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## Abstract

We study collusion among firms under imperfectly monitored environmental regulation. We develop a model in which firms increase variable profits by shading pollution and reduce expected noncompliance penalties by shading jointly. We apply our model to a case with three German automakers colluding to reduce the size of diesel exhaust fluid (DEF) tanks, an emission control technology used to comply with air pollution standards. To estimate our model, we use data from the European automobile industry from 2007 to 2018. We find that jointly choosing small DEF tanks lowers the expected noncompliance penalties by at least 188-976 million euros. Smaller DEF tanks improve buyer and producer surplus by freeing up valuable trunk space and saving production costs, but they create more pollution damages. Collusion reduces social welfare by 0.78-4.44 billion euros. Environmental policy design and antitrust play complementary roles in protecting society from collusion against regulation.



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# Colluding Against Environmental Regulation

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October 29, 2021

**Abstract**

We study collusion among firms under imperfectly monitored environmental regulation. We develop a model in which firms increase variable profits by shading pollution and reduce expected noncompliance penalties by shading jointly. We apply our model to a case with three German automakers colluding to reduce the size of diesel exhaust fluid (DEF) tanks, an emission control technology used to comply with air pollution standards. To estimate our model, we use data from the European automobile industry from 2007 to 2018. We find that jointly choosing small DEF tanks lowers the expected noncompliance penalties by at least 188–976 million euros. Smaller DEF tanks improve buyer and producer surplus by freeing up valuable trunk space and saving production costs, but they create more pollution damages. Collusion reduces social welfare by 0.78–4.44 billion euros. Environmental policy design and antitrust play complementary roles in protecting society from collusion against regulation.

**Keywords:** collusion, regulation, pollution, automobile market, noncompliance

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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, 2021). Most studies on noncompliance assume that firms choose actions independently from competitors. In settings where the regulator has imperfect information for detecting and punishing noncompliance, theoretical studies by Laffont and Martimort (1997, 2000) and Che and Kim (2006) have considered the possibility of agents colluding against the regulator. Compared to individual noncompliance, collusive noncompliance may further undermine regulation by increasing the extent of violation.

We develop and estimate a model of collusive noncompliance under imperfectly monitored environmental regulation. Our paper answers two questions: Why might firms collude on noncompliance, and what are the welfare impacts of collusive noncompliance? We apply our model to a novel antitrust case. In July 2021, the European Commission found that the German automakers BMW, Daimler, and Volkswagen colluded to restrict the effectiveness of diesel emission control technologies, in violation of competition law (European Commission, 2021). The case did not involve pricing; the Commission argued that coordinating to limit technical development is illegal under EU antitrust rules.

Our analysis begins with a model that explains why firms may collude on noncompliance with regulation.[1] Our principal, the regulator, sets a pollution standard. Firms' pollution abatement in response to the standard is costly because it increases marginal production costs or compromises desirable product characteristics. A firm's variable profit then increases when it abates less or when its competitors abate more. Firms choose their abatement actions either unilaterally or following a collusive proposal. They can enter the market with insufficient abatement actions by falsely reporting emissions at the time of market entry. Such behavior is possible because high monitoring costs prevent the regulator from observing firms' true emissions. After firms enter, the regulator may inspect firms and punish them in case of noncompliant market entry. In this regulatory environment, a firm's payoff is its variable profit minus potential expected noncompliance penalty.

We show that collusion on noncompliance can be rationalized by a reduction in the expected noncompliance penalties. A colluding firm's expected noncompliance penalty is lower under *joint* noncompliance—as in a collusive scheme with low abatement—than *unilateral* noncompliance—if that firm were the only violator of the regulation. We provide three mechanisms leading to

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

reductions in expected penalties from joint noncompliance. First, collusion may lower the ex post noncompliance penalty through diffusion of responsibility: A penalty for an individual firm may be lower when multiple violators are caught. Second, collusion gives all participants "skin in the game," which can lower the risk of a noncompliant firm being called out by compliant competitors whose business would be stolen by the noncompliant firm. Third, the probability of the regulator inspecting and detecting a firm's noncompliance can depend on observations of other firms' abatement actions.

Our model provides a framework to empirically study collusion on noncompliance in many regulatory settings with an imperfectly informed regulator. The participation constraints of the collusive agreement allow us to empirically bound the reduction in expected noncompliance penalties achieved by the collusion. Identifying the reduction in penalties is critical because it determines the degree to which firms can attain higher and more profitable levels of noncompliance by choosing abatement jointly. Furthermore, our model facilitates discussion about welfare and policy implications of collusion on noncompliance. The model decomposes the welfare effects into changes in buyer surplus, non-colluding firms' profits, and externality damages, as well as colluding firms' profits. The first three components constitute the "residual claim" that collusion causes in terms of welfare changes for other participants in the market. Che and Kim (2006) show that a regulator could prevent welfare losses from collusion and achieve a collusion-proof environment by making the cartel the residual claimant of these welfare changes. Our model enables us to compare the stringency of the EU regulatory environment to such a hypothetical collusion-proof policy.

The recent EU diesel emissions collusion case involves a $NO_x$ control technology called Selective Catalytic Reduction (SCR). Many 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 limiting the DEF tank sizes to guard against "an arms race with respect to DEF tank sizes" (Dohmen and Hawranek, 2017). The firms designed DEF refills to coincide with the annual vehicle maintenance to reduce inconvenience for drivers. Given an annual refill, a smaller DEF tank means lower DEF consumption per mile driven and more $NO_x$ pollution.

To apply our model to the collusion case, we use data on vehicle registrations and characteristics from the European automobile market 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 chooses

DEF tank sizes 8% smaller than other firms. Furthermore, we document widespread noncompliance behavior in the industry from on-road emission test results collected by an independent third party. On average, diesel vehicles exceed the $NO_x$ standard by a factor of three, and more than 70% of the tested diesel vehicles are out of compliance.

We estimate a structural model of vehicle demand and marginal costs that incorporates abatement costs through DEF tank size choices. Large DEF tanks reduce firms' variable profits because they take up trunk space, an attribute consumers value, as well as increase marginal production costs. Our demand estimates show that consumers would be willing to pay 283 euros to increase trunk space by the volume of an average DEF tank of 16 liters.[2] Our marginal production cost estimates show that the SCR system costs 543 euros, or 36 euros per liter of the DEF tank, which is similar to engineering estimates. 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. The antitrust case and supportive documents did not mention cost efficiencies, nor were upstream DEF suppliers involved in the case.

