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Colluding Against Environmental Regulation

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April 5, 2021

Abstract

We study collusion among firms in response to imperfectly monitored environmental regulation. Firms improve market profits by shading pollution and evade noncompliance penalties by shading jointly. We quantify the welfare effects of alleged collusion among three German automakers to reduce the size of diesel exhaust fluid (DEF) tanks, an emission control technology used to comply with air pollution standards. We develop a structural model of the European automobile industry (2007-2018), where smaller DEF tanks create more pollution damages, but improve buyer and producer surplus by freeing up valuable trunk space and reducing production costs. We find that choosing small DEF tanks jointly reduced the automakers' expected noncompliance penalties by at least 560 million euros. Antitrust and noncompliance penalties would reach between 1.46 and 14.63 billion euros to remedy the welfare damages of the alleged collusion.

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1 Introduction

Violation of environmental regulation is a pervasive problem (Duflo et al., 2018; Blundell et al., 2020; Reynaert and Sallee, 2021; Zou, Forthcoming). Most studies on noncompliance assume that agents choose actions independently from competitors. In settings where the regulator has imperfect information to detect and punish noncompliance, theoretical work by Laffont and Martimort (1997, 2000) and Che and Kim (2006) considers the possibility of agents colluding against the regulator. In practice, environmental regulators rarely consider collusion, and the authority to correct the harms of collusion falls on antitrust agencies.

We examine an ongoing case of alleged collusion on emission control technologies in response to vehicle emission regulation. The European Commission accused the German automakers BMW, Daimler, and Volkswagen of colluding to restrict the effectiveness of diesel emission control technologies, in violation of competition law (European Commission, 2019). Although there is no evidence that the automakers colluded on prices, coordination to limit technical development is illegal under the EU antitrust legislation. The case involves a NO_x control technology called Selective Catalytic Reduction (SCR). As the EU emission standards have become stricter, large diesel vehicles have increasingly needed this technology for compliance. SCR requires an extra tank of Diesel Exhaust Fluid (DEF) to neutralize NO_x emissions. The three German automakers, henceforth the "working group," were accused of having colluded to reduce the size of DEF tanks in their vehicles. Given the industry practice of limiting consumers to DEF tank refills of only once per year, a smaller DEF tank means lower DEF consumption per mile driven, leading to more NO_x pollution.

Why might firms collude against environmental regulation? We begin our analysis by presenting a model to answer this question and derive welfare implications. Our principal, the regulator, sets a pollution standard and observes firms' emission abatement actions, such as the specifications of the emission control technology. However, the regulator does not know firms' true emissions because of high monitoring costs. Firms can enter the market with insufficient abatement actions by falsely reporting emissions at the time of market entry. However, after entry, the regulator may inspect firms and punish them if noncompliance, or insufficient abatement, is discovered.

In the model, a firm's profit decreases with its own abatement action and increases with competitors' abatement actions, given that pollution is an externality. Thus, a firm will enjoy higher profits when it is the only one that abates insufficiently, than when its competitors join in noncompliance. Therefore, absent any cost efficiency gains, collusion on noncompliance is attractive to firms only if it reduces their expected penalties from *joint* noncompliance relative to *unilateral* noncompliance. This reduction in expected noncompliance penalties is possible for several reasons. First, the probability that the regulator investigates a firm for possible noncompliance could depend on the full profile of industry abatement actions. Such dependence creates a setting similar to yardstick competition (Schleifer, 1985) where collusion can manipulate the regulator's information, as studied by Tangerås (2002).[1] Second, collusion may lower the noncompliance penalties through diffusion of responsibility.[2] Third, by choosing noncompliance jointly, the collusive agreement gives all participants "skin in the game," which can lower the probability that a competitor calls out the noncompliance scheme.

We use our model to inform our empirical analysis in two ways. First, the model allows us to construct inequalities that we use to empirically bound the reduction in expected noncompliance penalties. This reduction is the key to generating incentives for firms to collude on noncompliance. Second, our model facilitates discussions about welfare and policy implications of collusion on noncompliance. We decompose the welfare effects into buyer surplus, non-colluding firms' profits, and pollution damages, as well as colluding firms' profits. The first three components constitute the "residual claim" that informs the combined antitrust and environmental noncompliance penalties necessary to repair the damages inflicted on other parties. Furthermore, a comparison between the collusive profits and the residual claim provides a lower bound on the imperfection of the current regulatory environment in addressing noncompliance.

More broadly, the incentive to collude on noncompliance may arise in other regulatory settings—not necessarily environmental ones—where the regulator does not perfectly observe compliance. Such incentives can increase both the number of violators and the degree of violation. While antitrust agencies primarily focus on price/quantity collusion, our work shows that colluding on noncompliance in response to imperfectly monitored regulation may have significant social welfare impacts.

We then turn to our empirical analysis of the alleged collusion of three German automakers in restricting the DEF tank sizes. Using data on vehicle registrations and characteristics from the seven largest European markets from 2007 to 2018, we find that the working group chose DEF tank sizes that were 8% less effective on average than other firms' choices. Furthermore, we document widespread noncompliance behavior in the whole industry; more than 95% of diesel models with DEF tanks have tank sizes insufficient for compliance, based on our econometric estimates of compliant sizes as well as engineering estimates.

To probe the German automakers' incentives, we quantify the benefits and costs of various DEF tank sizes by estimating a structural model of consumer vehicle demand and automaker costs. Large DEF tanks

[1] Collusion in this setting has been examined in lab experiments by Potters et al. (2004) and Dijkstra et al. (2017).

[2] Decker and Pope (2005) provide some evidence for complementarities in firms' compliance behavior within industries. Also, Bassetto and Phelan (2008) studies a setting where agents jointly move against a regulator in tax riots.

reduce firms' profits because they take up valuable trunk space and increase marginal production costs. Our demand estimates show that consumers would be willing to pay around 284 euros if the space for an average DEF tank were instead allocated to additional trunk space.[3] The marginal production cost estimates show that the SCR system costs roughly 543 euros, or 36 euros per liter of DEF, similar to engineering estimates. Furthermore, we fail to detect lower or different DEF costs for the working group relative to other firms, which we interpret as a lack of evidence that the collusive scheme induced cost efficiencies for the working group.

With the profit functions estimated from our structural model, we derive bounds on the expected noncompliance penalty faced by the working group when they choose small tanks jointly relative to unilaterally. Our estimated bounds show that the alleged collusion reduced the expected noncompliance penalty by at least 560 million euros for the working group compared to unilateral noncompliance.

We conduct counterfactual experiments to quantify the welfare effects of the alleged collusion. From a welfare perspective, the benefits of the alleged collusion come from increased industry profits and vehicle buyer surplus. These benefits come at the social cost of increased NO_x pollution. Increased pollution damages—measured by health damages from NO_x-induced PM2.5—outweigh the gains in industry profits and vehicle buyers' surplus. We find that the combined antitrust and noncompliance penalties should reach 4.28 billion euros in our main scenario to fully repair the welfare damages of this alleged collusion (and between 1.46–14.63 billion euros in other specifications). Combined with our finding that the working group gained 0.68–5.04 billion euros in variable profits from this alleged collusion, we infer that the existing regulatory regime achieved at most 34–46% of the full remedial penalties. In practice, antitrust fines are predominantly assessed based on effects in the relevant market. Our findings suggest that externalities should be an important consideration in antitrust policy.

The main contribution of this paper is to study firms' incentives to collude against regulation and to quantify them empirically. Most papers examine collusion on prices or quantities. A recent set of papers study collusion in other product dimensions, including a theoretical study by Nocke (2007) and empirical analyses by Sullivan (2017), Alé-Chilet and Atal (2020), Gross (Forthcoming), and Bourreau et al. (2019). We introduce the possibility of collusion among the regulated agents, as in Laffont and Martimort (1997, 2000), Tangerås (2002), and Che and Kim (2006). The firms in our context allegedly colluded on a product characteristic that is key to compliance with environmental regulation.[4] Regulation adds complexity to the

[3]Monetary values are in 2018 euros throughout this paper.

[4]We think of industry coordination and standard-setting, as studied in Shapiro (2001) and Li (2019), as cases where options

welfare analysis because the alleged collusion affected both buyer surplus and the regulated externality.

This paper also contributes to the literature on the enforcement of environmental regulation. The literature has considered cases when the regulator faces either a single firm or a perfectly competitive industry, such as Duflo et al. (2018) and Blundell et al. (2020). These studies show that monitoring technologies or surveillance schemes can make environmental regulation more robust to pollution hiding. Imperfect compliance in the European automobile sector, without collusion, has been studied in Reynaert and Sallee (2021) and Reynaert (2021). A few papers analyze the effects of the Volkswagen emission scandal in the U.S.: Alexander and Schwandt (2019) study the impact of diesel-gate on health outcomes, and Bachmann et al. (2019) find reputation spillovers to other German automakers not directly involved. We compute the welfare impacts of the alleged collusion, which includes health damages.

We proceed as follows. In Section 2, we present a model of colluding against environmental regulation. We describe in Section 3 our empirical context. Section 4 shows descriptive evidence for the alleged collusion of the German automakers and the widespread noncompliance in the industry. In Section 5, we present our empirical strategy and estimates of automobile demand and marginal costs. In section 6, we quantify the reduction in the expected noncompliance penalties due to the alleged collusion. Section 7 presents the welfare effects of the alleged collusion and calculates the combined antitrust and noncompliance penalties that would be needed to remedy the welfare damages. We conclude in Section 8.

2 Model

We describe a model in which firms can collude on compliance responses to regulation that aims to correct an externality.[5] The aim of this section is to understand the incentives firms might have to collude against the regulator, construct useful inequalities to quantify these incentives, and derive welfare implications.

2.1 Firm Types, Information, and Regulation

Firm types and emission production. The regulator faces n firms, indexed by $f \in \{1, 2, \ldots, n\}$, that produce or sell products that generate an externality.[6] We will refer to the externality using pollution and

may be more horizontally differentiated, and where social welfare hinges more upon *whether* firms coordinate rather than *which* outcome firms jointly choose.

[5] More generally, the regulator may seek to correct for a wedge between private and social preferences arising from internalities, externalities, or shrouded attributes.

[6] In the model, we assume single product firms $f = j$. In our empirical framework, we consider multi-product firms.

emissions, but our model applies to non-environmental externalities as well. Each firm has an exogenous type θ_f that measures its raw emissions before deploying emission control technology. A firm's pollution type θ_f consists of a component common to all the firms and an idiosyncratic i.i.d. shock. The common component introduces correlation among firm types, while the shock captures how firms differ in pollution types. Firm types with common components are also present in Auriol and Laffont (1992) and Schleifer (1985). Firms produce emissions according to their pollution types θ_f and abatement actions a_f:

$$e_f = \theta_f - a_f, \tag{1}$$

where emissions are decreasing in abatement actions.[7]

Information. We assume that the regulator is at an information disadvantage relative to the industry. The regulator knows the true distribution of common and random shocks, but does not know their realization. In contrast, there is no information asymmetry among the firms, and the realization of types is common knowledge within the industry.[8] Abatement actions are observable to the regulator.

Regulation. The regulatory environment consists of three phases: a permitting phase, a surveillance phase, and an antitrust phase. In the permitting phase, the regulator sets an emission standard e^* that firms need to reach before they can enter the market: $e_f \leq e^*$. Firms can potentially misreport their emissions and enter the market while not complying with the standard: $e_f > e^*$. Manipulation is not immediately obvious for the regulator because of the information disadvantage. We assume that misreporting in itself is not costly for a firm, but noncompliant firms risk penalties in the surveillance or antitrust phase.

In the surveillance phase, the regulator observes abatement actions $\boldsymbol{a}$ from all firms and can decide to inspect a firm more closely. We denote the probability of inspecting firm f given $\boldsymbol{a}$ as $P_f(\boldsymbol{a})$. The inspection outcome is a revelation of the true emission e_f. If the true externality exceeds the regulatory standard, $e_f > e^*$, the firm faces noncompliance penalties such as legal costs, government fines, product recalls, buyer compensations, and reputation damages. We denote the net present value of potential penalties as $K_f = K_f(\boldsymbol{e}(\boldsymbol{a}), e^*)$ which depends on the degree of noncompliance of the firm and its competitors. Below,

[7]Our model could be extended to more general specifications where the emission generating function is $e_f = e(a_f, \theta_f, x_f)$ where x_f is the vector of product characteristics, $\frac{\partial e}{\partial a_f} < 0$ and $\frac{\partial e}{\partial \theta_f} > 0$.

