

# Measuring Illegal Activity and the Effects of Regulatory Innovation: A Study of Diesel Fuel Tax Evasion

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## Abstract

The taxation of diesel fuel varies by use. Consumers using diesel fuel on-road must pay state and federal highway taxes while diesel fuel consumed for residential heating, industrial use, farming or off-road travel do not pay taxes. Variation in the taxation of diesel fuel creates the incentive for firms and individuals to evade on-road diesel taxes by purchasing untaxed diesel fuel and then using or reselling it for on-road use.

This paper studies the incentives for tax evasion and the effects of regulatory changes meant to limit evasion of on-road diesel taxes. We propose a model of fuel tax evasion in which firms choose to purchase quantities of taxed and untaxed diesel fuel based on a heterogenous cost of evading and an endogenously set level of regulatory enforcement. We use this model to propose an empirical test for evasion requiring only data on observed taxed quantities, not the potentially unobserved evaded quantities.

We then empirically study the effects of regulatory innovation in October 1993, including the addition of dye to untaxed diesel fuel, which increase the costs of evasion and lower the costs of regulatory enforcement. We estimate the effect of the regulatory changes on state-level sales of diesel fuel and untaxed heating oil. We find that sales of diesel fuel rose 29 percent following the regulatory change while sales of untaxed heating oil fell by a similar amount. This suggests that the regulatory changes substantially limited the amount of diesel fuel tax evasion. The increase in diesel consumption was higher in states with higher tax rates and in states with more legitimate home heating oil use.

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# 1 Introduction

Tax evasion and tax collection are important factors in fiscal policy. Lack of compliance with tax laws are likely to alter the distortionary costs of raising a given level of government revenue and may affect the distributional consequences of a given tax policy. Furthermore, resources spent evading taxes represent a deadweight loss to the economy.

Despite the central importance of tax evasion in public finance, our understanding of the degree of evasion and its response to the rate of taxation and government enforcement is limited. Theoretically, the response of evasion to tax rates is not clear. Allingham and Sandmo (1972) analyze the evasion decision, finding that evasion is positively related to tax rates. However, Yitzhaki (1974) shows that this result depends on the nature of penalty imposed on audited evaders and on the preferences of potential evaders.

Detecting tax evasion and testing theoretical predictions regarding how it responds to policy parameters have traditionally been difficult since those engaging in evasion wish to keep this behavior concealed. Furthermore, disentangling the effects of tax rates and audit intensity from other unobserved factors is not straightforward. Audit intensity is likely to be endogenously related to the propensity to evade, as auditors focus collection resources toward groups of taxpayers likely to evade. Also, variation in tax rates across individuals or firms is often correlated with evasion opportunities. For instance, higher income individuals face a higher marginal tax rate and at the same time may have more income from sources that are easier to conceal.

In this paper, we consider the effect of audit probabilities and tax rates on tax evasion in the context of a regulatory innovation that greatly decreased the cost of auditing for the compliance of on-road diesel fuel taxes. In October of 1993, the Federal Highway Administration began adding red dye to diesel sold for non-taxed purposes. The addition of the dye allows inspectors to readily check for the use of untaxed diesel through simple visual inspection, which reduced the cost of auditing and increased the cost of achieving a given level of diesel tax evasion.

The diesel market provides an interesting setting to study tax evasion. The taxation of diesel fuel varies significantly by use. In 2005, consumers using diesel fuel for on-road purposes faced federal quantity taxes of 24.4 cents per gallon in addition to state tax rates that range from 8 to 32.1 cents per gallon. Some localities tax on-road diesel as well, altogether placing the tax burden at over 50 cents per gallon in many states. Despite being virtually identical to the diesel used for on-road purposes, diesel fuel consumed for off-road use such as residential heating, industrial use, farming or off-road travel do not pay any taxes. The drastic differences in tax rates, along with the close substitutability of on-road and off-road diesel, provides strong

incentives for firms to evade diesel taxation by purchasing untaxed diesel fuel and using or reselling it for on-road use.

We begin by proposing a theoretical model of tax evasion. Firms choose to purchase quantities of taxed and untaxed diesel fuel based on a heterogeneous cost of evading, a fixed punishment if caught evading taxes by a regulator, and an endogenously set level of regulatory enforcement. Based on the heterogeneous cost of evasion, we separate firms into three groups: (1) Full evaders - firms which choose to fully evade and purchase only untaxed fuel, (2) Partial Evaders - firms which purchase a mix of taxed and untaxed fuel, and (3) Non Evaders - firms which fully comply by purchasing only taxed fuel. The comparative statics of the model suggest regulatory innovation lowering the cost of monitoring should increase monitoring intensity and reduce evasion. In addition, tax rates are negatively correlated with consumption of taxed fuel and positively correlated with the measure of firms who choose to fully evade fuel taxes.

We empirically evaluate the model using a monthly, state-level panel of sales of diesel fuel and a close substitute, untaxed distillate fuel oil. Following the regulatory innovation, we find that sales of diesel fuel rose 29 percent while sales of untaxed heating oil fell by a similar amount. This is consistent with regulatory changes substantially limiting the amount of diesel fuel tax evasion. Similarly, we utilize a test for evasion developed from the model that compares diesel's elasticity with respect to taxation with its elasticity with respect to prices. We find a significant gap between these two measures, indicating a rejection of the null hypothesis of no evasion.

Next, we exploit variation in state-level on-road diesel taxes to examine how tax rates alter the incentive to evade. Consistent with the model, we find that the change in diesel consumption after the implementation of the dyeing program is highest in states with higher tax rates and states where a high fraction of households use home heating oil.

Finally, we observe evidence of a dynamic response of evaders to the dyeing program. Prior to 1993, diesel sales were significantly more elastic with respect to diesel taxation than the price of diesel. As obtaining non-taxed substitutes was made more difficult under the dyeing program, the two elasticities converged for the 1994 to 1998 period. However, after 1998 the tax elasticity observed pre-dyeing reemerged, suggesting firms may have adapted by finding other tax evasion mechanisms. Fuel oil similarly experienced a significant pre-dye tax elasticity, which disappeared post-dye period. Unlike diesel however, this elasticity did not reemerge.

The techniques we develop to infer evasion by comparing tax and price elasticities relate closely to the work of Chetty et al (2007). They examine consumer tax salience by comparing the demand response to changes in specific liquor taxes, which are incorporated in the price

quoted to consumers, with the demand response to changes in ad valorem taxes, which are not part of the posted price but instead paid at the register. Due to the potential importance of tax salience, the technique we propose is likely to be only relevant for settings where the tax is already incorporated in the quoted price.

Our paper relates closely to the literature measuring tax evasion and its responsiveness to incentives. Several approaches have been taken in prior literature to measure tax evasion. An indirect approach involves observing aggregate quantities such as currency demand or national income and product accounts and inferring evasion from these quantities. For instance, Gutmann (1977) examines the currency to demand deposit ratio, and argues that changes in this ratio reflect changes in underground market activities. Feige (1979) utilizes total dollar transactions relative to GDP, while Pommerehne and Weck-Hannemann (1996) examine the discrepancy between income from tax return data and that from national income accounts across Swiss cantons.

A second approach utilizes cross-sectional variation across taxpayers in observed levels of compliance using the Taxpayer Compliance Monitoring Project (TCMP), which describes the outcome of IRS audits of randomly chosen tax returns. Clotfelter (1983) studies this cross-section of returns, finding a positive relationship between individuals' marginal tax rates and the degree of evasion. One difficulty faced in this study is that marginal tax rates are directly related to income. Feinstein (1991) addresses this problem by pooling two different years of the TCMP, which allows for the comparison of two individuals with the same income but facing different marginal tax rates. In contrast to Clotfelter, Feinstein finds a negative relationship between tax rates and tax evasion. Dubin and Wilde (1988) and Beron, Tauchen, and Witte (1992) use data from the TCMP aggregated to the three digit zip code level to investigate how the enforcement alters tax compliance, finding that increasing a zip codes chances of an IRS audit is associated with higher reported adjusted gross income.

A third approach taken in the literature uses experimental methods to investigate tax compliance and its response to tax rates and enforcement. Slemrod, Blumenthal, and Christian (2001) examine an experiment in Minnesota where randomly selected taxpayers were sent letters warning of close scrutiny of their tax returns. Low and middle income taxpayers responded by reporting higher AGI than the control group, but higher income individuals reported less, highlighting the potential distributional impact of tax evasion. Other studies taking an experimental approach include Wenzel and Taylor (2004) and Alm and McKee (2005).

The approach most closely related to that taken in our paper is that of Fisman and Wei

(2004), who examine the misclassification of Chinese imports from Hong Kong. They find that the gap at the detailed good level between reported Chinese imports from Hong Kong and reported exports from Hong Kong to China is largest for goods with high tax and tariff rates.

Section 2 presents some background related to diesel markets and taxation and Section 3 describes a model of the firms' tax evasion decision. Section 4 describes the data to be used. Section 5 presents the empirical model employed and the empirical results, and Section 6 concludes.

## 2 Regulatory Background

The taxation of diesel fuel varies by use. Diesel fuel used on-road is subject to federal highway taxes of 18.4 cents per gallon and state highway taxes ranging from 9 to 32.1 cents per gallon. In addition, environmental regulations limit the amount of allowable sulfur content of on-road diesel fuel.<sup>1</sup> Diesel fuel consumed for farming or off-road travel, or as fuel oil for residential, commercial or industrial boilers do not pay any taxes and does not meet similar sulfur limits.

Variation in taxation and environmental stringency by use create strong incentives for firms to evade taxation. Evaders purchase diesel fuel meant for off-road use and use or resell it for on-road use without paying or collecting the appropriate highway taxes. In the 1980's, the canonical method of evasion was the "daisy chain", in which a licensed company would purchase untaxed diesel fuel and resell the diesel fuel internally or to another company several times to make it more difficult to audit the transaction. Eventually, a distributor would sell the untaxed fuel to retail stations as fuel on which taxes had already been collected.<sup>2</sup> In 1992, the Federal Highway Administration estimated the "daisy chain" and other evasion schemes, allowed firms to evade between seven and twelve percent of on-road diesel taxes, approaching \$1.2 billion dollars of federal and state tax revenue annually. While evasion has also been documented for other fuels, including gasoline, kerosene and jet fuel, diesel fuel presents a special situation. Both taxable and non-taxable uses consume significant amounts of fuel. In 2004, 59.6 percent of distillate sales to end users were retail sales for on-highway use.<sup>3</sup> This creates both the incentive to develop evasion schemes to avoid taxes on large quantities of on-road diesel fuel, as well as provides access to substantial quantities of untaxed diesel fuel.

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<sup>1</sup>From October 1993 to August 2006, the allowable sulfur content for on-highway diesel fuel was 500 parts per million. Regulations did not constrain the sulfur content of diesel intended for other uses. Beginning September 1, 2006, diesel sold for on-highway use must meet new Ultra Low Sulfur Diesel Fuel requirements, with sulfur content not exceed 15 ppm.

<sup>2</sup>For documented examples of evasion, see the Federal Highway Administration Tax Evasion Highlights.

<sup>3</sup>Fuel Oil and Kerosene Sales Report, Energy Information Administration, 2004.