The estimated variable profit functions combine with the theoretical model to yield bounds on the expected noncompliance penalties faced by the working group. Estimating expected noncompliance penalties requires us to take a stand on what firms would have chosen under competition. We compute estimates for a range of plausible competitive counterfactual choices. We find that the collusion reduces the expected noncompliance penalties by at least 188–976 million euros compared to unilateral noncompliance. While this single collusive noncompliance event prevents us from separately identifying the roles of the three mechanisms in causing this reduction, we verify the extent to which the economic forces behind the three mechanisms are potentially present in our empirical context. Joint noncompliance would diffuse 16–81% of noncompliance penalties when penalties take the form of reputation damages; avoid stealing 12–39% of variable profit gains from each other; and help mask their otherwise suspiciously small DEF tanks.

Finally, we quantify the welfare effects of the collusion. The collusion increases industry profits and car buyer surplus due to larger trunk space and lower marginal costs. These benefits come at the cost of increased $NO_x$ pollution. Increased pollution damages outweigh the gains in industry profits and car buyer surplus. Across the scenarios we consider, the collusion reduces social welfare by between 0.78 and 4.44 billion euros. To repair the welfare damages, noncompliance penalties on the working group should reach between 1.46 and 7.37 billion euros. The Commission fined the

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

cartel 2.7 billion euros.

The existence of welfare-reducing collusion, despite the Commission's fine, indicates that the EU policy environment is not collusion-proof. We find that firms would collude as long as they perceive the probability of paying the residual claim as below 41%. Although we find antitrust fines not stringent enough in this case, our analysis points to the complementary roles for antitrust and regulatory authorities in enforcing regulation. By colluding on noncompliance, firms reduce the expected penalties of noncompliance, but could incur antitrust risk. In our setting, EU member states have the responsibility to enforce the emission regulation. Following the Volkswagen Dieselgate scandal, it has become apparent that member states failed their enforcement responsibility. The antitrust authority complements weak environmental enforcement in the EU. In the absence of stringent antitrust, environmental policy design should directly address the mechanisms that lead to reductions in expected penalties from joint noncompliance.

This paper provides an empirical framework for understanding collusion on noncompliance. The literature on the enforcement of environmental regulation has considered cases where 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 (2021). This literature shows that monitoring schemes and regulator discretion can make environmental regulation more robust to pollution hiding, but has not considered collusion among firms against the regulator. Accounting for the possibility of collusion has important implications for the design of environmental policy and highlights a potential complementary role for antitrust.

Collusion against regulation has been considered in theoretical settings in Laffont and Martimort (1997, 2000), and Che and Kim (2006). The key vulnerability of regulation to collusion in Schleifer (1985), Auriol and Laffont (1992), Tangerås (2002), and Rai and Sjöström (2004) is the ability of agents to coordinate on the information they report to the principal. Our analysis of collusion against regulation in an imperfectly competitive industry shows that information manipulation is not the only reason for collusion. Diffusion of reputation shocks and business stealing from unilateral noncompliance can also lead to collusive incentives.

We also contribute to the study of collusion in other dimensions than prices and quantities, including Nocke (2007), Alé-Chilet and Atal (2020), Gross (2020), Sullivan (2020), and Bourreau et al. (2021).[3] In our paper, firms collude on a product characteristic that is key to compliance with

[3]The semi-collusion literature has mainly focused on settings where firms collude on prices and compete in other dimensions. Our case is the reverse with collusion on technology and no evidence for collusion on prices. Collusion on prices is known to be illegal and frequently prosecuted, while collusion on technology choices is less well-defined and

environmental regulation. Regulation adds complexity to the analysis because collusion interacts with expected noncompliance penalties and produce externality damages. In contrast to coordination and standard-setting (such as in 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.

Lastly, our work adds to the literature on compliance issues in the automobile industry. 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 (forthcoming) and Holland et al. (2016) on health outcomes, Bachmann et al. (2021) on reputation spillovers among German automakers, and Ater and Yoseph (forthcoming) on the second-hand automobile market. The collusion we study predates the Volkswagen scandal.

We proceed as follows. In Section 2, we present a model of collusion on noncompliance. Section 3 describes our empirical context. Section 4 shows descriptive evidence for the collusion 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 collusion and discusses policy implications. We conclude in Section 8.

# 2 Model

We describe a model to understand firms' incentives to collude on regulatory noncompliance. The regulation is imperfect in the sense that firms can feign compliance at the risk of incurring noncompliance penalties. We show how the incentives to collude depend on the structure of expected noncompliance penalties. The model allows us to construct inequalities to quantify the incentives to collude in our empirical setting. We conclude with a discussion on welfare and policy design.

## 2.1 The Environment

**Firm types and emissions production.** The regulator faces $n$ firms, indexed by $f \in \{1, 2, \ldots, n\}$, which generate a negative externality in the form of emissions.[4] Each firm has an exogenous pollution type $\theta_f$ that captures the firm's raw emissions before taking pollution abatement actions $a_f$.

rarely prosecuted. The working group consisted of engineers, and operated separately from the pricing departments.

[4]In the model, we assume for simplicity that each firm produces a single product. In our empirical framework, we consider multi-product firms.

Firm $f$'s emissions $e_f$ are increasing in the pollution type and decreasing in the abatement action, $e_f = \theta_f - a_f$.

**Information.** We assume that the regulator is at an information disadvantage relative to the industry. The regulator observes firms' abatement actions $a_f$ but not their pollution types $\theta_f$. There is no information asymmetry among firms: pollution types are common knowledge within the industry.[5]

**Regulation.** The regulatory environment consists of two phases: a permitting phase and a surveillance phase. In the permitting phase, the regulator sets an emission standard $e^*$ as the maximum allowable emissions for firms to enter the market. However, firms can potentially misreport emissions and gain access to the market despite having higher emissions than the standard, $e_f > e^*$. Misreporting is not immediately obvious to the regulator because of the information disadvantage. We assume that misreporting in itself is not costly for a firm, but noncompliant firms risk penalties in the surveillance phase.