[8]Putting the regulator at a relative information disadvantage is consistent with most of the regulation literature, e.g., Baron and Myerson (1982) and Weitzman (1974).

we explain in detail how both the probability and the penalty depend on industry choices. We define firm f's expected noncompliance penalty, $\mathbb{E}K_f$, as the inspection probability times the net present value of potential environmental penalties.

The final phase of the regulatory environment is antitrust. Antitrust plays a role in our framework because firms may have an incentive to make joint decisions on abatement actions a_f. We apply a broad definition of antitrust, in line with EU Article 101(1)(b), and consider that any cartel agreement to limit or control production, markets, or technical development can be subject to penalties. This definition includes collusion on abatement actions a_f, which differs from more commonly considered price collusion or market-sharing agreements. We denote the expected antitrust penalty as $\mathbb{E}A_f$, defined as the probability of antitrust investigation times the net present value of penalties from an antitrust conviction A_f.

Given this regulatory framework that includes (i) a permitting phase that sets a pollution standard; (ii) a surveillance phase with a possible investigation into noncompliance with the standard; and (iii) an antitrust phase holding the potential to remedy the welfare damages from collusion, we now present firms' payoffs and strategies.

2.2 Firm Strategies

Timing. We describe the timing for the firms' decision process, including the proposal of a joint action profile for multiple firms by an independent third party (Laffont and Martimort, 1997). We name that third party the working group, in line with our case study.[9] Not every firm participates in the working group. We define the set of firms participating in the working group as $\mathcal{F}^{WG}$ and the firms not in the working group as $\mathcal{F}^{NWG}$, so that $\mathcal{F} = \mathcal{F}^{NWG} \cup \mathcal{F}^{WG}$:

1. Firms observe pollution types $\boldsymbol{\theta}$, the regulatory environment, and demand and cost conditions;

    1.1 The working group proposes collusive abatement actions to $\mathcal{F}^{WG}$;

    1.2 Each firm in $\mathcal{F}^{WG}$ rejects or accepts the working group proposal;

    1.3 The proposal is carried out if and only if all firms in $\mathcal{F}^{WG}$ accept it;

    1.4 Firms in $\mathcal{F}^{NWG}$ observe the abatement actions of $\mathcal{F}^{WG}$.[10]

[9] In reality, the third party that coordinates cartel activities need not be identical to the subset of colluding firms, for example in cases where there is a trade association (Alé-Chilet and Atal, 2020).

[10] In Section 4, we present empirical evidence in support of this assumption in our application.

2. Each firm f chooses abatement action a_f which determines emissions and compliance with the emission standard;

3. Each firm f chooses prices p_f competitively and collects variable profits.

In case the collusive proposal is accepted, we denote the action profile $\boldsymbol{a^C}$ when firms in $\mathcal{F}^{WG}$ accept the proposal and firms in $\mathcal{F}^{NWG}$ choose abatement actions competitively. In case a collusive proposal is not accepted, we denote the resulting action profile as $\boldsymbol{a^{NC}}$. We assume that compliance costs are moderate so that the set of firms entering the market does not change in response to the emission standard.[11] We also assume that prices are at the competitive level, so that we study a case of semi-collusion, where firms potentially collude on abatement actions but not on prices.

Variable profits. Firm f's expected payoffs are given by variable profits minus expected penalties should the firm enter without complying with the standard. We define the variable profit as:

$$\pi_f(\boldsymbol{a}) = [p_f - mc_f(a_f)]\, q_f(\boldsymbol{a}),$$

where mc_f is the marginal cost of firm f, and q_f the quantity. For expository convenience, we assume for now that prices are fixed. In the empirical section, we will allow for strategic Nash pricing responses to changes in abatement actions.[12]

Complying with the emission standard impacts variable profits in two ways. Emissions e_j are an externality in the sense that buyers have no demand for emission reductions.[13] However, abatement actions could reduce the willingness to pay for the product because it compromises product attributes that buyers value. We define this impact as the attribute effect of abatement actions on profits. Second, abatement actions may increase the marginal cost of production. Thus, the partial derivative of variable profits with respect to the abatement action is:

$$\frac{\partial \pi_f(\boldsymbol{a})}{\partial a_f} = \underbrace{(p_f - mc_f)\frac{\partial q_f}{\partial a_f}}_{\text{Attribute effect (-)}} \quad - \quad \underbrace{\frac{\partial mc_f}{\partial a_f} q_f}_{\text{Marginal cost effect (+)}} \quad < 0.$$

[11] If compliance costs are high, we would see product exit in response to the regulation. Our model does not account for product exit and entry. In the estimation, we would overestimate compliance costs if it would be more profitable not to offer certain products anymore.

[12] Empirically, we find price responses to be inconsequential in signing the profit changes due to changes in abatement actions.

[13] Our framework could accommodate consumers partially considering the externality, as long as the abatement action reduces demand more than it increases willingness to pay for the externality reduction.

Thus, the abatement action always reduces the variable profit. Following the same intuition, a competitor's abatement action increases the firm's variable profit, $\frac{\partial \pi_f(\boldsymbol{a},\boldsymbol{p})}{\partial a_{f'}} > 0$, because the competing firms have increased marginal cost, or decreases in a valuable attribute with abatement actions.

The assumptions on variable profits imply that in the absence of a binding emission standard ($e^* \geq \theta_f$) it is a dominant strategy for a firm to choose $a_f = 0$ because the firm has no profit incentive to reduce emissions. When there is a binding standard ($e^* < \theta_f$) and firm f complies, it chooses $a_f = \theta_f - e^*$ because there are no gains from over-compliance. If firm f decides to misreport emissions, it chooses $a_f < \theta_f - e^*$ while the firm misreports emissions to be compliant during the permitting phase. We assume that misreporting is not costly except for the risk of noncompliance penalties. A noncompliance choice involves a trade-off between the increase in variable profits and the expected noncompliance penalty. Our paper studies how this trade-off changes when firms choose abatement actions jointly or unilaterally.

Expected noncompliance penalty. Whenever firms are not compliant with the emission standard, they risk penalties. We describe the expected noncompliance penalty as a function of abatement actions in the industry:

$$\mathbb{E}K_f(\boldsymbol{a}) = P_f(\boldsymbol{a})K_f(\boldsymbol{e}(\boldsymbol{a}), e^*).$$

The expected noncompliance penalty may depend on competitor choices because collusion can change either the detection probability P_f or the actual penalty K_f. First, the *probability of detection* of noncompliance can decrease because pollution types are correlated through a common component, so the regulator might compare firms relative to the industry profile of abatement actions $\boldsymbol{a} \equiv (a_1, a_2, \ldots, a_n)$. This is similar to collusion in yardstick competition (Schleifer, 1985; Auriol and Laffont, 1992; Laffont and Martimort, 2000; Tangerås, 2002). Second, the noncompliance penalty upon detection may decrease because of *diffusion of responsibility*, which could reduce either individual fines or reputation damages when multiple firms are noncompliant. Third, increasing the number of firms that are able to sustain noncompliance and avoid detection increases the number of firms with *skin in the game*; these firms would rather remain noncompliant in the market than report their rivals to the environmental regulator.

2.3 Benefits of Collusion

We now discuss the benefits that firms obtain by colluding from a comparison between collusive profits and profits from unilateral. Because the abatement action profile $\boldsymbol{a^{NC}}$ is competitive, we have for each firm f

and each alternative abatement action $a'_f \neq a_f^{NC}$:

$$\pi_f(\boldsymbol{a^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^{NC}}) \geq \pi_f(a'_f, \boldsymbol{a^{NC}_{-f}}) - \mathbb{E}K_f(a'_f, \boldsymbol{a^{NC}_{-f}}), \tag{2}$$

where $-f$ denotes the set of firms other than f. One competitive equilibrium of interest is the compliance equilibrium, $\boldsymbol{a^*}$, with $a_f^* = \theta_f - e^*$ for every f. Because the expected noncompliance penalty for a compliant firm is zero, we have:

$$\pi_f(\boldsymbol{a^*}) \geq \pi_f(a'_f, \boldsymbol{a^*_{-f}}) - \mathbb{E}K_f(a'_f, \boldsymbol{a^*_{-f}}), \tag{3}$$

where we have used $K_f(\boldsymbol{a^*}) = 0$. For compliance to be an equilibrium, the expected noncompliance penalty for the violator when everyone else complies must exceed the variable profit gain from violating alone.

At the collusive equilibrium, $\boldsymbol{a^C}$, where firms in $\mathcal{F}^{WG}$ accept the collusive proposal and firms in $\mathcal{F}^{NWG}$ choose abatement actions competitively, we have for each firm $f \in \mathcal{F}^{WG}$:

$$\pi_f(\boldsymbol{a^C}) - \mathbb{E}K_f(\boldsymbol{a^C}) - \mathbb{E}A_f(\boldsymbol{a^C}) > \pi_f(\boldsymbol{a^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^{NC}}), \tag{4}$$

where $\mathbb{E}A_f(\boldsymbol{a^C}) \geq 0$ is the expected antitrust penalty. The condition states that the collusive proposal must be more profitable than competition for the participants. Additionally, at least one of the participants will have the incentive to deviate from the proposal, and the working group must therefore make the collusive agreement incentive compatible. Our empirical analysis does not investigate the dynamic enforcement of the cartel.[14]

Notice that in contrast to models of price/quantity collusion, deviation from the collusive proposal in this context leads to lower variable profits, while the deviation incentive comes from reduced penalties. Given the definition of collusion, we now show that a collusive equilibrium can only occur if it lowers expected compliance penalties relative to unilateral noncompliance:

Proposition 1. Assume that there exists a collusive equilibrium with $a_f^C \leq a_f^{NC}$ for all $f \in \mathcal{F}$ with strict inequalities for every $f \in \mathcal{F}^{WG}$, and that the variable profit increases with competitors' abatement actions. Then, for every $f \in \mathcal{F}^{WG}$, the expected noncompliance penalty under collusion must be lower than the

[14]In our model, a firm that deviates from the collusive agreement by increasing abatement actions may reduce its noncompliance penalty substantially so that the variable profit loss is bearable. The cartel's dynamic enforcement could take the form of reverting to a competitive equilibrium or—subject to stability constraints—excluding the deviant from future collusive proposals. Additionally, automakers collaborate in many dimensions of product development, so deviants may lose the opportunity to collaborate in other possible dimensions of product development.

penalty if the firm adopts a_f^C unilaterally, that is: $\mathbb{E}K_f(\boldsymbol{a^C}) < \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$.

Proof. Since a_f^C is an action available to firm $f \in \mathcal{F}^{WG}$, when played against a_{-f}^{NC} it must yield a payoff that does not exceed f's optimized, competitive payoff. Thus, applying Inequality (2) with $a'_f = a_f^C$, we have:

$$\pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) \leq \pi_f(\boldsymbol{a^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^{NC}}) \tag{5}$$

Combining Inequalities (4) and (5), we have:

$$\pi_f(\boldsymbol{a^C}) - \mathbb{E}K_f(\boldsymbol{a^C}) - \mathbb{E}A_f(\boldsymbol{a^C}) > \pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}). \tag{6}$$

Because the variable profit increases with competitors' abatement actions, we have $\pi_f(\boldsymbol{a^C}) < \pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$ given that $a_{-f}^C < a_{-f}^{NC}$. Inequality (6) then implies:

$$\mathbb{E}K_f(\boldsymbol{a^C}) + \mathbb{E}A_f(\boldsymbol{a^C}) < \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}),$$

and therefore $\mathbb{E}K_f(\boldsymbol{a^C}) < \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$ because $\mathbb{E}A_f(\boldsymbol{a^C}) \geq 0$. $\square$

Proposition 1 shows that for the same noncompliant abatement action of a given firm, the expected noncompliance penalty decreases when other firms also reduce abatement actions. Furthermore, the proof of the proposition provides empirically testable bounds on the expected noncompliance penalty. With knowledge of $\boldsymbol{\pi(\cdot)}, \boldsymbol{a^C}, \boldsymbol{a^{NC}}$, Inequality (6) allows us to derive a lower bound on the reduction in the expected penalties thanks to the collusive noncompliance relative to unilateral noncompliance. We implement this exercise in Section 6 using our data.

