (p - m - a)}{3L - 2}. \tag{26}$$

Properties of the Optimal Fuel Tax

Equation (26) is an expression for the optimal fuel tax in the discriminatory pricing case. This expression has several interesting features. First, notice it is possible for the optimal fuel tax to exceed marginal external road cost, α. In the previous section with FOB procurement prices, the optimal fuel tax was equal to marginal external road cost minus an adjustment to account for noncompetitive pricing. Now the optimal fuel tax can exceed marginal external road cost, despite noncompetitive pricing by the grain buyers.

There are two explanations for this result. First, as previously explained, with discriminatory pricing, the buyers absorb a fraction of any increase to the fuel tax whereas this is not the case with FOB pricing. A relatively higher fuel tax is therefore needed in the discriminatory pricing case, and the tax might actually exceed the marginal external road cost. The second reason why the optimal fuel tax is relatively higher with discriminatory pricing versus FOB pricing is, in the former case, the fuel tax reduces the average distance an average unit of grain is trucked as well as the volume of grain that is trucked.

Note from equation (20), $dx_A/d(\gamma f) = -(r - 1/3)$, $dx_B/d(\gamma f) = -(2/3 - r)$, and $dx_A/d(\gamma f) + dx_B/d(\gamma f) = -1/3$. These results indicate an increase in the fuel tax decreases total production at a particular location. More importantly, the decrease in the amount shipped to the more distant buyer exceeds the decrease in the amount shipped to the less distant buyer. Only at the center of the line segment are there no distance effects associated with the fuel tax. Because of reduced cross-hauling, the marginal external benefit of increasing the fuel tax (and thus the size of the optimal fuel tax) is relatively higher under discriminatory pricing.

Although the fuel tax raises overall welfare with discriminatory pricing, it is not an ideal policy instrument. Indeed, a fuel tax reduces but does not eliminate cross-hauling, and the fuel tax does not eliminate the socially undesirable result that production is independent of distance to the buyer. To illustrate the extent to which cross-hauling is reduced with the optimal fuel tax, it is useful to derive an expression for the average distance an average unit of grain is trucked (i.e., the volume-weighted average distance for trucking) and to compare this distance to the analogous expressions in the first-best case and the no-policy case. Using equation (20), with L set equal to 1 for convenience, an expression for the systemwide weighted average distance, denoted WAD, can be written as

$$(27) \qquad WAD(\gamma) = 2\int_0^1 \frac{r x_A(r)}{x_A(r) + x_B(r)}\, dr = \frac{(p - m - a) - f(\gamma + \phi)}{2(p - m - a) - f(\gamma + \phi)}.$$

It follows from equation (27) that for the no-tax case,

$$(28) \qquad WAD(0) = \frac{(p - m - a) - f\phi}{2(p - m - a) - f\phi},$$

and for the optimal tax case, where $\gamma^* = 3\alpha + 2f\phi - (p - m - a)$,

$$(29) \qquad WAD(\gamma^*) = \frac{\tfrac{2}{3}(p - m - a) - (\alpha + f\phi)}{(p - m - a) - (\alpha + f\phi)}.$$

In the previous section, the first-best road tax corresponding to the current set of assumptions is $\tau(r) = \alpha r - (p - m - \theta)$. The first-order condition for the farmer at location r can be expressed as $\theta - (a + x) - f(\gamma + \alpha)r + (p - m - \theta)$ or, after some rearranging, $x^*(r) = p - m - a - (f\phi + \alpha)r$. Integrating over this expression, we find the systemwide volume of grain production is $p - m - a - (f\gamma + \alpha)/4$. The weighted average distance for the first-best case can now be expressed as

$$WAD_{FirstBest} = 2\int_0^{0.5} \frac{(p-m-a)-(f\phi+\alpha)r}{(p-m-a)-(f\phi+\alpha)/4}\,dr = \frac{(p-m-a)-1/3(f\phi+\alpha)}{4(p-m-a)-(f\phi+\alpha)}. \tag{30}$$

The three *WAD* expressions given by equations (28) through (30) could be compared analytically, but a simple numerical comparison is sufficient to illustrate the point that the optimal fuel tax is only moderately efficient. Suppose $p = 1$, $m = 0.1$, $a = 0.1$, $f = 0.5$, and $\phi = 0.5$. With no external road cost (i.e., $\alpha = 0$), the optimal fuel tax, as implied by equation (26), is $f\gamma^* = -0.3$. The tax is negative because of noncompetitive pricing by the two buyers. With $\alpha = 0.1$, the optimal fuel tax rises to $f\gamma^* = 0$. Here, the benefits of the tax in terms of reducing the external road cost are just offset by the social cost of the tax in terms of further aggravating the noncompetitive pricing outcome. With $\alpha = 0.16$, the optimal road tax is $f\gamma^* = 0.18$. Now the optimal road tax exceeds the marginal external road cost, the reason for which was explained above.