In the surveillance phase, the regulator might inspect any firm in the market. We denote the probability of inspecting firm $f$ as $P_f \in [0, 1]$. The inspection outcome is a revelation of firm $f$'s true emission $e_f$. If the true emission exceeds the emission standard, $e_f > e^*$, the firm faces noncompliance penalties that include regulatory fines, litigation costs, product recalls, buyer compensations, and reputation damages. We denote the net present value of these noncompliance penalties as $K_f$. This magnitude of $K_f$ can depend on, for example, how much firm $f$'s true emissions exceed the emission standard. Define firm $f$'s expected noncompliance penalty, at the time of market entry, as the product of the inspection probability and the net present value of noncompliance penalties: $\mathbb{E}K_f = P_f \cdot K_f$. Both $P_f$ and $K_f$ faced by firm $f$ may be affected by other firms' abatement actions, which we explain in the next subsection.

## 2.2 Firm Payoffs

**Timing.** We describe the timing for the firms' decision process within the permitting phase. This process includes the proposal of a joint action profile by a third party (Laffont and Martimort, 1997), which we refer to as the working group. Not all firms receive the working group proposal, and we discuss the incentives of firms not in the working group below. The timing is:

1. Firms observe pollution types, the regulatory environment, and demand and cost conditions;

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

2. The working group proposes collusive abatement actions to each firm;

3. Each firm decides to reject or accept the proposal. The proposal is accepted if and only if all firms accept;

4. If the proposal is accepted, firms carry out the proposal; otherwise, firms choose abatement actions competitively;

5. Firms choose prices competitively.

If the working group's proposal is accepted, $\boldsymbol{a^C}$ denotes the industry's abatement action profile. If the collusive proposal is not accepted, $\boldsymbol{a^{NC}}$ denotes the resulting industry abatement action profile. The timing reflects semi-collusion: firms may collude on abatement actions but not on prices. We do not allow for firm entry and exit, by assuming that the emission standard is not so stringent that it drives firms out of the market.

After the permitting phase, firms enter the market with products that appear compliant. Firms may either honestly meet the standard or abate too little to comply. In the latter case, firms risk noncompliance penalties in the surveillance phase. Firm $f$'s expected payoff is its variable profit minus its expected noncompliance penalty.

**Variable profits.** The variable profit of firm $f$, denoted by $\pi_f$, depends on the industry profile of abatement actions. We make two assumptions about the variable profit function. First, variable profit decreases in a firm's own abatement action. This assumption implies that a firm has no incentive to reduce emissions absent a binding emission standard (i.e., when $e^* \geq \theta_f$), and that there are no gains from over-compliance. When firms comply honestly with a binding standard, they choose $a_f = \theta_f - e^*$. Second, variable profit increases in the abatement action of a competing firm. This would be the case if abatement increases a rival's marginal cost and price, or compromises desirable attributes of a rival's product. The effect of competitors' abatement actions on a firm's variable profit plays a crucial role in our framework.

**Expected noncompliance penalties.** When firms do not comply with the emission standard, they risk noncompliance penalties. A noncompliant choice involves a trade-off between the variable profit gain from abating less and the increase in the expected noncompliance penalty. This trade-off changes depending on whether firms choose abatement actions jointly or unilaterally. This is because the expected noncompliance penalty may depend on competitor choices for three reasons: diffusion of responsibility, skin in the game, and a reduction in the detection probability.

First, upon detection, joint noncompliance may reduce a firm's noncompliance penalty relative to unilateral noncompliance because of diffusion of responsibility. The profit losses from being the only firm with a penalty, including reputation damages, can be larger than when competitors also receive penalties and reputation damages. This mechanism generates the dependence of $K_f$ on other firms' abatement actions.

Second, when a firm violates the regulation by choosing low abatement, our variable profit assumptions imply that it will steal market share from compliant firms. This business stealing effect creates a risk that honest competitors may call out the noncompliance to the regulator. They may also sue the violator for damages in many legal settings. By jointly choosing noncompliance, competitors get "skin in the game:" competitors of noncompliant firms now have less incentive to report to the regulator and seek damages because they are also noncompliant.[6] This mechanism generates the dependence of both $P_f$ and $K_f$ on other firms' abatement actions.

Third, the probability of detecting firm $f$'s noncompliance could decrease when other firms are noncompliant. The regulator makes inspection decisions based on the observations of firms' abatement actions. When firms have correlated pollution types, the regulator might infer the sufficiency of one firm's abatement action by comparing it against other firms' abatement actions.[7] Firms can manipulate the regulator's information by colluding on abatement actions. This creates a setting similar to yardstick competition: a regulator relies on information provided by industry participants to make decisions that are payoff-relevant for individual firms, see Schleifer (1985). These settings are known to be vulnerable to collusion (Tangerås, 2002).

Appendix A1 presents an illustrative two-by-two game that shows how each of the three mechanisms can create a setting where joint noncompliance becomes a collusive outcome. The key is that each mechanism leads to a particular structure of the expected noncompliance penalties: they are lower under joint noncompliance than unilateral noncompliance. We now study how the presence of such a structure is key to generating the incentives to collude.

[6] The skin in the game mechanism is about limiting the exposure risk of noncompliance, not the stability of a cartel. Colluding firms have an incentive to unilaterally deviate from a collusive proposal absent dynamic cartel enforcement.

[7] Earnhart and Friesen (2021) provide evidence that the US Environmental Protection Agency inspectors implement this "competitive endogenous audit" mechanism, where firms that appear less compliant than other similar regulated firms are subject to more intensive audits.

### 2.3 The Incentives to Collude

A firm $f$ participates in the collusion and follows the collusive abatement action profile $\boldsymbol{a^C}$ only if it receives higher payoffs than under the competitive profile $\boldsymbol{a^{NC}}$:

$$\pi_f(\boldsymbol{a^C}) - \mathbb{E}K_f(\boldsymbol{a^C}) \geq \pi_f(\boldsymbol{a^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^{NC}}). \tag{1}$$

This participation constraint shows that the expected noncompliance penalty under collusion, $\mathbb{E}K_f(\boldsymbol{a^C})$, cannot be too large to erode the possible variable profit gain under collusion. Based on this participation constraint, the following proposition reveals that collusion suppresses the expected noncompliance penalty associated with low levels of abatement.