Finally, we examine how incentives of non-working-group firms change because of the working group. The working group's collusion may induce the non-working-group firms to also reduce their abatement actions below compliance. When this happens for some firm $g \in \mathcal{F}^{NWG}$, we have:

$$\pi_g(\boldsymbol{a^C}) - \mathbb{E}K_g(\boldsymbol{a^C}) > \pi_g(a_g^*, \boldsymbol{a_{-g}^C}). \tag{7}$$

Thus, for firm g that "follows along" instead of complying, it must be that the variable profit gain outweighs the expected noncompliance penalty that it now incurs. This inequality informs us of the upper bound on the expected noncompliance penalty for a non-working-group firm that chooses to ride along with the collusion.

2.4 Welfare Evaluation

We define the social welfare associated with abatement action profile $\boldsymbol{a}$ as:

$$W(\boldsymbol{a}) = BS(\boldsymbol{a}) + \sum_{f \in F} \pi_f(\boldsymbol{a}) - \sum_{f \in F} \phi e_f(a_f) q_f(\boldsymbol{a}),$$

where BS is the buyer surplus and ϕ the marginal damage of the externality. We split consumer surplus into buyer surplus and the externality because the incidence of the collusion has opposite effects on both. The social welfare change caused by the collusion relative to competition equals:

$$\Delta W = W(\boldsymbol{a^C}) - W(\boldsymbol{a^{NC}}). \tag{8}$$

A social planner implementing optimal regulation would seek to minimize the social welfare loss from potential collusion. In the optimal second-best regulation, collusion can be allowed to happen only when it does not make ΔW negative.

Suppose that we make the working group the residual claimant of the welfare it generates, regardless of whether the collusive proposal is accepted (in game step 1.2). By "selling the firm" to the working group, the regulation becomes robust to collusion, as in Che and Kim (2006). Regulation would achieve the optimal second-best and collusion would not reduce welfare.[15] In practice, a penalty equal to (the negative of) the residual claim would consist of the sum of penalties from the antitrust authority and the environmental regulator. Thus, antitrust could substitute for weakly enforced environmental regulation in the case of collusion. The residual claim $\Re$ colluding firms face equals:

$$\Re = \Delta W - \sum_{f \in F^{WG}} \pi_f(\boldsymbol{a^C}) + \sum_{f \in F^{WG}} \pi_f(\boldsymbol{a^{NC}}) \tag{9}$$

We construct a useful ratio to distinguish between several welfare scenarios of collusion as follows:

$$\lambda = \frac{\sum_{f \in F^{WG}} \pi_f(\boldsymbol{a^C}) - \sum_{f \in F^{WG}} \pi_f(\boldsymbol{a^{NC}})}{-\Re}. \tag{10}$$

[15] The idea of selling the firm to agents goes back further in the literature on moral hazard, including Laffont and Tirole (1986), and Baron and Myerson (1982).

Assume that $\Re < 0$, or that the collusion harms the rest of the society. Then, if $\lambda \leq 0$, then the collusion does not improve the working group profits relative to competition. The working group may then not collude at all. If $\lambda > 1$, then the collusion increases the working group profits more than it harms the rest of the society. Making the working group absorb the residual claim thus has a redistributive role, and the working group would still collude. Finally, if $\lambda \in (0, 1]$, then the collusion increases the working group profits less than it harms the rest of the society. Then, making the working group pay for the residual claim would prevent collusion.

In our empirical setting, firms make decisions under a regulatory environment that differed from the one that fully rights the wrong by making the working group pay for the residual claim. Thus, a $\lambda \in (0, 1]$ can be interpreted as an upper bound on the probability that firms assign to incurring penalties, should the penalties cover the residual claim. An alternative interpretation of λ is a lower bound on the distance from a collusion-proof regulatory environment.

3 Empirical Context

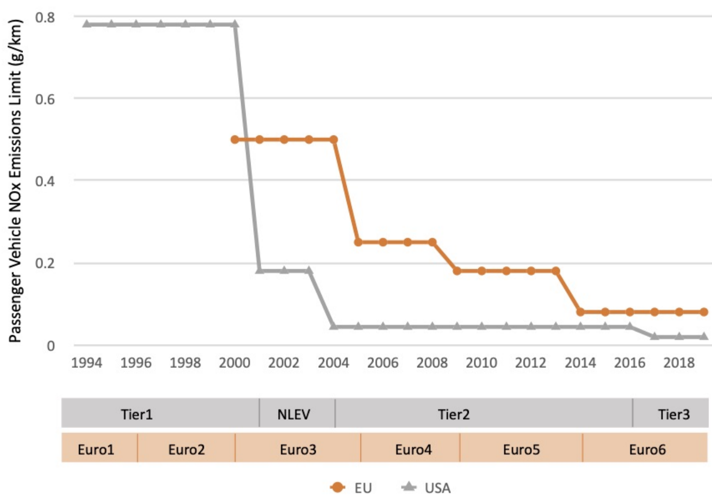
3.1 EU Regulations of Automobile NO_x Emissions

Nitrogen oxide (NO_x) is a family of poisonous gases, with adverse effects on the environment and human health. NO_x combines with atmospheric chemicals to form fine particulate matter (PM2.5). It also produces smog-causing ground-level ozone when combined with volatile organic compounds and sunlight. In 2015, the global death toll of PM2.5 is estimated at around 4.2 million from heart disease and stroke, lung cancer, chronic lung disease, and respiratory infections; ground-level ozone accounts for an additional 0.25 million deaths (Health Effects Institute, 2017). NO_x reduces crop and forest productivity, leading to more CO_2 in the atmosphere, and interacts with water to form acid rain. Road transport is responsible for about 40% of NO_x emissions in the EU and diesel vehicles emit 80% of those NO_x emissions from road transport (European Environment Agency, 2015).

Since 2000, the EU has adopted increasingly more stringent NO_x emission standards for diesel vehicles. In the period of our analysis, the relevant regulations are Euro 5 (September 2009 - August 2014) and Euro 6 (September 2014-). Figure 1 shows the NO_x emission standards over time in the EU and U.S. In the EU, those standards are enforced through "type approval". Before an automaker brings a vehicle "type" or a group of similar models to the market, the automaker is required to hire a third-party testing company to measure the emissions for each vehicle type.

We focus our study on vehicles released under type approval Euro 6 with a New European Driving Cycle (NEDC). In September 2017, the EU changed the type approval procedure for new vehicles, with several subsequent changes in response to the Volkswagen scandal. The new vehicle type approval happens under a Worldwide Harmonized Light Vehicle Test Procedure (WLTP) which partly accounts for Real Driving Emissions (RDE).[16] We end our study in 2018 when the large majority of vehicles registered were still approved under Euro 6 NEDC.

Figure 1: Diesel Passenger Vehicle NO_x Emission Standards in the EU and U.S.



Notes: NLEV standards for National Low Emission Vehicle, an emission standards applicable to the transitional period from Tier 1 to Tier 2, initiated by an agreement between Northeastern states and auto manufacturers.

3.2 Complying with NO_x Emission Standards

To comply with the Euro 5 emission standards (2009-2014), automakers mostly relied on the Exhaust Gas Recirculation (EGR) technology only.[17] With the reduction of NO_x emission limits from 0.18g/km in Euro 5 to 0.08g/km in Euro 6, EGR alone is not sufficient, and automakers could choose between two additional

[16]The exact details of the procedure changed several times and vehicles were temporarily allowed to emit more than the standard. How the regulator changed the testing procedure and how automakers responded to these changes are outside our scope.

[17]EGR recycles some exhaust gas back to the engine to lower the engine temperature, which in turn reduces the formation of NO_x emissions. It became a standard technology installed in diesel vehicles by default after 2009.

technologies. The first technology is Lean NO_x Trap (LNT), which is mainly used in small vehicles because of its fuel penalty.[18] The second technology is Selective Catalytic Reduction (SCR). Because SCR has virtually no fuel penalty, it is suitable for larger vehicles. However, SCR requires a tank to hold Diesel Exhaust Fluid (DEF), a urea solution that is sprayed into engine-out emissions and neutralizes nitric oxide into harmless water and nitrogen. LNT and SCR can also be combined to achieve more effective emissions control, but this option is less common.

While commercial diesel vehicles and trucks refill the DEF tank on a very regular basis,[19] DEF tanks in passenger cars are typically designed to be refilled annually.[20] In other words, a full tank of DEF is supposed to last for a year of driving. There are two reasons for this. First, automakers are wary of burdening consumers with the hassle and financial costs of refilling the DEF tank more frequently than routine check-ups to avoid making diesel cars less attractive than gasoline cars.[21] Second, it is technically difficult for passenger car owners to refill the DEF tank themselves because the refilling infrastructure has been optimized for trucks and post-refill tune-ups may be needed.[22]

3.3 The Antitrust Case

Since the 1990s, the leading German automakers have had a history of regularly meeting with each other to talk about technologies and specifications (Dohmen and Hawranek, 2017). The so-called "Circle of Five" was composed of BMW, Daimler, Volkswagen, Porsche, and Audi, where the last three are owned by the Volkswagen Group. In this paper, we refer to all subsidiary brands owned by BMW, Daimler and Volkswagen alternatively as the "working group".

As early as 2006, the working group started to discuss how to fit the extra DEF tank in their future models.

[18]The LNT system traps the NO_x from engine-out emissions, and when NO_x has accumulated in the system, the system uses fuel-rich operations to renew the system and catalytically reduce NO_x.

[19]Medium- to heavy-duty trucks can expect 13-20 refills every year. See https://www.capitalremanexchange.com/20-facts-you-need-to-know-about-diesel-exhaust-fluid-def/.

[20]The U.S. Environmental Protection Agency explicitly "demanded that the tanks contain enough urea to ensure that they would only have to be refilled during an inspection after about 16,000 kilometers. They were unwilling to accept the possibility that the tanks could be refilled between inspection dates(. . .)" Dohmen and Hawranek (2017).

[21]Dohmen and Hawranek (2017) report that the manufacturers' internal records show that DEF tanks are "designed so that customers would not have to refill them." Ewing and Granville (2019) writes that "refilling the tank would become an extra chore and expense for the owner, a potential turnoff for prospective customers," and that "Volkswagen wanted the fluid to last long enough to be refilled by dealers during regularly scheduled oil changes, so there would be no inconvenience to owners."

[22]Total, a fuel station brand, advises consumers against refilling themselves, pointing out that the DEF filler neck on the vehicle may be hard to access, that DEF pumps at gas stations are designed specifically for trucks but not passenger vehicles, and that many vehicles need a technical reset by a mechanic after the DEF refill. (https://www.lubricants.total.com/business/distributorreseller/products/adbluer-faqs). Likewise, Jaguar on their website asks consumers to book a refill with an authorized repairer when the vehicle alerts that DEF levels are critically low (https://www.jaguar.com/owners_international/electric-petrol-or-new-euro-6-diesel/jaguar-diesel-exhaust-fluid.html).

According to a working group report of chassis managers, the companies urgently needed a "coordinated approach" on tank sizes. Although larger DEF tanks reduce more NO_x, the chassis managers preferred smaller tanks because they were "lightweight, did not cost much, and left enough space for golf bags in the trunk." (Dohmen and Hawranek, 2017)

With the introduction of more stringent Euro 6 standards, the working group was allegedly aware that smaller tanks did not contain enough DEF to reduce NO_x emissions to compliant levels while lasting an entire year between refills. A 2011 internal report stated that the introduction of Euro 6 would lead to an increase in DEF consumption of up to 50 percent (Ewing, 2018). Moreover, it seemed that none of the companies wanted to request consumers to refill the DEF tanks more than once a year. In May 2014, Audi sent an email warning that the need to inject more fluid into the exhaust gas system as required by Euro 6 could "expand into an arms race with regard to tank sizes, which we should continue to avoid at all costs". Dohmen and Hawranek (2017) explained that "[i]f one manufacturer had installed larger [DEF] tanks, licensing and regulatory authorities would probably have become suspicious. The obvious question would have been why that one company's vehicles needed so much more urea to clean the exhaust gases, while the other manufacturers' cars supposedly managed with significantly less [DEF]". Apparently, the "arms race" with regard to tank sizes did not happen.

