Colluding Against Environmental Regulation

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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 188–976 million euros. Antitrust and noncompliance penalties would reach between 1.46 and 7.37 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; Kang and Silveira, Forthcoming). Most studies on noncompliance assume that firms choose actions independently from competitors. In settings where the regulator has imperfect information to detect and punish noncompliance, theoretical studies by Laffont and Martimort (1997, 2000) and Che and Kim (2006) consider the possibility of agents colluding against the regulator. In practice, environmental regulators rarely consider the possibility of 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 the European Commission found no evidence that the automakers colluded on prices, coordination to limit technical development is illegal under EU antitrust legislation. The case involves a NO_x control technology called Selective Catalytic Reduction (SCR). Large diesel vehicles need SCR to comply with increasingly stringent EU emission standards. SCR requires an extra tank of Diesel Exhaust Fluid (DEF) to neutralize NO_x emissions. The three German automakers, henceforth the "working group," were found to have communicated extensively through meetings and emails to agree on a "coordinated approach" of reducing the DEF tank size in their vehicles and to guard against "an arms race with respect to DEF tank sizes" (Dohmen and Hawranek, 2017). The firms limited the refill frequency for the DEF tanks to coincide with the annual maintenance to reduce inconvenience for drivers. Given an annual refill, a smaller DEF tank means lower DEF consumption per mile driven, leading to more NO_x pollution.

We begin our analysis with a model that studies why firms participate in collusion against regulation.[1] Our principal, the regulator, sets a pollution standard and observes firms' emission abatement actions, such as the emission control technology. Firms choose their abatement actions either unilaterally or by following a collusive proposal. The regulator does not know firms' true emissions because of high monitoring costs. Therefore, 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.

When firms choose insufficient abatement, they trade off variable profits with expected penalties from violating the standards. A firm enjoys higher variable profits when it abates less, because pollution is an externality and abatement is costly. 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

[1] We focus on the participation constraint of the collusive arrangement rather than its dynamic enforcement.

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).[2] Second, collusion may lower the noncompliance penalties through the diffusion of responsibility. Penalties for an individual firm may be lower when multiple violators are caught. Third, by choosing noncompliance jointly, the collusive agreement gives all participants "skin in the game," which can lower the probability that a compliant 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.

Our empirical analysis of the alleged collusion uses data on vehicle registrations and characteristics from seven representative European markets from 2007 to 2018. The data contain detailed information on DEF tank sizes, emission control systems, and trunk space. We find that the working group chose 8% smaller DEF tank sizes than other firms. Furthermore, we document widespread noncompliance behavior in the whole industry from on-road emission test data. On average, diesel vehicles exceed the NO_x standard by a factor of three, and more than 70% of the tested diesel vehicles are noncompliant with the emission standards.

To probe the German automakers' incentives to collude, we estimate a structural model of vehicle demand and automaker costs that incorporates the costs and benefits of abatement through DEF tank size choices. Large DEF tanks reduce firms' profits because they take up trunk space, an attribute consumers value, and increase marginal production costs. Our demand estimates show that consumers would be willing to pay around 283 euros to increase trunk space by the volume of the average DEF tank.[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.

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

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

We use the estimated variable profit functions and the collusion participation constraints to 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 188–976 million euros for the working group compared to unilateral noncompliance.

Finally, we quantify the welfare effects of the alleged collusion using our estimated model of demand and supply. From a welfare perspective, the benefits of the alleged collusion come from increased industry profits and vehicle buyer surplus from larger trunk space and reduced marginal costs. These benefits come at the social cost of increased NO_x pollution. Increased pollution damages outweigh the gains in industry profits and vehicle buyer surplus. Across the scenarios we consider, the combined antitrust and noncompliance penalties should reach between 1.46–7.37 billion euros to repair the welfare damages of this alleged collusion fully. Combined with our finding that the working group gained 0.68–2.83 billion euros in variable profits from this alleged collusion, we infer that the existing regulatory regime achieved at most 39–46% of the total remedial penalties.

Our findings reveal that antitrust and regulatory authorities have complementary roles in the enforcement of regulation. By colluding, firms may reduce the risk that the regulatory authority uncovers a violation at the risk of incurring antitrust scrutiny. In our setting, national EU member states have the responsibility to enforce the emission standards. Following the Volkswagen Dieselgate scandal, it became apparent that member states failed their enforcement responsibility. The EU antitrust authority thus complements weak environmental enforcement in the EU. While in practice, the surplus of consumers and firms within the relevant market is the predominant base for antitrust fines, our welfare analysis shows that antitrust should assess damages from externalities to remedy the damages correctly.

The main contribution of this paper is to study firms' incentives to collude against regulation and 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 Alé-Chilet and Atal (2020), Gross (2020), Sullivan (2020), and Bourreau et al. (2021).[4] Relative to these papers, we introduce the aspect of collusion among firms against a regulator, 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. Regulation adds complexity to the analysis because the alleged collusion interacts with expected penalties of violating the regulation and affects both buyer surplus and the regulated externality. In contrast to coordination and standard-setting (Shapiro 2001, and Li 2019) where social welfare hinges on *whether* firms coordinate, we study a case where social welfare also depends on *which* outcome firms jointly choose.

This paper also contributes to the literature on the enforcement of environmental regulation. The liter-

[4] The semi-collusion literature has mainly focused on settings where firms collude in the product market (prices or quantities) and compete in other dimensions (e.g., capacities) because prices/quantities are easier to observe and adjust. Our case is the reverse; extensive investigation by the European Commission produced no evidence for price collusion. We conjecture that the automakers were wary of colluding on prices but allegedly chose to collude on technology because price-fixing is known to be illegal and frequently prosecuted, while collusion on technology choices has been less well-defined and rarely prosecuted.

ature has considered cases when the regulator faces either a single firm or a perfectly competitive industry, such as Duflo et al. (2018), Blundell et al. (2020), and Kang and Silveira (Forthcoming). These studies show that monitoring schemes and regulator discretion 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 Dieselgate scandal in the US: Alexander and Schwandt (2019) on the impact on health outcomes, Bachmann et al. (2019) on reputation spillovers among German automakers, and Ater and Yoseph (2020) on the impact on the second-hand automobile market. The alleged collusion we study predates the Volkswagen scandal. The EU commission uncovered the collusion on emission control systems following investigations related to the scandal.

We proceed as follows. In Section 2, we present a model of collusion on noncompliance with environmental regulation. Section 3 describes 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 describe our empirical strategy for estimating vehicle demand and marginal costs and for bounding the impact of collusion on expected noncompliance penalties. In Section 6, we present estimation results. Section 7 presents the welfare effects of the alleged collusion and calculates the combined antitrust and noncompliance penalties needed to remedy the welfare damages. We conclude in Section 8.

2 Model

We describe a model in which firms can collude on noncompliance with a regulation that aims to correct an externality.[5] This section aims to understand the incentives that firms can have to collude against the regulator and to construct useful inequalities to quantify these incentives.

2.1 Preliminaries

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 in the form of emissions.[6] Each firm has an exogenous type θ_f that measures its raw emissions before deploying emission control technology. Firms produce emissions according to their pollution types θ_f and abatement actions a_f:

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

Emissions are increasing in pollution types and decreasing in abatement actions.[7]

[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.

[7] Our model could be extended to more general specifications where the firm f's emissions are $e_f(\theta_f, a_f, x_f)$, where x_f is the vector of product characteristics, with the properties that $\frac{\partial e_f}{\partial \theta_f} > 0$ and $\frac{\partial e_f}{\partial a_f} < 0$.

Information. We assume that the regulator is at an information disadvantage relative to the industry. The regulator knows the distribution but not realizations of pollution types. In contrast, there is no information asymmetry among firms, and pollution types are 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 limit e^* that firms need to stay below before they can enter the market. However, firms can potentially misreport their emissions in the permitting phase to gain access to the market, and return to their true emissions $e_f > e^*$ afterward. 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 will risk penalties in later phases.

In the surveillance phase, the regulator considers abatement actions from all firms and can decide to inspect some firms more closely. We denote the probability of inspecting firm f given the abatement action profile $\boldsymbol{a}$ as $P_f(\boldsymbol{a}) \in [0, 1]$. The inspection outcome is a revelation of the true emission e_f. If the true emission 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 noncompliance penalties as $K_f = K_f(\boldsymbol{e}(\boldsymbol{a}), e^*) \geq 0$. Below, we explain how both the probability and the penalty of a firm can depend on other firms' abatement actions. We define firm f's expected noncompliance penalties, $\mathbb{E}K_f$, as the inspection probability times the net present value of noncompliance 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. 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, which differs from more commonly considered price collusion or market-sharing agreements. We denote the expected antitrust penalties as $\mathbb{E}A_f$, defined as the probability of antitrust investigation times the net present value of antitrust penalties.