With $\alpha = 0.16$, equations (28) through (30) can be used to establish that $WAD(0) = 0.407$, $WAD(\gamma^*) = 0.333$, and $WAD_{FirstBest} = 0.238$. In other words, with no fuel tax, the average unit of grain in the system travels a distance of 0.407. With the same parameter values, a first-best road tax which completely eliminates the noncompetitive pricing and cross-haul effects results in an average distance of 0.238. With the optimal fuel tax, the average distance is 0.333. The tax has therefore reduced the average excess trucking distance by $(0.407 - 0.333)/(0.407 - 0.238) \approx 40\%$. This simple example illustrates that the optimal fuel tax is only partly effective at restoring economic efficiency in a discriminatory pricing environment.

Endogenous Elevator Spacing

In the long run, grain buyers make decisions about where to locate elevators as well as what price to set at each elevator. Decisions about spacing will almost certainly depend on the level of the fuel tax, and thus it is useful to reexamine the above results in light of this new variable. While a formal analysis of endogenous spacing is beyond the scope of the current study, it is possible to present some specialized results. Specifically, the previous model of discriminatory pricing can be used to determine how the optimal fuel tax will change if elevator spacing is endogenized. Basic intuition and previous research suggest that in an unregulated system with no fuel tax, the distance between competing elevators will be excessive. Consequently, the optimal fuel tax should be higher than that determined in the previous section in order to induce grain buyers to locate their elevators closer together. Simulation results from a simple example confirm this outcome.

The example is constructed as follows. Suppose the grain procurement area consists of a line of length T and an alternating series of evenly spaced elevators managed by two competing grain companies (i.e., first A, then B, then A, etc.). All elevators are assumed identical, and thus the problem reduces to choosing the distance between a representative pair of competing elevators, once again denoted L. The fixed cost of operating each elevator is assumed equal to F. Fixed costs should depend on L because of capacity considerations, but this feature is ignored in order to simplify the analysis. If π denotes the equilibrium profits of each elevator, then aggregate profits for one of the grain buyers is $(\pi - F)T/L$.[10] Similarly, if S is the overall surplus associated with a pair of competing elevators, then surplus for the entire system is $(S - F)T/L$. The grain buyers must choose between reducing competition and conserving on fixed costs by choosing a relatively large value of L, or conserving on farm-to-elevator transportation costs by choosing a relatively low value of L. The example is further simplified by assuming the grain buyers choose L cooperatively (i.e., to maximize joint profits) rather than non-cooperatively.

Equations (22) through (25) have been derived as a function of L, and they can now be used to calculate total surplus and total grain buyer profits for the system of elevators, as described above. Assume the taxing authority behaves as a Stackleberg leader and the grain companies as a Stackleberg follower in the tax-setting game. Specifically, when faced with a particular level of tax, the grain buyers choose L to maximize joint profits (the procurement price continues to be set non-cooperatively). The taxing authority adjusts the level of tax (taking into account the location and pricing response of the grain buyers) in order to maximize joint surplus for the system.

Suppose $p = 3$, $m = 0.5$, $a = 0$, $f = 0.5$, $\phi = 0.5$, $\alpha = 0.5$, $F = 0.2$, and $T = 100$. The level of tax which maximizes the joint surplus of the system (taking into account the location and pricing response of the grain companies) is $\gamma = 0.51$. In this case, the optimal spacing between elevators is $L = 1.152$, grain companies earn combined aggregate profits equal to 96.9, and combined aggregate surplus is equal to 185.94. Now suppose the spacing between the elevators is held fixed at $L = 1.152$ (i.e., consider the short-run outcome). This analysis is now similar to that considered in the previous section with $L = 1$. In this case, the level of tax that maximizes joint surplus is $\gamma = -0.403$ (recall a negative tax may be optimal to offset the noncompetitive pricing effects). With this revised tax, surplus for the system rises from 185.94 to 188.43, and combined profits for the two grain buyers rise from 96.9 to 118.50. Clearly, the optimal tax is much higher when elevator spacing is considered in the aggregate welfare function.

