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and the Effects of Regulatory Innovation:
A Study of Diesel Fuel Tax Evasion**

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2007

RPP-2007-02

Regulatory Policy Program

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CITATION

This paper may be cited as: Marion, Justin, and Erich Muehlegger. 2007. "Measuring Illegal Activity and the Effects of Regulatory Innovation: A Study of Diesel Fuel Tax Evasion," Regulatory Policy Program Working Paper RPP-2007-02. Cambridge, MA: Mossavar-Rahmani Center for Business and Government, John F. Kennedy School of Government, Harvard University. Comments may be directed to the authors.

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

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May 2007

Abstract

This paper examines tax evasion in the context of the diesel fuel market and the response of evaders to regulatory innovation. Diesel fuel used for on-road purposes is taxed, while other uses are untaxed, creating an 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. We examine the effects of a federal regulatory innovation in October 1993, the addition of red dye to untaxed diesel fuel at the point of distribution, which significantly lowered the cost of regulatory enforcement. We propose a model of the evasion decision that predicts that evasion increases as taxes rise and monitoring costs fall. Testing the predictions of the model, we find that sales of diesel fuel rose 26 percent following the regulatory change while sales of heating oil, which is an untaxed perfect substitute, fell by a similar amount. The effect on sales was higher in states with higher tax rates and in states likely to have higher audit costs. Heating oil sales are also found to be much less responsive to demand factors such as temperature and season prior to the dye program, indicating that a significant fraction of sales prior to dyeing was illegitimate. In addition, we find evidence that tax evaders found new methods of evading fuel dye regulations. We find that sales of kerosene and jet fuel, two undyed alternatives to untaxed diesel fuel, rose following the introduction of fuel dye. Furthermore, we find a pattern of price and tax elasticities consistent with innovation in new evasion techniques subsequent to the regulatory change. Finally, we examine the extent to which tax increases are incorporated into tax revenues, using the estimated tax and price elasticities to describe how this is affected by evasion. We estimate that the elasticity of tax revenues with respect to the tax rate was 0.60 prior to the dye program, yet would have been 0.85 in the absence of evasion.

*The authors thank Raj Chetty, Christopher Synder, and seminar participants at the Federal Trade Commission, UC Santa Cruz, International Industrial Organization Conference, Tufts, UC Berkeley, and UC Davis for helpful comments and conversations.

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1 Introduction

Tax evasion and tax collection are important elements of 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.

Detecting tax evasion and estimating how it responds to tax and enforcement policy 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. The value of providing empirical evidence regarding these questions is high, as even theoretically the response of evasion to tax rates is not clear.¹

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.

In this paper, we consider the impacts on tax evasion of a regulatory innovation that greatly decreased the cost of monitoring compliance with on-road diesel fuel taxes. In October 1993, the Federal Highway Administration began adding red dye to diesel sold for non-taxed purposes.

The dye allows inspectors to readily check for the use of untaxed diesel through simple visual

¹Allingham 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.

inspection, reducing the cost of auditing for regulators and increasing the cost of achieving a given level of diesel tax evasion for firms.

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, the reduction in evasion should be greater in states with high diesel tax rates, and hence a high incentive for evasion.

We empirically evaluate the model using a monthly, state-level panel of sales of diesel fuel and a perfect substitute, untaxed distillate fuel oil. We find evidence consistent with a reduction in evasion as a result of the fuel dye program. Following the regulatory innovation, sales of diesel fuel rose 25-30 percent while sales fuel oil fell by a similar amount. This is consistent with regulatory changes substantially limiting the amount of diesel fuel tax evasion. Consistent with the predictions of the model, the effect of the dyeing program had the largest effect on diesel sales in states with high tax rates, and states likely to have high monitoring costs. Moreover, sales of close substitutes to diesel fuel not subject to the dye program (such as kerosene) rose post-regulation, suggesting that firms engaged in evasion substituted away from untaxed diesel fuel to alternative petroleum products as a method of evading fuel taxes.

We then utilize a test for evasion 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 in the pre-dye period, rejecting the null hypothesis of no evasion. This gap disappears in the years following the dye program as untaxed substitutes were made more difficult to use, yet the gap reappears beginning in 1998. We take this as evidence of a dynamic response of evaders to the dyeing program.

Finally, we examine the extent to which tax increases are incorporated into tax revenues and use the estimated tax and price elasticities to describe how this is affected by the response of evasion to the tax rate. We estimate that the tax revenue elasticity with respect to the tax rate is 0.60 in the pre-dye period and 0.71 after the implementation of the dye program. If no evasion existed in this market, these values would be 0.85 and 0.90, respectively. Therefore,

the impact of tax changes on revenues increased in the post-dye period, and over half of this increase can be attributed to less evasion.

The techniques we use 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. Similarly, Rosen (1976) compares the response of female labor supply to taxes and wages. Tax salience is unlikely to be an issue with diesel sales, as the tax is incorporated in the price quoted to the consumer.

Our paper relates closely to the literature measuring tax evasion and its responsiveness to incentives, and more broadly to empirical studies attempting to uncover evidence of illegal activity. 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. In a similar vein, Hsieh and Moretti (2006) uncover evidence of underpricing and bribes in Iraq's oil for food program by comparing prices charged by Iraq for oil with prices of close substitutes sold on the world market. DellaVigna and La Ferrara (2006) use the response of the equity prices of weapons manufacturers to armed conflict events to uncover evidence of illegal arms sales.

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 primary empirical evidence, the response of sales to the dye program. Section 6 provides results implementing the test of evasion and derives estimates of the responsiveness of evasion to tax rates. Section 7 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.² Diesel fuel consumed for farming or off-road travel, or as fuel oil for residential, commercial or industrial boilers is not subject to highway taxes and is not required to 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

²From 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.

canonical method of evasion was the “daisy chain”, in which a 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.³ 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.⁴ 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.

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 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. Dyeing of diesel began upon the introduction of these regulations on October 1, 1993. 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 \$1000.⁵

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)

³For documented examples of evasion, see the Federal Highway Administration Tax Evasion Highlights.

⁴Fuel Oil and Kerosene Sales Report, Energy Information Administration, 2004.

⁵In 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.

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.

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.⁶ 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, γ .⁷ 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 $q_u > 0$.⁸

⁶Although 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.

⁷We 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 γ given by $\gamma \sim f[\theta_1, \theta_1 + \theta_2]$, and allowing $\frac{\partial \gamma_1}{\partial Q_u^L}, \frac{\partial \gamma_2}{\partial Q_u^L} \leq 0$, we can derive comparative statics with respect to Q_u^L .

⁸The fixed component of the penalty is a sufficient condition for the existence of entirely legal firms, so long as θ , the upper bound on the cost of evasion parameter, is sufficiently high.

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 .⁹ The regulator then chooses the probability with which it will audit firms, p_a , to maximize the regulatory objective function¹⁰

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

where Q_t is the total purchases of the taxed diesel. In the second step of the game, firms observe p_a, p , and t and, based on their heterogeneous cost of evasion, choose quantities of taxed and untaxed diesel fuel, q_t and q_u . Finally, the regulator randomly audits p_a proportion of the firms and punishes all 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 α , where $q_u = \alpha q$. A risk-neutral firm located at γ chooses q and α 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 cost of choosing untaxed quantity $q_u = \alpha q$, the cost of choosing taxed quantity $q_t = (1-\alpha)q$, and the expected punishment for firms choosing $\alpha > 0$. For an interior solution of $\alpha \in (0, 1)$, the first order conditions are

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

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

⁹If 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.