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.

[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).

2.2 Firm Strategies

Timing. We describe the timing for the firms' decision process within the permitting phase, including the proposal of a joint action profile for multiple firms by an independent third party (Laffont and Martimort, 1997). We refer to that third party as 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]
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 $\boldsymbol{a^C}$ as all firms' action profile when firms in $\mathcal{F}^{WG}$ accept the proposal and firms in $\mathcal{F}^{NWG}$ choose abatement actions competitively. If 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 standards.[11] We also assume semi-collusion; firms may collude on abatement actions but not on prices. For expository convenience, in this section we assume that prices are fixed. In our empirical analysis, we allow for strategic Nash-Bertrand pricing responses to changes in product attributes and marginal costs due to abatement actions.[12]

After these numbered steps within the permitting phase, firms may be subjected to noncompliance penalties in the surveillance phase and to antitrust penalties in the antitrust phase. Firm f's expected payoffs are given by variable profits minus possible expected penalties, should the firm enter without complying with the standard or should the firm follow the working group proposal.

Variable profits. We define firm f's variable profit as:

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

[9] As explained below, the working group schedules regular meetings between engineers of the three German automakers. In other settings, trade associations have enabled firms to communicate and collude (Alé-Chilet and Atal, 2020).

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

[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.

where mc_f and q_f are the marginal cost and quantity of firm f. Abatement actions impact 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 variable profits. Second, abatement actions may increase the marginal cost of production. The partial derivative of variable profits with respect to a firm's own abatement action is:

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

The derivative is negative: the abatement action reduces the variable profit. Following the same intuition, the abatement action of a competing firm f' increases the firm's variable profit, $\frac{\partial \pi_f(\boldsymbol{a})}{\partial a_{f'}} > 0$, because the competing firm reduced a valuable attribute with its abatement action. Therefore, firms have no incentive to reduce emissions in the absence of a binding emission standard (i.e., when $e^* \geq \theta_f$). When there is a binding standard and firm f complies, it chooses $a_f = \theta_f - e^*$ because there are no gains from over-compliance. If firm f misreports emissions in the permitting phase, it can choose $a_f < \theta_f - e^*$. A noncompliance choice involves a trade-off between the increase in variable profits and the increase in expected noncompliance penalty. As we will show below, this trade-off changes when firms choose abatement actions jointly or unilaterally.

Expected noncompliance penalty. Whenever firms are not compliant with the emission standards, they risk penalties. The expected noncompliance penalty faced by firm f is:

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

The expected noncompliance penalty may depend on competitor choices for three reasons. First, the *probability of detection* of firm f's noncompliance can be smaller when other firms are also noncompliant. When pollution types are correlated across firms, the regulator might infer the sufficiency of one firm's abatement action by comparing it against other firms' abatement actions. This is similar to collusion under yardstick competition (Schleifer, 1985; Auriol and Laffont, 1992; Laffont and Martimort, 2000; Tangerås, 2002). Second, upon detection, a firm's noncompliance penalty may also be reduced by joint noncompliance relative to unilateral noncompliance. This is because *diffusion of responsibility* could reduce either individual fines or reputation damages when multiple firms are detected noncompliant. Third, when a firm violates the regulation by choosing a small abatement action, our variable profit function implies that the firm will steal market share from compliant firms. This creates a risk that honest competitors call out the noncompliance to the regulator to prevent business stealing. By jointly choosing noncompliance, firms have *skin in the game*: noncompliant firms competitors will not report to the environmental regulator. In Appendix A1 we

[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.

illustrate in a simple two-by-two game how each of the three mechanisms can create a setting where firms benefit from joint noncompliance. We also report suggestive evidence for the relevance of those mechanisms in our empirical context in Section 6.

In the remainder of this section, we show that the fact that firms collude on noncompliance necessarily implies that one firm's expected noncompliance penalty depends on the abatement actions of all firms. We will remain agnostic about which mechanism is at play in generating this dependence.

2.3 Benefits of Collusion

We discuss the benefits from collusion by comparing firm payoffs under joint and unilateral noncompliance. Because the abatement action profile $\boldsymbol{a^{NC}}$ is competitive, for each firm f and each alternative abatement action $a'_f \neq a_f^{NC}$ we have:

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

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, it must be that 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.

Finally, because this is collusion rather than coordination,[14] at least one of the participants should have the unilateral incentive to deviate from the collusive proposal, by increasing its abatement action. By doing so, the deviant may reduce its expected noncompliance penalty substantially so that the variable profit loss is bearable. To preclude this incentive, the working group must therefore design inter-temporal punishment schemes. Our empirical analysis does not investigate the dynamic enforcement of collusion.

In contrast to models of price/quantity collusion, deviation from the collusive proposal in our context leads to lower variable profits, while the deviation incentive comes from reduced penalties. Given the definition of

[14] In coordination games, an equilibrium where opponents choose the same actions exists without deviation incentives of the participants. In our empirical case, there is evidence that at least one firm tried to deviate from the collusive equilibrium by increasing abatement actions.

collusion, we now show that a collusive equilibrium can only occur if joint noncompliance 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 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. 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 $\mathbb{E}A_f(\boldsymbol{a^C}) \geq 0$. □

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 bounds on the expected noncompliance penalty that can be empirically obtained. 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 5 and report the bounds in Section 6.

Lastly, 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:

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

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, which we report in Section 6.

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).

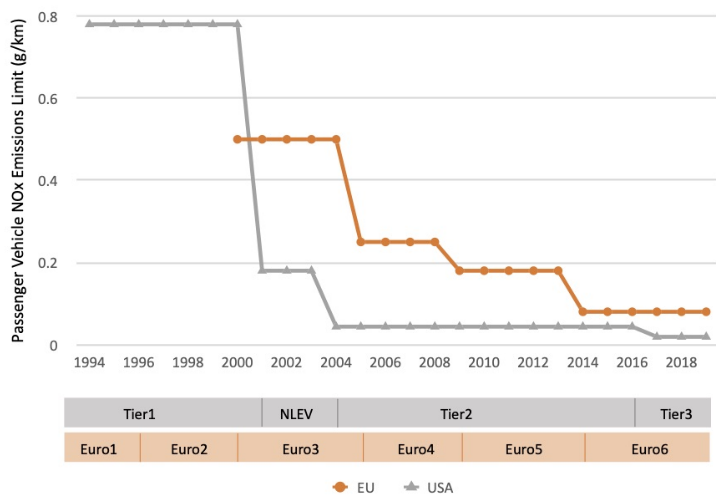
Since 2000, the EU has adopted increasingly more stringent NO_x emission standards for diesel vehicles. In the period of our analysis, the relevant regulations are Euro 5 (September 2009–August 2014) and Euro 6 (September 2014–). Figure 1 shows the NO_x emission standards over time in the EU and US. 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 September 2015 Volkswagen Dieselgate scandal. The new vehicle type approval happens under a Worldwide Harmonized Light Vehicle Test Procedure (WLTP) which partly accounts for Real Driving Emissions (RDE).[15] We end our study in 2018 when the large majority of vehicles registered were still approved under Euro 6 NEDC.

Following the Volkswagen scandal, it became clear that many diesel vehicles did not attain the Euro 6 emission standards on the road. Enforcement of the emission standards is the responsibility of member states. Strikingly, in contrast to Volkswagen in the US, none of the automakers faces explicit lawsuits for infringing the EU 6 standards in the EU. The laws describing the standards do not specify in sufficient detail the extent to which the use of defeat devices is forbidden. Instead, automakers face a series of ongoing lawsuits by consumer groups and shareholders for dishonesty. In contrast, the EU has legal authority to address collusion that restricts market competition.

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

Figure 1: Diesel Passenger Vehicle NO_x Emission Standards in the EU and US



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.[16] 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 technologies. The first technology is Lean NO_x Trap (LNT), which is mainly used in small vehicles because of its fuel penalty.[17] 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,[18] DEF tanks in passenger cars are typically designed to be refilled annually.[19] 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.[20] Second, it is technically

[16]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.

[17]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.

[18]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/`.

[19]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).