In October 2017, the European Commission began its initial inquiries into possible collusion by inspecting the premises of BMW, Daimler, Volkswagen (including Audi) in Germany. In September 2018, The Commission opened an in-depth investigation. In April 2019, the European Commission sent a statement of objections to the working group to inform them of the preliminary view that the working group "participated in a collusive scheme, in breach of EU competition rules, to limit the development and rollout of emission cleaning technology [. . .]" (European Commission, 2019).

4 Data and Descriptive Evidence

4.1 Data Sources

Our vehicle sales and prices data are from a market research firm (JATO Dynamics). The data contain new registrations, retail prices, and attributes of all passenger vehicles sold in the seven largest European markets (Germany, UK, France, The Netherlands, Belgium, Spain, Italy)[23] from 2007 to 2018. This sample

[23]These markets represent about 90% of the European market.

period starts with the working group's early adoption of the Selective Catalytic Reduction (SCR) technology to control NO_x emissions, before the Euro 6 emission standards took effect in 2014. The sample period also ends before the Dieselgate scandal began to affect new vehicle designs.

We augment the JATO data with data from ADAC, a German automobile association.[24] The ADAC data give us information on the NO_x control technology, Diesel Exhaust Fluid (DEF) tank size, trunk space, and designations of series and series generation. We define a vehicle (our unit of observation) as a combination of brand, engine displacement, horsepower, body type, fuel type, transmission type, trunk space, emission control technology, Euro emission standards, and DEF tank size (when applicable).

We also include information on the location and plant of production of each vehicle from PWC autofacts. We collect additional data on population, gross domestic products, price indices, and input costs from statistical agencies.

Finally, we obtain Real Driving Emissions (RDE) data from Emissions Analytics, an independent global RDE testing and data company based in the UK. The company conducted nearly a thousand emission tests on on-road NO_x emissions and fuel consumption between 2011 and 2020.

4.2 Market Structure

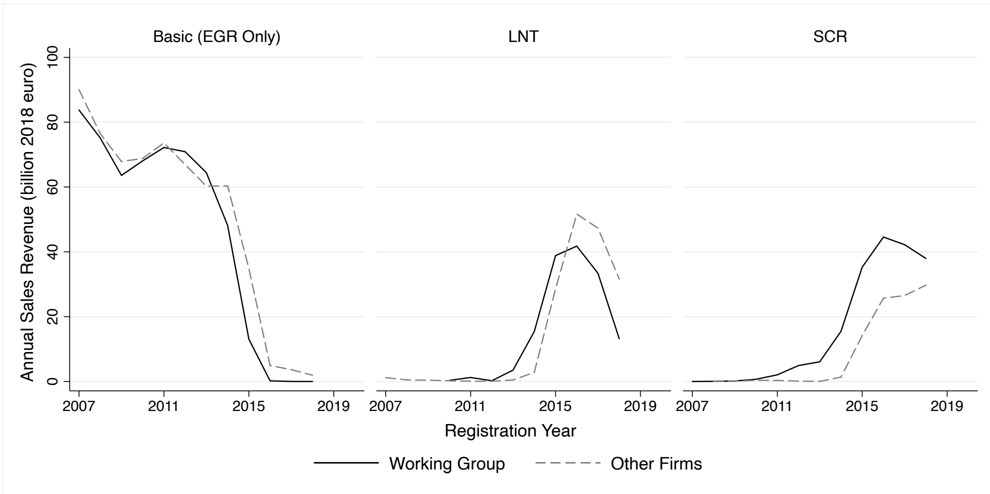
In our sample period 2007-2018, the EU automobile industry consists of the working-group firms—BMW, Daimler, and Volkswagen—and 17 other firms.[25] The working group accounts for about half of the revenue share in our sample. Diesel vehicles are an important source of revenue for the working group. For example, the working group generated around 80 billion euros in revenue from diesel vehicles and 50 billion euros from gasoline in 2017, compared with 78 billion and 65 billion euros for non-working-group firms, respectively.

Within the diesel segment, the working group relied strongly on SCR to control NO_x emissions. Figure 2 plots the annual sales revenue of diesel vehicles by NO_x control technology for the working group and other firms, respectively. Before Euro 6 emission standards started in September 2014, SCR was not needed for compliance with Euro 5, and yet the burgeoning SCR sales revenue almost completely went to the working group. After Euro 6 kicked off, when virtually all new diesel vehicles were equipped with SCR or Lean NO_x Trap (LNT) to comply, the working group's SCR revenue kept overshadowing the rest of the industry. The

[24]According to industry sources, Germany has the most comprehensive market, containing almost all vehicles available in other European countries (although vehicles may vary in their aesthetic trims across countries). This is confirmed by the performance of our data-matching script, which matches 93% of observations (or 96% of registrations) in the JATO data with the detailed characteristics data from the German automobile association.

[25]A firm can have multiple brands. For example, BMW has BMW, MINI, and Rolls-Royce; Daimler has Maybach, Mercedes, and Smart; and Volkswagen has Audi, Bentley, Cupra, Lamborghini, Porsche, SEAT, Skoda, and VW.

Figure 2: Annual Sales Revenue of Diesel Vehicles with Various NO_x Control Technologies



Notes: This figure shows annual diesel sales revenue for the different NO_x control technologies: Basic (Exhaust Gas Recirculation/EGR only), Lean NO_x Trap (LNT), and Selective Catalytic Reduction (SCR). Calculated based on new registrations of diesel passenger vehicles in the seven largest European markets (Germany, UK, France, The Netherlands, Belgium, Spain, Italy) multiplied by country-year-specific retail prices in 2018 euros. Not plotted is a small share of vehicles equipped with both LNT and SCR.

working group's SCR revenue peaked in 2016 at 45 billion euros, when other firms' SCR revenue was only 26 billion euros. In Appendix Table A1 we show that SCR is installed on larger and more powerful vehicles than LNT, consistent with Yang et al. (2015).

4.3 Suggestive Evidence for Collusion

We provide evidence that the working group suppressed the effectiveness of their SCR systems relative to firms outside the working group. To measure SCR effectiveness, we introduce the notion of a dosage. The SCR system works by first sensing the amount of NO_x produced by the engine and then adding a dose of DEF to decompose NO_x into harmless nitrogen and water. The dosage is the percent of DEF added to each liter of diesel the engine consumes, a common measure of SCR effectiveness in the engineering literature.

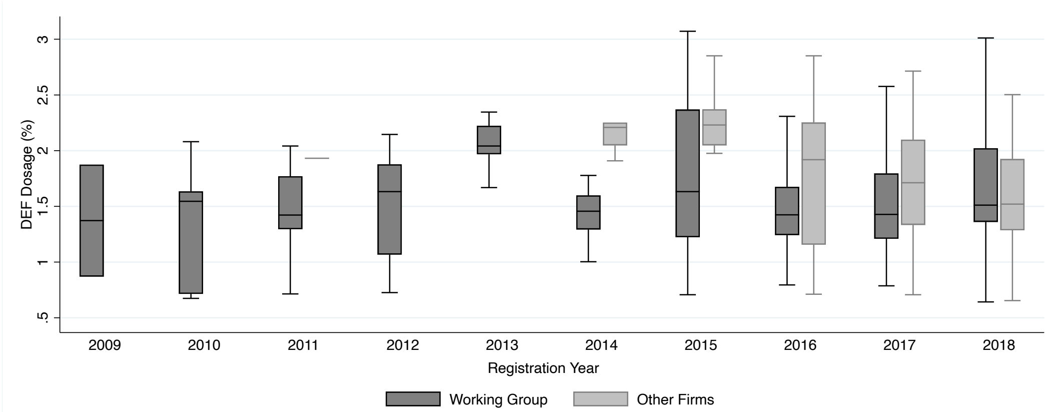
We convert DEF tank sizes observed in the data to a measure of dosage. We assume the distance a vehicle is designed to travel before the DEF tank is depleted and a refill required. A drawback of the SCR system is that once the DEF tank is empty, there is no fluid left to reduce engine-out NO_x emissions. The EU specifies that engines need to be disabled as soon as the DEF tank is below a critical level. As described in Section

3, firms chose DEF tanks that were supposed to run for a year of driving to avoid burdening consumers with the extra hassle, financial costs, and the technical difficulties of refilling the tanks on their own. By combining the distance the tank should last with the fuel consumption of the vehicle, we can compute the implied dosage as a percent of the total annual fuel consumption:

$$dosage = 100 * \frac{DEFTankSize}{AnnualFuelConsumption},$$

where we obtain the annual fuel consumption for each vehicle by multiplying an annual mileage of 20,000 km with the fuel consumption (liter per km driven) of the vehicle.[26] Alternative annual mileage assumptions are included in our robustness checks.

Figure 3: Distributions of DEF Dosages by the Working Group and Other Firms



Notes: Box plot based on all diesel SCR vehicle approved for Euro 6, including both New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicel Test Procedure (WLTP). Dosage is derived by dividing the observed DEF tank size by the fuel consumption for an annual mileage of 20,000km. The lines within the box plot indicate the median. Box edges represent the 25th and 75th percentiles. End points represent the lower and upper adjacent values. Outside values are omitted.

In Figure 3, we plot the evolution of the distribution of DEF dosages adopted by the working group and other firms for all diesel vehicles approved for Euro 6. It shows the working group moved well before the Euro 6 emission standards took effect in 2014; they sold SCR vehicles as early as in 2009. Virtually all other firms introduced SCR vehicles after Euro 6 started. The interquartile values of the working group's dosages

[26]The average annual mileage of diesel vehicles is higher than that for gasoline vehicles. The UK travel survey reports that diesels travel 17,200km on average (`https://www.gov.uk/government/collections/national-travel-survey-statistics`), whereas based on odometer readings, the Dutch statistical agency reports diesel vehicles travel on average 23,000km per year (`https://opendata.cbs.nl/statline/#/CBS/nl/dataset/80428ned/table?dl=295AF`).

were roughly between 1% and 2%. Until 2018, the interquartile ranges of their dosages were consistently below those of other firms. The dosages of the two groups became comparable in 2018.

Table 1: Suggestive Evidence for Coordination on Smaller DEF Tanks

	(1) Log Dosage	(2) Log Dosage	(3) Log Dosage	(4) Log Dosage
Working Group	−0.032	−0.156***	−0.080***	0.123***
	(0.017)	(0.024)	(0.022)	(0.022)
Euro 6 Cycle	Both	NEDC	NEDC	WLTP
Controls			X	X
N	1437	791	791	645
Adjusted R^2	0.002	0.049	0.182	0.281

Notes: An observation is a diesel SCR vehicle approved for Euro 6. Dosage is derived by dividing the observed DEF tank size by the fuel consumption for an annual mileage of 20,000km. Controls include power, engine size, curb weight, drive type, and series start year. Robust standard errors in parentheses. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

To quantify the differences in the DEF dosages, we report in Table 1 the results from regressing log DEF dosages on the working group indicator. Column (1) shows that the working group's suppression of dosages relative to other firms does not appear statistically significant, if we include all Euro 6 diesel vehicles. When we separate Euro 6 vehicles approved under the New European Driving Cycle (NEDC) and the more stringent Worldwide Harmonized Light Vehicle Test Procedure (WLTP), Columns (2) and (3) show that the working group suppressed the SCR effectiveness for vehicles in the former group but not in the latter. Because the share of WLTP vehicles increased towards 2018, we see the narrowing (albeit not reversal) of the gap in dosages towards 2018 in Figure 3. Controlling for a full set of emission-related vehicle characteristics, Column (4) shows that the working group adopted 8% lower dosages than other firms on comparable SCR vehicles approved under the Euro 6 NEDC. Our analysis of the economic effects of the alleged collusion will focus on the Euro 6 NEDC vehicles.

4.4 Suggestive Evidence for Widespread Noncompliance

What do the automakers' DEF choices imply for Euro 6 compliance? We use the RDE data to estimate the relationship between DEF choices and on-road NO_x emissions. The on-road emission for vehicle j, measured in mg/km, is:

$$e_j = \theta_j - RemovalRate \times a_j + \epsilon_j \tag{11}$$

where θ_j is the untreated emission, which depends on vehicle characteristics such as fuel consumption and the presence of a supplementary LNT system, a_j is the DEF tank size (the amount of DEF that lasts for one year's driving), and ϵ_j is an i.i.d. idiosyncratic error. The parameter of interest is $RemovalRate$, which is the mass of NO_x neutralized by a liter of DEF (as determined by the underlying chemical reaction) normalized by the annual mileage.