¹⁰We 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.

implying,

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

Let \bar{q} denote the quantity of diesel fuel satisfying (4) for interior solutions of α , given by

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

We group firms into one of three classes based on their heterogenous cost of evasion, γ : full evaders who choose $\alpha^* = 1$, partial evaders who choose an interior solution for α^* 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

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

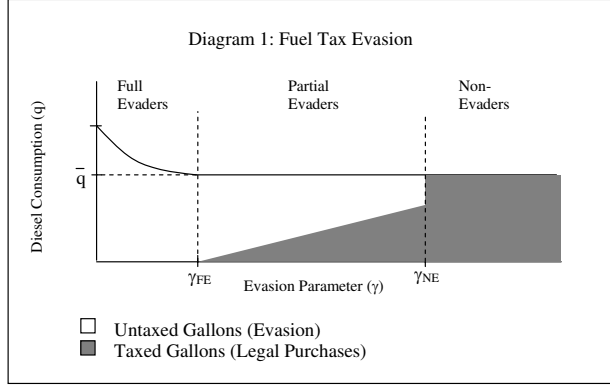
and

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

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

For firms above the non-evasion cutoff, $\hat{\gamma}_{NE}$, the expected penalty outweighs the benefits of evasion. These firms fully comply with the regulations by only purchasing taxed diesel. 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.¹¹ For partially-evading firms with lower heterogenous cost of evasion, γ , firms continue to purchase \bar{q} units of diesel fuel, but purchase both taxed and untaxed diesel fuel. At the optimum, partial

¹¹Absent 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.



evaders equate the marginal cost of evasion with the tax rate. For lower values of γ , firms substitute 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 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

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

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

Unlike the firm problem which, conditional on p_a , is independent of the distribution of γ , the regulator's choice of p_a^* depends on the distribution of γ . Since $\hat{\gamma}_{NE}$ is itself a function of p_a ,

more than one value of p_a may solve the first order condition.¹² 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.¹³ 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 $\frac{\partial Q_u}{\partial p_a} < 0$.

3.3 Empirical Predictions

We derive two sets of testable predictions which we would expect to hold if fuel tax evasion exists and if the addition of fuel dye reduces evasion. The first set of empirical predictions test the discontinuity in sales before and after the introduction of the fuel dye. The second set of empirical predictions compare the price and tax elasticity of diesel fuel.

To derive the first set of testable predictions, we substitute (15) into (12) and (13) and derive the comparative statics for Q_t and Q_u with respect to c_a . Since the cost of auditing only affects demand for taxed and untaxed diesel through the regulator's choice of p_a^* , $\frac{\partial Q_t}{\partial c_a} < 0$ and $\frac{\partial Q_u}{\partial c_a} > 0$. In our context, diesel fuel dye reduces the cost of monitoring firm compliance with diesel fuel taxes. 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) should fall and consumption of taxed diesel (compliance) should rise with the introduction of diesel dye.

The theoretical model also predicts a correlation between state characteristics and the magnitude of the discontinuity in sales at the time of the fuel dye introduction. State tax rates are positively correlated with the incentive for firms to evade. Unlike the cost of auditing which only affects firms through the regulator's choice of audit intensity, the tax rate also affects the partial and non-evader consumption of diesel, \bar{q} , and the cutoffs for full evasion and non-evasion, $\hat{\gamma}_{FE}$ and $\hat{\gamma}_{NE}$. If a unique solution to the regulator's problem exists, we can unambiguously sign $\frac{\partial Q_t}{\partial t} < 0$. 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

¹²If the distribution of γ 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.

¹³A sufficient condition for a unique non-zero solution is $f(\gamma)$ weakly monotonically increasing in γ . 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 $p_a \in (0, 1)$.

hence, untaxed diesel consumption) for partial evaders. The first effect outweighs the second effect - thus, the model predicts that untaxed sales rise with taxes.¹⁴

Thus, our first set of empirical predictions states that 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.

We derive a second set of testable predictions based on the short-run price and tax elasticity of diesel fuel.¹⁵ From (12), p has two effects on Q_t : an increase in p lowers total diesel consumption of partial and non-evaders, and increases the full-evasion cutoff. A change in the tax rate has an identical effect on total diesel consumption of partial and non-evaders. With evasion, though, an increase in t has three additional effects. An increase in t increases the full-evasion cutoff more than an increase in p , increases the non-evasion cutoff and, conditional on γ , increases evasion for all partial evaders.¹⁶ Comparing the derivative of Q_t with respect to p and the derivative of Q_t with respect to t , we have

$$\frac{\partial Q_t}{\partial p} = \frac{\partial \bar{q}}{\partial p} [1 - F(\hat{\gamma}_{FE})] \quad \text{and} \quad (16)$$

$$\frac{\partial Q_t}{\partial t} = \frac{\partial \bar{q}}{\partial t} [1 - F(\hat{\gamma}_{FE})] - 2F(\hat{\gamma}_{NE}) - \int_{\hat{\gamma}_{FE}}^{\hat{\gamma}_{NE}} \frac{1}{\gamma} f(\gamma) d\gamma \quad (17)$$

Identifying the relative magnitudes of (16) and (17) is straightforward. Since $\frac{\partial \bar{q}}{\partial p} = \frac{\partial \bar{q}}{\partial t}$, the first terms in (16) and (17) are equivalent - the first terms capture the effect of a change in the tax-inclusive price on total diesel consumption by partial and non-evaders. The second and third terms in (17), 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, the introduction of diesel dye has a differential effect on $\frac{\partial Q_t}{\partial t}$ and $\frac{\partial Q_t}{\partial p}$. Specifically, a change in the cost of auditing (and hence regulator choice of audit intensity) affects $\frac{\partial Q_t}{\partial t}$, but does not affect $\frac{\partial Q_t}{\partial p}$. We can express the derivative of $\frac{\partial Q_t}{\partial t}$ with respect to c_a as a decreasing function of c_a . Thus, as enforcement increases (either exogenously or through lower cost of enforcement), the effect on taxed sales of a change in taxes becomes similar to the effect of a change in tax-exclusive price.

These results suggest a testable hypotheses for the presence of evasion - if evasion exists,

¹⁴In 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.

¹⁵By short-run, we mean the price and tax elasticity, conditional on the regulator's choice of p_a .

¹⁶With multiple jurisdictions, increase tax in one jurisdiction will also have a border crossing effect.

we would expect taxable sales to respond more to a change in taxes than a change in prices.¹⁷ Furthermore, if diesel dye reduces the cost of monitoring and increases 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,

$$\text{Log}(Q_t) = \alpha + \beta_1 \text{Log}(p) + \beta_2 \text{Log}\left(1 + \frac{t}{p}\right) + X\Theta + \epsilon, \quad (18)$$

we can derive the appropriate null and alternative hypotheses.

Taking derivatives with respect to p and t , we have

$$\frac{1}{Q_t} \frac{\partial Q_t}{\partial p} = \frac{1}{p} (\beta_1 - \beta_2 \frac{t}{p+t}) \quad (19)$$

$$\frac{1}{Q_t} \frac{\partial Q_t}{\partial t} = \beta_2 \left(\frac{1}{p+t}\right) \quad (20)$$

If no evasion occurs¹⁸, we would expect a unit change in price and a unit change in consumer tax incidence to have the same effect on taxed diesel sales. 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

$$\frac{1}{Q_t} \frac{\partial Q_t}{\partial p} = \frac{1}{Q_t} \frac{\partial Q_t}{\partial t} \rightarrow \beta_1 \frac{1}{p} - \beta_2 \frac{t}{p(t+p)} = \beta_2 \frac{1}{(t+p)} \rightarrow H_0 : \beta_1 = \beta_2. \quad (21)$$

In summary, our model provides a number of testable predictions that we would expect to see if firms evaded fuel taxes in the pre-dye period and the introduction of diesel dye reduced evasion:

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.)

¹⁷Note 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.

¹⁸In 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)

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 be reduced after the introduction of dye.

3.4 Estimating Evasion

In addition to the testable predictions above, we derive two expressions of potential policy interest: the change in evasion (E) with respect to the tax rate, and the elasticity of diesel tax revenues with respect to the tax rate. Both expressions are functions of the regression coefficients β_1 and β_2 , the tax rate, the tax-exclusive price and total taxable diesel sales, and thus could plausibly be estimated from the empirical framework above, using observable data on taxed sales alone.