**Proposition 1.** Assume that there exists a collusive profile with $a_f^C < a_f^{NC}$ for each firm $f$, and that the variable profit increases with competitors' abatement actions. Then, each firm's expected noncompliance penalty under collusion must be lower than if that firm adopts $a_f^C$ unilaterally: $\mathbb{E}K_f(\boldsymbol{a^C}) \leq \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$. This inequality is strict if the variable profit is strictly increasing in competitors' abatement actions.

*Proof.* Since $a_f^C$ is an abatement action available to firm $f$ but is not played in the competitive profile $\boldsymbol{a^{NC}}$, it must yield a payoff no higher than the firm's competitive payoff:

$$\pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) \leq \pi_f(\boldsymbol{a^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^{NC}}) \tag{2}$$

Combining Inequalities (1) and (2), we have:

$$\pi_f(\boldsymbol{a^C}) - \mathbb{E}K_f(\boldsymbol{a^C}) \geq \pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}). \tag{3}$$

Because the variable profit increases with competitors' abatement actions by assumption, we have $\pi_f(\boldsymbol{a^C}) \leq \pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$ given that $a_{-f}^C < a_{-f}^{NC}$. Inequality (3) then implies:

$$\mathbb{E}K_f(\boldsymbol{a^C}) \leq \mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}). \tag{4}$$

When the variable profit is strictly increasing in competitors' abatement actions, we have $\pi_f(\boldsymbol{a^C}) < \pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$, and Inequality (4) becomes strict. □

Proposition 1 shows the necessary role of the reduction of expected noncompliance penalties in rationalizing the collusion. Its proof also provides bounds on those expected noncompliance penalties that we can estimate. With the knowledge of $\boldsymbol{\pi}(\cdot)$, $\boldsymbol{a^C}$, $\boldsymbol{a^{NC}}$, Inequality (3) allows us to derive a lower bound on the reduction in the expected penalties due to joint low abatement relative to unilateral low abatement. We implement this exercise in Section 5 and report the bounds in Section 6.

We focus exclusively on collusion that leads to lower-than-competitive abatement actions, $a_f^C < a_f^{NC}$. This is because our empirical case is about automakers limiting, rather than overusing, the emission control technology. Documentary evidence indicates that individual automakers were tempted to deviate from the collusive choices by increasing abatement technology. Appendix A2 provides a theoretical discussion on the conditions for collusion to feature lower or higher-than-competitive abatement actions.

The documentary evidence about the deviation incentives, together with the conviction of the cartel, leads us to use the term "collusion" rather than "coordination." A coordination game would involve multiple Nash equilibria featuring profiles of similar actions, and there would be no incentive to deviate unilaterally. In collusion, however, the working group must preclude deviation incentives by imposing an inter-temporal punishment scheme. Our analysis does not investigate this dynamic enforcement of collusion.

In contrast to price/quantity collusion, deviation from the collusive scheme in our context leads to lower variable profits. The incentive to deviate to more abatement comes from an associated reduction in the expected noncompliance penalties and not from a temporary increase in variable profits. Collusion on prices/quantities allows firms to avoid negative externalities on each other's variable profit. Collusion on noncompliance enables firms to exert positive externalities on each other's expected noncompliance penalty.

### 2.4 Collusion by a Subgroup of Firms

In our empirical setting, the working group is a subset of the firms in the industry. We now consider the effect of collusion on the incentives of other firms in the market. We define the set of firms participating in the working group as $\mathcal{F}^{WG}$ and that of firms not in the working group as $\mathcal{F}^{NWG}$, so that the set of all firms is $\mathcal{F} = \mathcal{F}^{NWG} \cup \mathcal{F}^{WG}$. We slightly alter the game's timing so that between the working group proposing and the firms choosing abatement choices, non-working-group firms learn about the acceptance of a proposal. Non-working-group firms choose abatement actions with the knowledge that collusion is incentive compatible for the participating firms.[8]

When the working group's collusion induces the non-working-group firms to reduce their abatement actions below compliance, we have for a firm $g \in \mathcal{F}^{NWG}$:

$$\pi_g(\boldsymbol{a^C}) - \mathbb{E}K_g(\boldsymbol{a^C}) \geq \pi_g(a_g^*, \boldsymbol{a^C_{-g}}). \tag{5}$$

For firm $g$ that chooses noncompliance with the presence of a working group in the market, its variable profit gain must outweigh the expected noncompliance penalty that it incurs. This inequality informs us of the upper bound on the expected noncompliance penalty for a non-working-group firm that chooses low compliance levels in response to the working group's collusion.

### 2.5 Welfare and Policy Implications

The social welfare associated with the abatement action profile $\boldsymbol{a}$ is defined as:

$$W(\boldsymbol{a}) = BS(\boldsymbol{a}) + \sum_{f \in F} \pi_f(\boldsymbol{a}) - \sum_{f \in F} \phi e_f(a_f) q_f(\boldsymbol{a}), \tag{6}$$

which includes buyer surplus $BS$, firm profits, and externality damages. The externality damages are the product of the marginal damage $\phi$ and the total amount of emissions, where $q_f$ is the sales quantity. The social welfare change caused by collusion relative to competition equals:

$$\Delta W = W(\boldsymbol{a^C}) - W(\boldsymbol{a^{NC}}). \tag{7}$$

We discuss policy design with the imperfectly monitored environmental regulation as given. The regulator should aim to prevent collusive schemes that reduce social welfare ($\Delta W < 0$). Our framework points out that an imperfectly informed regulator should recognize the possibility of welfare-reducing collusion on noncompliance whenever the regulatory environment is susceptible to diffusion of responsibility, skin in the game, or reduction in the detection probability. These mechanisms lower the expected noncompliance penalty at a joint low abatement profile, $\mathbb{E}K_f(\boldsymbol{a^C})$, so that the participation constraint for the collusive scheme is more likely to hold.