As illustrated by this simple example, when endogenous spacing is accounted for, there are additional roles for the fuel tax, and the determination of the optional fuel tax is even more complex. A high tax is desirable because it addresses the road cost externality, reduces the amount of cross-hauling, and induces competing grain buyers to choose more efficient spacing between their delivery points. On the other hand, a higher tax further reduces the equilibrium procurement price and thus exacerbates an existing price distortion. In a dynamic environment where firms first choose location and then choose price, the determination of the optimal fuel tax would be even more complex.

Discussion

In this study, the efficiency properties of a trucking fuel tax were examined for the case of farm-to-elevator grain trucking. The main conclusions are as follows. In the absence of noncompetitive pricing by grain buyers, the optimal road tax is equal to the sum of the marginal external cost at all points between a farmer and the point of delivery. If marginal external cost is an increasing function of volume, then the average tax per unit distance will decline for more distant farmers because the marginal external cost is

[10] For purposes of this illustration, ignore the fact that profits for the two elevators located near each end of the line segment will generally be different than profits for an interior elevator.

lower for more distant road segments. Because the fuel tax is proportional to distance, it generally cannot replicate the optimal road tax. With noncompetitive FOB pricing by grain buyers, the optimal road tax should be reduced by an amount that is constant across farmers at different locations. A fuel tax cannot achieve this type of reduction, and thus once again results in an inefficient outcome.

If buyers strategically compete and are able to perfectly price discriminate across buyers, then cross-hauling emerges as an additional source of inefficiency. A fuel tax is particularly inefficient with discriminatory pricing because it only partially eliminates cross-hauling and may not reverse the inefficient outcome that production does not decline as the distance to market increases. In a simple example, the average excess travel distance was reduced by less than 50% after the implementation of the optimal fuel tax. The optimal fuel tax is unexpectedly high with discriminatory pricing because buyers pass on only a portion of the fuel tax to farmers. If the spacing between elevators is endogenized, then a higher fuel tax can enhance long-run social welfare by reducing the spacing toward the efficient level.

Perhaps the biggest disadvantage associated with the fuel tax (not captured by the model) is that it is generally not possible to set different tax levels for different industries. A common tax rate across all transport-based industries will undoubtedly worsen the efficiency properties of the fuel tax. Because of growing public concern about greenhouse gas emissions, taxes on trucking fuel will likely begin to rise in various taxing jurisdictions around the world. Given the extent of noncompetitive pricing in grain procurement, it is not clear whether a fuel tax increase will necessarily increase system welfare in the grain transport sector. Indeed, even in a region such as Saskatchewan, with an extensive network of truck-sensitive rural roads, it is not clear if increasing the fuel tax will necessarily increase net welfare. Key to answering this question is determining the current level of cross-hauling by farmers, the extent to which farmers are likely to absorb an increase in trucking fuel costs, and the sensitivity of external road costs to cumulative grain volumes.

An important shortcoming of the current model is that the function $\omega(X(s))$ may not accurately describe external road costs for the case of farm-to-elevator grain delivery. In the general transportation literature (e.g., Small), $\omega(X(s))$ is often assumed to be a power function because external costs are primarily in the form of congestion, accidents, and emissions. With primary grain transportation, road damage is the predominant external cost, and it is not clear that road damage cumulates with truck volume according to some smooth and monotonic increasing function. Indeed, road damage depends on many complex factors such as month of transport (e.g., spring thaw versus summer), axle and wheel configuration and speed of the truck, and overall road durability. Roads are generally more durable near major delivery points, and thus in some cases there may exist an inverse correlation between truck volume and external road damage.

Similarly, it is important to ask how the optimal fuel tax is likely to depend on the size of the truck. This question is difficult to answer because varying the size of the truck varies the number of truck trips and the overall level of fuel consumption. In some instances, larger trucks and fewer trips will result in lower overall damage, whereas in other cases (e.g., a soft road in the springtime) a single trip by a large truck can cause extensive damage to a road. In most grain-producing regions, truck size is highly heterogeneous, and this heterogeneity will further mask the economic properties of a fuel tax.

Clearly, more research on the form of the external damage function is needed before a definitive conclusion about the optimal fuel tax can be reached.

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