To derive the expression for the change in evasion, we use the identity $Q_u = Q - Q_t$. Noting that a change in untaxed quantities from a change in the tax rate arises purely through evasion, we have

$$\frac{\partial E}{\partial t} = \frac{\partial Q_u}{\partial t} = \frac{\partial Q}{\partial t} - \frac{\partial Q_t}{\partial t}. \quad (22)$$

Expanding the derivative of total diesel sales with respect to taxes, we have

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

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

$$\frac{\partial E}{\partial t} = \frac{\partial Q_t}{\partial p} - \frac{\partial Q_t}{\partial t}. \quad (23)$$

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 as 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 (19) and (20) into (23) we can express the derivative of evasion with respect to taxes as a function of β_1 and β_2

above.

$$\frac{\partial E}{\partial t} = \frac{Q_t}{p}[\beta_1 - \beta_2]. \quad (24)$$

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 - in our empirical work, we exploit the availability of data to evaluate the performance of the evasion estimate.¹⁹

Ideally we would like to state the above derivative of evasion with respect to taxes as an elasticity, though in a setting where the level of untaxed gallons is unobserved this is not possible. To put the evasion-tax gradient into perspective, we instead examine how tax revenues respond to changes in the tax rate, and how this is altered by tax evasion. In other words, rather than examining directly the elasticity of evasion to taxes, we describe the magnitude of the evasion-tax gradient in terms of its effect on the tax base. To derive the elasticity of tax revenues with respect to the tax rate, note that

$$\frac{\partial t Q_t}{\partial t} \frac{t}{t Q_t} = 1 + \frac{t}{Q_t} \frac{\partial Q_t}{\partial t} = 1 + \frac{t}{t+p} \beta_2. \quad (25)$$

The elasticity captures the change in tax revenues arising from both decreased consumption of taxed diesel fuel by compliant firms and substitution from legal to illegal purchases by non-complaint firms. To see how evasion contributes to this elasticity, consider adding and subtracting β_1 , giving:

$$\frac{\partial t Q_t}{\partial t} \frac{t}{t Q_t} = 1 + \frac{t}{t+p} \beta_1 - \frac{t}{t+p} (\beta_1 - \beta_2) \quad (26)$$

$$= 1 + \frac{t}{p+t} \beta_1 - \frac{tp}{Q_t(p+t)} \frac{\partial E}{\partial t} \quad (27)$$

If evasion responds positively to increases in taxes, this results in an erosion of the tax base and reduces the elasticity of revenues with respect to the tax rate.

4 Data

To estimate fuel tax evasion and evaluate our testable predictions, we collect state-level data from the Energy Information Administration (EIA) and the Federal Highway Administration

¹⁹In appendix A, we derive the necessary and sufficient conditions for (24). 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.

(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. No. 2 diesel fuel and No. 2 fuel oil are chemically equivalent and distinguished by use in the EIA data. The EIA defines diesel fuel as No. 2 distillate sold for use in an engine, while the EIA classifies fuel oil as No. 2 distillate sold for residential, commercial or industrial use in a boiler or furnace. 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 U.S. sales of number 2 distillate. In Figure 3, 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 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 2003.²⁰ Within state variation

²⁰Oregon does not tax diesel sold for trucking, instead taxing the number of weight-miles driven in the state. For

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. Figure 2 plots the tax over time to further describe the variation we will exploit. In Panel A, we show the federal tax in cents per gallon, which has seen five major increases during the sample period, though only a 1 cent per gallon change in the post-dye period. Panel B plots the average state tax. The average state tax has increased monotonically over time, starting at approximately 12 cents per gallon in 1983 and increasing to over 21 cents per gallon in 2003. This figure also plots the number of states changing their tax rates in each year. It is common for a state to change its tax rate as in most years there are between 6 and 23 states experience diesel tax changes. In two years, 1983 and 2000, only one state changes its tax rate.

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 from the 1990 census using the fraction of households in a state reporting fuel oil as the primary energy source used for home heating.

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 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

this reason, we exclude Oregon from the subsequent analysis.

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 Dye Program and Diesel Misreporting

5.1 Response of sales to dye program

In this section we examine the response of No. 2 diesel and No. 2 fuel oil sales to the diesel dye program. The addition of dye to No. 2 distillate used for untaxed purposes represented a large decline in the cost of monitoring for evasion in the form of misreporting taxed uses for untaxed uses. We showed in Section 3 that as the cost of monitoring declines, we expect firms to report more taxed purchases and fewer untaxed purchases, with total usage of No. 2 distillate unaffected. Since evasion here simply involves mislabelling the use of gallons of No. 2 distillate, there should be no adjustment costs in production and therefore the primary effect of the dye program on quantities should be seen immediately.²¹

To assess this substitution between taxed and untaxed uses of No. 2 distillate, we estimate

²¹It is possible that some adjustment may occur over time if firms learn over time about the effect of the program on the likelihood of getting caught, or if detecting evaders becomes easier as fewer firms evade. While plausible, these mechanisms are difficult to distinguish empirically from unrelated shifts in demand for diesel over time.

a specification of the break in trend of log quantity of the form

$$\ln q_{it} = \beta_0 + \delta_1 \text{postdye}_t + \Pi X_{it} + f(t) + \alpha_i + \epsilon_{it} \quad (28)$$

where $\ln q_{it}$ is the log of the quantity of diesel or fuel oil sold in state i in month t , X_{it} is a vector of state-month covariates, and γ_i represents a state fixed effect. The function $f(t)$ reflects overall time trends in the demand for gallons, which we parameterize using a flexible quadratic polynomial whose slope is allowed to vary in the pre- and post-dye periods.

Table 2 displays the results from estimating (28). In column 1, we show the estimated discontinuity in diesel sales controlling only for the quadratic time trend. Sales of No. 2 diesel rose by an estimated 29 percent upon dye implementation. Panel A of Figure 4 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. In the specifications shown in columns 2 and 3 of Table 2, we include state effects and other state-month covariates, and find that the estimated discontinuity is stable when adding these controls. In the full specification, the estimated discontinuity in diesel is 26 percent.

Counteracting the increase in diesel sales observed at the point of dyeing is a decrease in sales of fuel oil. Columns 4-6 of Table 2 display estimates of the discontinuity of fuel oil sales. We estimate that the average state experienced a 31 percent decrease in fuel oil sales, controlling only for the quadratic time trend. Again the estimated coefficient is fairly stable when adding covariates. In the full specification, we estimate a 39 percent decrease in fuel oil sales due to the dyeing program. As with diesel fuel, the quadratic time trend is successful at capturing the time path of fuel oil sales, as evidenced by Panel B of Figure 4.

Based on the significant increase in diesel sales and corresponding decrease in fuel oil, we conclude that there is significant evidence of substitution between taxed and untaxed uses in the pre-dye period. Columns 7-9 of Table 2 display the results of a similar specification for fuel oil's share of No. 2 distillate. This specification is desirable as it provides a sense of the importance of this substitution as a share of all No. 2 distillate, and it provides for a more direct comparison with the evasion parameter α from the model. Fuel oil's share of distillate fell by 11 percent when the dye program was implemented, and this estimated discontinuity changes little when additional covariates are included. In the full specification, we estimate a discontinuity of 12.5 percent in the average state's share of No. 2 distillate.

5.2 Sales response 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.

Panel A of Table 3 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 31.6 percent, compared with high agriculture states, who saw diesel sales rise by 20.6 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 as reported in the 1990 census. Consistent with our hypothesis, the dye response is heavily concentrated in high heating oil states. These states experienced a 39.0 percent increase in heating oil use, compared with a 10.2 percent increase in states with a low prevalence of home heating oil.

We last split the sample between low and high diesel tax states, as measured by states' tax rates in December of 1992, prior to the announcement of the dye program. The estimated break in the diesel series is larger in states with high tax rates, with an estimated break of 31.5 percent. The increase is 20.7 percent in low tax states.

Panel B of Table 3 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.