In this paper, we study regulatory innovations by the Internal Revenue Service (IRS) and the Environmental Protection Agency (EPA) meant to decrease the amount of evasion of on-road diesel taxes and environmental regulations. The EPA regulations, introduced October 1, 1993, require that all diesel fuel failing to meet the low-sulfur on-road requirements be dyed, to distinguish it from fuel meeting on-road sulfur limits. The IRS regulations, enacted as part of the Omnibus Budget Reconciliation Act of 1993 and put into effect on January 1, 1994, place similar dyeing requirements on diesel fuel on which taxes had not been collected. In addition, the IRS regulations move the point at which federal taxes are collected on diesel fuel up the supply chain to the wholesale terminal. The regulations require that any untaxed diesel fuel sold from the wholesale terminal be dyed. The federal penalty for consuming or selling dyed fuel (“red diesel”) for on-road use is the greater of \$10 per gallon of fuel or \$1000.<sup>4</sup>

The IRS and EPA regulations have two effects on fuel tax evasion: (1) the regulations reduce the cost of regulatory enforcement, and (2) the regulations increase the cost of common evasion schemes like the “daisy chain.” The use of fuel dye primarily decreases the cost of regulatory monitoring. Dyeing diesel fuel for which on-road taxes have not been collected or which fails to meet on-road sulfur requirements allows regulators to more easily monitor and enforce on-road regulations through random testing of trucks. In conjunction with lower enforcement costs, IRS monitoring intensity rose following the introduction of fuel dye into diesel fuel. Baluch (1996) tabulates IRS staff hours related to audits and enforcement of diesel fuel taxes and finds that staff hours rose approximately three and a half times, from 151,190 hours in 1992 to 516,074 hours in 1994.

Moving the point of taxation up the supply chain to the point of sale from the wholesale terminal serves a dual purpose. Prior to 1994, the government collected fuel taxes from both wholesale terminals and the diesel distributors - firms who transported diesel from the wholesale terminal to the retail station. Moving the point of taxation reduces the number of firms responsible for collection on-road taxes, making it less costly to collect taxes and enforce dyeing of untaxed fuel. In addition, moving the point of taxation increases the costs of evasion for standard “daisy chain” evasion, which relies on being able to purchase untaxed diesel and eventually misrepresenting it as diesel on which taxes have been collected, without collecting the appropriate taxes. Moving the point of taxation, along with dyeing untaxed fuel, substantially increase the cost of evasion for common evasion schemes used prior to the regulations.

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<sup>4</sup>In addition to penalties for evading federal taxes, individual states penalize firm caught evading state taxes. Denison and Eger (2000) document fuel evasion penalties for a subset of states in 1997.

### 3 A Model of Fuel Tax Evasion

To motivate our empirical model, we consider a model of fuel tax evasion with a continuous measure of firms purchasing diesel fuel for on-road (taxed) use.<sup>5</sup> Firms choose quantities of untaxed and taxed diesel fuel,  $q_u$  and  $q_t$  to produce output  $x(q_u + q_t)$ . Normalizing the price of output to 1, firms can choose to comply with regulations by purchasing taxed diesel fuel at price  $p + t$  or may choose to evade taxation by purchasing untaxed diesel fuel at price  $p$ . If a firm located at  $\gamma \sim f[0, \theta]$  chooses to evade, it incurs a heterogeneous cost of evasion. We assume that the costs of evasion,  $c_e(q_u, \gamma) = \gamma q_u^2/2$ , are quadratic in consumption of untaxed fuel,  $q_u$ , and an increasing function of a firm's heterogeneous cost parameter,  $\gamma$ .<sup>6</sup> In addition to paying the cost of evasion, firms are penalized if caught evading taxes by the regulator. The regulator deters tax evasion by randomly auditing firms with an endogenous probability  $p_a$  and assessing a fixed penalty,  $z$ , if  $q_u > 0$ .<sup>7</sup>

The game proceeds in three steps. First, the regulator observes the punishment associated with evasion,  $z$ , the distribution of the evasion cost parameters,  $f(\gamma)$ , a parameter capturing the cost of auditing,  $c_a$ , and relevant market parameters,  $p$  and  $t$ .<sup>8</sup> The regulator then chooses the probability with which it will audit firms,  $p_a$ , to maximize the regulatory objective function<sup>9</sup>

$$W = tQ_t - c_a \frac{p_a^2}{2}, \quad (1)$$

where  $Q_t$  are the total purchases of the taxed good. In the second step of the game, firms observe  $p_a, p, t, Q_u^L$  and, based on their heterogeneous cost of evasion, choose quantities  $q_u$  and  $q_t$ . In the third step, the regulator randomly audits  $p_a$  proportion of the firms and punishes all

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<sup>5</sup>Although we consider the case of a firm purchasing evading taxes on an input to production, we could analogously frame the problem as one of a consumer choosing quantities of a legally and illicitly purchased good. As an example, we could consider legal music purchases and illegal music downloads.

<sup>6</sup>We also consider cases in which, additionally, the cost of evasion is decreasing in the size of the legal market for untaxed diesel fuel,  $Q_u^L$ . In markets where legal sales of untaxed fuel are rare, evasion is likely to be more costly. In the model, we omit legal sales of untaxed diesel fuel,  $Q_u^L$ , from our parameterization of  $c_e$ . If legal sales affect all firms heterogeneous cost of evasion, we can model the effects as either a shift or a scalar expansion of  $f(\gamma)$ . Allowing a more general distribution of  $\gamma$  given by  $\gamma \sim f[\theta_1, \theta_1 + \theta_2]$ , and allowing  $\frac{\partial \gamma}{\partial Q_u^L}, \frac{\partial \gamma}{\partial Q_t^L} \leq 0$ , we can derive comparative statics with respect to  $Q_u^L$ .

<sup>7</sup>The fixed component of the penalty is a sufficient condition for the existence of entirely legal firms, so long as  $\theta$ , the upper bound on the cost of evasion parameter, is sufficiently high.

<sup>8</sup>If the regulator can choose both  $p_a$  and  $z$ , the optimal decision for the regulator is to set extremely high penalties and low enforcement. Since this is inconsistent with the actual penalties for fuel tax evasion, we treat  $z$  as exogenously given.

<sup>9</sup>We present the model in which fines do not enter into the regulator's objective function. The comparative static results do not substantively change with this inclusion or exclusion of the fines. Furthermore, we assume that the regulator credibly commits to  $p_a$  in the first stop of the game. This is consistent with the regulator either setting a binding enforcement budget in the first period or a regulator wishing to establish a reputation for credible commitment in a dynamic context.

audited firms choosing  $q_u > 0$  with penalty  $z$ .

### 3.1 Firm Purchase Decision

For convenience, we analyze the equivalent problem in which firms choose total diesel purchases  $q$  and the percent of diesel taxes they will evade  $\alpha$ , where  $q_u = \alpha q$ . A risk-neutral firm located at  $\gamma$  chooses  $q$  and  $\alpha$  to maximize expected profits given by

$$E[\Pi] = x(q) - (p\alpha q + \gamma \frac{(\alpha q)^2}{2}) - (p+t)(1-\alpha)q - p_a z I(\alpha > 0) \quad (2)$$

subject to

$$q \geq 0, \alpha \in [0, 1]. \quad (3)$$

where the respective terms in (2) are firm revenues, the costs associated with choosing untaxed quantity,  $q_u = \alpha q$ , and taxed quantity,  $q_t = (1-\alpha)q$ , and the expected punishment associated with evasion for firms choosing  $\alpha > 0$ . For an interior solution of  $\alpha \in (0, 1)$ , the first order conditions are

$$\frac{\partial \Pi}{\partial q} = x'(q) - p\alpha - \gamma q \alpha^2 - (p+t)(1-\alpha) = 0, \quad \text{and} \quad (4)$$

$$\frac{\partial \Pi}{\partial \alpha} = tq - \alpha \gamma q^2 = 0. \quad (5)$$

implying,

$$\alpha^* = \frac{t}{q\gamma}. \quad (6)$$

Let  $\bar{q}$  denote the quantity of diesel fuel satisfying (4) for partial evaders given by

$$x'(\bar{q}) = p+t. \quad (7)$$

We group firms into one of three classes based on their heterogenous cost of evasion,  $\gamma$ : full evaders who choose  $\alpha^* = 1$ , partial evaders who choose an interior solution for  $\alpha^*$  and, non-evaders who choose  $\alpha^* = 0$ . The cutoff for full evasion,  $\hat{\gamma}_{FE}$ , is defined by setting (6) equal to 1, and the cutoff for non-evasion,  $\hat{\gamma}_{NE}$ , is defined by equating  $E[\Pi|\alpha = \frac{t}{q\gamma}]$  and  $E[\Pi|\alpha = 0]$ .

$$\hat{\gamma}_{FE} = t/\bar{q} \quad (8)$$

$$\hat{\gamma}_{NE} = \frac{t^2}{2p_a z}. \quad (9)$$

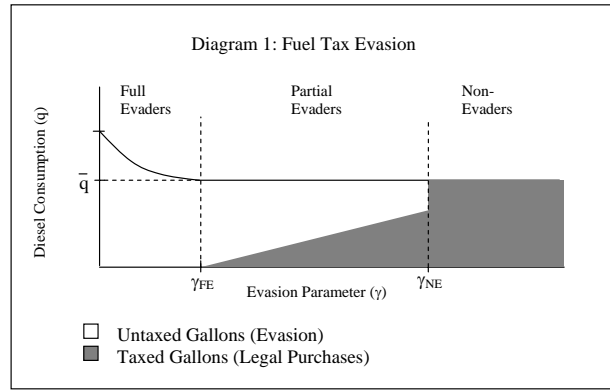
Thus, conditional on  $p_a$ , the optimal choices of  $q^*(\gamma|p_a)$  and  $\alpha^*(\gamma|p_a)$  are given by

$$q^*(\gamma|p_a) = \begin{cases} x'(q) = p + \gamma q & \text{for } \gamma \in [0, t/\bar{q}] \\ \bar{q} & \text{for } \gamma \in (t/\bar{q}, \frac{t^2}{2p_a z}) \\ \bar{q} & \text{for } \gamma \in [\frac{t^2}{2p_a z}, \theta], \end{cases} \quad (10)$$

and

$$\alpha^*(\gamma|p_a) = \begin{cases} 1 & \text{for } \gamma \in [0, t/\bar{q}] \\ \frac{t}{\bar{q}\gamma} & \text{for } \gamma \in (t/\bar{q}, \frac{t^2}{2p_a z}) \\ 0 & \text{for } \gamma \in [\frac{t^2}{2p_a z}, \theta]. \end{cases} \quad (11)$$

Diagram 1 graphically represents how taxed and untaxed diesel consumption vary with the evasion cost parameter,  $\gamma$ .



Firms above the non-evasion cutoff,  $\hat{\gamma}_{NE}$ , will choose to fully comply with the regulations as the benefits of evasion do not outweigh the potential penalty. A firm located at  $\hat{\gamma}_{NE}$  is indifferent between fully complying with fuel taxes and partial evasion. The discontinuity in taxed fuel consumption at  $\hat{\gamma}_{NE}$  is a result of the fixed punishment. With a fixed penalty, a strategy purchasing an epsilon amount of untaxed fuel is dominated by non-evasion.<sup>10</sup> For partially-evading firms with lower heterogeneous cost of evasion,  $\gamma$ , firms continue to purchase  $\bar{q}$  units of diesel fuel, but substitute away from taxed diesel to untaxed diesel until  $\hat{\gamma}_{FE}$ . Below this point, firms fully-evade regulations, purchasing  $q^*(\gamma)$  solving  $x'(q) = p + \gamma q$ .

Given the optimal choices of quantity and evasion by firms, we can express consumption of

<sup>10</sup> Absent a fixed component to the penalty function, all firms would have the incentive to be at least partial evaders. A similar discontinuity can be derived with a general penalty function if firms face a fixed cost associated with evasion.

taxed diesel and untaxed diesel as

$$Q_t = \int_{t/\bar{q}}^{\frac{t^2}{2p_a z}} \bar{q}(1 - \alpha)f(\gamma)d\gamma + (1 - F(\frac{t^2}{2p_a z}))\bar{q} \text{ and} \quad (12)$$

$$Q_u = \int_0^{t/\bar{q}} q^*(\gamma)f(\gamma)d\gamma + \int_{t/\bar{q}}^{\frac{t^2}{2p_a z}} \bar{q}\alpha f(\gamma)d\gamma. \quad (13)$$

The terms of  $Q_t$  correspond to taxed purchases by partial evaders and non-evaders respectively. The terms of  $Q_u$  correspond to untaxed purchases (evasion) by full evaders and partial evaders respectively.