Table 2: Determinants of On-Road Emissions, mg/km

	(1)	(2)
DEF Size (L)	−8.19***	−7.71*
	(2.03)	(3.63)
LNT+SCR Relative to SCR	−109.39**	−72.18
	(50.55)	(58.87)
On-road Fuel Consumption (l/100km)	68.35*	69.06**
	(35.03)	(31.02)
Euro 6 Cycle	Both	NEDC
Controls	X	X
N	143	90
Adjusted R^2	0.338	0.374

Notes: An observation is a Euro 6 diesel vehicle equipped with DEF tanks (including those with a supplementary LNT) in the on-road emission data set. Controls include the brand fixed effects, power, vehicle segment fixed effects, number of cylinders, curb weight, ambient temperature, ambient pressure, and relative humidity. Standard errors clustered at the brand level are in parentheses. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

Table 2 reports the regression results using Equation (11) based on the RDE test results of Euro 6 vehicles equipped with SCR tanks (including those with a supplementary LNT). Column (1) shows that the emissions decrease with the DEF size and the presence of a supplementary LNT system, and increases with fuel consumption. Because Table 1 shows that the alleged collusion on restricting SCR effectiveness most likely affected only NEDC vehicles, we restrict to this subsample in Column (2) and obtain a DEF removal rate estimate of 7.71 mg/km per liter of DEF. We calculate the implied compliant DEF sizes by replacing the left-hand side of Equation (11) with the Euro 6 emission limit of 80 mg/km and find that the average implied dosage is 2.7%. This is consistent with engineering studies that discuss the potential of SCR after-treatment to comply with Euro 6 in real driving conditions. Holderbaum et al. (2015) test a vehicle with different NO_x treatment systems and conclude that compliance in real driving conditions can be obtained with DEF dosages between 2.9% and 3.6%.[27] Similarly, Op De Beeck et al. (2013) report a compliant dosage of 3%, and Sala et al. (2018) report 3-5%. In the counterfactual analysis, we consider the effect of the 3% dosage on firm profits and consumer welfare as the main scenario, and consider other dosages and assumptions on annual mileage and fuel consumption as robustness checks.[28]

Table 3: DEF Tank Size, Dosage, Refill, and NO_x Exceedance Factor

	Mean	St.Dev.	Min	25th Per.	75th Per.	Max
Main Dataset						
Observed DEF tank size	16.18	5.03	8.00	12.00	17.00	38.70
Implied dosage	1.71	0.55	0.64	1.29	2.15	3.25
3% dosage: DEF tank size	29.40	6.69	17.89	24.68	33.28	59.09
3% dosage: Annual refills	1.97	0.71	0.92	1.40	2.32	4.67
RDE Dataset						
Observed DEF tank size	16.42	6.40	8.00	12.00	17.00	33.40
Implied dosage	1.67	0.58	0.81	1.25	2.14	3.21
NO_x exceedance factor	3.01	2.61	0.12	1.00	3.95	13.76

Notes: "Implied dosage" is derived by dividing the observed DEF tank size by the fuel consumption for an annual mileage of 20,000km. "3% dosage: DEF tank size" is derived by multiplying the fuel consumption with 3%. "3% dosage: Annual refills" is derived by dividing the "3% dosage: DEF tank size" by the observed DEF tank size. NO_x exceedance factor is the on-road emission divided by the Euro 6 emission limit. Each observation is a diesel SCR vehicle approved under the Euro 6 NEDC. The main dataset has 791 such vehicles and the RDE dataset has 84.

Comparing the actual choices of DEF tank sizes with the compliant benchmark reveals a widespread noncompliance problem involving not only the working group. The top panel of Table 3 shows that the implied dosage of the DEF tank sizes on all NEDC vehicles in our main data set is on average 1.71% with a minimum as low as 0.64%. The vast majority adopt dosages below 3%. If the tank sizes would not change, increasing the dosage of each vehicle to 3% would require consumers to refill the DEF tank twice a year on average. This is what automakers want to avoid. We observe that up to 4-5 refills would be required in our sample to be compliant with Euro 6 with a 3% dosage.

To avoid frequent refills and obtain low emissions, another option would be to scale up the tank size. Given an annual mileage of 20,000 km and a dosage of 3%, tank sizes would need to increase from an average

[27] The study runs tests with 6.8 liter/100km vehicles and reports urea usage of 2 to 2.5 liter/1000km to obtain compliance.

[28] It is not feasible to use the estimates in Table 2 to derive the compliant DEF size *for each vehicle* because of the relatively low R squared.

from 16 liters to 29 liters.[29] As we have described in Section 3, the working group's own argument for preferring small DEF tanks is that they were "lightweight, did not cost much, and left enough space for golf bags in the trunk" (Dohmen and Hawranek, 2017). In Appendix Table A2, we report that one liter increase in the DEF tank size reduces the trunk space by 0.91 liter and increases the curb weight by 1.27 kg. Thus, an average DEF tank of 16 liters takes up 3.6% of an average trunk space of a diesel vehicle and adds 1% of the average weight. We focus on the DEF tanks' trade-off with trunk space as well as their marginal cost.[30]

The lower panel of Table 3 shows the same issue of under-dosing in the RDE dataset; as a result the SCR vehicles emitted on average three times the NO_x emission limit on the road. The widespread noncompliance, when combined with the early move of the working group in adopting low dosages, suggests that the working group could have intentionally set the implicit standard for the rest of the industry to follow.

5 Structural Model and Estimates

5.1 Demand

We estimate the random coefficient logit demand model as in Berry et al. (1995). We define a market as country-year and suppress the subscript for notational ease. Each consumer i has conditional indirect utility from purchasing vehicle j:

$$U_{ij} = \delta_j + \mu_{ij} + \varepsilon_{ij},$$

with δ_j representing the mean utility of vehicle j that is the same for every consumer, and μ_{ij} representing individual deviations from the mean utility. Individual-vehicle-specific taste shocks, ε_{ij}, are assumed to be i.i.d. and follow the Type-I extreme value distribution.

The mean utility is:

$$\delta_j = \alpha p_j + x_j \beta + \xi_j,$$

where p_j is the retail price and x_j is a vector of vehicle characteristics including trunk space, horsepower, engine size, weight, footprint, height, fuel cost, range, a foreign indicator, country-specific year trend, and indicators for country, drive type, transmission type, body type, fuel type, EU emission standards, and

[29]In Appendix Figure A1 we visualize how observed DEF size increases with fuel consumption relative to how a 3% dosage tank increases with fuel consumption. The observed relationship is much flatter than what we would observe under compliance.

[30]Ewing (2018) describes only the trade-off with trunk space.

series. Unobserved vehicle-specific attributes and demand shocks are represented by ξ_j. We do not include the Diesel Exhaust Fluid (DEF) tank size explicitly in the demand for two reasons. First, consumers are likely uninformed about the technical function of DEF or the DEF tank size.[31] Second, as discussed in Section 2, the refill of the DEF tank is typically designed to be annual regardless of the DEF tank size. For similar reasons, we also consider NO_x to be a pure externality for consumers; NO_x emissions are not listed in owner's manuals or displayed in dealerships, and curious consumers may already be satisfied with knowing simply that the vehicle passes the emission test but care little about the exact test values.

The individual deviation from the mean utility is:

$$\mu_{ij} = \sigma_p p_j \nu_{ip} + \sum_k \sigma_k x_{jk} \nu_{ik},$$

where ν_{ip}, ν_{ik} are standard normal draws. The outside choice is not purchasing a vehicle, and the indirect utility for the outside choice is normalized to:

$$u_{i0} = \varepsilon_{i0}.$$

Consumer i chooses vehicle j if $U_{ij} \geq U_{ij'}$ for all alternatives (including the outside option) in the same market. The market share for vehicle j comes from integrating over individual choices:

$$s_j = \int \frac{exp(\delta_j + \mu_{ij})}{\sum_{j'} exp(\delta_{j'} + \mu_{ij'})} \mathrm{d}\nu_i.$$

The parameters from the demand model to be estimated are (α, β, σ).

As is standard in the literature, we allow for correlation between prices and the product unobservable ξ_j. Additionally, we consider strategic choices of DEF tanks that affect trunk space. We instrument for prices and trunk space with three groups of instrumental variables. First, we include BLP instruments (Berry et al., 1995) constructed from vehicle characteristics including horsepower, engine size, trunk space, weight, footprint, height, and fuel cost. The BLP instruments are the sums of each of those exogenous characteristics of other vehicles produced by the same automaker and of vehicles produced by other automakers on the same market. Second, we include a set of cost instruments related to production organization. We compute the number of engine versions produced on the same production line, and a dummy capturing changes in

[31] In fact, there is no mention of DEF tank sizes in most owner's manuals. Also, there appears to be widespread confusion about how big the tank is in online owners' forums (see, e.g., `https://www.bimmerfest.com/forums/showthread.php?t=884875`).

production lines, assuming that production line changes affect costs. Third, we instrument for trunk space using gross trunk space. In the data, we observe $x_j = \tilde{x}_j - f(a_j)$ where $f(a_j)$ is the unobserved space occupied by the DEF tank. We assume gross trunk space $\tilde{x_j}$, before DEF tank choice, to be mean-independent of the demand unobservable: $E[\tilde{x}_j|\xi_j] = 0$. Automakers fix physical dimensions for vehicles about two to four years before the series generation launches. By the time a vehicle from that series generation launches and demand shocks realize, the automaker is unable to adjust the gross trunk space. Vehicles that do not install a DEF tank (gasoline engines and small diesel engines) have $x_j = \tilde{x}_j$. For all vehicles with a DEF tank, the trunk space of other engine versions without DEF tanks in the same series is strongly correlated with the trunk space of the DEF vehicle. Therefore, we use $\tilde{x}_{k\neq j}$ as an instrument for x_j where k is in the same series, market, and year as j but does not have a DEF tank. The instrumental variable for trunk space we use equals x_j whenever $a_j = 0$, and when $a_j > 0$ it equals the average of x_k of other vehicles with $a_k = 0$ in the same series and market.

Table 4 reports the demand estimates. The logit specification in Column (1) implies that the willingness to pay for a 15-liter increase in the trunk space, or equivalently removing an average-sized DEF tank of 16 liters to release 3.5% of an average diesel vehicle's trunk space, is 284 euros.[32] The random coefficient logit specification in Column (2) shows that there is significant heterogeneity in the price and range coefficients but not in the trunk space or power coefficient. In an unreported specification, we include the DEF tank size in the vector of vehicle characteristics and find the coefficient to be statistically insignificant. This is consistent with our modeling choice that NO_x emissions are a pure externality.

5.2 Marginal Costs

Given our demand estimates, we proceed to estimate marginal costs. We back out marginal costs from the price elasticities assuming that firms compete on prices. Let Ω be the ownership matrix, where the element Ω_{jh} indicates whether product j and product h are sold by the same firm. Let $S(\boldsymbol{a}, \boldsymbol{p})$ be the shares matrix whose element S_{jh} is the partial derivative of the share of product h, s_h, with respect to the price of product j, p_h; that is, $S_{jh} = -\frac{\partial s_h(\boldsymbol{a},\boldsymbol{p})}{\partial p_j}$. Notice that the products' market shares depend on both the vector of DEF tank sizes $\boldsymbol{a}$ and the vector of prices $\boldsymbol{p}$. Then, the first-order condition of the firms' maximization problem entails that the vector of marginal costs is:

[32]To obtain this number, we compute: $1.50/1000 \times 15/2.78 \times 35091 = 284$ euros using the average GDP per capita of 35,091 euros.