[20]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

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.[21]

It is difficult for a regulator to understand exactly how much DEF is needed to make a vehicle compliant with the Euro 6 standards. Automakers have several engine tuning options that interact with the combustion process to determine engine-out emissions. The exact amount of NO_x that needs to be removed by the SCR system is unknown to the regulator, and so is the exact efficacy of the DEF fluid in passenger vehicles. The amount of DEF is just one element in a very complicated process that results in tailpipe emissions.

3.3 The Antitrust Case

Since the 1990s, engineers of the leading German automakers have had regularly meetings to discuss technologies and engine specifications (Dohmen and Hawranek, 2017). The so-called "Circle of Five" working group 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 BMW, Daimler, Volkswagen, and all their subsidiary brands 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. 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 in 2014, 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". We interpret this statement as evidence for the existence of individual automakers' unilateral incentive to deviate from the agreement (absent inter-temporal punishment schemes), a defining feature of collusion. 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,

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."

[21] 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`).

while the other manufacturers' cars supposedly managed with significantly less [DEF]". Apparently, the "arms race" with regard to tank sizes did not happen and firms sold vehicles with small DEF tanks that are supposedly compliant with the Euro 6 NEDC standards between 2014 and 2018.

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. The investigation followed the September 2015 Volkswagen scandal that led to increased scrutiny of emission technology choices of EU automakers. 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 roll-out 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)[22] from 2007 to 2018. This sample 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.[23] 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.

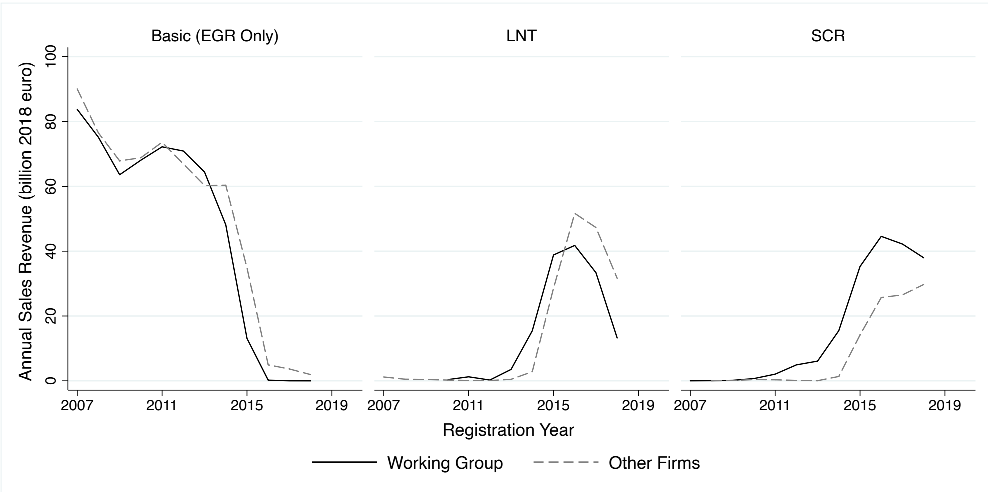
[22]These markets represent about 90% of the European market.

[23]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.

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.[24] 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.

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.

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. Before Euro 6 emission standards started in September 2014, SCR was not needed for compliance with Euro 5, yet the working group started collecting substantial sales revenue from SCR sales. After Euro 6 kicked off, virtually all new diesel vehicles were equipped with SCR or LNT. The working group's SCR revenue kept overshadowing the rest of the industry. The 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 and moved earlier in releasing SCR vehicles under Euro 6 relative to firms outside the working group. The SCR system

[24]The firms own multiple brands. BMW owns BMW, MINI, and Rolls-Royce; Daimler owns Maybach, Mercedes, and Smart; and Volkswagen owns Audi, Bentley, Cupra, Lamborghini, Porsche, SEAT, Skoda, and VW.

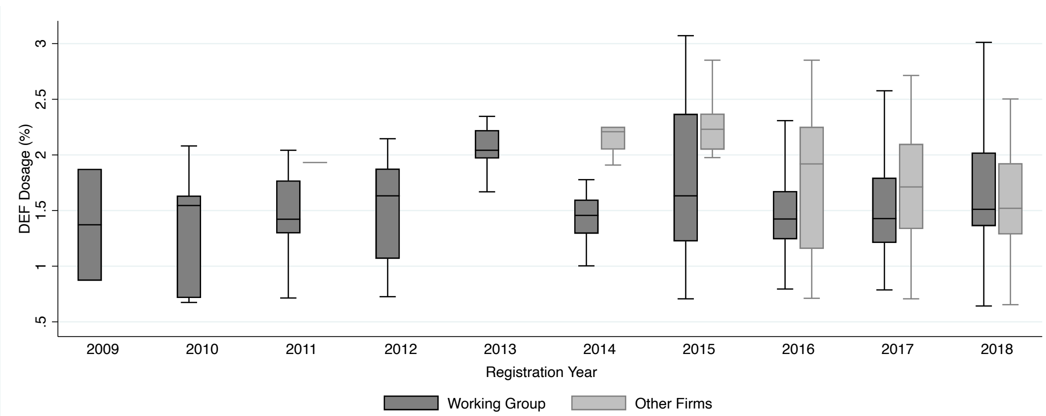
works by adding a dose of DEF to decompose engine-out NO_x emissions into harmless nitrogen and water.

To measure SCR effectiveness, we introduce the notion of a dosage. The dosage is the percent of DEF added to each liter of diesel the engine consumes. The dosage is a common measure of SCR effectiveness in the engineering literature. To calculate the dosage, we use information on 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. 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.[25]

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



Notes: Box plot based on all diesel SCR vehicles approved for Euro 6, including both New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicle 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 were roughly between 1% and 2%. Until 2018, the interquartile ranges of their dosages were consistently

[25]The UK travel survey reports that diesels travel 17,200km per year 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`).

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 (2–4) 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 between the Working Group and the other firms towards 2018 in Figure 3. Controlling for a full set of emission-related vehicle characteristics, Column (3) 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 are the implications of the automakers' DEF choices 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:

$$e_j = \theta_j - RemovalRate \times a_j + \epsilon_j \tag{8}$$

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 (8) 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 use this estimated relationship to calculate the DEF sizes needed to achieve compliance, by replacing the left-hand side of Equation (8) with the Euro 6 emission limit of 80 mg/km. After converting those compliant DEF sizes to dosages, we find that the average compliant dosage for NEDC vehicles in our RDE dataset would be 2.7%. This average compliant dosage is much higher than the average observed dosage of 1.67% reported in the top panel of Table 3. In fact, it exceeds the 75th percentile of observed dosages. Correspondingly, the RDE test results show that those vehicles emitted on average three times the NO_x emission limit on the road, and almost three-quarters of the tested models emit more than the emission limit. Engineering studies that discuss the potential of SCR to comply with Euro 6 corroborate our compliance calculations. 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%.[26] Similarly, Op De Beeck et al. (2013) report a compliant dosage of 3%, and Sala et al. (2018) report 3–5%.

Based on this evidence, we adopt three compliance scenarios in our analysis. The first compliance scenario uses a 2% dosage, in favor of automakers. In the second scenario, we use a 3% dosage. The third scenario,

[26]The study tested vehicles with fuel consumption of 6.8 liters/100km and reports urea usage of 2 to 2.5 liters/1000km to obtain compliance.

which we call "3% dosage plus", keeps the 3% dosage but increases the fuel consumption by 30%. This choice stems from research showing that on-road fuel consumption for EU vehicles is higher than official fuel consumption (Reynaert and Sallee, 2021).[27]

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

	Mean	St.Dev.	Min	25th Per.	75th Per.	Max	% Noncompliant
Real Driving Emissions Dataset							
Observed DEF tank size (L)	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	73.8
Main Dataset							
Observed DEF tank size (L)	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	
Compliant DEF tank size (L)							
2% dosage	19.60	4.46	11.92	16.45	22.19	39.40	66.1
3% dosage	29.40	6.69	17.89	24.68	33.28	59.09	99.1
3% dosage plus	38.22	8.70	23.25	32.08	43.27	76.82	100

Notes: Implied dosage is derived by dividing the observed DEF tank size by the fuel consumption for an annual mileage of 20,000km. Compliant DEF tank sizes under "2% dosage" and "3% dosage" are derived by multiplying fuel consumption for 20,000km with the respective dosage, and those under "3% dosage plus" are derived by multiplying real-driving fuel consumption (30% above official fuel consumption, see Reynaert and Sallee (2021)) with 3%. 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 Real Driving Emissions dataset has 84 such vehicles and our main dataset has 791.