### 3.2 Regulator Enforcement Problem

Conditional on  $p_a$ , the decision of the each firm is independent of the distribution of  $\gamma$ . Unlike the choice of the firm, though, the regulator's choice of  $p_a^*$  depends on the distribution of  $\gamma$ . The regulator endogenously chooses  $p_a$  to maximize its objective function, given by

$$W = tQ_t - c_a p_a^2/2. \quad (14)$$

Substituting (12) into the objective function, the solution to regulator enforcement problem solves the first-order condition

$$p_a = \sqrt{\frac{t^2}{c_a} f(\hat{\gamma}_{NE})}. \quad (15)$$

Since  $\hat{\gamma}$  is itself a function of  $p_a$ , more than one value of  $p_a$  may solve the first order condition.<sup>11</sup> In the event that more than one local solution to the first order condition exists, the regulator selects the solution for which the objective function is maximized.<sup>12</sup> Consistent with intuition, the intensity of enforcement,  $p_a$ , decreases with the cost of auditing,  $c_a$  and increases with the tax rate,  $t$ . An increase in  $t$  increases the marginal benefit of auditing - an increase in  $c_a$  increases the marginal cost of auditing.

With a fixed penalty,  $z$ , the regulator's choice of audit intensity only affects  $\hat{\gamma}_{NE}$ . Thus,  $\frac{\partial Q_t}{\partial p_a} > 0$  and  $\frac{\partial Q_u}{\partial p_a} < 0$ .

Substituting (15) into (12) and (13), we derive the comparative statics for  $Q_t$  and  $Q_u$  with respect to  $c_a$  and  $t$ . Noting that  $c_a$  only affects  $Q_t$  and  $Q_u$  through the regulator's choice of

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<sup>11</sup>If the distribution of  $\gamma$  has a finite upper bound, note that a trivial solution to the first order condition is given by  $p_a = 0$ . In the context of diesel fuel tax enforcement, we focus on interior solutions for  $p_a$  consistent with regulator revealed preference.

<sup>12</sup>A sufficient condition for a unique non-zero solution is  $f(\gamma)$  weakly monotonically increasing in  $\gamma$ . The sufficient condition, that there are weakly more consumers with higher costs of evasion than lower costs of evasion, is reasonable in the context of diesel fuel tax evasion and follows from constraining  $\frac{\partial^2 W}{\partial p_a^2}$  to be negative for  $p_a \in (0, 1)$ .

$p_a^*$ ,  $\frac{\partial Q_t}{c_a} < 0$  and  $\frac{\partial Q_u}{c_a} > 0$ . With lower auditing costs, the regulator increases audit intensity and affects the decision of the marginal firm choosing between partial evasion or non-evasion. Consumption of untaxed diesel (evasion) rises with monitoring costs and consumption of taxed diesel (compliance) falls with monitoring costs.

Unlike  $c_a$  which only affects firms through the regulator's choice of audit intensity,  $t$  affects also has direct effects on the partial and non-evader consumption of diesel,  $\bar{q}$ , and the cutoffs for full evasion and non-evasion,  $\hat{\gamma}_{FE}$  and  $\hat{\gamma}_{NE}$ . In particular, audit intensity will rise with the tax rate, diesel consumption by partial and non-evaders will fall with taxes and the full evasion cutoff will rise regardless of the distribution of  $\gamma$ .

$$\frac{\partial p_a^*}{\partial t} > 0, \frac{\partial \bar{q}}{\partial t} < 0, \text{ and } \frac{\partial \hat{\gamma}_{FE}}{\partial t} > 0, \quad (16)$$

Furthermore, we can unambiguously sign,  $\frac{\partial \hat{\gamma}_{NE}}{\partial t} > 0$  and  $\frac{\partial Q_t}{\partial t} < 0$  if the sufficient condition for uniqueness holds,  $f(\gamma)$  is weakly increasing in  $\gamma$ . Is not possible to sign  $\frac{\partial Q_u}{\partial t}$  without functional form assumptions on  $x'(q)$ . In the case of untaxed sales,  $t$  unambiguously increases the measure of firms who either fully or partially evade the regulations, but decreases total diesel consumption (and hence, untaxed diesel consumption) for partial evaders.

### 3.3 Empirical Predictions

The comparative statics in the previous section, generate two testable predictions. If the introduction of fuel dye and the change in the point of taxation were effective, we would expect taxable sales to rise and untaxed sales to fall in response to the regulatory innovation. Furthermore, we would expect the magnitude of the change in sales of taxed fuel to be greater in high tax jurisdictions.<sup>13</sup>

In this section, we derive additional testable predictions from our model based on the elasticity of taxable fuel demand with respect to tax-exclusive price and tax rate. In addition, we derive an estimate on the extent of evasion based on the difference between the elasticity of demand with respect to the tax-exclusive price and the tax rate.

Conditioning on the regulator's choice of  $p_a$ , we first consider the short-run tax and price elasticity of taxable diesel sales, and show that for an arbitrary distribution of gamma,  $|\frac{\partial Q_t}{\partial p}| < |\frac{\partial Q_t}{\partial t}|$ . We initially consider short-run changes in  $p$  and  $t$  for which the regulator does not have

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<sup>13</sup>In addition, if the cost of evasion is decreasing in the size of the legal market of untaxed sales, we would expect the change in sales of taxed fuels to be greater in jurisdictions with high legal demand for untaxed diesel fuel. In our empirical specification, we proxy for legal demand using the share of state GDP from agriculture and the proportion of households heating their homes with fuel oil.

the opportunity to update  $p_a$ . From (12),  $p$  has affects  $Q_t$  two ways through partial evaders and non-evaders choices of total diesel consumption,  $\bar{q}$ . First, an increase in  $p$  directly lowers total diesel consumption of partial and non-evaders, and second an increase in  $p$  indirectly increases the full-evasion cutoff. A change in the tax rate not only affects  $Q_t$  through firms' diesel consumption, but has three addition effects - and increase in  $t$  further increases the full-evasion cutoff, increases the non-evasion cutoff and conditional on  $\gamma$  increases evasion for all partial evaders.<sup>14</sup> Comparing the derivative of  $Q_t$  with respect to  $p$  and the derivative of  $Q_t$  with respect to  $t$ , we have

$$\frac{\partial Q_t}{\partial p} = \frac{\partial \bar{q}}{\partial p} [1 - F(\frac{t}{\bar{q}})] \quad \text{and} \quad (17)$$

$$\frac{\partial Q_t}{\partial t} = \frac{\partial \bar{q}}{\partial t} [1 - F(\frac{t}{\bar{q}})] - 2F(\frac{t^2}{2p_a z}) - \int_{\frac{t}{\bar{q}}}^{\frac{t^2}{2p_a z}} \frac{1}{\gamma} f(\gamma) d\gamma \quad (18)$$

Identifying the relative magnitudes of (17) and (18) are straightforward. Since  $\frac{\partial \bar{q}}{\partial p} = \frac{\partial \bar{q}}{\partial t}$ , the first terms in (17) and (18) are equivalent - the first terms capture the effect of tax-inclusive price on total diesel consumption by partial and non-evaders. The second and third terms in (18), capturing the effects of tax rate on evasion, are negative and imply  $\frac{\partial Q_t}{\partial p} > \frac{\partial Q_t}{\partial t}$ .

Furthermore,  $p_a$  or  $c_a$  affect the difference between  $\frac{\partial Q_t}{\partial p}$  and  $\frac{\partial Q_t}{\partial t}$ . Since  $p_a$  has no effect on  $\frac{\partial Q_t}{\partial p}$ , we can express the effect of  $p_a$  on the difference between  $\frac{\partial Q_t}{\partial p}$  and  $\frac{\partial Q_t}{\partial t}$  as a decreasing function of  $p_a$ , given by

$$\frac{\partial}{\partial p_a} \left( \frac{\partial Q_t}{\partial p} - \frac{\partial Q_t}{\partial t} \right) = -2f(\frac{t^2}{2p_a z}) \left( \frac{t^2 + p_a z}{p_a^2 z} \right) < 0. \quad (19)$$

Since  $c_a$  only affects firm behavior through the regulator's choice of  $p_a$ , the analogous result for  $c_a$  is

$$\frac{\partial}{\partial c_a} \left( \frac{\partial Q_t}{\partial p} - \frac{\partial Q_t}{\partial t} \right) = \frac{\partial}{\partial c_a} \frac{\partial p_a}{\partial c_a} \left( \frac{\partial Q_t}{\partial p} - \frac{\partial Q_t}{\partial t} \right) > 0. \quad (20)$$

Consistent with intuition, as enforcement increases (either exogenously or through lower cost of enforcement), an increase in taxes leads to less of an increase in evasion.

These results suggest a testable hypotheses for the presence of evasion - if evasion exists, we would expect taxable sales to respond more to a change in taxes than a change in prices.

<sup>15</sup> Furthermore, if the addition of dye reduced the cost of regulatory monitoring and increased

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<sup>14</sup>It is important to note that with multiple jurisdictions, increase tax in one jurisdiction will also have a border crossing effect.

<sup>15</sup>Note that in the presence of multiple markets, we also have to consider the effect of cross-border sales in response to differential taxation. A second approach for detecting the presence of evasion would test whether to which untaxed sales respond to changes in the tax rate.

regulatory enforcement, we would also expect that the difference in relative effect on taxable sales from a change in price and a change in tax to be less following the regulatory innovation. Under the empirical specification we introduce in the following section,

$$\text{Log}(Q_t) = \alpha + \beta_1 \text{Log}(p) + \beta_2 \text{Log}\left(1 + \frac{t}{p}\right) + X\Theta + \epsilon, \quad (21)$$

we can derive the appropriate null and alternative hypotheses.