5.3 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 4 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. The importance of these alternatives are limited, as sales of kerosene and kerosene-type jet fuel are small relative to diesel.

5.4 Evidence of legitimate fuel oil sales

Two factors that should be significantly correlated with monthly fuel oil demand are the weather and the prevalence of home heating oil use. Based on the evidence presented in Table 2, we estimate that at least 39 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, season, and home heating oil use would be less successful in explaining fuel oil sales.

In Table 5, we present estimates of a specification of fuel oil demand, estimated separately for the pre-dye and post-dye periods. We regress 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, the interaction of these two variables,

and a set of month dummies. In the pre-dye period, none of these variables are significant, and they are able to explain seven 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 nearly triples to 0.18. In Figure 5, we display the estimated month effects from these regressions. The seasonal factors are considerably larger in the post-dye period. For instance, the post-dye coefficient on the January dummy of 1.42 indicates that fuel oil sales since October of 1993 are 4.1 times as large as sales in July, while the pre-dye coefficient of 0.94 implies a January-July ratio of 2.6. This provides further evidence suggesting that a significant portion of the pre-dye fuel oil sales were not intended for home heating use.

6 Evasion estimation with only taxed gallons

In this section, we empirically apply three aspects of the model developed in Section 3. First, we test for evasion in the pre-dye and post-dye periods by estimating separate price and tax elasticities. Second, we use these estimated coefficients to obtain estimates of the gradient of evasion with respect to taxes. Finally, we describe how evasion's response to the tax rate alters the revenue effects of increasing the diesel tax. The advantage of each of these applications is that they require only observing taxed gallons, and as a consequence, could be broadly applied outside of the context of diesel fuel. In the current application, we have are able to observe the primary untaxed alternative, which we can use to support the validity of our estimates of the evasion-tax gradient.

6.1 Testing for evasion

As shown in equation (18), the tax and price elasticities can be separately identified by factoring price out of $\ln(p + t)$. We will therefore estimate a version of (28) for diesel fuel that includes the log of the price and the log of $1 + t/p$ as separate regressors:

$$\ln q_{it} = \beta_0 + \beta_1 \ln(p_{it}) + \beta_2 \ln(1 + \tau_{it}/p_{it}) + \Pi X_{it} + f(t) + \alpha_i + \epsilon_{it}. \quad (29)$$

Under the null hypothesis of no evasion, it should be the case that demand responds the same to both changes in taxes and prices. The tax and price elasticity should therefore match in the pre- and post-dye periods absent evasion, which we would reject if $\beta_1 \neq \beta_2$. Our results to this point have suggested that the dye program significantly curtailed the extent of evasion, so

we are also interested in testing this hypothesis separately for the pre- and post-dye periods. Therefore, we will also allow the coefficients β_1 and β_2 to differ in the pre- and post-dye periods.

We present the results of this estimation in columns 1 and 2 of Table 6. In the specification shown in column 1, β_1 and β_2 are constrained to be time invariant. We see that the tax and price elasticities are significantly different, with the price elasticity estimated to be -0.44 and the tax elasticity estimated to be -1.20. In column 2, we interact the post-dye dummy variable with the tax and price variables to allow for different elasticities depending on the time period. In the pre-dye period, the price and tax elasticities are estimated to -0.52 and -1.41, respectively, and again their difference is statistically significant. In the post-period, demand is in general estimated to be less elastic, as the estimated price elasticity falls to -0.28. This is consistent with the findings of Hughes, Knittel and Sperling (forthcoming), who find that gasoline demand elasticity was lower earlier this decade than in the late seventies. We find that the tax elasticity also shrinks toward zero during the post-dye period to -0.83. While the estimated tax elasticity shifted by more than the price elasticity, the difference between these two coefficients is still statistically significant. We therefore cannot reject the no evasion hypothesis in either the pre- or post-dye periods.

We also investigate the response of fuel oil to the tax levied on diesel. In the absence of evasion, the tax on diesel should have no direct impact on fuel oil demand as it only effects the user cost of on-highway diesel.²² In columns (3) and (4) of Table 6, we present the results of estimating (29) for fuel oil sales. The tax rate on diesel has a significant and positive impact on fuel oil sales. Taking into consideration the full sample, the estimated tax elasticity is 0.78 and statistically significant. In column 4, we document a striking pattern over time. In the pre-dye period, the estimated tax elasticity is 2.18, and this drops to 0.09 and statistically insignificant in the post-dye period.²³ Therefore, while we reject the absence of evasion in the post-dye period, the results suggest that fuel oil has ceased to be the mechanism for evasion.

We next examine the pattern of elasticities over time by allowing the price and tax elasticities to vary by year. We estimate the following equation:

$$\ln q_{it} = \beta_0 + \beta_{1t} \ln(p_{it}) + \beta_{2t} \ln(1 + \tau_{it}/p_{it}) + \varphi_t + \Pi X_{it} + \gamma_i + \eta_{it} \quad (30)$$

where we obtain estimates of β_{1t} and β_{2t} by interacting year dummies with the price and

²²This is assuming that the tax on diesel has no indirect effects on fuel oil sales through supply.

²³The positive coefficient on the price variable leads to some concern regarding the estimation of the demand curve, since the variation in prices may be due to shifts in demand. This is a concern even when only considering the tax coefficient, since price appears in the denominator of the tax rate. To ameliorate this concern, we have also estimated this specification only considering the log of the level of the tax rather than its rate and found identical results.

tax rate series. Examining the time path of elasticities is meant to accomplish two things. First, constraining these coefficients to be constant over time masks any dynamic patterns of evasion. Second, exploiting the timing of changes in the estimated elasticities ameliorates concerns regarding bias in the demand estimation. Our estimates of the price and tax elasticities could be biased since variation in price could reflect shifts in demand and therefore movements along the supply curve. Estimating the elasticities by year allows us to examine the timing of the shift in the tax elasticity relative to the price elasticity. While estimates of the gap between these two may be biased, there is little reason for shifts in this gap to coincide with the timing of the dye program aside from a reduction in evasion.

In Figure 6, we plot the yearly estimates of β_1 and β_2 for log diesel sales. In the pre-dye period, there is a consistent gap between the estimated tax and price elasticities. Over time, demand appears to become less price sensitive. In the years immediately following the dye program's implementation, the gap between the tax and price elasticities is virtually zero, suggesting that the addition of dye may have significantly curbed diesel tax evasion. An interesting pattern emerges in the latter portion of the sample. During this time, the gap between the tax and price elasticities reappears. This may point toward a dynamic response of evaders, who may have developed new evasion technologies in response to the dye program.

To lend further evidence that the timing of the tax responsiveness coincided with the dye program by examining the time path of the elasticity of fuel oil with respect to the diesel tax rate. In Figure 7, we plot the estimated yearly fuel oil tax rate elasticity. For almost every year prior to 1993, we estimate a positive tax elasticity. In 1993, this elasticity drops to close to zero. Unlike our estimates for diesel fuel, the responsiveness of fuel oil to the tax rate does not seem to reappear. This suggests that if new evasion methods were developed, they did not involve fuel oil.

6.2 Evasion response to tax

A parameter of significant interest in the public finance literature is the responsiveness of evasion to the tax rate. In the previous section, we arrived at a reasonable pre-dye estimate for this measure by examining the response of fuel oil to the tax rate, as this seems to be a primary mechanism for evading the diesel tax. In most settings, observing evasion directly is not possible. In addition to suggesting a test for evasion using estimates of the price and tax elasticities, the model of Section 3, also demonstrates how the coefficients for β_1 and β_2 can be used to obtain

an estimate of the degree evasion responds to the tax rate. Restating equation (24)

$$\frac{\partial E}{\partial t} = \frac{Q_t}{p}[\beta_1 - \beta_2] \quad (31)$$

We can plug in for the each element of (31) to obtain the derivative of evasion with respect to taxes. We obtain average values for Q_t and p from Table 1. In the pre-dye period, we estimate that each cent increase in the tax rate increased the quantity of unreported gallons by 16.5 thousand per day. In the post-dye period, this falls modestly to 15.4 thousand gallons per day. These values represent 1.1 percent and 0.7 percent of the average level of taxed diesel sold per day, respectively.