We now apply our compliant dosages to our main dataset, which covers the universe of NEDC SCR models available in the seven representative European markets. Comparing the actual choices of DEF tank sizes with our computed compliant sizes confirms the widespread noncompliance problem involving not only the working group. The lower 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%. Given an annual mileage of 20,000 km and a dosage of 3%, tank sizes would need to increase from an average of 16 liters to an average of between 19.6 and 38.2 liters, depending on the compliance scenarios.[28] Between 66.1% and 100% models have insufficient DEF tank sizes. The working group's own argument for preferring small DEF tanks, as described in Section 3, 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 a one-liter increase in the DEF tank size reduces the trunk space by 0.91 liters and increases the curb weight by 1.27 kg. These estimates imply that 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.[29]

The widespread noncompliance, when combined with the early move of the working group in adopting

[27] We do not use the estimates in Table 2 to derive the compliant DEF size *for each vehicle* because of the relatively low R squared.

[28] 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.

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

low dosages, suggests that the working group could have set the implicit standard for the rest of the industry to follow.

5 Estimation

We begin this section with a demand model to estimate consumer preferences and substitution patterns. We show how abatement choices can affect vehicle marginal costs and describe how to bound the expected penalties of noncompliant firms. These bounds allow us to quantify the reduction in the expected penalties by the alleged collusion. Finally, we discuss assumptions on non-collusive equilibria needed to calculate expected penalties and welfare.

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.

We define the mean utility δ_j as:

$$\delta_j = \alpha p_j + x_j(a_j)\beta + \xi_j,$$

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 series. Unobserved vehicle-specific attributes and demand shocks are represented by ξ_j. We do not include abatement choice a_j, measured as the size of the DEF tank, explicitly in the demand. Nevertheless, vehicle characteristics x_j depend on abatement because larger DEF tanks take up trunk space, an attribute consumers likely consider when choosing a vehicle. The DEF tank size and the resulting NO_x are assumed to be an externality for consumers. Consumers are uninformed about the DEF tank size and NO_x because these attributes are not listed in owner's manuals or displayed in dealerships. Additionally, as discussed in Section 2, the refill of the DEF tank is typically designed to be annual regardless of the DEF tank size.

The individual deviation from the mean utility is:

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

where ν_{ip}, ν_{ik} are standard normal draws. We expect DEF tanks to implicitly affect the individual-specific utility. Some consumers will likely care more about trunk space (e.g. families or golfers) and DEF tanks reduce an attribute these consumers particularly care about. 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:

$$s_j = \int \frac{exp(\delta_j + \mu_{ij})}{\sum_{j'} exp(\delta_{j'} + \mu_{ij'})} \mathrm{d}\nu_i. \tag{9}$$

The parameters from the demand model to be estimated are $\theta = (\alpha, \beta, \sigma)$.

As is standard in the literature, we allow for correlation between prices and the product unobservable ξ_j. Additionally, we allow for the potential correlation of trunk space and ξ_j, through the strategic abatement choice of the DEF tanks. 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 in 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 production lines, assuming that production line changes affect costs. Third, we instrument for trunk space using *gross* trunk space: In the data, we observe the *net* trunk space $x_j = \tilde{x}_j - f(a_j)$ where $f(a_j)$ is the unobserved encroachment into the trunk by the DEF tank.[30] We assume gross trunk space $\tilde{x_j}$, i.e., the trunk space before the DEF tank choice, to be mean-independent of the demand unobservable: $E[\tilde{x}_j|\xi_j] = 0$. Automakers fix physical dimensions for vehicles two to four years before the series generation launches. Hence, by the time of a vehicle sale and demand shocks realization, the automaker is unable to adjust the gross trunk space. Notice that 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.

We estimate the market share system with a general method of moments estimator. For every parameter guess, we invert the market system using a contraction mapping to obtain $\xi(\theta)$. Define Z to be the matrix

[30] We do observe the DEF tank sizes but not the amount by which DEF tanks reduce trunk space because the DEF tanks are partly fitted into idle space next to the fuel tank.

of instruments and A a weighting matrix. We estimate θ by:

$$min_\theta \, \xi(\theta)' Z A Z' \xi(\theta).$$

5.2 Marginal Costs

Firms earn variable profits as described in Section 2.2, with quantity q equal to market shares multiplied by total market size. We assume Nash Bertrand competition in prices and back out marginal costs from the first-order conditions of variable profit. 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 a 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:

$$\boldsymbol{mc} = \boldsymbol{p} + (\Omega \odot S(\boldsymbol{a}, \boldsymbol{p}))^{-1} \boldsymbol{s}, \tag{10}$$

where $\boldsymbol{s}$ is the vector of products' market shares, and $\odot$ is the element-by-element matrix multiplication operator. We then regress these marginal costs on product attributes and membership of the working group to estimate the implications of abatement choices and the alleged collusion on marginal costs:

$$mc_j = \eta_x x_j + \eta_a a_j + \eta_{wg} a_j I(F_j \in \mathcal{F}^{WG}) + \omega_j,$$

where $I(F_j \in \mathcal{F}^{WG})$ is an indicator equal to one whenever a product is in the product set F_j of a collusive firm, and zero otherwise, and ω_j is a marginal cost unobservable. If collusive firms achieved cost savings relative to other firms, we would expect the parameter η_{wg} to be negative. We estimate marginal costs with a rich set of fixed effects to control for the potential endogeneity of the DEF tank size.

5.3 Bounds on Expected Penalties

Proposition 1 shows how incentives to participate in collusion must come from the reduction in expected penalties. We can estimate a bound on this reduction by simulating automakers' variable profits at different abatement action profiles. We obtain this bound in three steps.

First, we derive a lower bound on the expected noncompliance penalty faced by each working-group firm if it chooses noncompliance alone. Rearranging Inequality (5), we have:

$$\mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) \geq \pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \pi_f(\boldsymbol{a^{NC}}) + \mathbb{E}K_f(\boldsymbol{a^{NC}}), \tag{11}$$

which indicates that the expected penalty of unilateral noncompliance must more than offset the associated variable profit gain, plus any applicable penalty at the competitive profile. This is because the noncompliant action a_f^C is not a best response to $\boldsymbol{a_{-f}^{NC}}$. A conservative lower bound on the expected noncompliance penalty of unilateral noncompliance is simply $\pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \pi_f(\boldsymbol{a^{NC}})$, because $\mathbb{E}K_f(\boldsymbol{a^{NC}}) \geq 0$.

Second, we obtain an upper bound on the expected noncompliance and antitrust penalties faced by each working-group firm from the participation constraint in Inequality (4):

$$\mathbb{E}K_f(\boldsymbol{a^C}) + \mathbb{E}A_f(\boldsymbol{a^C}) < \pi_f(\boldsymbol{a^C}) - \pi_f(\boldsymbol{a^{NC}}) + \mathbb{E}K_f(\boldsymbol{a^{NC}}). \tag{12}$$

That is, the expected noncompliance and antitrust penalties of joint noncompliance must be smaller than the variable profit gain from the alleged collusion, plus any applicable penalty at the competitive profile.

Third, we combine the lower and upper bounds from above to obtain:

$$\underbrace{\mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^C}) - \mathbb{E}A_f(\boldsymbol{a^C})}_{\text{Reduction in Expected Penalties}} > \underbrace{\pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \pi_f(\boldsymbol{a^C})}_{\text{Reduction in Variable Profit}}, \tag{13}$$

which provides a lower bound on the *reduction* in the expected penalties from joint noncompliance relative to unilateral noncompliance. We make three observations. First, unlike the lower bound in Inequality (11) and the upper bound in Inequality (12), this combined lower bound on the reduction in expected penalties does not depend on $\mathbb{E}K_f(\boldsymbol{a^{NC}})$, which cancels out. Second, this inequality can also be derived directly from Inequality (6) in Section 2. Finally, the right hand side of this inequality provides a conservative bound on the reduction in the expected *noncompliance* (with environmental regulation) penalties $\mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^C})$, because $\mathbb{E}A_f(\boldsymbol{a^C}) \geq 0$.