Table 4: Demand Estimates

	(1) Logit		(2) Random Coef Logit	
	Param.	Std. Err.	Param.	Std. Err.
			Mean Valuations	
Retail Price/Per Capita GDP	-2.78	(0.09)	-3.44	(0.40)
Trunk space (cubic m)	1.50	(0.14)	1.56	(0.15)
Power (100 kW)	0.59	(0.05)	0.71	(0.11)
Engine Size (L)	0.18	(0.02)	0.20	(0.02)
Curb Weight (ton)	-1.50	(0.08)	-1.37	(0.10)
Footprint (sq m)	1.95	(0.04)	1.97	(0.04)
Fuel cost/Per Capita GDP	-33.33	(1.67)	-42.84	(2.97)
Foreign	-0.68	(0.02)	-0.67	(0.02)
Range (100 km)	0.12	(0.00)	0.05	(0.02)
			Standard Deviations	
Retail Price / Per Capita GDP			0.44	(0.12)
Trunk space			0.00	(0.00)
Power			0.00	(0.00)
Range			0.09	(0.00)
N	200,067		200,067	

Notes: All specifications include country-year trend, country FE, drive type FE, transmission FE, series-body FE, fuel FE, euro standards FE, and FE. We use 1000 MLHS draws. We instrument for both retail price and trunk space using cost shifters (number of vehicles on the same platform, number of vehicles in the same plant, and change in production platform), trunk IV, as well as BLP instruments constructed from power, engine size, range, curb weight, footprint, and fuel cost divided by per capita GDP. The logit standard errors are clustered on the series-body level. The random coefficient logit standard errors are those from optimal instruments.

$$\boldsymbol{mc} = \boldsymbol{p} + (\Omega * S(\boldsymbol{a}, \boldsymbol{p}))^{-1}\boldsymbol{s},$$

where $\boldsymbol{s}$ is the vector of products' market shares, and $*$ is the element-by-element matrix multiplication operator.

Table 5 reports the marginal cost estimates for diesel vehicles. Column (1) shows that the marginal cost of DEF tanks is 36 euros. Column (2) includes the fixed cost of DEF tanks, which is statistically insignificant. Column (3) estimates the average cost of the Selective Catalytic Reduction (SCR) technology to be 543 euros and the LNT technology 357 euros. These are roughly consistent with the engineering estimates in Sanchez et al. (2012) that SCR costs about 494 dollars (for large vehicles) and LNT about 320 dollars (for small vehicles). Columns (4)-(6) add interaction terms with the working group indicator to the previous

Table 5: Marginal Cost Estimates, in 2018 euros

	(1)	(2)	(3)	(4)	(5)	(6)
LNT	342.54**	307.61*	356.63**	401.48*	388.06*	404.98*
	(115.74)	(120.68)	(120.79)	(168.81)	(164.51)	(167.41)
DEF Size (L)	36.46***	62.91*		56.89**	76.99	
	(9.65)	(31.45)		(20.65)	(59.22)	
SCR		−469.48	542.85***		−315.23	786.83**
		(516.94)	(161.75)		(741.59)	(272.99)
LNT × Working Group				−83.47	−151.65	−80.59
				(242.70)	(263.07)	(254.89)
DEF Size × Working Group				−27.07	−1.86	
				(24.44)	(74.51)	
SCR × Working Group					−528.84	−358.06
					(1115.14)	(368.68)
Controls	X	X	X	X	X	X
Fixed Effects	X	X	X	X	X	X
N	87097	87097	87097	87097	87097	87097
Adjusted R^2	0.645	0.645	0.645	0.645	0.645	0.645

Notes: Diesel vehicles only. Control variables include engine size, horsepower, torque, wheelbase, footprint, height, fuel consumption, acceleration, curb weight, country-specific year trend, and unit labor cost. Fixed effects include series generation, registration country, transmission, drive type, body type, numbers of doors, number of gears, number of valves, fuel injection, engine platform, and producing plant. Standard errors clustered at the series generation level are in parentheses. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

three specifications. They show that the working group does not appear to experience different SCR/DEF costs from other firms. This implies that the alleged collusion does not seem to have brought the benefit of lowering technology costs for the working group more than the rest of the industry. We now turn to the benefits of the alleged collusion in collectively hiding noncompliance.

6 Bounds on Expected Noncompliance Penalty

In Section 2, we show that to rationalize collusion against environmental regulation, the expected penalty that a noncompliant firm faces depends necessarily on other firms' abatement actions. Proposition 1 shows that for the same noncompliant abatement action of a given firm, its expected penalty decreases as other firms also dial back abatement actions. We quantify such reductions by simulating automakers' variable profits at any abatement action profile with our estimated demand and supply.

In particular, we rearrange Inequality (6) from Section 2 as follows:

$$\underbrace{\mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^C})}_{\text{Reduction in Expected Noncompliance Penalty}} > \underbrace{\pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \pi_f(\boldsymbol{a^C})}_{\text{Simulated Reduction in Variable Profit}} + \mathbb{E}A_f(\boldsymbol{a^C}). \tag{12}$$

Thus, we hold fixed a working-group firm f's small DEF tank size a_f^C, and let other firms change from non-collusive sizes $\boldsymbol{a_{-f}^{NC}}$ to noncompliant sizes $\boldsymbol{a^C}$. This change reduces firm f's expected noncompliance penalty, because of the reduction in the investigation probability (e.g., due to yardstick competition) or the reduction in the noncompliance penalty (e.g., due to diffusion of responsibility). This reduction in firm f's expected noncompliance penalty is on the left of Inequality (12). At the same time, because the other firms' vehicles now boast larger trunk space and lower marginal cost, firm f will also experience a reduction in its variable profit. This reduction is part of the right-hand side of the inequality. The fact that firm f participated in the alleged collusion implies that the reduction in the expected noncompliance penalty must more than compensate for the reduction in the variable profit. In other words, the latter provides a lower bound on the reduction in the expected noncompliance penalty as other firms join in noncompliance. The lower bound is conservative, because it does not include the expected antitrust penalty $\mathbb{E}A_f(\boldsymbol{a^C}) \geq 0$.

We simulate the reduction in variable profits for each noncompliant working-group firm as other firms also reduce their DEF tank sizes and report the results in Table 6. We take the noncompliant collusive choices a_f^C as the observed DEF tank sizes, and the non-collusive choices a_f^{NC} as the DEF tank sizes consistent with 3% dosage. The latter assumption is valid as long as the environmental regulator can detect and punish the *sole* violator with a large enough probability or penalty *when all other firms comply.*[33] We assume that the enforcement of environmental regulation is effective enough to deter the sole violator in this "obvious" case, even with imperfect monitoring. In the unlikely case where enforcement was too weak, some firms might choose smaller-than-compliant DEF sizes even in the competitive profile $\boldsymbol{a_{-f}^{NC}}$, and our bound estimates in Table 6 would be biased upwards.

Table 6 shows that as more firms join in the collective shading, each working-group firm is able to reduce more expected noncompliance penalty. For example, suppose that BMW is considering adopting small DEF tanks (sizes observed in our data) while all other firms introduce compliant vehicles. Because

[33]Formally, under mild regularity conditions on the variable profit and expected noncompliance penalty functions, there is a competitive equilibrium in which all firms honestly comply, if and only if for every firm f:

$$-\frac{\partial \mathbb{E}K_f(a^*)}{\partial a_f} \geq -\frac{\partial \pi_f(a^*)}{\partial a_f}.$$

Table 6: Alleged Collusion Reduced Expected Noncompliance Penalties

If the following switch(es) from compliance to noncompliance	Expected noncompliance penalty for this firm would be reduced by at least (million euro)		
	BMW	Daimler	Volkswagen
BMW	-	9.30	42.37
Daimler	30.87	-	104.61
Volkswagen	81.35	62.81	-
Rest of Working Group	112.12	72.07	146.91
Rest of Industry	162.37	109.34	298.82

Notes: Noncompliance corresponds to choosing the observed DEF tank sizes, and compliance corresponds to choosing DEF tank sizes that achieve a 3% dosage. In million 2018 euros.

the DEF tanks stand out as being too small, BMW faces some expected noncompliance penalties. Now suppose that Daimler decides to adopt small tanks as well. Our simulation shows that Daimler's move toward noncompliance reduces BMW's expected noncompliance penalty by at least 30.87 million euros over our sample period of 2007-2018. When both Daimler and Volkswagen join BMW in adopting small tanks, BMW's expected noncompliance penalty is reduced by at least 112.12 million euros. In reality, the working group allegedly colluded on adopting small tanks, and the non-working-group firms apparently followed. This corresponds to the last row of Table 6, which shows that BMW's expected noncompliance penalty is reduced by at least 162 million euros from the counterfactual benchmark of BMW being the only adopter of small tanks. Comparing across the working-group firms, we find that the biggest "externality" of one firm's action in reducing another firm's expected noncompliance penalty occurs from Daimler to Volkswagen in the amount of at least 104.61 million euros. Finally, the last row implies that compared to unilateral shading, collective shading reduces the working group's expected noncompliance penalty by at least 560 million euros. This number represents the penalty in expectation. If the probability of detection is below 0.46 (see Section 7), then the ex-post penalty the working-group firms expected was at least 1.217 billion euros.

Why did non-working-group firms choose to suppress their DEF tank sizes as well? Our simulation shows that, conditional on the alleged collusion, the variable profits of non-working-group firms would drop by 677 million euros if they did not suppress DEF tank sizes. If their expected noncompliance penalties from noncompliance were at most this amount, then the non-working-group firms would be happy to follow along with shading. However, the non-working-group firms would wish that the working group had complied. We find that non-working-group firms would gain 27 million euros in variable profits by moving from the status quo to industry-wide compliance.

7 Welfare Effects of Collusion

In this section, we evaluate the welfare effects of the alleged collusion among the German automakers in response to the imperfectly enforced environmental regulation. The alleged collusion changed industry profits and buyer surplus, and caused health damages due to more air pollution. Industry profits changed due to the alleged collusion because different Diesel Exhaust Fluid (DEF) tank sizes led to different trunk space, different marginal production costs, and different prices. The buyer surplus changed because of different trunk space and prices. Health damages occurred because DEF tank sizes both directly changed the effectiveness of NO_x control measures in diesel vehicles and indirectly changed the sales quantity of those vehicles. Calculating the changes in the first two welfare components is standard in antitrust analysis. Yet, the third component—the health damages—is unique to our setting, but necessary when firm collusion creates health or environmental externalities (Barkley, 2020). In particular, even if firm collusion benefits both firms and consumers in the immediate market, the externality damages may be large enough to counteract the producer and buyer surpluses. As we have discussed in Section 2, fully accounting for those various welfare components informs the minimum amount of antitrust and noncompliance penalties required to repair damages to the society.[34]

7.1 Competitive Scenarios

To compute the welfare effects of the alleged collusion, we need to know what the competitive choices would have been. Figure 3 shows that working-group firms were releasing vehicles approved for Euro 6 even before the regulation became binding with DEF dosages comparable to what they would choose later. We interpret these early DEF dosage choices as the working group announcing their low compliance choices to the industry. The non-working-group firms then had the choice to follow the working group by adopting low dosages too. Thus, if the working group firms had not announced their choices, the industry may not have followed suit and may have rather chosen compliant dosages. Thus, under these circumstances, the alleged collusion did not only lead to smaller DEF tanks among the working group, but also led the rest of the industry to shade their pollution types, albeit to a lesser degree. Therefore, we take the competitive outcome to be full industry

[34]Section 2 derives the *expected* antitrust and noncompliance penalties to cover the "residual claim" that would make the regulatory environment collusion-proof in the sense of Che and Kim (2006). When the probability of detection and prosecution is less than one, the ex-post penalties will be larger than the expected, and hence the modifier "minimum" for those penalties.

compliance. As discussed in Section 6, full industry compliance is a competitive outcome if environmental regulation can detect and punish the sole violator with a large enough probability or penalty.

We consider three alternative scenarios for what a compliant DEF tank size and dosage should be. First, we assume 3% DEF dosage (or DEF tank size divided by the annual fuel consumption) with an annual mileage of 20,000km. This is the dosage we used in Sections 4 and 5 based on several engineering studies of full compliance with Euro 6 standards. Thus, the 3% dosage is our preferred compliance scenario. Second, in favor of automakers, we use a 2% dosage. This dosage is the lowest reference we found to achieve compliance for passenger vehicles. Third, we keep the 3% dosage but increase the annual mileage to 30,000km. The UK travel survey reported above shows that 9% of households travel more than 24,000 km. Assuming a higher annual mileage leads to a larger DEF tank size that should comfortably last a year regardless of the driving style. Additionally, we increase fuel consumption by 30%, as evidence shows that on-road fuel consumption for EU vehicles is much higher than official fuel consumption (Reynaert and Sallee, 2021).

To check the robustness of our welfare results to alternative assumptions on the competitive equilibrium, in Appendix Table A4 we report the welfare results under a more conservative view of what the alleged collusion had achieved relative to competition. Notice that despite observing the working-group firms' DEF tank sizes, non-working-group firms chose tanks competitively. As such, the achievement of the working group could have been simply to reduce DEF dosages just below what we observe for non-working-group firms. Thus, we operationalize this scenario computing counterfactual outcomes where we shift the distribution of working-group DEF dosages to have the same median as non-working-group firms. The welfare effects of the alleged collusion in this alternative scenario are within the range of effects in the three compliance scenarios.