While these estimates rely solely on observing taxed gallons, we can assess their validity by comparing them to the pre-dye response of fuel oil to tax changes. From (30), we use the parameter estimate β_2 to obtain $\frac{\partial Q_u}{\partial t} = \frac{Q_u}{p+t}\beta_2$. Plugging in for the average price, tax, and untaxed quantity in the pre-dye period, we find that increasing taxes by one cent increased purchases of fuel oil by 25.4 thousand gallons per day. This estimate is slightly larger than that obtained from taxed gallons, indicating that the latter may represent a conservative estimate of the evasion-tax gradient.

6.3 Evasion and tax revenues

We next turn to the question of how tax revenues respond to increases in the tax rate. Increases in the tax rate directly increase revenues by charging more per gallon sold, yet have an indirect behavioral response as the effective price of diesel rises relative to other goods. Evasion contributes to this response, as underreporting taxed sales becomes more attractive as the tax rate rises. Restating equation (26),

$$\frac{\partial tQ_t}{\partial t} \frac{t}{tQ_t} = 1 + \frac{t}{t+p}\beta_1 - \frac{t}{t+p}(\beta_1 - \beta_2) \quad (32)$$

In the absence of evasion, β_1 and β_2 are identical, leading the latter term to disappear. We can therefore use our estimates of the price elasticity β_1 to obtain an estimate of the revenue effects of changing taxes if evasion were not present. In the pre-dye period, this implies an elasticity of revenue with respect to the tax rate of 0.85, and in the post-dye period this increases to 0.90. The erosion of the tax base due to greater evasion when taxes are increased, as documented in section 6.2, has a significant impact on the fraction of tax increases that are incorporated into revenues. Allowing for evasion, and therefore for the differing values of β_1 and β_2 , we find

a revenue-tax elasticity of 0.60 in the pre-dye period and 0.71 in the post-dye period. A tax increase in the dye regime translates into 11 percent higher revenues than in the pre-dye period. Based on the estimates absent evasion, the lower price sensitivity post-dye can account for less than half of this.

7 Conclusion

This paper considers the evasion of diesel taxes, and how this evasion responds to the large shift in the cost of conducting an audit represented by the addition of red dye to untaxed diesel. 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, as there are significant discontinuities in the sales of No. 2 diesel and No. 2 fuel oil, yet little change in overall No. 2 distillate sales.

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 apply 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. Finally, we use these measures to describe how evasion affects the tax revenue response to tax increases, a parameter of considerable interest in public economics.

One important aspect we leave 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 (24). 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 (24).

Proof. Equation (24) 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 (24) 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 α 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

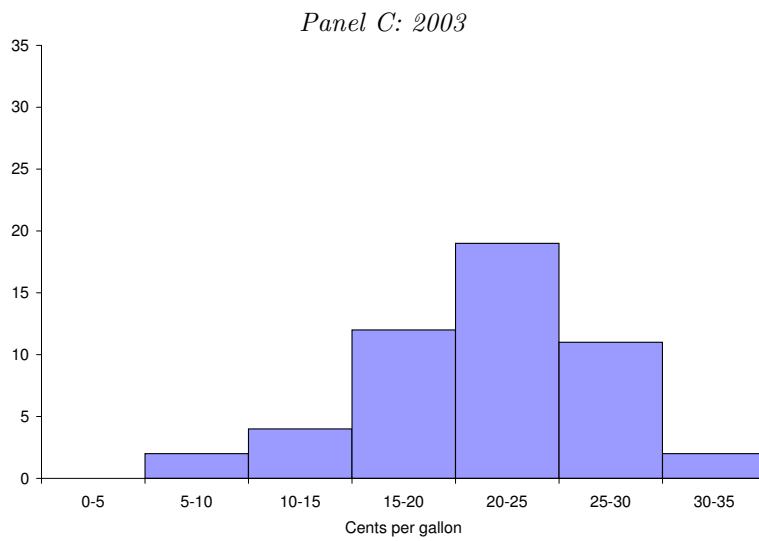
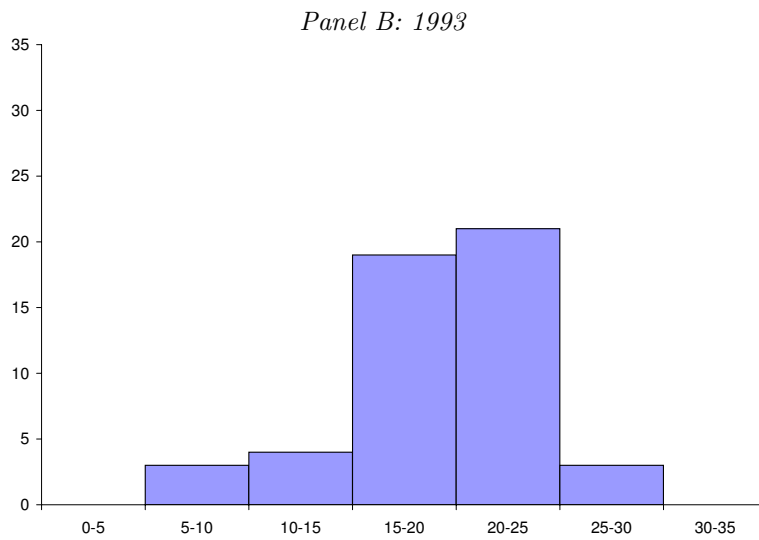
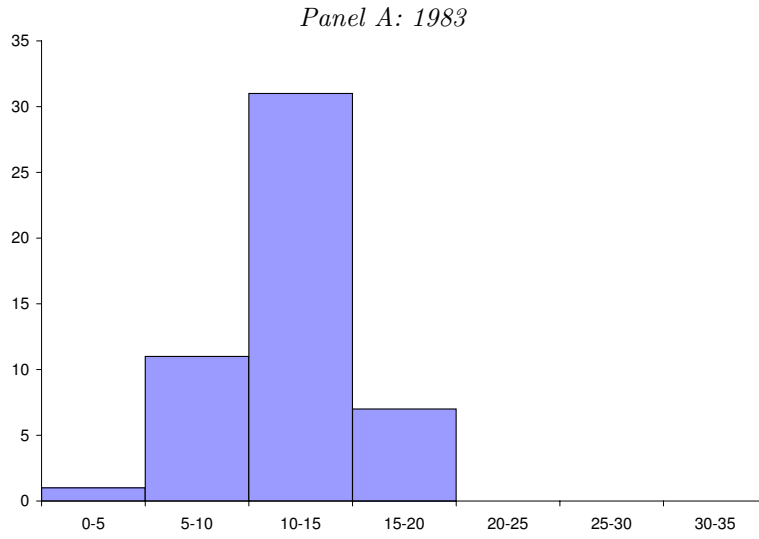


Figure 2: Time Series of Diesel Tax Rates (c/gall)