5.4 Non-Collusive Equilibria

To quantify the bounds on expected penalties characterized by Inequalities (11)–(13), we need to estimate variable profits $\pi_f(\boldsymbol{a^C})$, $\pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$, and $\pi_f(\boldsymbol{a^{NC}})$ for each working-group firm f. We estimate the first profit from observed quantities and Nash-Bertrand markups defined in Equation (10). To estimate the other two profit levels, we need to know what tank sizes would have been chosen in a competitive equilibrium, which is not observed in the data. Using the competitive DEF tank choices from non-working-group firms to inform identification (using a first-order condition approach, for example) would require strong functional form assumptions on the expected noncompliance penalties.[31] Instead, we assume that the competitive equilibrium is compliant, and we present our bound estimates in the three compliant scenarios defined in Section 4: 2% dosage, 3% dosage, and 3% dosage with real-world fuel consumption. These scenarios provide a wide interpretation of the definition of compliance, with average DEF tank sizes ranging from 19 to 38 liter and average increases of 3 to 22 liters. Therefore, we think that the scope for noncompliant equilibria of economic relevance outside of the range of the scenarios we consider is small.

[31] Noncompliance penalties may be discontinuous as firms and their competitors move in and out of compliance, which presents difficulties for the first-order condition approach and assumptions about continuity of noncompliance penalties with respect to DEF tank sizes.

We also find suggestive evidence for our assumption that compliance is a competitive equilibrium in Figure 3. Working-group firms released vehicles approved for Euro 6 even before the regulation became binding in 2016. The early DEF dosages are comparable to what firms chose in 2016–2018. We see these early DEF dosage choices of the working group as a signal of their low compliance choices to the industry. When Euro 6 standards started to bind, the non-working-group firms had the choice to follow the working group or to deviate. As discussed in 6.5, the fact that the non-working-group chose to follow into noncompliance implies that doing so must be more profitable than compliance. In this way, 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. With this interpretation, it is likely the industry would have moved into compliance in the absence of the alleged collusion.[32]

6 Estimation Results

In this section, we first present our demand and marginal costs estimates. Next, we analyze the incentives of the working group to participate in the collusive scheme. To do so, we compute bounds on the reduction of expected noncompliance penalties achieved by the working group, and present evidence for several mechanisms behind the reduction. Finally, we describe how the collusive scheme affects the compliance choices of firms outside the working group.

6.1 Demand Estimates

Table 4 reports the demand estimates. A comparison of the logit OLS results in Column (1) with the logit IV results in Column (2) shows that the instrumental variables substantially change the price coefficient and only slightly change the trunk space coefficient. The logit specification in Column (2) implies that the willingness to pay for a 15-liter increase in the trunk space, or equivalently removing an average-sized DEF tank, is 283 euros.[33] The random coefficient logit specification in Column (3) shows significant heterogeneity in the price and range coefficients but not in the trunk space or power coefficient. We use the random coefficient logit model from Column (3) in all the subsequent estimates.

6.2 Marginal Cost Estimates

We report in Table 5 the marginal cost estimates for diesel vehicles. Column (1) estimates that the Selective Catalytic Reduction (SCR) technology costs 543 euros and the LNT technology costs 357 euros. These estimates are roughly consistent with the engineering estimates in Sanchez et al. (2012), who report SCR to

[32] In the Appendix, we also report results under a more conservative view of what the alleged collusion achieved relative to competition. Instead of assuming that the alleged collusion induced non-working-group firms to go into noncompliance, we assume that they would have chosen noncompliance absent the alleged collusion. Under this assumption, we compute the competitive choice of working-group firms by shifting the distribution of working-group DEF dosages to have the same median as non-working-group firms. The results are very close to the 2% dosage scenario.

[33] To obtain this number, we compute: $1.50/1000 \times 15/2.79 \times 35091 = 283$ euros using the average GDP per capita of 35,091 euros.

Table 4: Demand Estimates

	(1) Logit OLS		(2) Logit IV		(3) Random Coeff Logit	
	Param.	St. Err.	Param.	St. Err.	Param.	St. Err.
					Mean Valuations	
Retail Price/Per Capita GDP	-0.23	(0.04)	-2.79	(0.10)	-3.44	(0.40)
Trunk Space (cubic m)	1.25	(0.55)	1.50	(0.14)	1.56	(0.15)
Power (100kw)	-0.53	(0.10)	0.60	(0.05)	0.71	(0.11)
Engine Size (L)	0.08	(0.05)	0.19	(0.02)	0.20	(0.02)
Curb Weight (ton)	-1.81	(0.26)	-1.50	(0.08)	-1.37	(0.10)
Footprint (sq m)	1.73	(0.16)	1.95	(0.04)	1.97	(0.04)
Fuel Cost/Per Capita GDP	-65.19	(3.26)	-33.33	(1.67)	-42.84	(2.97)
Foreign	-0.89	(0.05)	-0.68	(0.02)	-0.67	(0.02)
Range (100 km)	0.07	(0.02)	0.12	(0.01)	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	200088		200067		200067	

Notes: All specifications include country-year trend, country-fuel type FE, drive type FE, transmission FE, series-body FE, Euro emissions standards FE, and market duration FE. In Columns (2)-(3), 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 discussed in Section 5, as well as BLP instruments constructed from power, engine size, range, curb weight, footprint, and fuel cost divided by per capita GDP. Column (3) uses 1000 Modified Latin Hypercube Sampling (MLHS) draws. The logit standard errors are clustered on the series-body level. The random coefficient logit is estimated by optimal two-step GMM.

cost 494 dollars (for large vehicles) and LNT to cost 320 dollars (for small vehicles). To estimate how the marginal cost of a vehicle increases with every liter of the DEF tank size, Column (2) shows that DEF tanks are on average 36 euros per liter. We use this estimate in our counterfactual analysis when we change DEF tank sizes. Columns (3)-(4) add interaction terms with the working group indicator to the previous two specifications. All the interaction terms have statistically imprecise parameters. This means the working group did not appear to achieve cost savings from the alleged collusion differently from non-working-group firms.

6.3 Estimates of Bounds on Expected Penalties

To estimate the bounds on the expected penalties, we simulate the variable profits at appropriate DEF tank size choices according to Inequalities (11)–(13). We take the 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 the three compliance scenarios discussed in Section 5.4: 2% dosage, 3% dosage, and 3% dosage with 30% higher fuel consumption. For each scenario, we recompute marginal costs and trunk space as a function of the DEF tank size choices, and find new equilibrium prices and quantities.

Table 6 reports the lower bound on the expected noncompliance penalty under unilateral noncompliance,

Table 5: Marginal Cost Estimates (2018 euros)

	(1)	(2)	(3)	(4)
LNT	356.63**	342.54**	404.98*	401.48*
	(120.79)	(115.74)	(167.41)	(168.81)
SCR	542.85***		786.83**	
	(161.75)		(272.99)	
DEF Size (L)		36.46***		56.89**
		(9.65)		(20.65)
LNT × Working Group			−80.59	−83.47
			(254.89)	(242.70)
SCR × Working Group			−358.06	
			(368.68)	
DEF Size × Working Group				−27.07
				(24.44)
Controls	X	X	X	X
Fixed Effects	X	X	X	X
N	87097	87097	87097	87097
Adjusted R^2	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. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

the upper bound on the expected noncompliance and antitrust penalties under joint noncompliance, and their difference, under the three compliance scenarios. Compared to unilateral noncompliance, joint noncompliance reduces the expected penalties by at least 54–272 million euros for BMW, 38–177 million euros for Daimler, and 96–528 million euros for Volkswagen. Taken together, the alleged collusion brings down the expected penalties faced by the working group by at least 188 to 976 million euros across the three scenarios. These numbers represent the penalties in expectation. If the probability of detection is below 0.46 (see Section 7), then the ex-post penalties that the working group counted on the alleged collusion to reduce would be at least 409 million to 2.12 billion euros, depending on the compliance scenario.

6.4 Evidence for Mechanisms that Reduce Expected Penalties

The previous subsection showed that joint noncompliance reduced the expected penalties of the working group substantially. This subsection provides quantitative evidence for the three mechanisms put forward in Section 2 that could explain this reduction: reduction in the detection probability, diffusion of responsibility, and skin in the game.[34]

First, we show that each working-group firm's DEF tank sizes would have stood out had it been the sole violator. Joint noncompliance, therefore, can reduce the probability of each working-group firm being

[34] We are not able to separately identify the importance of each mechanism empirically. Also, we illustrate those mechanisms with a stylized game in Appendix A1.