7.2 Computation of Welfare Components

To compute welfare changes, we use the estimated demand and marginal costs from Section 5. For every counterfactual dosage and the implied DEF tank size of each diesel vehicle with a DEF tank approved under Euro 6 New European Driving Cycle (NEDC), we compute corresponding changes in marginal production costs and trunk space. Given these new marginal production costs and trunk space, we solve for a new Bertrand-Nash equilibrium in prices, from which we compute quantities, firm profits, and buyer surplus represented by the inclusive value of the choice sets.

We calculate the NO_x damages from an affected vehicle j registered in year t as follows:

$$\sum_{\tau=0}^{T} \delta^{\tau} \left[q_{jt} \underbrace{(e^{*} + (a_j^{*} - a_j) RemovalRate)}_{\text{On-road emission}} - q_{jt}^{*} e^{*} \right] \times AnnualMileage \times \phi \tag{13}$$

where T is the lifetime of a vehicle, δ is the discount factor, q_{jt} is sales quantity of vehicle j in year t, e^* is the compliant emission, a_j is the DEF tank size, q_{jt}^* and a_j^* are the counterfactual sales quantity and DEF tank sizes. $RemovalRate$ is the reduction in NO_x emissions per unit of DEF tank size per distance driven, $AnnualMileage$ is the annual mileage of the vehicle, and ϕ is the marginal damage of a unit of NO_x emissions. We formulate the on-road emissions as predicted values, because we do not observe the exact on-road emissions for each vehicle registered from 2007-2018.

We can further decompose the NO_x damages in Equation (13) into two effects: those from increased demand due to more attractive vehicles, and those from excess emissions beyond the emission limit:

$$\sum_{\tau=0}^{T} \delta^{\tau} \left[\underbrace{(q_{jt} - q_{jt}^{*}) e^{*}}_{\text{increased demand}} + \underbrace{q_{jt} (a_j^{*} - a_j) RemovalRate}_{\text{excess emission}} \right] \times AnnualMileage \times \phi$$

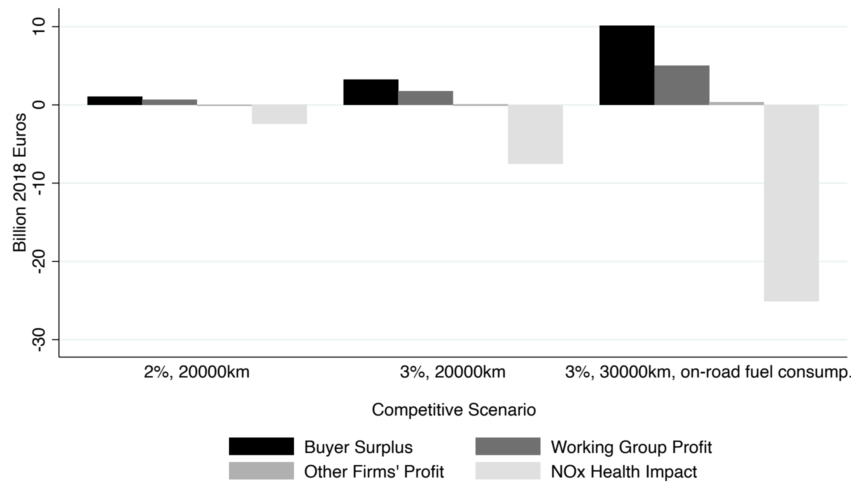
To parameterize the avoided damage formula, we take $\delta = 0.943$ which corresponds to a yearly discount rate of 6%, $T = 14$, $e^* = 80$ mg/km which is the Euro 6 emission limit, $AnnualMileage = 20,000$ km except for the third counterfactual scenario where we use $30,000$ km. We take the marginal damage estimate from Oldenkamp et al. (2016) at \$78 per kg of NO_x (in 2013 dollars), calculated from a disability adjusted cost of 20 life years per kton from the PM2.5 pathway induced by NO_x across the EU and a value of a statistical life (VSL) of \$7.6 million.[35] We emphasize that these are only the health damages from NO_x-induced PM 2.5, not including damages from NO_x-induced ozone, agricultural productivity loss, compromised visibility and recreation, and reduced absorption of carbon dioxide by affected biomass. We take a removal rate of 7.71 as estimated in Section 4.

7.3 Welfare Results

Figure 4 reports the welfare effects of the alleged collusion under the three scenarios of industry compliance. The figure shows that across compliance scenarios, car buyers benefited greatly from the alleged collusion

[35]This number is comparable to the current VSL recommended by the U.S. Environmental Protection Agency at 7.4 million in 2006 dollars.

Figure 4: Decomposing the Welfare Effects of the Alleged Collusion, 2007-2018



Notes: The calculations in the figure use an estimated NO_x removal rate of 7.71 mg/km/L from Section 4, a discount rate of 6%, a vehicle lifetime of 14 years, an annual mileage of 20,000 km, marginal health damages from NO_x-induced PM2.5 at $78 per kg of NO_x (in 2013 dollars). Monetary values are shown in 2018 Euros; dollars are inflated from 2013 to 2018 using the CPI (from 232.957 to 251.107) and converted to Euro using the 2018 exchange rate of 1 euro to 1.18 dollar.

because of the larger trunk space and because of lower prices. The working group firms also benefited because they sold more diesel vehicles than other firms, and also more powerful (and more polluting) ones. In addition, the profit impact on non-working-group firms was positive, but small. The profit impact of the alleged collusion on other firms is the result of two opposing forces. On the one hand, non-working-group firms were able to follow along with the working group in producing vehicles with small DEF tanks, which were more profitable than the compliant vehicles they would have had to produce but for the alleged collusion. On the other hand, the working group's vehicles with even smaller DEF tanks were able to steal consumers from the non-working-group firms. The figure shows that the two opposing forces almost offset each other. Yet, the positive sign may provide a reason for why the non-working-group did not report the noncompliance. Finally, the health damages of excess NO_x were substantial in all scenarios. About 95% of those damages came from excess emissions beyond the emission limit, and 5% from increased demand for more attractive vehicles.

In Appendix Table A3, we report the changes in market outcomes induced by the alleged collusion. In all scenarios, the alleged collusion enabled both the working group and other firms to charge higher prices on Euro 6 NEDC DEF-equipped vehicles and sell more such vehicles. The prices and quantities of other diesel and gasoline vehicles experienced only slight decreases. For example, compared with the competitive scenario of 3% dosage, the working group produced Euro 6 NEDC DEF-equipped vehicles featuring 8% larger trunk space, priced them 5% higher, and sold 6% more of them (we weigh the trunk space and price changes by sales quantity). Likewise, other firms produced 6% larger trunk space, with 4% higher prices and more sales. The prices and quantities of other vehicles by either group of firms were reduced by no more than 0.35%.

Table 7: Summarizing the Welfare Effects of the Alleged Collusion, 2007-2018

	Competitive Scenario		
	I	II	III
changes in billion euros	2% dosage 20,000km mileage	3% dosage 20,000km mileage	3% dosage, on-road fuel consump., 30,000km
A. Working Group's Profit	0.68	1.77	5.04
B. Residual Claim	-1.46	-4.28	-14.63
NO_x health impact	-2.43	-7.52	-25.07
Buyer surplus	1.08	3.26	10.12
Other firms' profit	-0.10	-0.03	0.32
Net Welfare $(A + B)$	-0.78	-2.51	-9.58
Ratio $\lambda = A/(-B)$	0.46	0.41	0.34

Notes: Competitive Scenario I - the industry achieve 2% dosage compliance. Competitive Scenario II - the industry achieves 3% dosage compliance. Competitive Scenario III - the industry achieves 3% dosage compliance under higher mileage and fuel consumption. We use an estimated NO_x removal rate of 7.71 mg/km/L from Section 4, a discount rate of 6%, a vehicle lifetime of 14 years, an annual mileage of 20,000 km for Scenarios I and II and 30,000 for Scenario III, marginal health damages from NO_x-induced PM2.5 at $78 per kg of NO_x (in 2013 dollars). Monetary values are shown in 2018 Euros; dollars are inflated from 2013 to 2018 using the CPI (from 232.957 to 251.107) and converted to Euro using the 2018 exchange rate of 1 euro to 1.18 dollar.

Table 7 takes a closer look at the welfare components and what they imply about the remedial antitrust and noncompliance penalties. The net welfare cost of the alleged collusion summed over 2007-2018 was 2.51 billion euros in our preferred specification (Scenario II), and ranges between 0.78 to 9.58 billion euros depending on what constitutes compliance. The NO_x damages overwhelmed the gains in firm profit and buyer surplus. Put differently, using the welfare framework we introduce at the end of Section 2, we find that the working group incurred a residual claim larger (in magnitude) than what the firms profited from the alleged collusion. An expected antitrust and noncompliance penalty of 4.28 billion euros (1.46 or 14.63 billion euros in Scenarios I and III, respectively) would be necessary to fully repair the harms of alleged collusion. This is the amount in expectation that would cover the residual claim and make the regulatory environment collusion-proof. The ex-post penalties, however, should be even higher to account for imperfect detection, or if penalties have a deterrent function as well as punitive. Therefore, if those penalties are to be implemented by mostly antitrust fines, they will rank among the highest antitrust fines that the EU has ever imposed.[36]

In the last row of Table 7, we compute the ratio λ of the working group's profit over the (negative of the) residual claim to be between 0.34 and 0.46. As discussed in Section 2, this ratio has two interpretations. First, the ratio is an upper bound on the probability that the working group would assign to being detected and prosecuted, should the ex-post penalties fully cover the residual claim. Second, this ratio is also a lower bound on the distance of the current regulatory environment from a collusion-proof policy.

8 Conclusion

We study the causes and welfare effects of firms colluding on abatement technologies in response to imperfectly monitored environmental regulation. We do so in the context of the alleged collusion among BMW, Daimler, and Volkswagen in restricting the effectiveness of their diesel NO_x control technologies since 2006. We build and estimate a structural model of vehicle demand and technology choices, in which there is a trade-off between unilateral and cooperative choices of compliance. We find that the payoff structure in our setting is in line with the alleged collusion being beneficial for the German automakers. By jointly choosing small tanks rather than going alone, the German automakers substantially reduced the expected noncompliance penalties.

Compared with various competitive scenarios, the alleged collusion is also beneficial for car buyers. However, those benefits to automakers and car buyers come at the cost of grave NO_x damages. Our findings are essential to interpret the consequences of the alleged collusion in light of imperfect regulatory enforcement. The EU resorts to antitrust infringements to seek ex-post reparations for noncompliance with environmental standards. The alleged collusion in this market did not reduce other market participants' profits or surplus, but damaged public health, an externality not usually considered in antitrust cases. Our welfare results imply that the combined antitrust and environmental penalties would have to reach between 1.46 billion and 14.63 billion euros to remedy the welfare damages of this alleged collusion.

[36]The top three antitrust fines that the EU has imposed are 4.34 billion euros in 2018, 2.43 billion euros in 2017, and 1.49 billion euros in 2019, all on Google.

References

Alé-Chilet, J. and Atal, J. P. (2020). Trade Associations and Collusion among Many Agents : Evidence from Physicians. *RAND Journal of Economics*, 51(4):1197–1221.

Alexander, D. and Schwandt, H. (2019). The impact of car pollution on infant and child health: Evidence from emissions cheating. IZA Discussion Paper No. 12427,.

Auriol, E. and Laffont, J.-J. (1992). Regulation by duopoly. *Journal of Economics & Management Strategy*, 1(3):507–533.

Bachmann, R., Ehrlich, G., Fan, Y., and Ruzic, D. (2019). Firms and Collective Reputation: a Study of the Volkswagen Emissions Scandal. *Working Paper*.

Barkley, A. (2020). The human cost of collusion: Health effects of a mexican insulin cartel. Technical report, Working Paper.

Baron, D. P. and Myerson, R. B. (1982). Regulating a monopolist with unknown costs. *Econometrica: Journal of the Econometric Society*, pages 911–930.

Bassetto, M. and Phelan, C. (2008). Tax Riots. *The Review of Economic Studies*, 75(3):649–669.