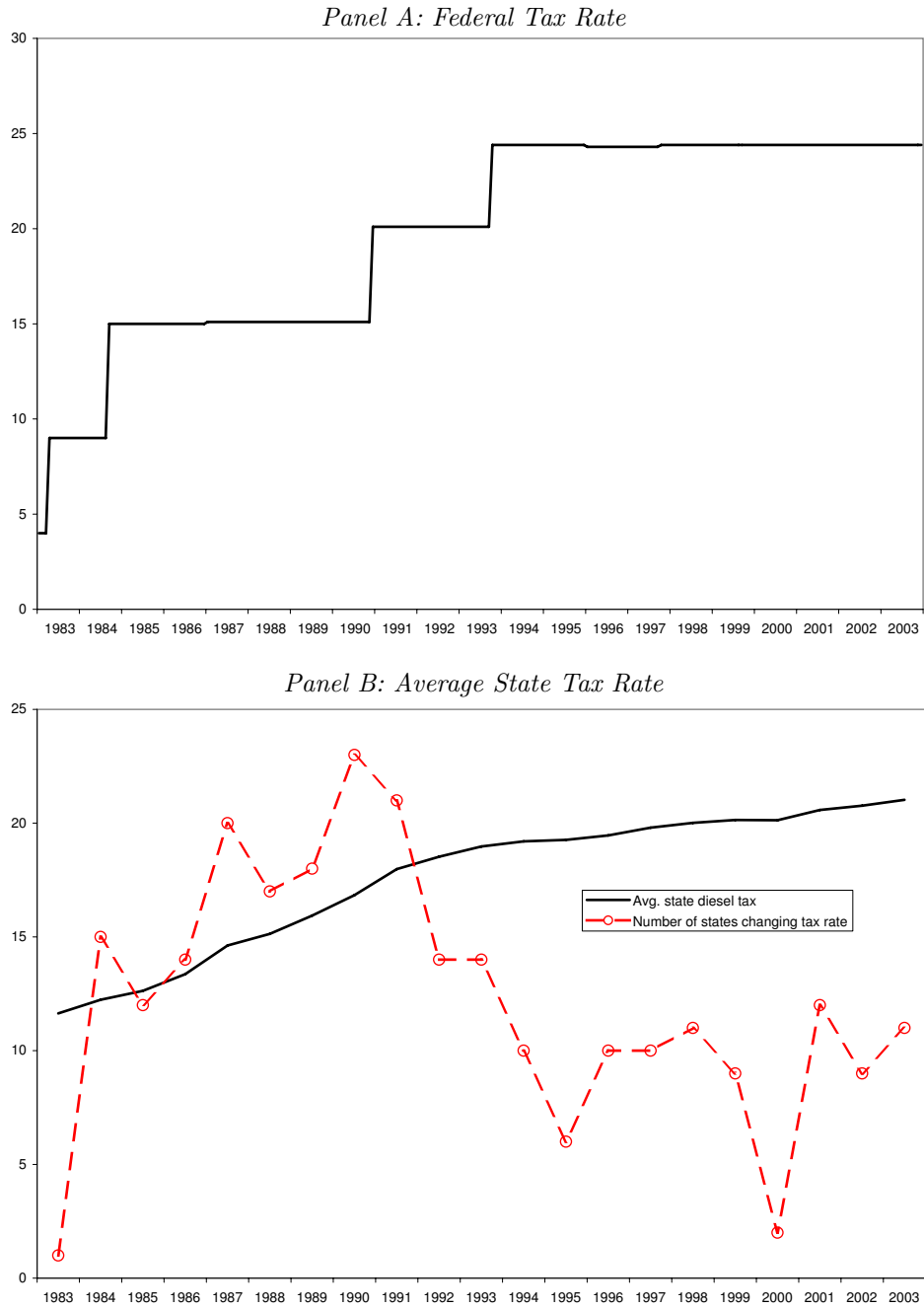


Figure 3: U.S. Sales of No. 2 Distillate

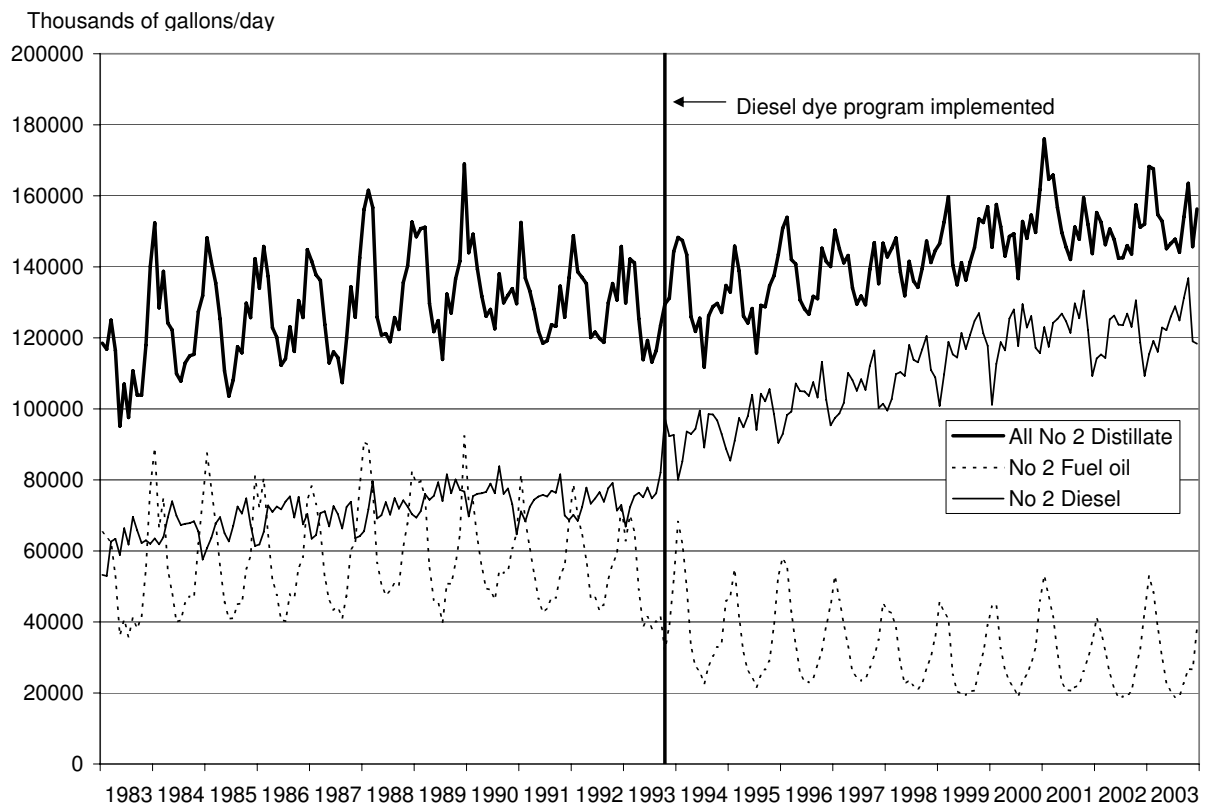


Figure 4: Average Predicted Versus Actual Log Quantities Sold

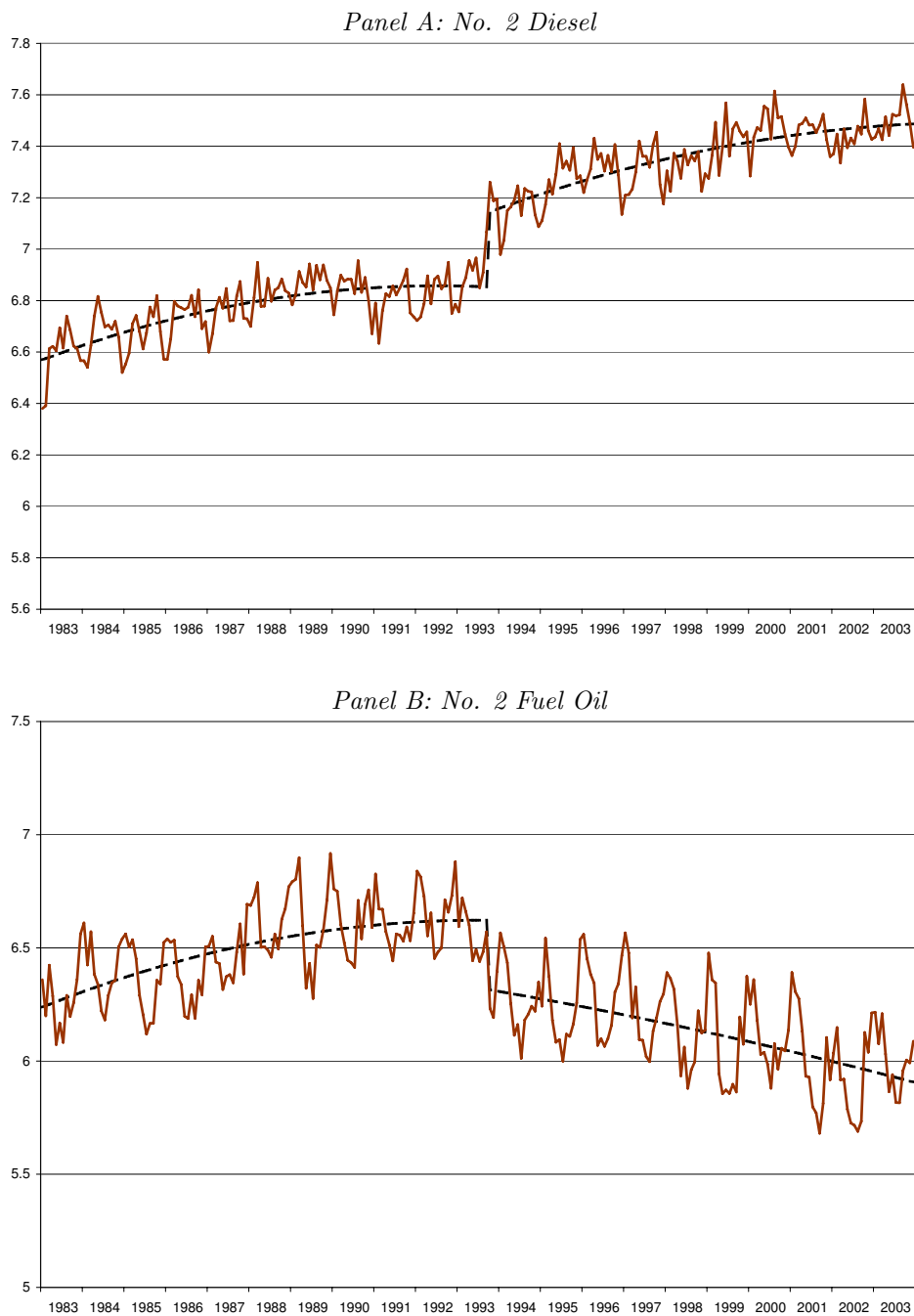


Figure 5: Estimated Month Effects, Pre- versus post-dye

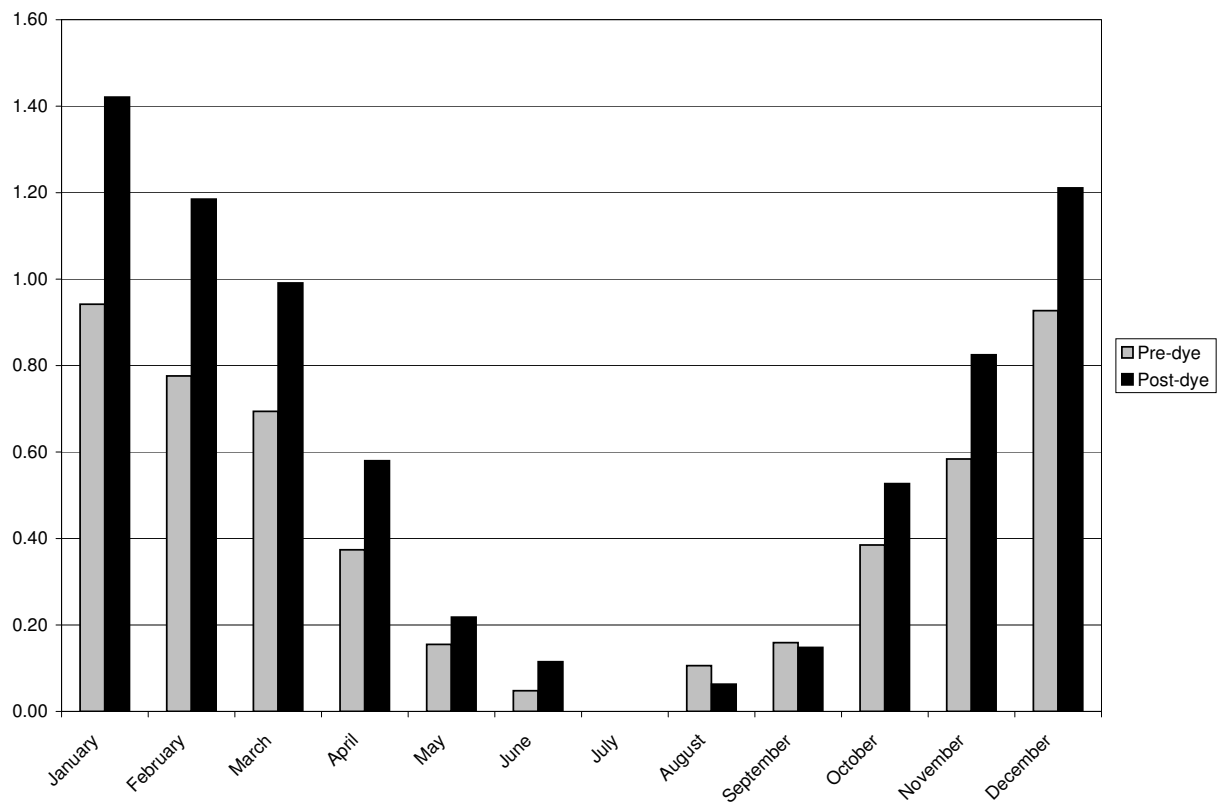


Figure 6: Price and Tax Elasticities by Year, Diesel Sales

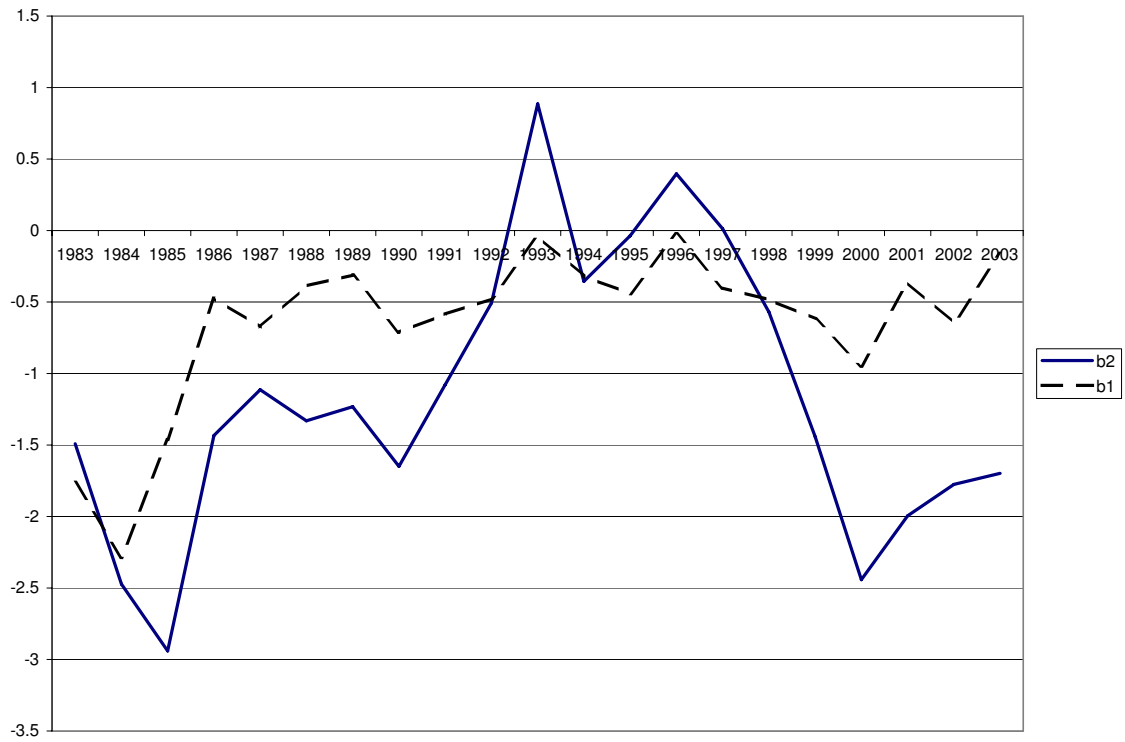


Figure 7: Elasticity to 1+Diesel Tax Rate, Fuel Oil Sales

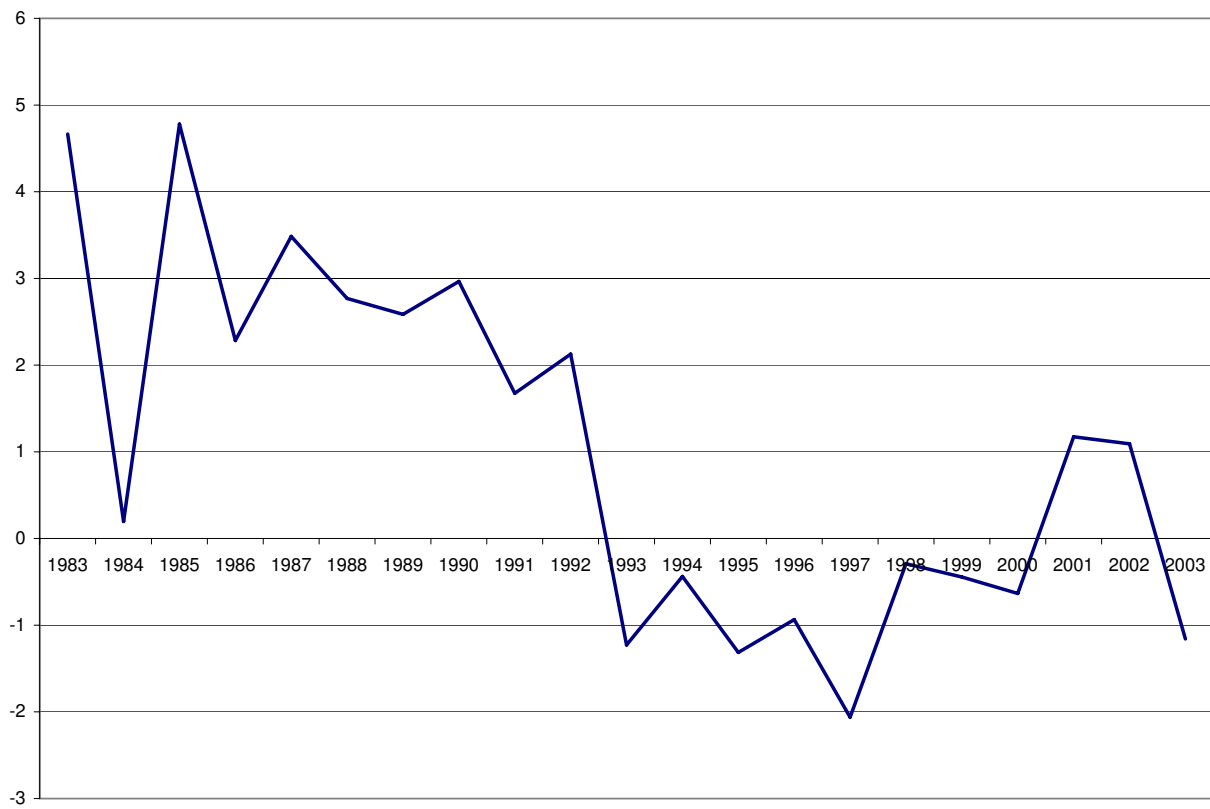


Table 1: Summary Statistics

	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: Sales Response to Diesel Dye

	Log Deisel Sales			Log Fuel Oil Sales			Fuel Oil's Share of No. 2 Distillate		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post-dye	0.293 (0.033)***	0.268 (0.030)***	0.256 (0.020)***	-0.308 (0.054)***	-0.375 (0.056)***	-0.394 (0.032)***	-0.113 (0.015)***	-0.123 (0.015)***	-0.125 (0.008)***
Log (p+t)			-0.134 (0.031)***			0.193 (0.055)***			0.063 (0.009)***
Degree days (X100)			-0.026 (0.003)***			-0.049 (0.008)***			-0.003 (0.002)*
Deg. days*% HH oil			0.040 (0.003)***			0.243 (0.018)***			0.038 (0.003)***
Log of state GSP			0.371 (0.045)***			-0.814 (0.126)***			-0.149 (0.014)***
State unemp. rate			0.000 (0.003)			-0.011 (0.008)			-0.000 (0.001)
Quadratic time trend	X	X	X	X	X	X	X	X	X
State fixed effects		X	X		X	X		X	X
Month dummies			X			X			X