A collusion-proof regulatory environment would only allow collusion to happen when it does not harm social welfare. This regulatory environment prevents welfare-reducing collusion, but allows

[8]Section 4 reports that the working group had introduced a small number of SCR models in the years before the emission standard tightened. We interpret this as the working group communicating their acceptance of a proposal to non-working-group firms.

for cooperation among firms when it increases social welfare. Che and Kim (2006) introduce a residual claim penalty to achieve such collusion-proofness: The residual claim captures the welfare effect that the working group's collusion has on the rest of the society:

$$\Re = \Delta W - \Delta \pi, \tag{8}$$

where $\Delta \pi$ is the working group's profit gain from collusion, $\sum_{f \in F^{WG}}[\pi_f(\boldsymbol{a^C}) - \pi_f(\boldsymbol{a^{NC}})]$. Under a residual claim policy, the working group becomes the residual claimant of the welfare it generates, regardless of whether the collusive proposal is accepted.[9] A collusive proposal then becomes incentive compatible only when it does not damage social welfare relative to the welfare under competition. The residual claim policy transforms the participation constraints (1) into $\Delta \pi + \Re = \Delta W \geq 0$, so that the working group's incentives are perfectly aligned with a regulator who seeks to prevent social welfare damages, or $\Delta W \geq 0$. The firms accept the collusive proposal $\boldsymbol{a}^C$ only when collusion is not welfare-reducing.[10]

The residual claim serves as a benchmark to evaluate the actual policy environment. When environmental regulation is susceptible to collusion, an actual policy environment may also include antitrust authorities because they have the jurisdiction to punish collusive welfare-reducing conduct. Antitrust fines act against the reduction in the expected noncompliance penalties, reducing the incentive to collude on noncompliance. Antitrust works in the same way as a residual claim policy: it transforms the participation constraint for collusion. Whether antitrust is stringent enough relative to a residual claim policy is an empirical question. We propose a measure that allows us to quantitatively evaluate the European policy environment.

Focusing on cases when $\Re < 0$, when the welfare effect of collusion on non-working-group firms, buyers and the externality is negative, we construct this measure:

$$\lambda = \frac{\Delta \pi}{-\Re}. \tag{9}$$

In a collusion-proof regulatory environment, we should only observe collusion if $\Delta W \geq 0$, or $\lambda \geq 1$. However, the actual policy environment is not necessarily collusion-proof; the value of $\lambda$

[9] 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).

[10] We have rewritten the participation constraint as the sum of the firm-specific constraints. The residual claim is given to the working group rather than individual firms. If the working group finds a transfer scheme between firms that satisfy firm-specific participation constraints, the working group would be allowed to implement it (see Che and Kim, 2006).

from observed collusion can be mapped to three scenarios. If $\lambda \geq 1$, then the collusion increases the working group profits more than it harms the rest of the society. Making the working group the residual claimant has a re-distributive role, but the working group would still collude as it generates enough profits to pay the claim. Such profitable collusion would indicate that the emission standard is too stringent. Collusion increases efficiency but does so by harming other market participants. If $\lambda \in (0, 1)$, collusion increases the working group profits less than it harms the rest of the society. This indicates that the observed regulatory environment is not collusion-proof. We interpret a $\lambda \in (0, 1)$ as an upper bound on the probability that a working group assigns to incurring noncompliance penalties, should the penalties cover the residual claim. An alternative interpretation of a $\lambda \in (0, 1)$ is a lower bound on the distance from a collusion-proof regulatory environment. Finally, if $\lambda \leq 0$, there exists no profitable collusive proposal, and we should never observe collusion in practice.

In the absence of antitrust action, the design of environmental regulation should be adjusted to prevent welfare-reducing collusion. Even when firms can feign compliance with the standard, the punishment scheme and inspection policy of environmental regulation can be designed to counter the incentives to collude stemming from the three mechanisms. First, fines can increase with the number of noncompliant firms to undo the diffusion of reputation damages.[11] Second, policymakers can provide incentives for firms to reveal noncompliance, similar to leniency programs for price collusion, to reduce skin in the game. Third, inspection decisions in the surveillance phase can incorporate the possibility that a seemingly consistent abatement choice in the industry may result from a joint decision.

# 3 Empirical Context

## 3.1 EU Regulation 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 through heart disease and stroke, lung cancer, chronic lung disease, and respiratory infections was 4.2 million; ground-level ozone accounted for an additional 0.25 million deaths (Health Effects Institute, 2017). $NO_x$ reduces crop and forest

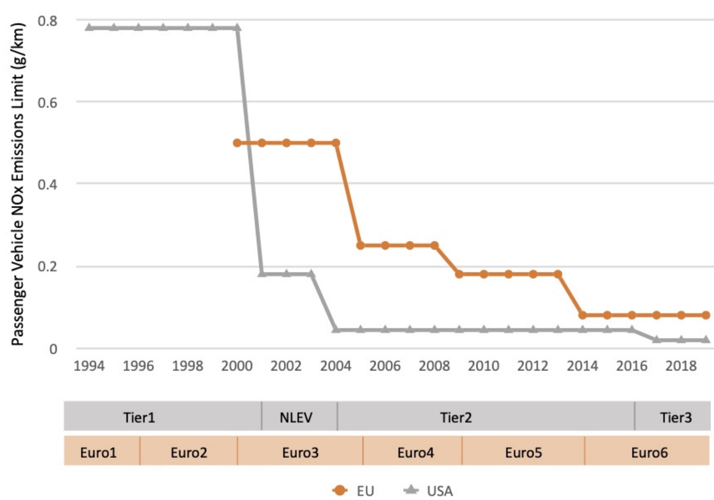
[11] Increasing fines with the number of violators may be hard to justify from a legal perspective without a legal basis or proof of explicit conspiracy.

productivity, leading to more $CO_2$ in the atmosphere, and interacts with water to form acid rain. Road transport generates about 40% of $NO_x$ emissions in the EU, of which 80% come from diesel vehicles (European Environment Agency, 2015).

Since 2000, the EU has adopted increasingly stringent $NO_x$ emission standards for diesel vehicles. The EU enforces the standards through "type approval." Before an automaker brings a vehicle "type" to the market, it must hire a third-party testing company to measure the emissions. A vehicle type can only enter the market if it complies with the emission standards during the test.

Figure 1 plots the $NO_x$ emission standards over time in the EU and US. The relevant EU emission standard for our analysis is Euro 6 (2014–2018). The vehicles affected by the collusion obtained type approval under Euro 6 with the New European Driving Cycle (NEDC). From 2017 onwards, the EU changed the type-approval procedure several times in response to the Dieselgate scandal. New Euro 6 standards adopt the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), partly accounting for Real Driving Emissions (RDE).[12] We end our study in 2018 when the majority of vehicles registered were still approved under Euro 6 NEDC.

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




Notes: NLEV stands 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.