Berry, S., Levinsohn, J., and Pakes, A. (1995). Automobile Prices in Market Equilibrium. *Econometrica*, 63(4):841.

Blundell, W., Gowrisankaran, G., and Langer, A. (2020). Escalation of Scrutiny: The Gains from Dynamic Enforcement of Environmental Regulations. *American Economic Review*, 110(8):2558–85.

Bourreau, M., Sun, Y., and Verboven, F. (2019). Market Entry, Fighting Brands and Tacit Collusion: The Case of the French Mobile Telecommunications Market.

Che, Y.-K. and Kim, J. (2006). Robustly Collusion-Proof Implementation. *Econometrica*, 74(4):1063–1107.

Decker, C. S. and Pope, C. R. (2005). Adherence to environmental law: the strategic complementarities of compliance decisions. *The Quarterly Review of Economics and Finance*, 45(4-5):641–661.

Dijkstra, P. T., Haan, M. A., and Mulder, M. (2017). Industry structure and collusion with uniform yardstick competition: theory and experiments. *International Journal of Industrial Organization*, 50:1–33.

Dohmen, F. and Hawranek, D. (2017). The Cartel: Collusion Between Germany's Biggest Carmakers.

Duflo, E., Greenstone, M., Pande, R., and Ryan, N. (2018). The Value of Regulatory Discretion: Estimates From Environmental Inspections in India. *Econometrica*, 86(6):2123–2160.

European Commission (2019). Antitrust: Commission sends Statement of Objections to BMW, Daimler and VW for restricting competition on emission cleaning technology.

European Environment Agency (2015). Air Quality in Europe — 2015 Report. Technical report.

Ewing, J. (2018). *Faster, Higher, Farther: The Inside Story of the Volkswagen Scandal*. W. W. Norteon & Company, New York, NY.

Ewing, J. and Granville, K. (2019). VW, BMW and Daimler Hindered Clean-Air Technology, European Regulator Says.

Gross, D. P. (Forthcoming). Collusive Investments in Technological Compatibility: Lessons from U.S. Railroads in the Late 19th Century. *Management Science*.

Health Effects Institute (2017). State of Global Air 2017. Technical report, Boston, MA.

Holderbaum, B., Kind, M., Menne, C., Wittka, T., Gmbh, F. E. V., and Italia, F. E. V. (2015). Potential for Euro 6 Passenger Cars with SCR to meet RDE Requirements. In *Internationales Wiener Motorensymposium*.

Laffont, J.-J. and Martimort, D. (1997). Collusion Under Asymmetric Information. *Econometrica*, 65(4):875–911.

Laffont, J.-J. and Martimort, D. (2000). Mechanism Design with Collusion and Correlation. *Econometrica*, 68(2):309–342.

Laffont, J.-J. and Tirole, J. (1986). Using Cost Observation to Regulate Firms. *Journal of Political Economy*, 94(3):614–641.

Li, J. (2019). Compatibility and Investment in the U.S. Electric Vehicle Market.

Nocke, V. (2007). Collusion and dynamic (under-) investment in quality. *The RAND Journal of Economics*, 38(1):227–249.

Oldenkamp, R., Van Zelm, R., and Huijbregts, M. A. (2016). Valuing the human health damage caused by the fraud of Volkswagen. *Environmental Pollution*, 212:121–127.

Op De Beeck, J., Thompson, J., and Booth, N. (2013). Upcoming emission regulations for passenger cars: Impact on SCR system requirements and developments. *SAE Technical Papers*, 2.

Potters, J., Rockenbach, B., Sadrieh, A., and van Damme, E. (2004). Collusion under yardstick competition: an experimental study. *International Journal of Industrial Organization*, 22(7):1017–1038.

Reynaert, M. (2021). Abatement strategies and the cost of environmental regulation: Emission standards on the european car market. *The Review of Economic Studies*, 88(1):454–488.

Reynaert, M. and Sallee, J. M. (2021). Who benefits when firms game corrective policies? *American Economic Journal: Economic Policy*, 13(1):372–412.

Sala, R., Krasowski, J., Dzida, J., and Woodburn, J. (2018). Experiment of selective catalytic reduction retrofit for euro 6 NOx emission level compliance for euro 5 light duty vehicle. *IOP Conference Series: Materials Science and Engineering*, 421(4).

Sanchez, F. P., Bandivadekar, A., and German, J. (2012). Estimated cost of emission reduction technologies for LDVs. Technical report, The International Council on Clean Transportation.

Schleifer, A. (1985). A Theory of Yardstick Competition. *The RAND Journal of Economics*, 16(3):319 – 327.

Shapiro, C. (2001). Setting compatible standards: Coordination or collusion? In *Expanding the Bounds of Intellectual Property*, pages 81–101. Oxford University Press.

Sullivan, C. (2017). The Ice Cream Split: Empirically Distinguishing Price and Product Space Collusion.

Tangerås, T. P. (2002). Collusion-proof yardstick competition. *Journal of Public Economics*, 83(2):231–254.

Weitzman, M. L. (1974). Price vs. quantities. *Review of Economic Studies*, 41(4):477–491.

Yang, L., Franco, V., Campestrini, A., German, J., and Mock, P. (2015). NOX control technologies for Euro 6 diesel passenger cars: Market penetration and experimental performance assessment (white paper). Technical report, International Council on Clean Transportation.

Zou, E. (Forthcoming). Unwatched pollution: The effect of intermittent monitoring on air quality. *American Economic Review*.

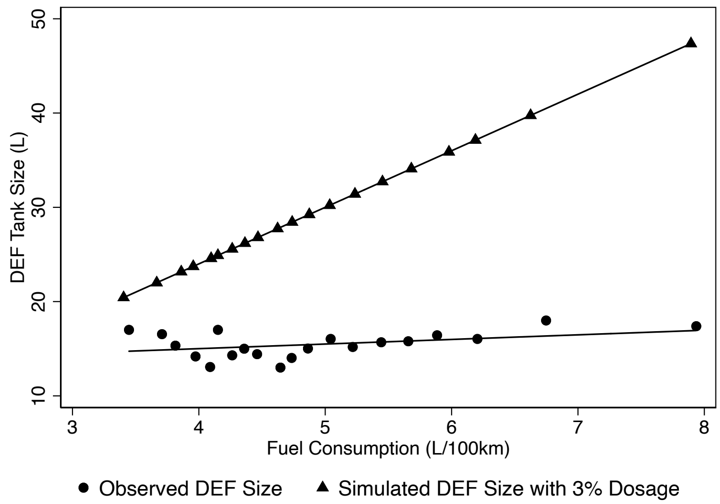
Appendix

Table A1: Summary Statistics of Selected Characteristics by NO_x Control Technology

	Basic (EGR only)	LNT	SCR
Retail Price (10,000 euro)	3.86	3.59	5.08
	(1.69)	(1.33)	(2.16)
Trunk Space (cubic m)	0.45	0.44	0.53
	(0.13)	(0.11)	(0.12)
Footprint (sq. m)	8.20	8.11	8.73
	(0.77)	(0.67)	(0.68)
Range (100 km)	11.27	12.66	12.57
	(1.88)	(1.80)	(2.21)
Curb Weight (ton)	1.56	1.48	1.70
	(0.26)	(0.20)	(0.28)
Fuel Cost (euro per 100 km)	7.64	5.76	6.55
	(2.01)	(1.27)	(1.76)
Power (kW)	113.12	109.99	136.43
	(36.62)	(35.84)	(45.16)
Engine Size (L)	2.06	1.86	2.18
	(0.51)	(0.37)	(0.55)
Foreign Share	0.87	0.87	0.83
	(0.34)	(0.34)	(0.38)
N	61396	19558	13160

Notes: This table shows the mean and standard deviation of vehicle characteristics by the different NO_x control technologies: Basic (Exhaust Gas Recirculation/EGR only), Lean NO_x Trap (LNT), and Selective Catalytic Reduction (SCR). Standard deviations in parenthesis. Each observation is a diesel vehicle - registration country - registration year. Not included are 1,788 vehicles equipped with both LNT and SCR.

Figure A1: Observed and Compliant DEF Tank Sizes and Fuel Consumption



Notes: Binned scatter plot based on all diesel SCR vehicles by both the working group and other firms approved for Euro 6. "Simulated DEF tank with 3% dosage" is derived by multiplying 3% with the fuel consumption for an annual mileage of 20,000km.

Table A2: DEF Tradeoff with Trunk Space and Weight

	(1) Trunk Space (L)	(2) Curb Weight (kg)
DEF Tank Size (L)	−0.91*	1.27*
	(0.45)	(0.62)
Control	X	X
Sample	SCR only	SCR only
N	1446	1446
Adjusted R^2	0.969	0.964

Notes: An observation is a diesel SCR vehicle. Controls for the trunk tradeoff include series body fixed effects, series generation start year, volume, drive type, and fuel tank size. Controls for the weight tradeoff include additionally engine size, power, and transmission type. Robust standard errors are in parentheses. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

Table A3: Changes in Market Outcomes by the Alleged Collusion, 2007-2018

	Competitive Scenario		
	I	II	III
changes in %	2% dosage 20,000km mileage	2% dosage 20,000km mileage	3%, on-road fuel consump., 30,000km
Quantity-Weighted Trunk	0.09	0.25	0.74
Working-group Euro 6 NEDC DEF	2.97	8.41	28.72
Non-working-group Euro 6 NEDC DEF	1.51	6.22	24.21
Quantity-Weighted Price	0.05	0.13	0.37
Working-group Euro 6 NEDC DEF	1.70	4.90	16.51
Non-working-group Euro 6 NEDC DEF	1.19	4.12	14.05
Working-group other diesel	-0.09	-0.26	-0.81
Non-working-group other diesel	-0.08	-0.25	-0.78
Working-group gasoline	-0.12	-0.34	-1.02
Non-working-group gasoline	-0.09	-0.27	-0.86
Quantity	0.04	0.12	0.37
Working-group Euro 6 NEDC DEF	2.18	6.10	20.14
Non-working-group Euro 6 NEDC DEF	0.84	3.93	15.78
Working-group other diesel	-0.05	-0.16	-0.47
Non-working-group other diesel	-0.04	-0.12	-0.37
Working-group gasoline	-0.08	-0.23	-0.67
Non-working-group gasoline	-0.04	-0.14	-0.45

Notes: Competitive Scenario I - the industry achieve 2% dosage compliance. Competitive Scenario II - the industry achieves 3% dosage compliance. Competitive Scenario III - the industry achieves 3% dosage compliance under higher mileage and fuel consumption. We use an estimated NO_x removal rate of 7.71 mg/km/L from Section 4, a discount rate of 6%, a vehicle lifetime of 14 years, an annual mileage of 20,000 km for Scenarios I and II and 30,000 for Scenario III. Sales are in 2018 euros.

Table A4: Welfare Effects and Market Changes under an Alternative Competitive Scenario, 2007-2018

Welfare Effects, billion 2018 euros	
A. Working Group's Profit	0.90
B. Residual Claim	-1.63
NO_x health impact	-2.32
Buyer surplus	1.01
Other firms' profit	-0.32
Net Welfare $A + B$	-0.73
Ratio $\lambda = A/(-B)$	0.55

Market Changes, %	Quantity-Weighted Trunk	Quantity-Weighted Price	Quantity
Working-group Euro 6 NEDC DEF	3.55	2.61	2.12
Non-working-group Euro 6 NEDC DEF	-0.14	-0.10	-0.15
Working-group other diesel		-0.08	-0.05
Non-working-group other diesel		-0.07	-0.03
Working-group gasoline		-0.11	-0.08
Non-working-group gasoline		-0.08	-0.04

Notes: In this table, we take the more conservative stance that the alleged collusion merely allowed the working group to adopt lower dosages than the rest of the industry. Thus, the competitive outcome could be the working group adopting DEF tanks of the same median size as the observed median size from other firms in the same series-generation start year. We use an estimated NO_x removal rate of 7.71 mg/km/L from Section 4, a discount rate of 6%, a vehicle lifetime of 14 years, an annual mileage of 20,000 km, marginal health damages from NO_x-induced PM2.5 at $78 per kg of NO_x (in 2013 dollars). Monetary values are shown in 2018 Euros; dollars are inflated from 2013 to 2018 using the CPI (from 232.957 to 251.107) and converted to Euro using the 2018 exchange rate of 1 euro to 1.18 dollar. Trunk space and price changes are weighted by sales quantity.