Table 6: Bounds on the Expected Penalties (million 2018 euros)

	Unilateral Noncompliance	Joint Noncompliance	Reduction by Alleged Collusion
	Lower bound on $EK_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$	Upper bound on $EK_f(\boldsymbol{a^C}) + EA_f(\boldsymbol{a^C})$	Lower bound on the difference
		I. 2% dosage	
BMW	83	28	54
Daimler	179	141	38
Volkswagen	602	506	96
Working Group Total	864	675	188
		II. 3% dosage	
BMW	194	31	162
Daimler	521	412	109
Volkswagen	1629	1330	299
Working Group Total	2344	1774	571
		III. 3% dosage plus	
BMW	305	33	272
Daimler	974	798	177
Volkswagen	2532	2004	528
Working Group Total	3811	2835	976

Notes: Noncompliance corresponds to choosing the observed DEF tank sizes, and compliance corresponds to choosing DEF tank sizes that achieve I. 2% dosage, II. 3% dosage, and III. 3% dosage with 30% higher fuel consumption.

detected noncompliant by the environmental regulator. Figure 4(a) shows the distribution of DEF tank sizes as observed under the allegedly collusive scheme. Figure 4(b) plots the observed DEF tank sizes of each working-group firm against the 3% compliant distribution for the rest of the industry. These plots suggest that vehicles released by BMW, Daimler, and Volkswagen would likely look suspicious relative to a compliant rest-of-industry. The working group, therefore, potentially benefited from reduced scrutiny by moving into noncompliance jointly.

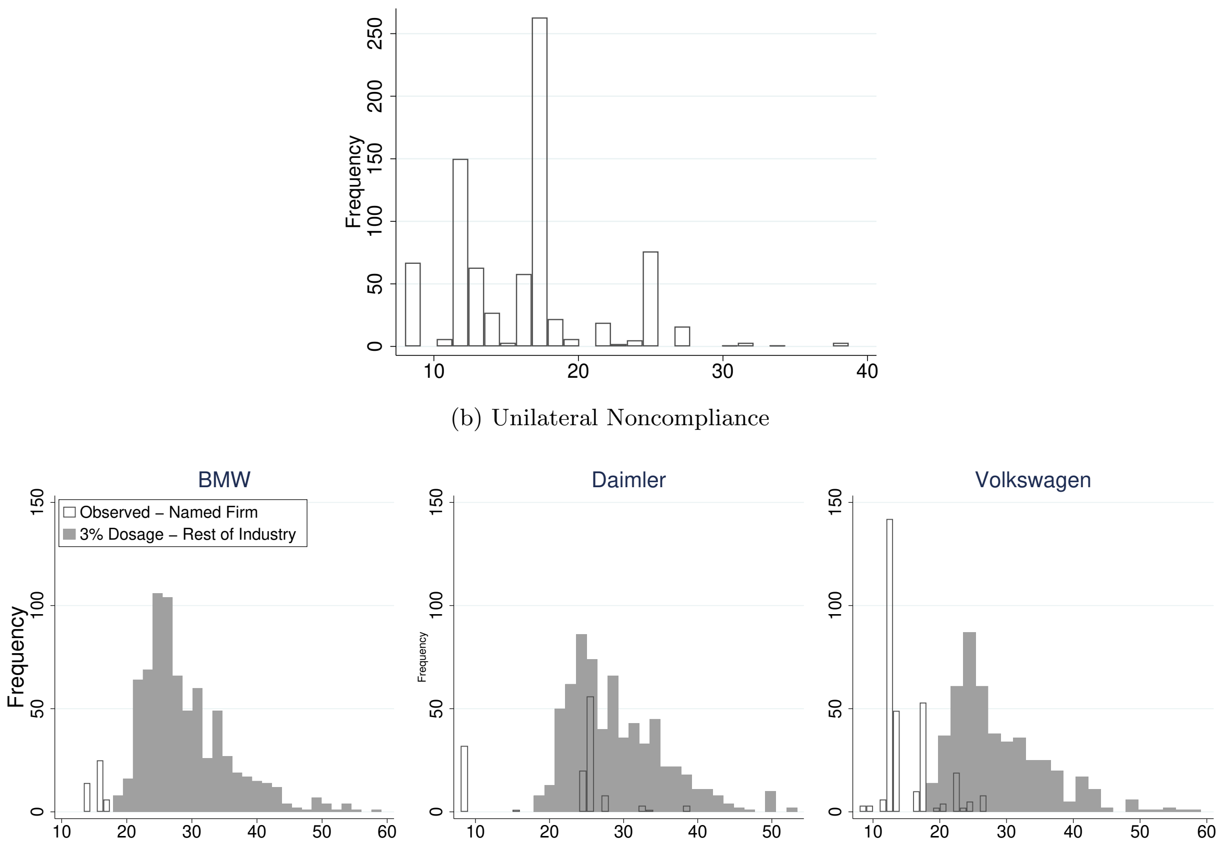
Next, we examine the diffusion of responsibility mechanism by quantifying the degree to which noncompliance penalties could diffuse when multiple violators are caught. We simulate the impacts of reputation shocks, as a form of noncompliance penalties, and report the results in Table 7. We compare the variable profit effect of a joint reputation shock that hits the whole industry with a unilateral shock that hits only one firm.[35] To scale the joint reputation shock, we reduce buyers' indirect utility by a firm-specific additive shock s_f until each firm gets the same variable profit (after reaching a new price equilibrium) as under the 3% compliant dosage. Thus, we calibrate those reputation shocks so that they reduce the variable profits by the same amount as the upper bound on the expected penalties under joint noncompliance reported in Table 6. We find that Daimler would require the largest reputation shock and BMW the smallest. Next, we give the additive shock s_f to one firm at a time, and compute prices and profits when all other firms would receive no reputation shock, $s_{-f} = 0$. In Table 7, we find that reputation damages to one working-group firm are 16% to 81% smaller when other working-group firms also receive reputation shocks. We interpret these results as evidence that the penalties could be lower when firms are caught jointly and part of the

[35] Bachmann et al. (2019) study collective reputation, while we assign reputation shocks to individual firms.

Figure 4: Mechanism 1 - Reduction in the Detection Probability by Joint Noncompliance

(a) Observed DEF Tank Sizes of All Firms

(b) Unilateral Noncompliance



Notes: The lower sub-panels plot the distribution of DEF tank sizes of each working-group firm against a counterfactual distribution of compliant DEF tank sizes (at 3% DEF dosage) for the rest of the industry.

penalties stems from reputation damages.

Finally, Table 8 quantifies the skin in the game mechanism by computing the extent to which a unilateral violator would reduce the variable profits of its competitors. If the competitors can legally recoup the variable profit damages inflicted by the violator by informing the regulator, the violating firm may want to reduce such risks by including its competitors in a collusive scheme. Whenever each working-group firm violates unilaterally, Table 8 reports that 12% to 39% of the variable profit gains from unilateral violation stem from stealing business from other firms in the working group. Coordinating on violation takes away this risk because when every member of the working group violates the regulation, every member has skin in the game.

6.5 Estimated Incentives of the Non-Working-Group Firms

Our empirical analysis of the non-working-group variable profits is consistent with the leader-follower story suggested in Section 4. The non-working-group firms would gain a total of 27 million euros in variable

Table 7: Mechanism 2 - Diffusion of Responsibility with Reputation Shocks (million 2018 euros)

	Joint Shock Effect $\pi_f(s_f, s_{-f}) - \pi_f$	Unilateral Shock Effect $\pi_f(s_f, 0) - \pi_f$	Effect Difference $\pi_f(s_f, s_{-f}) - \pi_f(s_f, 0)$	% Diffused
BMW	-31	-172	141	81%
Daimler	-412	-496	84	17%
Volkswagen	-1330	-1586	256	16%

Notes: Reputation shock s_f is an additive reduction in indirect utility of consumers for firm f that reduces its variable profit, after all firms adjust to equilibrium prices, to the variable profit under the 3% dosage compliance. The last column computes the percentage of reputation damages that are diffused by joint shocks relative to unilateral shocks (e.g., $100 \times 141/172 = 81\%$).

Table 8: Mechanism 3 - Skin in the Game with Business Stealing (million 2018 euros)

	Variable Profit Change			% Variable Profit Change Stolen
	BMW	Daimler	Volkswagen	from the Rest of the Working Group
BMW	55.6	-4.4	-17.5	39%
Daimler	-8.4	103.6	-29	36%
Volkswagen	-21.4	-16.9	318.1	12%

Notes: This table gives the change in variable profits when a firm in a row is the unilateral violator of the regulation: the firm chooses tank sizes a_f^C while competitors choose a_{-f}^* from the 3% compliance scenario. The final column computes the percentage of the increase in profits from violation that is stolen from other firms in the working group (e.g., $100 \times (4.4+17.5)/55.6 = 39\%$).

profits if the industry were to move to full compliance from the observed equilibrium. However, conditional on the working-group firms' collusive noncompliance, non-working-group firms would also prefer to choose noncompliance. Under the 3% compliance scenario, the non-working-group firms would gain 677 million euros in variable profits by following the working group into noncompliance. These variable profit gains could be interpreted as an upper bound on the noncompliance penalties that the non-working-group firms expected.