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

### 3.2 (Not) Complying with $NO_x$ Emission Standards

To comply with the Euro 5 emission standards (2009–2014), automakers relied on Exhaust Gas Recirculation (EGR).[13] As Euro 6 reduced the $NO_x$ emission limit from 0.18g/km to 0.08g/km, EGR alone was not sufficient, and automakers could choose to add two other technologies. Small vehicles mainly use a Lean $NO_x$ Trap (LNT). LNT reduces fuel efficiency and is not suitable when the engine emits too much $NO_x$.[14] 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 sprayed into engine-out emissions to neutralize nitric oxide into harmless water and nitrogen. LNT and SCR can be combined to achieve more effective emissions control, but this option is less common.

While commercial diesel vehicles and trucks refill their DEF tanks frequently, automakers design DEF tanks in passenger cars to have an annual refill. 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 annual check-ups to avoid making diesel cars less attractive than gasoline cars.[15] Second, passenger car owners may find it challenging to refill DEF tanks themselves, because the refilling infrastructure has been optimized for trucks, and tune-ups may also be needed after refills.[16]

It is difficult for a regulator to understand precisely how much DEF is needed for a vehicle to comply 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 $NO_x$ to be removed by the SCR system is unknown to the regulator, and so is the exact efficacy of DEF. The amount of DEF is just one element in a highly complex process that results in tailpipe emissions.

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

[14] 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 reduce $NO_x$.

[15] 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." and 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[...]". Ewing and Granville (2019) write that "refilling the tank would become an extra chore and expense for the owner, a potential turnoff for prospective customers," and that "Volkswagen wanted the fluid to last long enough to be refilled by dealers during regularly scheduled oil changes, so there would be no inconvenience to owners."

[16] 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. 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. Persistent URLs in Appendix.

Following the Volkswagen scandal, it became clear that many diesel vehicles did not attain the Euro 6 emission standards on the road. The scandal revealed that firms could circumvent emission standards by deploying defeat devices. These devices consist of sensors that identify test conditions and software that changes the vehicle's operation to emit less during laboratory testing than on the road.

With defeat devices, automakers were able to obtain type approval for vehicles not compliant with the standard. However, deploying the defeat devices is risky. First, it is legally dubious, and several countries have started legal investigations into the practice. Strikingly, in contrast to Volkswagen in the US, no automaker has faced explicit lawsuits for infringing the Euro 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. Second, automakers face a series of ongoing lawsuits by consumer groups and shareholders for dishonesty. Third, the exposure of high diesel pollution causes reputation damages for the diesel segment and the brands that engage in dishonest behavior.

In sum, this setting aligns with the model described in the previous section. Firms face an emission standard, and the regulator is at an information disadvantage about firms' true emissions and the amount of abatement needed for compliance. Firms have the option of using defeat devices and can choose to enter the market with vehicles that are not compliant in practice. Noncompliance, however, is costly because it may lead to legal fines and reputation damages.

### 3.3 The Antitrust Case

Since the 1990s, engineers of the leading German automakers have met regularly to discuss many different technologies and engine specifications (Dohmen and Hawranek, 2017). The so-called "Circle of Five" was composed of BMW, Daimler, Volkswagen, Porsche, and Audi, where the Volkswagen Group owns the last three. We refer to BMW, Daimler, Volkswagen, and their subsidiary brands as the "working group".

As early as 2006, the working group discussed fitting a DEF tank in future models. According to an internal working-group report, after the failure of an initial agreement to effectively limit the DEF tank sizes, the automakers sensed the "urgent need for cooperation". They applied pressure on their managers to hold additional meetings and reach an agreement. 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. 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 make customers refill 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, along with the failure of firms' early attempt to limit DEF tank sizes, as evidence that individual automakers would have had a unilateral incentive to deviate to larger DEF tanks absent inter-temporal punishment schemes. The working group sold vehicles with small DEF tanks that were supposedly compliant with the Euro 6 NEDC standards between 2014 and 2018.

In October 2017, the European Commission began initial inquiries into possible collusion by inspecting the premises of BMW, Daimler, and Volkswagen 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 Commission sent a statement of objections to the working group with 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). The investigation concluded in July 2021. The Commission imposed a total fine of 875 million euros for the collusion (European Commission, 2021), of which BMW received 373 million, and VW received 502 million after a leniency discount of 45% for cooperating with the investigation. Both fines reflected a 10% settlement discount. Daimler avoided an aggregate fine of 727 million euros for being the whistleblower. A 20% novelty discount was also applied because this was the first time the Commission prosecuted a cartel for restricting technical development. The total fines without any discount amount to 2.7 billion euros. Additional future damages payments are possible from follow-on litigation.

# 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 European markets (Germany, UK, France, The Netherlands, Belgium, Spain, Italy), representing

90% of the European market. Our sample period starts in 2007, which captures the working group's earliest adoption of Selective Catalytic Reduction (SCR) to control $NO_x$. We end our sample in 2018 when the large majority of vehicles registered were still approved under Euro 6 NEDC, and before the Volkswagen Dieselgate scandal began to affect new vehicle designs.

We augment the JATO data with data from ADAC, a German automobile association.[17] The ADAC data provide 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 as a combination of brand, engine displacement, horsepower, body type, fuel type, transmission type, trunk space, emission control technology, Euro emission standards, and (when applicable) DEF tank size.

Additional data include the location and plant of production of each vehicle from PwC Autofacts; population, GDP, price indices, and input costs from statistical agencies; and Real Driving Emissions (RDE) data from Emissions Analytics, an independent RDE testing and data company. The company conducted a thousand tests on on-road $NO_x$ emissions and fuel consumption between 2011 and 2020.