Taking derivatives with respect to  $p$  and  $t$ , we have

$$\frac{1}{Q_t} \frac{\partial Q_t}{\partial p} = \frac{1}{p} \left( \beta_1 - \beta_2 \frac{t}{p+t} \right) \quad (22)$$

$$\frac{1}{Q_t} \frac{\partial Q_t}{\partial t} = \beta_2 \left( \frac{1}{p+t} \right) \quad (23)$$

If no evasion occurs<sup>16</sup>, we would expect a unit change in price and a unit change in consumer tax incidence to have the same effect on quantity demanded. Equating  $\frac{1}{Q_t} \frac{\partial Q_t}{\partial p}$  and  $\frac{1}{Q_t} \frac{\partial Q_t}{\partial t}$  and solving for the appropriate null hypothesis, we have

$$\frac{1}{Q_t} \frac{\partial Q_t}{\partial p} = \frac{1}{Q_t} \frac{\partial Q_t}{\partial t} \rightarrow \beta_1 \frac{1}{p} - \beta_2 \frac{t}{p(t+p)} = \beta_2 \frac{1}{(t+p)} \rightarrow H_0 : \beta_1 = \beta_2. \quad (24)$$

Moreover, we can express the change in evasion ( $E$ ) with respect to the tax rate as a function of  $\beta_1$  and  $\beta_2$ . Using the identity  $Q_u = Q - Q_t$  and noting that a change in untaxed quantities due to a change in the tax rate arises purely through evasion, we have

$$\frac{\partial E}{\partial t} = \frac{\partial Q_u}{\partial t} = \frac{\partial Q}{\partial t} - \frac{\partial Q_t}{\partial t}. \quad (25)$$

Noting that

$$\begin{aligned} \frac{\partial Q}{\partial t} &= \frac{\partial}{\partial t} \left[ \int_0^{\frac{t}{\bar{q}}} q^*(\gamma) f(\gamma) d\gamma + \bar{q} \left[ 1 - F\left(\frac{t}{\bar{q}}\right) \right] \right] \\ &= \bar{q} f\left(\frac{t}{\bar{q}}\right) \left[ \frac{\bar{q} - t \frac{\partial \bar{q}}{\partial t}}{\bar{q}^2} \right] + \frac{\partial \bar{q}}{\partial t} \left[ 1 - F\left(\frac{t}{\bar{q}}\right) \right] - \bar{q} f\left(\frac{t}{\bar{q}}\right) \left[ \frac{\bar{q} - t \frac{\partial \bar{q}}{\partial t}}{\bar{q}^2} \right] \\ &= \frac{\partial \bar{q}}{\partial t} \left[ 1 - F\left(\frac{t}{\bar{q}}\right) \right] \\ &= \frac{\partial Q_t}{\partial p}, \end{aligned}$$

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<sup>16</sup>In the multijurisdictional context, it is important to account for cross border sales in the specification. If our empirical specification is  $\text{Log}(Q_{it}) = \alpha + \beta_1 \text{Log}(p_i) + \beta_2 \text{Log}\left(1 + \frac{t_i}{p_i}\right) + \beta_3 \text{Log}(p_i + t_i - (p_j + t_j)) + \epsilon$ , we can work out a very similar result this case. In this case, the appropriate null hypotheses are  $\beta_1 = \beta_2$  (no evasion) and  $\beta_3 = 0$  (no cross border effect)

we can express the derivative of evasion with respect to taxes as

$$\frac{\partial E}{\partial t} = \frac{\partial Q_t}{\partial p} - \frac{\partial Q_t}{\partial t}. \quad (26)$$

In this framework,  $\frac{\partial Q_t}{\partial p}$  captures "true" reduction in taxed diesel demand from a price increase (ie. firms want less diesel at the price rises) and  $\frac{\partial Q_t}{\partial t}$  captures both the "true" reductions in demand as well as reductions in demand coming from evasion. Substituting (22) and (23) into (26) we can express the derivative of evasion with respect to taxes as a function of  $\beta_1$  and  $\beta_2$  above.

$$\frac{\partial E}{\partial t} = \frac{Q_t}{p}[\beta_1 - \beta_2]. \quad (27)$$

Importantly, this metric of evasion only depends on information about taxed sales, which are presumably observable. In fact, the case of fuel tax evasion provides an unusual example in which untaxed sales are also available - we exploit the availability of data to evaluate the performance of the evasion estimate above.<sup>17</sup>

In summary, if evasion responds to economic incentives, our theoretical model provides a number of testable predictions:

1. Sales of taxed (untaxed) diesel should rise (fall) with the introduction of the fuel dye program.
2. The change in consumption of taxed and untaxed diesel fuel in response to the introduction of fuel dye should be greater in states with higher tax rates.
3. The change in consumption of taxed and untaxed diesel fuel before and after the regulatory change should be greater in states with substantial legal consumption of untaxed diesel (farm, home heating use, etc.)
4. Demand for taxed fuel should be more elastic with respect to taxes than with respect to prices prior to the introduction of dye.
5. The elasticity of taxed fuel with respect to taxes should increase after the introduction of dye.

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<sup>17</sup>In appendix A, we derive the necessary and sufficient conditions for (27). Under the assumption that firms are price takers, a sufficient condition is that the cost of evasion is quadratic in the amount of untaxed gallons purchased.

## 4 Data

In this paper, we are interested in detecting fuel tax evasion and estimating the extent to which evasion is correlated with the magnitude of the incentive for evasion using a discrete change in regulatory enforcement. We exploit variation in state taxes to capture the effect of a common discrete change in regulatory enforcement across areas with different ex-ante incentives for fuel tax evasion. We test for evidence not only of tax evasion, but also that tax evasion fell more in response to the regulatory innovation in areas where the ex-ante incentives for evasion are greater.

To estimate fuel tax evasion, we collect state-level data from the Energy Information Administration (EIA) and the Federal Highway Administration (FHA) on sales of diesel fuel and No 2 fuel oil and state tax rates over 1983-2003. We collect state-level quantity data from the EIA Petroleum Marketing Monthly. The EIA tracks Prime Supplier Sales, sales by firms to end-users, retail stations, and local distributors, of No. 2 diesel fuel and No. 2 fuel oil by state from 1983 to the present. In addition, from 1994 to the present, the EIA differentiates No. 2 diesel fuel sales by sulfur content. No 2 diesel fuel and No 2 fuel oil are chemically equivalent classifications of No 2 distillate oil. The distinction between the two in the EIA data is one of use. Diesel fuel is defined as No 2 distillate made to be burned in a gasoline engine, while the EIA classifies fuel oil as No 2 distillate to be used in a residential, commercial or industrial boiler. The chemical properties of No. 2 diesel fuel and No. 2 fuel oil are essentially equivalent - the two products can be used interchangeably to power a diesel engine or a burner.

Two of the main results of the paper can be seen by examining the monthly time series of sales of U.S. sales of number 2 distillate. In Figure 2, we show the time path of sales of number 2 diesel, number 2 fuel, and total number 2 distillate sales. This figure shows that in the pre-dye period, sales of the two types of number 2 distillate were at similar levels, and both experiencing a fairly flat time trend. In the month of the implementation of the diesel dye program, sales of diesel increased noticeably. In September of 1993, 82.0 million gallons of diesel were sold per day in the United States and this figure increased to 97.4 million gallons per day in October of 1993. Interestingly, this also corresponded to a change in trend for the diesel series, which had previously been flat in the 1983-1993 period. Sales of number 2 fuel oil declined noticeably in the period after the dye program was implemented, even though the discontinuity in the month of implementation is less striking than with diesel due to the seasonality of fuel oil sales. Overall, the increase in diesel is largely canceled out by the decrease in fuel oil sales, at least in the first year of implementation.

The EIA also publishes the price of No. 2 distillate separately by the type of end user. Prices are available for the majority of states. When unavailable for a particular state, we utilize the price in the Petroleum Administration for Defense District (PADD) in which the state is located. To measure the price of No. 2 heating oil, we use the price of sales to residential users, which is likely to be largely composed of sales for the purpose of home heating. To measure the price of No. 2 diesel for on-road purposes, we use the price to end users through retail outlets. This price is virtually a perfect match of the low-sulfur diesel price, which is almost exclusively for on-highway use in the post-dye period.

We collect information about the federal and state on-road diesel tax rates from 1981 to 2003 from the Federal Highway Administration Annual Highway Statistics. Federal on-road diesel taxes were four cents per gallon in 1981, rising to the current level of 24.4 cents per gallon in 1993. State on-road diesel taxes rise throughout the period as well, from a weighted average tax rate of 9.2 cents per gallon in 1981 to 19.4 cents per gallon in 2003.<sup>18</sup> Within state variation also rises throughout the period. In 1981, state on-road diesel taxes vary from a low of 0 cents per gallon in Wyoming to 13.9 cents per gallon in Nebraska. In 2003, Alaska imposes the lowest state diesel taxes, at 8 cents per gallon, while Pennsylvania imposed the highest taxes of 30.8 cents per gallon. Figure 1 displays the distribution of state diesel tax rates separately for 1983, 1993, and 2003. In 1983, state tax rates were concentrated between 10 and 15 cents per gallon, with all but seven states having tax rates below 15 cents. During the course of the sample, diesel taxes grew and became more disperse across states. By 2003, 26 percent of states had a diesel tax rates of at least 25 cents per gallon, higher than the federal rate of 24.4 cents per gallon.

In our model of No. 2 fuel oil, we also wish to capture real demand factors, primarily related to temperature and prevalence of the use of fuel oil as a home heating source. We obtain data on monthly degree days by state from the National Climate Data Center at the National Oceanic and Atmospheric Administration. The number of degree days in a month is often used to model heating demand, and is a measure of the amount by which temperatures fell below a given level on a particular day, summed across the days of the month. We also measure state heating oil prevalence using the fraction of households in a state reporting to use fuel oil as the primary energy source used for home heating from the 1990 census.

Table 1 displays summary statistics of the data used in the empirical models. The average tax in the pre-dye period represents a significant fraction of the purchase price in the typical state. In the pre-dye period, the average state plus federal tax is 30.5 cents per gallon, compared

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<sup>18</sup>Oregon does not tax diesel sold for trucking, instead taxing the number of weight-miles driven in the state. For this reason, we exclude Oregon from the subsequent analysis.

with a tax excluded price of 77.8 cents per gallon for purchasers of diesel through retail outlets. This represents 28 percent of the final purchase price. Taxes are growing over time, representing 35 percent of the purchase price in the post-period. The price of sales to residential users, which is likely to represent sales of home heating oil, is higher than the price of No. 2 distillate, tax excluded, sold through retail outlets. This is likely due to the incorporation of the delivery cost to residential users. Note that the price of sales to all end users is lower than both the price through retail outlets and to residential users, as it also includes sales to commercial and industrial users.

The average state-month in the pre-dye period saw 1.4 million gallons of diesel sold per day, slightly greater than the 1.3 million gallons of fuel oil sold per day. This difference grows considerably in the post-period, when diesel sales rise to 2.3 million gallons per day while fuel oil sales fall to 0.8 million gallons per day. One can see that No. 2 distillate is far more important than the other distillates. In the pre-dye period, 67 thousand gallons of No. 1 distillate is sold, and 133 thousand gallons of No. 4 distillate is sold.

Missing values are common in the EIA quantity series. The EIA quantities are derived from a survey of prime suppliers. In months where few suppliers are serving a particular state, the quantity value is suppressed if it is possible to infer the sales from a particular firm. For diesel, 9 percent of observations are missing in the pre-dye period compared to 20 percent in the post-dye period. In the case of fuel oil, missing values represent 10 and 24 percent of the state-months in the pre- and post-dye periods, respectively. Our empirical results will be estimated off of the non-missing observations only, however we have found that the results change little when we instead interpolate the missing values using state specific time trends.

## 5 Empirical Model and Results

To uncover evidence of tax evasion, we estimate a trend-break model from the state-level data to identify the response of taxed and untaxed No. 2 distillate sales to the diesel dye program. We account for general trends in demand and supply using a quadratic time trend, which is allowed to differ between the pre-dye and post-dye periods.

We also empirically apply the model of diesel fuel and untaxed heating oil demand derived in section 3 by separately identifying the demand response to variation in price from the response of demand to variation in taxes. Quantity taxes under the null hypothesis of no evasion make the effective post-tax diesel price linear in the pre-tax price and the tax:  $p + \tau$ . Given the large differences in the level of demand across states, and since the amount of evasion is likely to be

proportional to the quantity of diesel consumed, the empirical specifications we estimate will relate log quantities to the log of the effective price. To separately isolate the tax component, we factor out the pre-tax price from the after-tax price:  $\ln(p + \tau) = \ln(p) + \ln(1 + \tau/p)$ . This leads to our main empirical specification:

$$\begin{aligned} \ln q_{it} = & \beta_0 + \gamma \text{post}_t + \beta_1 \ln p_{it} + \beta_2 \ln(1 + \tau_{it}/p_{it}) + \beta_1^{\text{post}} \text{post}_t * \ln p_{it} + \beta_2^{\text{post}} \text{post}_t * \ln(1 + \tau_{it}/p_{it}) \\ & + f(t) + \Pi X_i + \gamma_i + \epsilon_{it} \end{aligned} \quad (28)$$

where  $\ln q_{it}$  is the log of the quantity of diesel sold in state  $i$  in month  $t$ ,  $X_{it}$  is a vector of state-month covariates, and  $\gamma_i$  represents a state fixed effect. As shown in section 3, under the null hypothesis of no evasion  $\beta_1 = \beta_2$ . We can therefore uncover the presence of evasion either by comparing the estimates of these two coefficients, or by examining the response of consumption of taxed gallons to the discrete decrease in auditing costs described by the coefficient  $\gamma$ .