Observations	10606	10606	10236	10236	10236	9866	10061	10061	9710
R-squared	0.09	0.95	0.96	0.03	0.79	0.83	0.12	0.85	0.89

Robust standard errors are in parentheses allowing for clustering by year*month.

***, ***, ** denote significance at the 90%, 95%, and 99% level, respectively. The variable % HH oil represents the percentage of households in the state reporting in the 1990 census using fuel oil for home heating. The price is that charged for diesel through retail outlets. The quadratic time trend is allowed to differ in the pre-dye and post-dye periods.

Table 3: Sales Response, by State Characteristics

	By Ag Share of GSP		By Heating Oil Use		By 1993 Tax	
	(1)	(2)	(3)	(4)	(5)	(6)
	Low Ag	Hi Ag	Low Oil	Hi Oil	Low Tax	Hi Tax

Panel A: Log Diesel Sales

Post-dye	0.316 (0.018)***	0.206 (0.026)***	0.102 (0.017)***	0.390 (0.031)***	0.207 (0.022)***	0.315 (0.020)***
Observations	5598	4638	4827	5409	5492	4744
R-squared	0.96	0.96	0.95	0.96	0.96	0.96

Panel B: Fuel Oil's Share of No. 2 Distillate Sales

Post-dye	-0.114 (0.008)***	-0.139 (0.010)***	-0.101 (0.005)***	-0.143 (0.012)***	-0.108 (0.008)***	-0.139 (0.009)***
Observations	5386	4324	4366	5344	5128	4582
R-squared	0.91	0.84	0.77	0.86	0.88	0.90

Robust standard errors corrected for clustering by year*month are in parentheses.

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