### 4.2 Market Structure

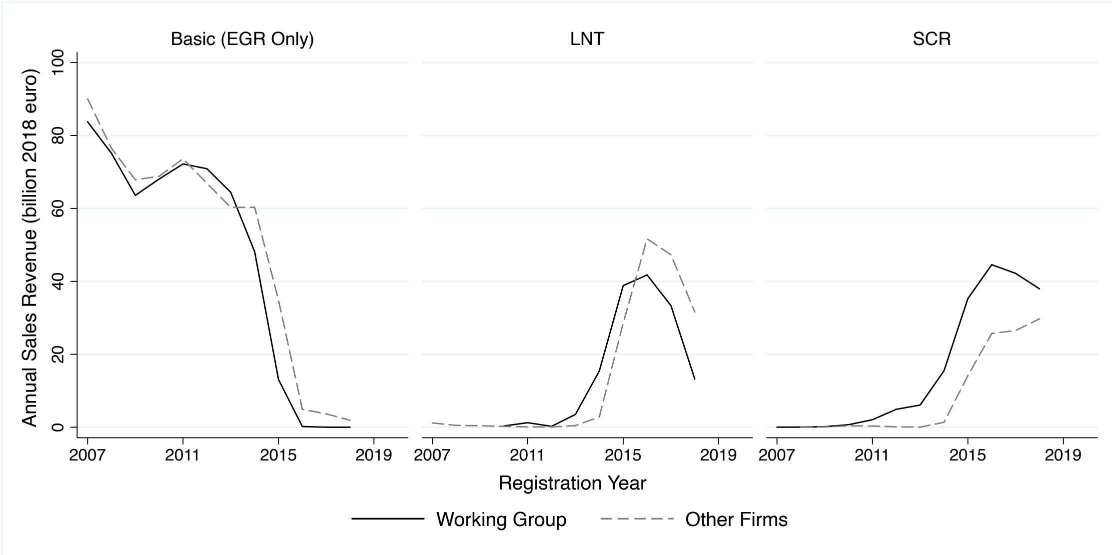
In our sample period 2007–2018, the EU automobile industry consists of the working-group firms—BMW, Daimler, and Volkswagen—and 17 other firms.[18] The working group accounts for about half of the revenue share in our sample. The diesel segment is an important source of revenue for the working group. For example, the working group generated 81 billion euros in revenue from diesel vehicles and 55 billion euros from gasoline in 2017, compared with 78 billion and 72 billion euros for non-working-group firms, respectively.

Within the diesel segment, the working group relies 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, and yet the working group's SCR sales started to climb. After Euro 6 kicked off, virtually all new diesel vehicles are equipped with SCR or LNT. The working group's SCR revenue overshadowed the rest of the industry; it peaked in 2016 at 45 billion euros

[17] Vehicle models available in Germany cover almost all vehicles available in other European countries, though aesthetic trims and packages may vary across countries. We match 93% of observations (or 96% of registrations) in the JATO data with the detailed characteristics data from ADAC.

[18] The working-group 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.

Figure 2: Annual Sales Revenue of Diesel Vehicles by $NO_x$ Control Technology




Notes: The figure shows annual diesel sales revenue computed from JATO data by $NO_x$ control technology: EGR only, LNT, and SCR. Not plotted is a small share of vehicles equipped with both LNT and SCR.

when other firms' SCR revenue was only 26 billion euros. Appendix Table A1 shows that SCR is installed on larger and more powerful vehicles than LNT, consistent with Yang et al. (2015).

### 4.3 Observed Abatement Choices

We provide evidence that the working group suppresses the effectiveness of their SCR systems. The SCR system 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 consumption. The dosage is a common measure of SCR effectiveness in the engineering literature. To calculate the dosage, we use the vehicle's fuel efficiency and the distance the vehicle travels before the DEF tank is depleted and requires a refill.[19] The dosage of a vehicle is:

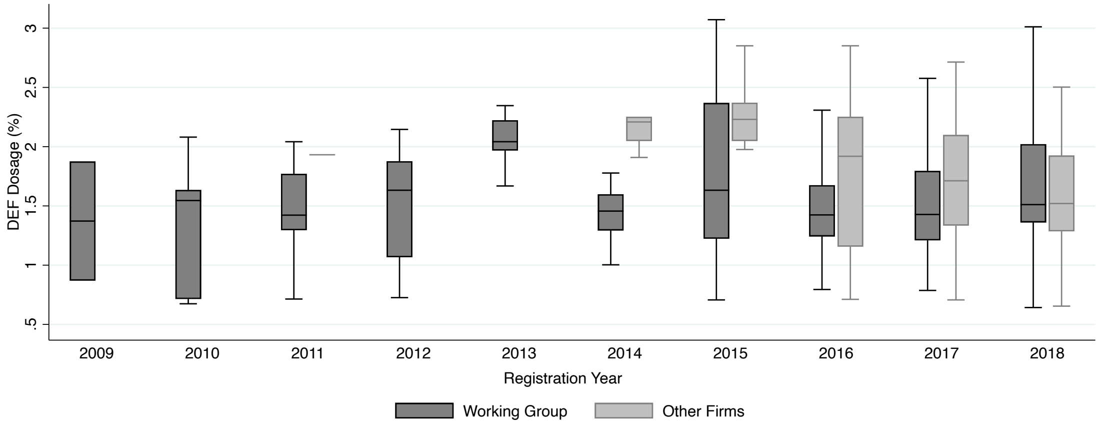
$$dosage = 100 * \frac{DEFTankSize}{AnnualFuelConsumption},$$

where we obtain the annual fuel consumption for each vehicle by multiplying an annual average mileage of 20,000 km with the vehicle-specific fuel consumption (liter per km driven).[20]

[19] 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 when the DEF tank is below a critical level.

[20] The UK travel survey reports that diesels travel 17,200km per year on average, see National Travel Survey Table NTS0902, whereas based on odometer readings, the Dutch statistical agency reports diesel vehicles travel on average 23,000km per year, see Centraal Bureau voor de Statistiek, "Dienst voor het wegverkeer, gemiddelde jaarkilometrage."

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




Notes: Box plot based on all diesel SCR vehicles (NEDC and WLTP) approved for Euro 6. Dosage equals DEF tank size divided by the fuel consumption for an annual mileage of 20,000km. 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.

Figure 3 plots the evolution of the distribution of DEF dosages adopted by the working group and other firms for all diesel vehicles approved for Euro 6. The working group had sold SCR vehicles as early as 2009 before the Euro 6 emission standards took effect in 2014. The number of these early SCR vehicles is small: the working group introduced an average of 12 SCR vehicles per year before 2014, compared with 141 afterward. Except for a single vehicle in 2011, all other firms introduced SCR vehicles after Euro 6 started. The interquartile values of the working group's dosages are between 0.7% and 2.4%. Until 2018, the interquartile ranges of their dosages are consistently below those of other firms. The dosages of the two groups become comparable in 2018.