We are also interested in studying the pattern of the price and tax elasticities over time. We first allow the coefficients  $\beta_1$  and  $\beta_2$  to differ between the pre- and post-dye periods. This allows us to test for the presence of evasion in the post-dye period and examine the change in evasion elasticity as a particular form of evasion is made less desirable. We also consider a less restrictive specification where the coefficients  $\beta_1$  and  $\beta_2$  are allowed to vary by year:

$$\ln q_{it} = \beta_0 + \beta_{1t} \ln(p_{it}) + \beta_{2t} \ln(1 + \tau_{it}/p_{it}) + \varphi_t + \Pi X_{it} + \gamma_i + \eta_{it} \quad (29)$$

where  $\varphi_t$  represents a year dummy. This will allow for a potentially dynamic response of evasion to changes in the regulatory environment. The more flexible specification also allows for the inspection of the timing of the post-dye change in evasion elasticity to verify that it corresponded with the implementation of the diesel dye program.

As noted, the presence of a quantity tax makes the effective price of on-road diesel additive in the pre-tax price and the tax. This may not be an appropriate model for sales of fuel oil, as this is sold untaxed. Therefore, we also consider a specification analogous to (28) where demand is a function of the form  $\beta_1 \ln p_{it} + \beta_2 \ln \tau_{it}$ . We present estimates of this specification for both diesel and fuel oil.

## 5.1 Results for diesel sales

Table 2 displays the results of estimating (28) for log diesel sales. In column (1), we show estimates of a specification considering only the log of the pre-tax price and the term  $\ln(1 + \tau/p)$ . The estimate of  $\beta_1$ , -0.35, is significantly different than the estimate of  $\beta_2$ , -0.735. This specification controls for state fixed effects and a quadratic time trend interacted with the post-dye dummy. Panel A of Figure 3 shows the fit of the quadratic time trend to average actual log diesel sales. The quadratic time trend seems highly successful at fitting the time profile of diesel sales.

The specification shown in column (2) includes the after dye dummy variable. The estimated coefficient on this variable indicates that diesel sales increased 29 percent for the average state in the post-dye period. Column (3) interacts the post-dye dummy variable with the demeaned price and tax series. We see that in the pre-dye period, the estimate of  $\beta_1$  is -0.52 compared with the estimate of  $\beta_2$  of -1.41. Together, these two results suggest a significant level of evasion of diesel fuel taxes.

The average diesel price and tax elasticity can be recovered from equations (22) and (23). In the pre-period, we estimate a price elasticity of -.124 and a tax elasticity considerably larger at -1.012. In the post period, the gap between  $\beta_1$  and  $\beta_2$  declined substantially, indicating a substantial decline in the tax elasticity relative to the price elasticity. While we estimate that the post-dye price elasticity diesel fell to 0.010, the tax elasticity of taxed diesel fell further to -0.54.

Next, rather than allowing  $\beta_1$  and  $\beta_2$  to change only at the implementation of the dye program, we allow for these coefficients to depend arbitrarily on the year. Figure 4 plots the time-varying estimates of  $\beta_1$  and  $\beta_2$ . We see that in the period prior to 1993,  $\beta_2$  was substantially below  $\beta_1$ . From 1993 until 1998, the two coefficients converge to levels that are not significantly different. Subsequently, the difference between the two coefficients reappears. This suggests that the model only allowing for a single change in the tax and price elasticities masks a notable intertemporal pattern that points toward a dynamic response of evasion to the regulatory change associated with the dye. This is the pattern we would expect if firms took time to learn about and implement alternative evasion schemes.

Finally, in columns (4)-(6) of Table 2 we show the analogous specifications where the log of the state tax rate and log of the state retail diesel price enter separately. This is done for comparison purposes to the fuel oil regressions, for which this may be the more appropriate specification. These estimates are consistent with those displayed in columns (1)-(3). The

coefficient on the log tax variable is significantly larger in magnitude than the price coefficient, and this difference shrinks dramatically after the addition of dye to the diesel. Furthermore, the estimated break in log diesel sales is similarly estimated to be an increase of 30 percent for the average state.

## 5.2 Results for Fuel oil sales

Table 3 displays specifications of the log of fuel oil sales and fuel oil's share of number 2 distillate. We depart from the specifications of diesel fuel, which treated demand as a function of  $p + \tau$ . This seems a less appropriate model for fuel oil demand, and in fact from the model equation (6) describing the share of untaxed fuel purchases suggests that a more appropriate specification has the log of the tax rate entering separately from the log of the price.

Columns (1)-(3) present estimates with the log fuel oil quantity as the dependent variable. For the average state, fuel oil sales fell by 35-45 percent after the implementation of the diesel dye program. Furthermore, fuel oil sales are positively related to state tax rates. The results shown in column (2) indicate that a 10 percent increase in the diesel tax rate is associated with a 3.2 percent increase in fuel oil sales. In the specification shown in column (3), this effect is split between the pre-dye and post-dye periods. Pre-dye, the oil tax elasticity coefficient is 0.45. After the addition of dye to the untaxed fuel oil, the tax elasticity declines substantially to -0.176, which is not significantly different from zero. Each of these specifications include a quadratic time trend, allowed to differ in the post-dye period. In Panel B of Figure 3, we show that this is able to fit the actual average log fuel oil quantity well.

Figure 5 shows a striking pattern of the fuel oil tax elasticity parameter over time. Pre-dye it is positive and significantly different from the price elasticity. In 1993, the first year of the dye program, it drops to essentially zero. Moreover, unlike the time pattern of the diesel coefficients, the fuel oil tax elasticity remains close to zero for the entire post period.

In columns (4)-(6) of Table 3 we present similar estimates with fuel oil share of No. 2 distillate as the dependent variable. This specification may be desirable since it corresponds to the choice parameter  $\alpha$ , the fraction of gallons that are untaxed, in the theoretical model. The results are qualitatively identical to that presented in Table 3. In the post-dye period, the share of No. 2 distillate accounted for by fuel oil fell by 14 percentage points. Fuel oil's share is also significantly positively related to the state diesel tax rate. An increase in the tax rate of 10 percent leads to an increase in the fuel oil share of 1 percentage point. This effect disappears in the post-dye period.

Two factors that are significantly correlated with monthly fuel oil demand in the specifications shown in Table 3 are the weather and the prevalence of home heating oil use. Based on the results presented up to this point, we estimate that potentially 45 percent of fuel oil purchases in the pre-dye period were illegally used for on-highway purposes. We therefore expect that in the pre-dye period, real demand factors such as weather and home heating oil use would be less successful in explaining fuel oil sales. In Table 4, we present estimates of a regression of log fuel oil sales on the number of degree days in a particular state-month, the fraction of households in the state who reported in the 1990 census using heating oil as the primary home heating fuel, and the interaction of these two variables. In the pre-dye period, none of these variables are significant, and they are able to explain 4.9 percent of the variation in fuel oil sales. In the post-dye period on the other hand, both the number of degree days and its interaction with household heating oil usage is significantly related to fuel oil sales, and the R-squared triples to 0.136. This adds further evidence that a significant portion of the pre-dye sales were not intended for home heating use.

### 5.3 Effect of dye program by state characteristics

We next investigate the extent to which the break in diesel and fuel oil sales is correlated to factors that alter *ex ante* evasion incentives. First, we estimate the break in trend separately for states with many legitimate uses for untaxed No. 2 distillate versus taxed on-road diesel. In states with more legitimate uses of untaxed distillate, evaders may find it easier to acquire the untaxed alternative, and it will likely be more difficult for auditors to detect illegitimate users. Second we estimate the trend break separately for states with high tax rates versus states with low tax rates. According to the model, states with higher tax rates should experience greater evasion, and therefore should see a larger increase in taxed diesel at the dye implementation date.

Table 5 shows the results for log diesel. First, the sample is split between those states where agriculture's share of state output is less than the median versus those above the median. We see that the break in trend is in fact somewhat larger in low agriculture states, who saw diesel sales rise by 37.2 percent, compared with high agriculture states, who saw diesel sales rise by 23.4 percent. A likely explanation for this result is that untaxed distillate sold for agriculture use is counted as part of No. 2 diesel sales. Therefore, evaders in hi-ag states may prefer to evade the diesel tax by reporting agriculture use for the gallons they purchase untaxed, and a shift from untaxed to taxed gallons would therefore not be observed by this group.

Next, we split the sample by the prevalence of heating oil use for home heating. Consistent with our hypothesis, the dye response is heavily concentrated in high heating oil states. These states experienced a 40.9 percent increase in heating oil use, compared with a 14.4 percent increase in states with a low prevalence of home heating oil.

We last split the sample between low and high diesel tax states. The estimated break in the diesel series is larger in states with high tax rates, with an estimated break of 33.3 percent. The increase is 27.5 percent in low tax states.

Table 6 shows the results of similar specifications for the fuel oil share of No. 2 distillate. Similar to the diesel results, the fuel oil share fell by more in states with high heating oil use by households and in states with higher tax rates. Interestingly, the oil share results diverge from the diesel results when splitting states by agriculture's share of output. The decline in fuel oil's share is greatest in higher agriculture states. This provides some support for our conjecture that the smaller diesel response for high agriculture states is due to the incorporation of farm gallons in the No. 2 diesel measure.

## 5.4 Results for other fuels

We next examine the break in trend at the implementation of the diesel dye program for fuels other than No. 2 distillate. It is useful to examine the response of other fuels for two reasons. First, we wish to rule out the possibility that distillate supply shocks may happen to coincide with the implementation of the dye program. Second, other untaxed fuels not associated with the dye program may be substitutes for No. 2 diesel. For instance, dye was not added to kerosene until 1998, despite the fact that the untaxed kerosene can be blended with taxed diesel, lowering the tax per unit.

We consider seven fuels: gasoline, kerosene jet fuel, propane, kerosene, No. 1 distillate, No. 4 distillate, and residual fuel oil. For many of these fuels, missing values are a serious problem at the state level. For instance, 58 percent of the state-months are missing for No. 1 distillate, 42 percent for residual fuel oil, and 85 percent for No. 4 distillate. For this reason, in this section we focus on monthly national sales of the various types of fuels.

Table 7 presents the results of regressing log quantity separately for each fuel type on an after-dye dummy variable, a quadratic time trend interacted with the after-dye dummy variable, and the log of the WTI crude oil spot price. For gasoline, propane, and Nos. 1 and 4 distillate, the coefficient on the after dye coefficient is insignificant. It is interesting to note that two of the significant coefficients are in the specifications of kerosene type jet fuel and kerosene, two fuels

that can be blended with diesel. This suggests that in response to the dye program, evaders may have substituted toward alternative forms of evasion.

## 6 Conclusion

This paper considers the evasion of diesel taxes, and how this evasion responds to a large shift in the cost of conducting an audit and to *ex ante* evasion opportunities. The setting we consider provides a unique opportunity to observe both a taxed commodity as well as an untaxed substitute. We find that reducing the cost of audit greatly improves tax compliance, and that diesel tax evasion responds positively to tax rates. The estimated responses of diesel and fuel oil to the dyeing program are strikingly similar. We estimate that diesel sales rose by 29 percent, or 420 thousand gallons per day for the average state, after the dye program implementation. This closely aligns with the post-dye decline in fuel oil of 35 percent, or 441 thousand gallons per day.