Other controls match those in the full specification shown in Table 2. 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 4: 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.

Table 5: Fuel Oil Demand Pre- vs. Post-Dye
Dependent variable: Log Fuel Oil Sales

	Before	After
Degree days X100	-0.077 (0.058)	-0.139 (0.045)***
Degree days * HH Oil Fraction	0.097 (0.069)	0.232 (0.059)***
Fraction of HH Oil	1.202 (0.944)	1.272 (0.815)
Observations	5665	4353
R-squared	0.07	0.18

Robust standard errors clustered by state are in parentheses.
Other controls include month dummies.
*, **, *** denote significance at the 90%, 95%, and 99% level,
respectively.

Table 6: Price and Tax Elasticity Estimates

	Log Deisel Sales		Log Fuel Oil Sales	
	(1)	(2)	(3)	(4)
Log(1+tax rate)	-1.203 (0.112)***	-1.409 (0.143)***	0.775 (0.233)***	2.184 (0.303)***
Post-dye*log(1+tax rate)		0.579 (0.119)***		-1.995 (0.287)***
Log(Price)	-0.439 (0.043)***	-0.521 (0.052)***	0.360 (0.082)***	0.442 (0.094)***
Post-dye*log(Price)		0.241 (0.045)***		0.077 (0.134)
Observations	10236	10236	9866	9866
R-squared	0.96	0.96	0.83	0.83

Robust standard errors corrected for clustering by year*month are in parentheses.
*, **, *** denote significance at the 90%, 95%, and 99% level, respectively.

Each specification also includes controls identical to those in the full specification shown in Table 2. The pre-tax price in the diesel specifications is the price charged through retail outlets.