7 Welfare Effects of Collusion

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:

$$\Delta W = W(\boldsymbol{a^C}) - W(\boldsymbol{a^{NC}}). \tag{14}$$

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 Step 1.2 of the timing described in Section 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.[36] 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:

$$\Re = \Delta W - \sum_{f \in F^{WG}} \pi_f(\boldsymbol{a^C}) + \sum_{f \in F^{WG}} \pi_f(\boldsymbol{a^{NC}}). \tag{15}$$

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

$$\lambda = \frac{\sum_{f \in F^{WG}} \pi_f(\boldsymbol{a^C}) - \sum_{f \in F^{WG}} \pi_f(\boldsymbol{a^{NC}})}{-\Re}. \tag{16}$$

Assume that $\Re < 0$, so that the collusion harms the rest of the society. Then, if $\lambda \leq 0$, the alleged collusion does not improve the working group profits relative to competition and the working group cannot make a profitable collusive proposal. If $\lambda > 1$, then the alleged collusion increases the working group profits more than it harms the rest of the society. Making the working group absorb the residual claim has a redistributive role, but the working group would still collude as it generates enough profits to pay the claim. Finally, if $\lambda \in (0, 1]$, then the alleged 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. A $\lambda \in (0, 1]$ can therefore 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.

To compute welfare changes, we use the estimated demand and marginal costs from Section 5. For every counterfactual DEF tank size distribution, we use again 2% dosage, 3% dosage, and 3% dosage with higher fuel consumption, of each diesel vehicle with a DEF tank approved under Euro 6 New European Driving Cycle (NEDC), to 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

[36] 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).

of the choice sets.

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. Therefore, we operationalize this scenario by 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.

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

$$\sum_{\tau=0}^{T} \delta^{\tau} \left[q_{jt} \underbrace{(e^* + (a_j^* - a_j) RemovalRate)}_{\text{On-road emission}} - q_{jt}^* e^* \right] \times AnnualMileage \times \phi, \tag{17}$$

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.

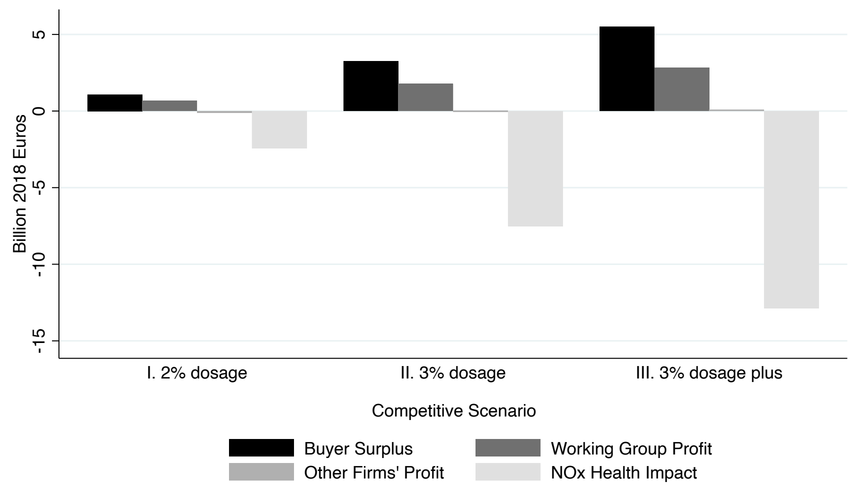
To parameterize the avoided damage formula, we take $\delta = 0.943$ which corresponds to a yearly discount rate of 6%, $T = 14$, $e^* = 80$ mg/km which is the Euro 6 emission limit, and $AnnualMileage = 20,000$ km. We take the marginal damage estimate from Oldenkamp et al. (2016) at $78 per kg of NO_x (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.[37] 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 use a removal rate of 7.71 as estimated in Section 4.

Figure 5 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 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. The health damages of excess NO_x were substantial in all scenarios.

In Appendix Table A3, we report the changes in market outcomes induced by the alleged collusion. In

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

Figure 5: Decomposing the Welfare Effects of the Alleged Collusion, 2007-2018



Notes: Competitive Scenario I - the industry achieve 2% dosage for compliance. Competitive Scenario II - the industry achieves 3% dosage for compliance. Competitive Scenario III - the industry achieves 3% dosage for compliance with 30% higher 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, and 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.

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 9 summarizes the welfare components and the implied remedial antitrust and noncompliance penalties. The net welfare cost of the alleged collusion summed over 2007-2018 ranges between 0.78 to 4.44 billion euros across our scenarios. 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 between 1.46 to 7.37 billion euros 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

Table 9: Summarizing the Welfare Effects of the Alleged Collusion, 2007-2018

	Competitive Scenario		
	I	II	III
changes in billion euros	2% dosage	3% dosage	3% dosage plus
A. Working Group's Profit	0.68	1.77	2.83
B. Residual Claim	-1.46	-4.28	-7.37
NO_x health impact	-2.43	-7.52	-12.86
Buyer surplus	1.08	3.26	5.49
Other firms' profit	-0.10	-0.03	0.09
Net Welfare $(A+B)$	-0.78	-2.51	-4.44
Ratio $\lambda = A/(-B)$	0.46	0.41	0.39

Notes: Competitive Scenario I - the industry achieve 2% dosage for compliance. Competitive Scenario II - the industry achieves 3% dosage for compliance. Competitive Scenario III - the industry achieves 3% dosage for compliance with 30% higher 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, and 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.

fines that the EU has ever imposed.[38]

In the last row of Table 9, we compute the ratio λ of the working group's profit over the (negative of the) residual claim to be between 0.39 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.

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

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 7.37 billion euros to remedy the welfare damages of this alleged collusion.

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Appendix

A1 Illustration of Mechanisms that Reduce Expected Noncompliance Penalties

We present a simple game with two firms and two actions to illustrate the three mechanisms that can rationalize joint noncompliance with environmental regulation: reduction in the detection probability, diffusion of responsibility, and skin in the game. We first discuss how these mechanisms create benefits from coordination and then discuss how they also fit a collusive setting where the coordinated outcome is not a Nash equilibrium.

Two firms choose between two actions, C (cheating) and H (honest compliance). Firms receive symmetric variable profits and expected noncompliance penalties as a function of the action profile. The expected noncompliance penalty is the product of the detection probability and the (ex-post) noncompliance penalty. We have $EK_{(H,H)} = 0$ by definition. This payoff structure represents a simplified two-by-two game of our model in Section 2. For illustrating purposes, consider the stage-game payoff matrix below:

		Firm 2: C	Firm 2: H
Firm 1	C	$5 - EK_{(C,C)}, 5 - EK_{(C,C)}$	$7 - EK_{(C,H)}, 1$
	H	$1, 7 - EK_{(H,C)}$	$4, 4$

The variable profits are given in numbers such that profits increase with the competitor's compliance level but decrease in a firm's own compliance level. Variable profits are also higher at (C,C) than at (H,H), so that joint cheating yields more variable profits than joint compliance. A firm has the highest variable profit of 7 when it chooses C and the other player chooses H.

We start by analyzing the game when the expected noncompliance penalties are constant across action profiles: $EK_{(C,C)} = EK_{(C,H)} = EK_{(H,C)} \geq 0$. In this case, there exists no EK that generates benefits from coordinating on (C,C). To see this, (1) when $0 \leq EK \leq 3$, (C,C) itself is the only Nash equilibrium, obviating the need to coordinate; (2) when $3 < EK \leq 4$, both (C,C) and (H,H) are Nash equilibria, but (H,H) yields higher payoffs than (C,C), and (3), when $EK > 4$, (H,H) will be the only competitive outcome, and it yields higher payoffs than (C,C). Therefore, when the expected noncompliance penalties do not vary across action profiles, there exists no payoff in this game where firms would choose to coordinate on (C,C).

We now examine how each of the three mechanisms generates benefits from coordinating on (C,C). Finally, we discuss how each mechanism can eliminate (C,C) as a *competitive* outcome, leading to the use of intertemporal incentives to support (C,C) as a *collusive* outcome.