While the current application has the luxury of observing the evasion vehicle, untaxed fuel oil, it is often the case that only taxed quantities are observed. We suggest a simple method for detecting the evasion of specific quantity taxes from the observed taxed quantities, and show how this method can be used to estimate the response of evasion to the tax rate, a parameter of considerable interest in public economics. This parameter can be obtained from equation (26). Plugging into this equation the average pre-dye taxed diesel quantity and price, and the estimated pre-dye coefficients  $\beta_1$  and  $\beta_2$ , we estimate that before the implementation of the diesel dye program each one cent increase in the per gallon diesel tax increased the amount of on-highway diesel tax evasion by 16.5 thousand gallons per day. Through fuel oil sales, we have a measure of a primary mechanism for diesel tax evasion, and it is interesting to compare this estimate to the response of fuel oil to diesel taxation. We estimate a fuel oil tax elasticity of 0.452 in the pre-dye period. Based on this coefficient and an average pre-dye tax rate of 30.54 cents per gallon and fuel oil consumption of 1.262 million gallons per day, a one cent increase in the tax rate resulted in an 18.4 thousand gallon increase in fuel oil sales. The striking similarity of these estimates lends some credence to our ability to estimate the evasion response to taxes if only taxed quantities are observed.

These results have potential policy implications. Ad valorem and specific taxes are often suggested as an alternative to income taxation due to the low administrative and compliance costs experience by states in implementing retail sales taxes. The results in this paper suggest that direct taxation may also be subject to significant evasion, particularly if taxes are not

applied in a uniform manner across goods.

Finally, one factor left for future study is the response of tax policy and administration to the diesel dye program. Alt (1983), Kau and Rubin (1981), and Balke and Gardner (1991) among others point to the importance of tax collection in shaping the tax structure. Given the magnitude of the response of sales of taxable diesel we observe it is likely that the federal or state government responds to the diesel dye program by adjusting tax rates.

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## A Appendix

In the following proposition, we derive the necessary and sufficient conditions for equation (27). It is important to note that we assume that the firm is a price taker with regard to the taxed and untaxed fuel, that taxed and untaxed fuel are interchangeable from a production standpoint, and that total diesel demand for partial and non-evaders responds equally to a unit increase in price and an unit increase in tax.

**Proposition 1.** *The condition*

$$\int_{\hat{\gamma}_{FE}}^{\hat{\gamma}_{NE}} \frac{\partial}{\partial p} \alpha(\gamma) q(\gamma) f(\gamma) d\gamma = 0 \quad (\text{A1})$$

is a necessary and sufficient condition for equation (27).

*Proof.* Equation (27) holds if and only if  $\frac{\partial Q}{\partial t} = \frac{\partial Q_t}{\partial p}$ . Expanding out each of these partial derivatives and recalling that  $\frac{\partial \hat{\gamma}_{FE}}{\partial p}, \frac{\partial \hat{\gamma}_{FE}}{\partial t}, \frac{\partial \hat{\gamma}_{NE}}{\partial t} > 0$ ,  $\frac{\partial \hat{\gamma}_{NE}}{\partial p} = 0$  and  $q(\gamma) = \bar{q}$  for all  $\gamma > \hat{\gamma}_{FE}$ , we have

$$\begin{aligned} \frac{\partial Q}{\partial t} &= \frac{\partial Q^{FE}}{\partial t} + \frac{\partial Q^{PE}}{\partial t} + \frac{\partial Q^{NE}}{\partial t} \\ &= \frac{\partial \hat{\gamma}_{FE}}{\partial t} q(\hat{\gamma}_{FE}) f(\hat{\gamma}_{FE}) \\ &\quad + \int_{\hat{\gamma}_{FE}}^{\hat{\gamma}_{NE}} \frac{\partial q(\gamma)}{\partial t} f(\gamma) d\gamma + \left[ \frac{\partial \hat{\gamma}_{NE}}{\partial t} q(\hat{\gamma}_{NE}) f(\hat{\gamma}_{NE}) - \frac{\partial \hat{\gamma}_{FE}}{\partial t} q(\hat{\gamma}_{FE}) f(\hat{\gamma}_{FE}) \right] \\ &\quad + \int_{\hat{\gamma}_{NE}}^{\theta} \frac{\partial q(\gamma)}{\partial t} f(\gamma) d\gamma - \frac{\partial \hat{\gamma}_{NE}}{\partial t} q(\hat{\gamma}_{NE}) f(\hat{\gamma}_{NE}) \\ &= [F(\theta) - F(\hat{\gamma}_{FE})] \frac{\partial \bar{q}}{\partial t}, \end{aligned} \quad (\text{A2})$$

and

$$\begin{aligned} \frac{\partial Q_t}{\partial p} &= \frac{\partial}{\partial p} \int_{\hat{\gamma}_{FE}}^{\hat{\gamma}_{NE}} (1 - \alpha(\gamma)) q(\gamma) f(\gamma) d\gamma + \int_{\hat{\gamma}_{NE}}^{\theta} q(\gamma) f(\gamma) d\gamma \\ &= -\frac{\partial \hat{\gamma}_{FE}}{\partial p} (1 - \alpha(\hat{\gamma}_{FE})) q(\hat{\gamma}_{FE}) f(\hat{\gamma}_{FE}) + \int_{\hat{\gamma}_{FE}}^{\hat{\gamma}_{NE}} \frac{\partial}{\partial p} [(1 - \alpha(\gamma)) q(\gamma)] f(\gamma) d\gamma \\ &\quad + \int_{\hat{\gamma}_{NE}}^{\theta} \frac{\partial}{\partial p} q(\gamma) f(\gamma) d\gamma \\ &= \int_{\hat{\gamma}_{FE}}^{\hat{\gamma}_{NE}} \frac{\partial}{\partial p} [(1 - \alpha(\gamma)) \bar{q}] f(\gamma) d\gamma + [F(\theta) - F(\hat{\gamma}_{NE})] \frac{\partial \bar{q}}{\partial p}. \end{aligned} \quad (\text{A3})$$

Noting that  $\frac{\partial \bar{q}}{\partial p} = \frac{\partial \bar{q}}{\partial t}$ ,

$$\frac{\partial Q}{\partial t} = \frac{\partial Q_t}{\partial p} \iff \int_{\hat{\gamma}_{FE}}^{\hat{\gamma}_{NE}} \frac{\partial}{\partial p} [\alpha(\gamma)\bar{q}] f(\gamma) d\gamma = 0. \quad (\text{A4})$$

□

**Corollary 2.** *If the cost of evasion is quadratic in the amount of the untaxed product purchased, equation (27) holds.*

*Proof.* Although this is the example we use in the text, we work through the derivation here. If the cost of evasion is quadratic in the amount of untaxed product purchased, recall that the derivative of expected profits with respect to  $\alpha$  for a partial evader is given by  $\alpha^*(\gamma) = \frac{t}{\gamma \bar{q}}$ . Thus,  $\frac{\partial \alpha(\gamma)\bar{q}}{\partial p} \frac{\partial t}{\partial \gamma} = 0$ , satisfying the necessary and sufficient condition above. □

Note that the necessary and sufficient conditions continue to hold if the regulator assesses a two-part penalty with a fixed component and a component linear in the amount of evasion.

Figure 1: Distribution of State Diesel Tax Rates

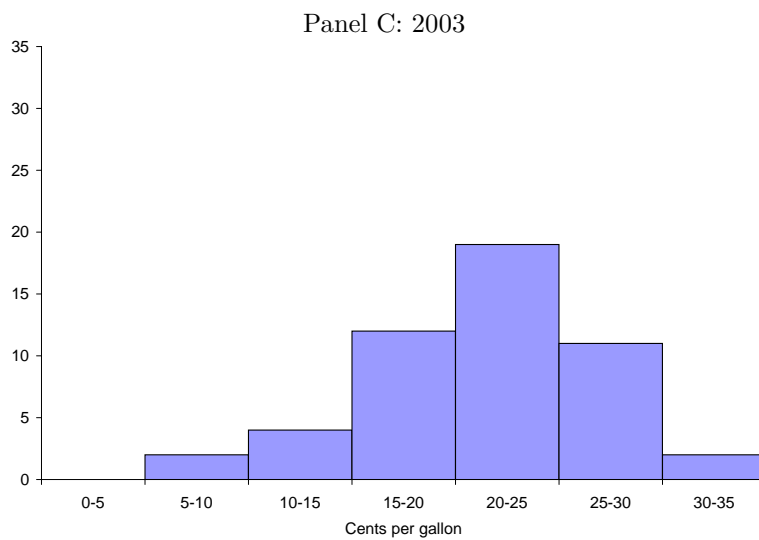
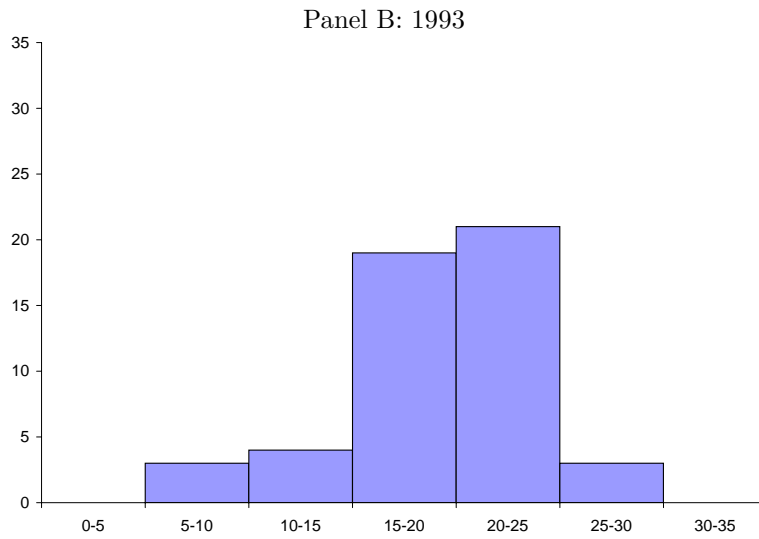
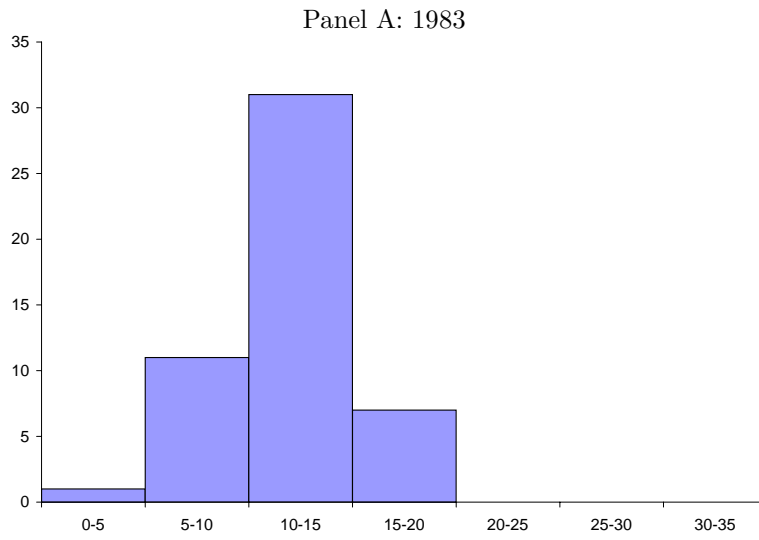


Figure 2: U.S. Sales of No. 2 Distillate

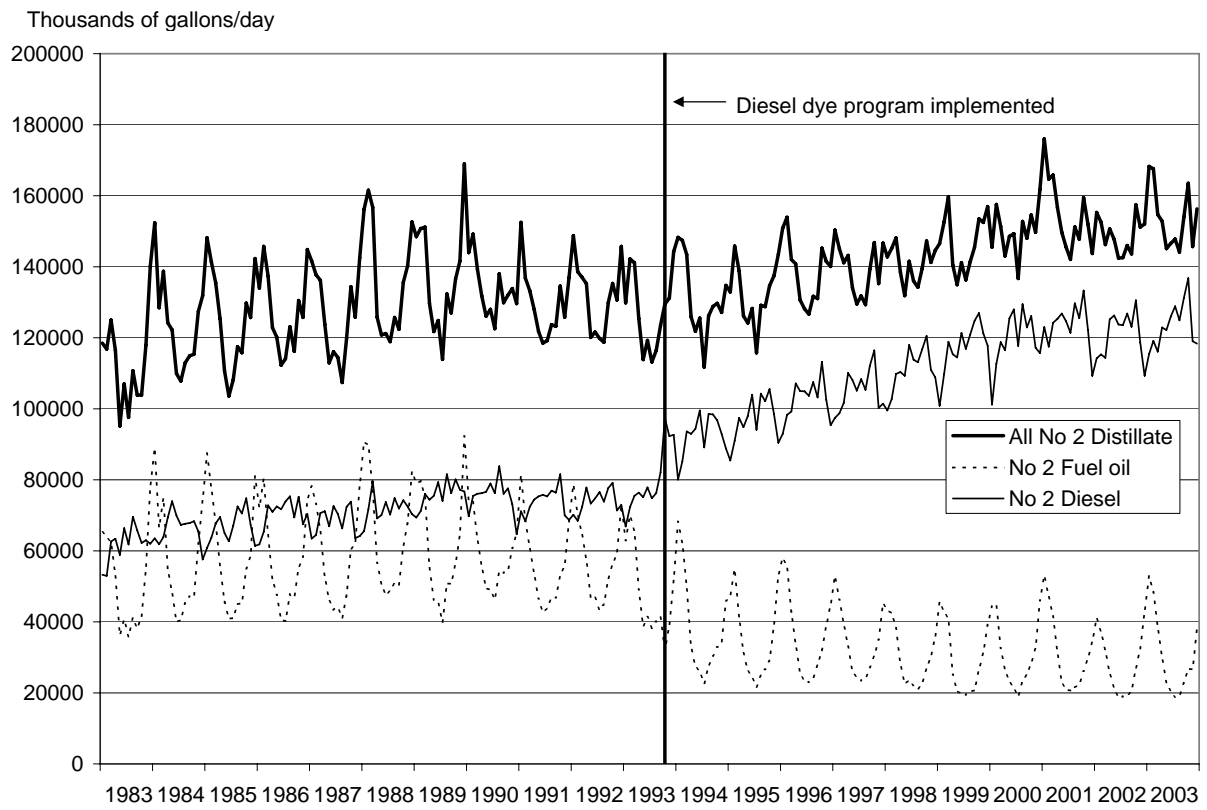


Figure 3: Average Predicted Versus Actual Log Quantities Sold

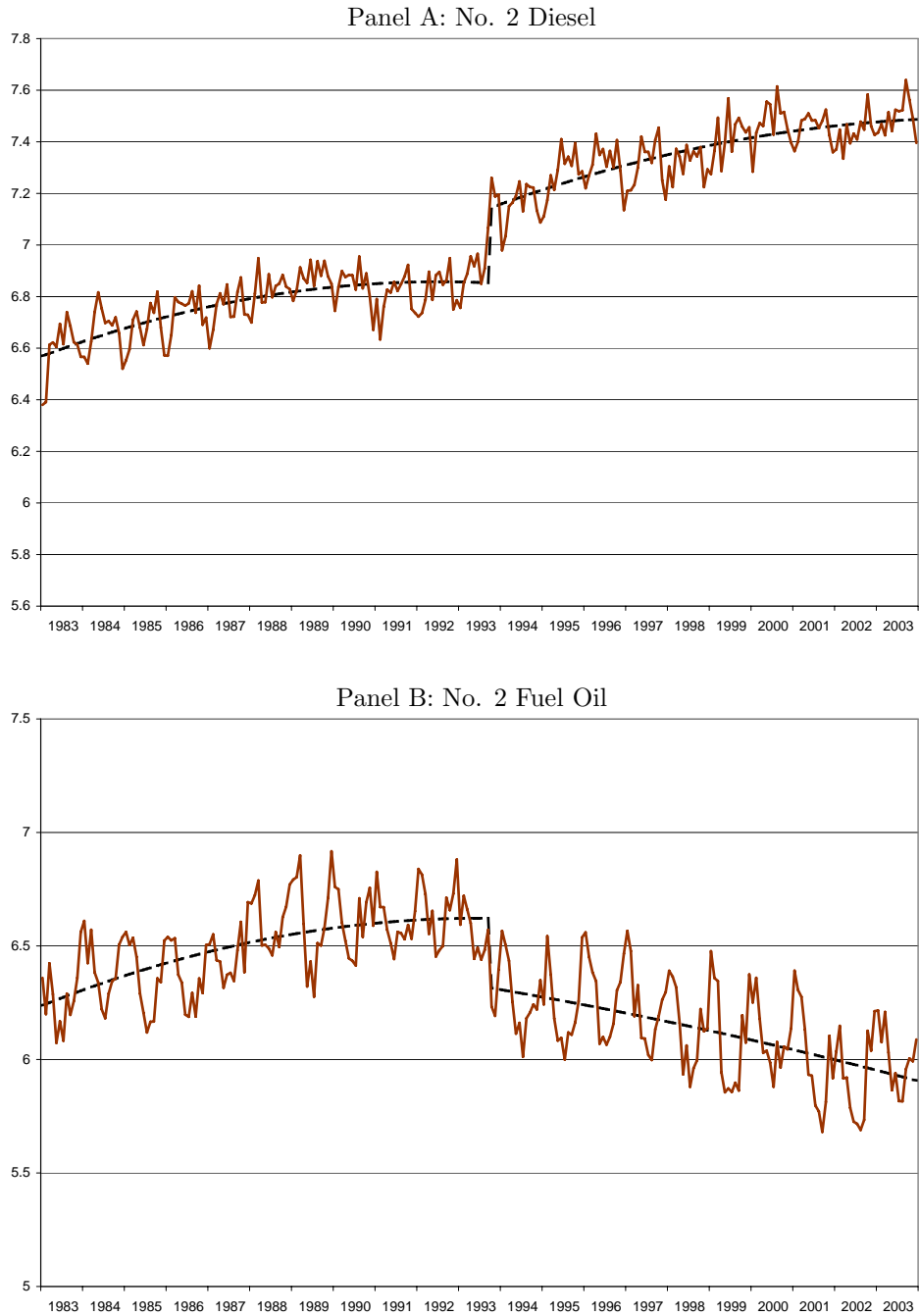


Figure 4: Coefficients  $\beta_1$  and  $\beta_2$  by Year, Log Diesel Sales

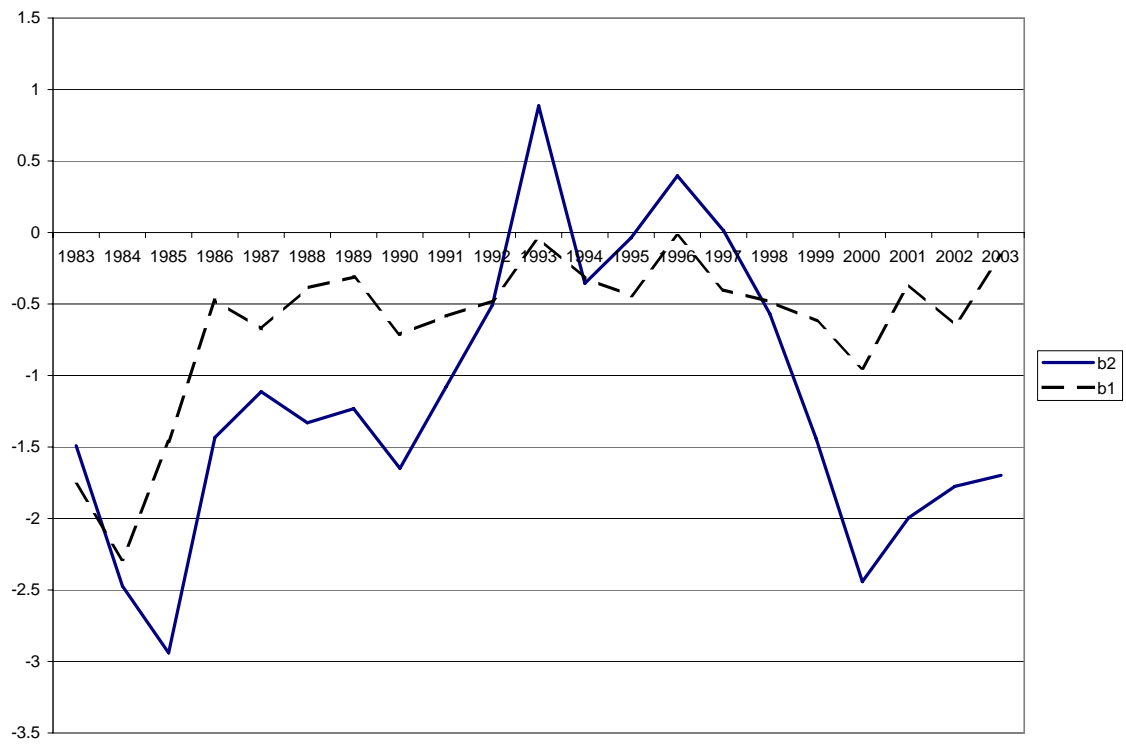


Figure 5: Tax Versus Price Elasticity, Log Fuel Oil Sales

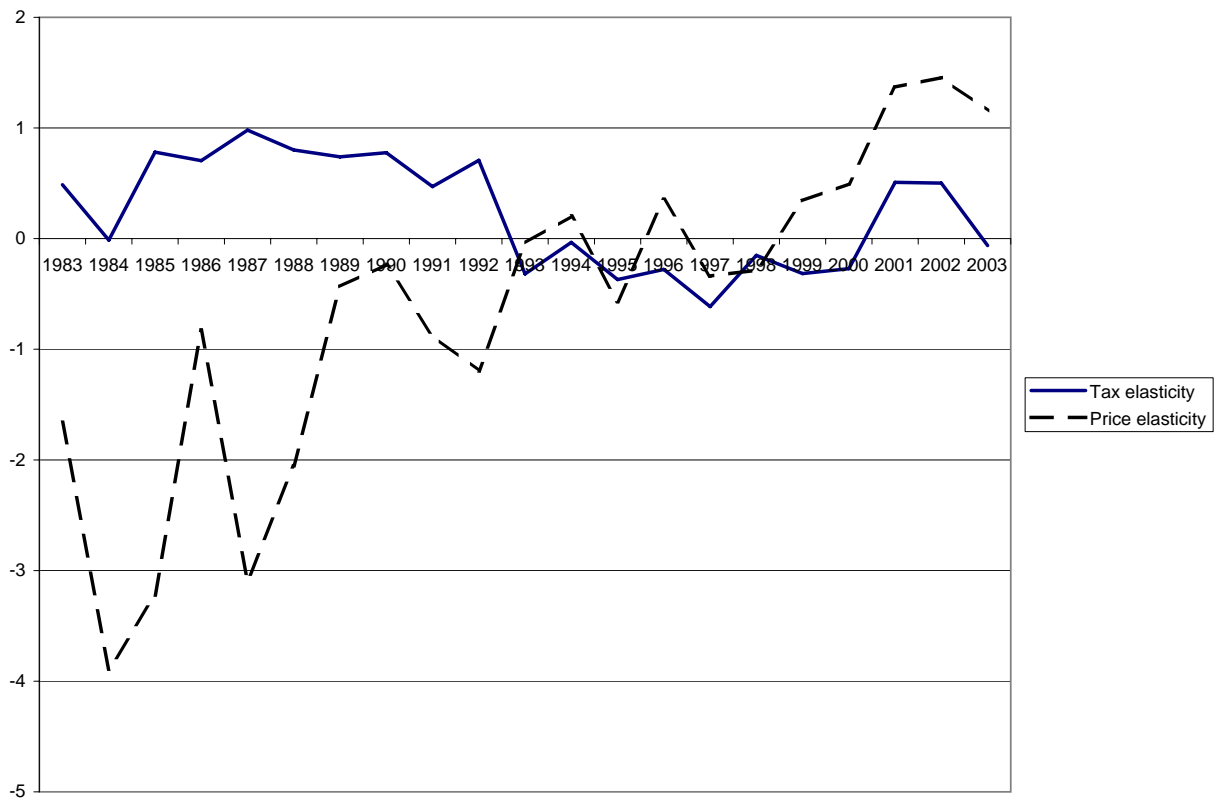


Table 1: Summary Statistics

	Pre-Dye (1)	Post-Dye (2)
State + federal diesel tax (c/gall)	30.54 (7.02)	44.47 (4.87)
No. 2 Distillate Price:		
All end users	75.49 (15.32)	81.17 (18.46)
Residential users	88.68 (14.19)	97.28 (19.81)
Sold through retail outlets	77.79 (14.21)	82.61 (17.96)
No. 2 Diesel	1449.31 (1855.85)	2315.93 (2134.98)
No. 2 Low sulfur		2005.81 (1848.74)
No. 2 High Sulfur		462.34 (544.49)
No. 2 Fuel oil	1262.08 (1711.04)	859.15 (1169.89)
No. 1 Distillate	67.26 (94.84)	85.22 (109.07)
No.4 Distillate	133.26 (243.26)	130.00 (219.14)
Residual fuel oil	1441.77 (2067.73)	1074.25 (1343.51)
Degree days	441.14 (438.22)	433.40 (419.15)
Missing No. 2 Diesel	0.09	0.20
Missing No. 2 Fuel Oil	0.10	0.24
Fraction of HH using heating oil		0.14

Standard errors are in parentheses. Quantity variables are in thousands of gallons per day. The No. 2 low sulfur and high sulfur values added together do not match the total No. 2 diesel value due to missing values.

Table 2: Log No. 2 Diesel Sales

	(1)	(2)	(3)	(4)	(5)	(6)
After		0.294 (0.012)***	0.272 (0.013)***		0.302 (0.012)***	0.293 (0.014)***
Ln(1+t/p)	-0.735 (0.091)***	-1.203 (0.089)***	-1.409 (0.105)***			
After*Ln(1+t/p)			0.579 (0.120)***			
Ln(Pre-tax price)	-0.350 (0.034)***	-0.439 (0.033)***	-0.521 (0.036)***	-0.113 (0.015)***	-0.052 (0.015)***	-0.114 (0.021)***
After*Ln(price)			0.241 (0.045)***			0.130 (0.029)***
Ln(t)				-0.176 (0.026)***	-0.320 (0.028)***	-0.329 (0.030)***
After*Ln(t)						0.059 (0.042)
Degree days (X100)		-0.027 (0.002)***	-0.027 (0.002)***		-0.027 (0.002)***	-0.027 (0.002)***
Deg. days*% of HH using oil		0.041 (0.003)***	0.041 (0.003)***		0.041 (0.003)***	0.041 (0.003)***
Log(GSP)		0.369 (0.037)***	0.355 (0.036)***		0.356 (0.037)***	0.360 (0.036)***
Unemployment rate		0.004 (0.002)**	0.004 (0.002)**		0.006 (0.002)**	0.005 (0.002)**
Constant	8.800 (0.184)***	5.221 (0.466)***	5.819 (0.459)***	8.100 (0.120)***	4.333 (0.440)***	4.607 (0.435)***
Observations	10459	10236	10236	10459	10236	10236
R-squared	0.96	0.96	0.96	0.96	0.96	0.96

Robust standard errors are in parentheses.

\*, \*\*, \*\*\* denote significance at the 90%, 95%, and 99% level, respectively.

Each specification also includes controls for state fixed effects, a quadratic time trend interacted with the post-dye dummy, and month dummy variables. The pre-tax price in the diesel specifications is the price charged through retail outlets.

Table 3: No. 2 Fuel Oil

	Log Fuel Oil Sales			Fuel Oil's Share of No. 2 Distillate		
	(1)	(2)	(3)	(4)	(5)	(6)
After		-0.445 (0.029)***	-0.349 (0.032)***		-0.144 (0.005)***	-0.118 (0.006)***
Ln(t)	0.144 (0.066)**	0.324 (0.070)***	0.452 (0.075)***	0.048 (0.011)***	0.106 (0.012)***	0.133 (0.013)***
After*Ln(t)			-0.628 (0.105)***			-0.153 (0.018)***
Ln(Pre-tax price)	0.292 (0.046)***	0.124 (0.046)***	-0.201 (0.051)***	0.084 (0.007)***	0.036 (0.007)***	0.011 (0.009)
After*Ln(price)			0.753 (0.082)***			0.062 (0.013)***
Degree days (X100)		-0.053 (0.004)***	-0.055 (0.004)***		-0.003 (0.001)***	-0.003 (0.001)***
Deg. days*% HH using oil		0.243 (0.008)***	0.243 (0.008)***		0.037 (0.001)***	0.037 (0.001)***
Log(GSP)		-0.730 (0.107)***	-0.634 (0.107)***		-0.171 (0.017)***	-0.158 (0.016)***
Unemployment rate		-0.014 (0.006)***	-0.022 (0.006)***		-0.002 (0.001)**	-0.003 (0.001)**
Constant	4.701 (0.323)***	13.455 (1.226)***	13.472 (1.218)***	-0.126 (0.056)**	1.864 (0.199)***	1.731 (0.189)***
Observations	9748	9542	9542	9625	9429	9429
R-squared	0.80	0.83	0.84	0.86	0.89	0.89

Robust standard errors are in parentheses.

\*, \*\*, \*\*\* denote significance at the 90%, 95%, and 99% level, respectively.

Each specification also includes controls for state fixed effects, a quadratic time trend interacted with the post-dye dummy, and month dummy variables. The pre-tax price in the oil specifications is the price charged to residential users.