Mechanism 1: Reduction in the detection probability. Assume that the detection probability is lower when both firms play C, or $p_{C,H} = p_{H,C} > p_{C,C}$. We keep the (ex-post) noncompliance penalties constant across action profiles. Together, this implies $EK_{C,H} = EK_{H,C} > EK_{C,C}$. As explained in the main text, this could result from a yardstick principle: the regulator relies on observed information from the industry to investigate violation, and when the industry looks homogeneous there is less suspicion. A reduction in the detection probability at (C,C) such that $EK_{C,C} < 1$ while $EK_{H,C} > 3$ generates a game with payoffs so that coordinating on (C,C) is beneficial. This is because, (1) for (H,H) to be a competitive outcome, we need $EK_{H,C} = EK_{C,H} > 3$; and (2) for firms to prefer (C,C) over the competitive outcome (H,H), we need $EK_{C,C} < 1$.[39]

Mechanism 2: Diffusion of responsibility. When part of the noncompliance penalties involve reputation damages, those penalties might be lower when multiple firms are caught cheating than when a single firm is. The profit losses from being the only firm with a reputation shock can be very large, because the competitor still has a good reputation. When both firms are caught cheating they will lose market share to the outside good, but there will be no business stealing. Such diffusion of responsibility causes the noncompliance penalties to differ between action profiles (C, C) and $(C, H), (H, C)$. In turn, the resulting payoffs may also create a game where there are benefits to reaching (C,C) in a coordinated manner. Let $p_{C,H} = p_{H,C} = p_{C,C}$ and $K_{C,H} = K_{H,C} > K_{C,C}$. Then, a diffusion of responsibility such that $EK_{C,C} < 1$ and $EK_{H,C} = EK_{C,H} > 3$ will incentivize firms to coordinate on (C, C).

Mechanism 3: Skin in the game. If a firm violates the regulation and plays C, the firm reduces the variable profit of a competitor playing H. In our payoff matrix, the variable profit for an honest firm decreases from 4 to 1 when the other firm plays C. This damage imposed on the competitor creates a situation where the honest firm might want to call out the illegal behavior. In our setting, firms understand each others' technology choices and they might inform the regulator about the cheating. In many legal settings, the honest firms can sue the violator for damages. Define those damages as $D > 0$ and assume that an honest firm can recoup damages with certainty from a violator. This would change the payoff matrix as follows:

		Firm 2: C	Firm 2: H
Firm 1	C	$5 - EK_{(C,C)}, 5 - EK_{(C,C)}$	$7 - EK_{(C,H)} - D, 1 + D$
Firm 1	H	$1 + D, 7 - EK_{(H,C)} - D$	$4, 4$

We keep the expected noncompliance penalties constant across the action profiles. Then, when $EK < 1$ and $D > 2$, this new payoff matrix presents benefits from coordinating on (C, C). This is because, even with EK constant and $EK < 1$, the presence of $D > 2$ makes C no longer a dominant action, leading to (H,H) becoming a competitive outcome that is inferior to (C,C). We call this the "skin in the game" mechanisms.

[39] (C,C) will also lead to the highest total payoff because $10 - 2EK_{C,C} > 8 > 8 - EK_{H,C}$.

Without coordination, an honest competitor can prevent a firm from cheating. Once in coordination, firms have "skin in the game" and there is no damage transfer between honest and cheating firms anymore. In Section 6, we quantify the extent of business stealing from competitors when firms choose C unilaterally.

Turning coordination into collusion. The first two mechanisms both lead to a coordination game with two Nash equilibria (C,C) and (H,H). No firm would have the unilateral incentive to deviate from the (C,C) profile, because the deviation payoff of 1 is dominated by the payoff at (C,C). This result generalizes to any variable profit function that is increasing in other firm's compliance level. As long as $EK_{C,H} = EK_{H,C} \geq EK_{C,C}$ and $\pi_{(H,C)} < \pi_{(H,H)}$, we will not have a Prisoners' Dilemma setup where the working group needs to punish to prevent deviations from (C,C).[40] We need to explain why the working group needed collusion with inter-temporal punishment, and not just coordination.

Under the first mechanism of reduction in the detection probability, the simple example has restricted the action set to be binary. We have shown that firms do not have the unilateral incentive to deviate to H from (C, C). However, deviation does not necessarily have to be deviating to honest compliance. There is likely a third action, M, such that $\pi_{(C,C)} - EK_{(C,C)} < \pi_{(M,C)} - EK_{(M,C)}$ where $\pi_{(M,C)} - EK_{(M,C)} \geq \pi_{(H,H)}$. Then, firms would have an incentive to unilaterally deviate to M from (C,C) and there is a need for the working group to forestall those deviations.

Second, with the diffusion of responsibility, an honest firm might benefit from the reputation loss of its cheating rival. This could increase the deviation payoff from playing H when the rival plays C. When the reputation gain is large enough, a punishment mechanism might thus be needed to prevent firms from playing honest and trying to obtain reputation gains relative to the cheater.

Finally, in the skin in the game mechanism, we have described how damages D lead to (C,C) being the preferred equilibrium. Whenever these damages are attributed to the complaining firm the payoff from deviating to H from (C,C) increase from 1 to $1 + D$. The temptation to deviate comes from the benefits one can accrue from calling out a cheating rival when D is large enough.

[40] Indeed, for firms to be tempted to deviate from (C,C) we would need $\pi_{(C,C)} - EK_{(C,C)} < \pi_{(H,C)}$ and $\pi_{(C,C)} - EK_{(C,C)} > \pi_{(H,H)}$, but because $\pi_{(H,C)} < \pi_{(H,H)}$, we have $EK_{(C,C)} > EK_{(H,C)}$, a contradiction.

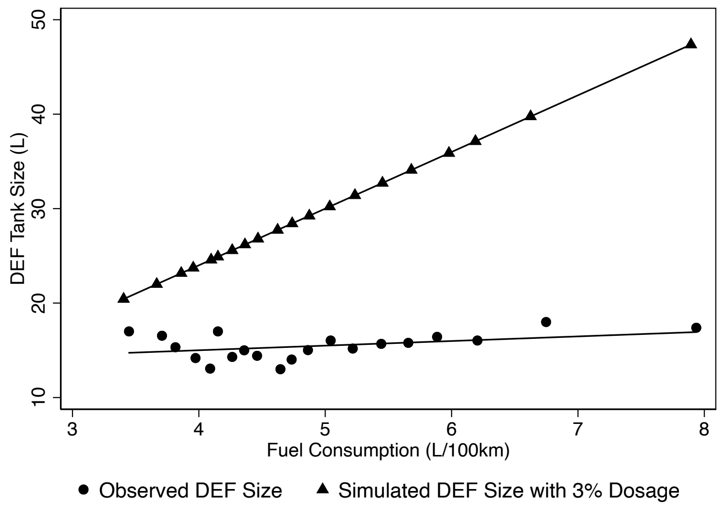
A2 Additional Figures and Tables

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 Trade-off 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
	2% dosage	3% dosage	3% dosage plus
Quantity-Weighted Trunk	0.09	0.25	0.41
Working-group Euro 6 NEDC DEF	2.97	8.41	14.33
Non-working-group Euro 6 NEDC DEF	1.51	6.22	11.56
Quantity-Weighted Price	0.05	0.13	0.21
Working-group Euro 6 NEDC DEF	1.70	4.90	8.36
Non-working-group Euro 6 NEDC DEF	1.19	4.12	7.05
Working-group other diesel	-0.09	-0.26	-0.44
Non-working-group other diesel	-0.08	-0.25	-0.42
Working-group gasoline	-0.12	-0.34	-0.56
Non-working-group gasoline	-0.09	-0.27	-0.46
Quantity	0.04	0.12	0.20
Working-group Euro 6 NEDC DEF	2.18	6.10	10.27
Non-working-group Euro 6 NEDC DEF	0.84	3.93	7.52
Working-group other diesel	-0.05	-0.16	-0.26
Non-working-group other diesel	-0.04	-0.12	-0.20
Working-group gasoline	-0.08	-0.23	-0.37
Non-working-group gasoline	-0.04	-0.14	-0.24

Notes: Competitive Scenario I - the industry achieve 2% dosage for compliance. Competitive Scenario II - the industry achieves 3% dosage for compliance. Competitive Scenario III - the industry achieves 3% dosage compliance under 30% higher 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, and an annual mileage of 20,000 km. 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.