Table 4: Fuel Oil Demand Pre- vs. Post-Dye  
*Dependent variable: Log Fuel Oil Sales*

	Before	After
Degree days X100	-0.013 (0.024)	0.0403 (.022)*
Degree days*hh oil fraction	0.099 (0.084)	0.235 (.077)***
Fraction of HH Oil	0.930 (1.065)	0.844 (0.887)
Constant	6.313 (0.234)	5.931 (.192)
R2	0.049	0.136
N	5665	4353

Robust standard errors are in parentheses.

\*, \*\*, \*\*\* denote significance at the 90%, 95%, and 99% level, respectively.

Table 5: Log No. 2 Diesel, by State Characteristics

	By Ag Share of GSP		By Heating Oil Use		By 1993 Tax	
	(1) Low Ag	(2) Hi Ag	(3) Low Oil	(4) Hi Oil	(5) Low Tax	(6) Hi Tax
After	0.372 (0.016)***	0.234 (0.018)***	0.144 (0.013)***	0.409 (0.018)***	0.275 (0.017)***	0.333 (0.017)***
Ln(1+t/p)	-1.601 (0.112)***	-1.028 (0.145)***	-1.184 (0.109)***	-0.735 (0.122)***	-1.912 (0.122)***	-0.673 (0.133)***
Ln(no 2 pre-tax price)	-0.502 (0.041)***	-0.457 (0.054)***	-0.419 (0.041)***	-0.304 (0.046)***	-0.647 (0.045)***	-0.272 (0.050)***
Constant	10.689 (0.634)***	2.397 (0.562)***	8.427 (0.432)***	-0.071 (0.760)	4.066 (0.597)***	7.369 (0.633)***
N	5598	4638	4827	5409	5492	4744
R-squared	0.96	0.96	0.95	0.96	0.96	0.96

Robust standard errors are in parentheses.

\*, \*\*, \*\*\* denote significance at the 90%, 95%, and 99% level, respectively.

Each specification also includes controls for state fixed effects, a quadratic time trend interacted with the post-dye dummy, and month dummy variables. The pre-tax price is the average price of number 2 distillate sold through retail outlets less the tax due. Low agriculture states are states whose 1993 agriculture share of GSP is less than that of the median state. Low oil states are states where the fraction of households using home heating oil is less than that of the median state. Finally, low tax states are those whose diesel tax rate in October of 1993 is less than the median state.

Table 6: Fuel Oil Share of No. 2 Distillate, by State Characteristics

	By Ag Share of GSP		By Heating Oil Use		By 1993 Tax	
	(1) Low Ag	(2) Hi Ag	(3) Low Oil	(4) Hi Oil	(5) Low Tax	(6) Hi Tax
After	-0.126 (0.006)***	-0.171 (0.009)***	-0.129 (0.006)***	-0.152 (0.008)***	-0.134 (0.008)***	-0.153 (0.007)***
Ln(t)	0.041 (0.009)***	0.019 (0.012)	-0.025 (0.009)***	0.080 (0.011)***	0.030 (0.010)***	0.058 (0.010)***
Ln(Pre-tax price)	0.091 (0.013)***	0.151 (0.027)***	0.111 (0.016)***	0.090 (0.015)***	0.092 (0.018)***	0.153 (0.016)***
Constant	0.924 (0.312)***	2.464 (0.244)***	-2.060 (0.253)***	3.955 (0.245)***	1.009 (0.263)***	3.969 (0.278)***
N	5261	4168	4035	5394	4959	4470
R-squared	0.91	0.84	0.78	0.87	0.88	0.91

Robust standard errors are in parentheses.

\*, \*\*, \*\*\* denote significance at the 90%, 95%, and 99% level, respectively.

Each specification also includes controls for state fixed effects, a quadratic time trend interacted with the post-dye dummy, and month dummy variables. The pre-tax price is the average of price of number 2 distillate to all residential users. Low agriculture states are states whose 1993 agriculture share of GSP is less than that of the median state. Low oil states are states where the fraction of households using home heating oil is less than that of the median state. Finally, low tax states are those whose diesel tax rate in October of 1993 is less than the median state.

Table 7: Trend Break of Other Log Fuels

	Gasoline (1)	Kerosene Jet Fuel (2)	Propane (3)	Kerosene (4)	No. 1 Distillate (5)	No. 4 Distillate (6)	Residual Fuel Oil (7)
After-dye	0.001 (0.018)	0.075 (0.017)***	0.150 (0.098)	0.482 (0.288)*	0.025 (0.283)	0.298 (0.202)	-0.209 (0.068)***
Constant	12.710 (0.040)***	10.650 (0.045)***	10.289 (0.242)***	7.167 (0.646)***	7.815 (0.786)***	7.510 (0.503)***	10.868 (0.149)***
Observations	252	252	252	251	252	252	252
R-squared	0.75	0.94	0.12	0.04	0.08	0.48	0.80

Robust standard errors are in parentheses.

\*, \*\*, \*\*\* denote significance at the 90%, 95%, and 99% level, respectively.

The dependent variable is the log of the national quantity of the given variable. Each specification includes a quadratic time trend interacted with the post-dye dummy, and the log of the WTI crude oil spot price.