Table 1: Suggestive Evidence for Coordination on Smaller DEF Tanks

| | (1)<br>Log Dosage | (2)<br>Log Dosage | (3)<br>Log Dosage | (4)<br>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 NEDC and WLTP, Columns (2–4) show that the working group suppresses the SCR effectiveness for vehicles in the former group but not in the latter. Because the share of WLTP vehicles increases in 2017 and 2018, we see a narrowing (albeit not reversal) of the gap in dosages between the working group and the other firms. Controlling for a set of emission-related vehicle characteristics, Column (3) shows that the working group adopts 8% lower dosages than other firms on comparable SCR vehicles approved under the Euro 6 NEDC. Our analysis of the economic effects of the collusion focuses on the Euro 6 NEDC vehicles.

The working group's argument for preferring small DEF tanks is that they are "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. These estimates imply that an average DEF tank of 16 liters takes up 3.6% of an average trunk space of a diesel vehicle.[21]

## 4.4 Evidence for Widespread Noncompliance

We now assess the extent to which the observed DEF choices are compliant with the Euro 6 emission standard. 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:

$$e_j = \theta_j - \mathit{RemovalRate} \times a_j + \epsilon_j, \tag{10}$$

where $\theta_j$ is the untreated emission (or pollution type), which depends on vehicle characteristics such as fuel consumption and the presence of a supplementary LNT system, $a_j$ is the DEF tank size (or the amount of DEF that lasts for one year's driving), and $\epsilon_j$ is an i.i.d. idiosyncratic error. The parameter of interest is $\mathit{RemovalRate}$: the mass of $NO_x$ neutralized by a liter of DEF normalized by the annual mileage.

Table 2 reports the regression results using Equation (10) based on the RDE test results of Euro 6 vehicles equipped with SCR tanks. Column (1) shows that the emissions decrease with the DEF size and the presence of a supplementary LNT system. Emissions increases with fuel consumption. Because the collusion on restricting SCR effectiveness affected NEDC vehicles, we restrict to this

[21]We focus on the DEF tanks' trade-off with trunk space and their marginal cost. A DEF tank also increases curb weight by 1%, affecting, in turn, fuel consumption. We focus on trunk space because it is the most important margin. Ewing (2018) describes only the trade-off with trunk space.

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 diesel SCR vehicle approved for Euro 6 in the on-road emission dataset. 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. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

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. We replace the left-hand side of Equation (10) with the Euro 6 emission limit of 80 mg/km. After converting 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. The average compliant dosage 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 that almost three-quarters of the tested models emit more than the emission limit. Engineering studies about the potential of SCR to help achieve Euro 6 compliance 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 requires DEF dosages between 2.9% and 3.6%.[22] 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, which we call "3% dosage plus," keeps the 3% dosage but increases the

[22] 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.

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

| | Mean | St.Dev. | Min | 25th Per. | 75th Per. | Max | % Noncompliant |
|---|---|---|---|---|---|---|---|
| Panel A: Real Driving Emissions Dataset | | | | | | | |
| Observed DEF 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 |
| Panel B: Main Dataset | | | | | | | |
| Observed DEF 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 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 are computed for the three scenarios described in the text. Each observation is a diesel SCR vehicle approved under Euro 6 NEDC. The RDE dataset has 84 such vehicles and our main dataset has 791.

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).[23]

We apply the compliant dosage scenarios informed by the RDE dataset to our main dataset, covering 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 shows widespread noncompliance beyond 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 dataset is on average 1.71%. DEF tank sizes would need to increase on average from 16 liters to between 19.6 and 38.2 liters.[24] Between 66.1% and 100% of models have insufficient DEF tank sizes.

## 5 Estimation

We begin with a demand model to estimate consumer preferences, substitution patterns, and how abatement choices affect demand. Next, we present a supply model to estimate how abatement choices change vehicle marginal costs and variable profits. With the estimated variable profit function, we show how Proposition 1 can be used to quantify the reduction in the expected noncompliance penalties due to collusion. Finally, we discuss assumptions on non-collusive equilibria to enable this calculation.

[23] We do not use the estimates in Table 2 to predict the compliant DEF size for each vehicle because of the low R-squared of the regression.

[24] Appendix Figure A2 depicts how observed DEF size increases with fuel consumption and how a 3% dosage tank increases with fuel consumption. The observed relationship is much flatter than what we would observe under compliance.

### 5.1 Demand

The demand model is a random coefficient logit model as in BLP (Berry et al., 1995). A market is a country-year, and we suppress the market subscript for notational ease. Each consumer $i$ has conditional indirect utility from purchasing vehicle $j$:

$$U_{ij} = \delta_j + \mu_{ij} + \varepsilon_{ij}, \tag{11}$$

where $\delta_j$ is the mean utility of vehicle $j$ that is the same for every consumer, and $\mu_{ij}$ is the individual deviation from the mean utility. Taste shocks specific to each consumer-vehicle pair, $\varepsilon_{ij}$, are assumed to be i.i.d. and follow the Type-I extreme value distribution.

The mean utility $\delta_j$ of vehicle $j$ is:

$$\delta_j = \alpha p_j + x_j(a_j)\beta + \xi_j, \tag{12}$$

where $p_j$ is the retail price and $x_j$ is a vector of vehicle characteristics. Unobserved vehicle-specific attributes and demand shocks are represented by $\xi_j$. The abatement choice $a_j$, measured as the size of the DEF tank, enters the indirect utility function through its effect on vehicle characteristics $x_j$, such as trunk space. Pollution reduction is considered to be an externality and does not enter the indirect utility independently.[25] We empirically verify this assumption in Section 6 and think it is plausible in this setting. First, consumers are likely uninformed about the DEF tank size. DEF tank sizes are not listed in owner's manuals or displayed at dealerships. Second, DEF refills are designed to coincide with the annual vehicle maintenance without intervention from consumers.

The individual deviation $\mu_{ij}$ from the mean utility is:

$$\mu_{ij} = \sigma_p p_j \nu_{ip} + \sum_k \sigma_k x_{jk}(a_{jk})\nu_{ik}, \tag{13}$$

where $\nu_{ip}, \nu_{ik}$ are standard normal draws. We allow the DEF tank size to affect this individual-specific utility through trunk space. Some consumers may care more about trunk space (e.g., families and golfers). Additionally, we allow for random coefficients on prices, power, and range. The outside option is not purchasing a vehicle, with its indirect utility 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

[25] Our framework could accommodate consumers partially considering pollution, as long as the private willingness to pay for pollution reduction is less than its social value.

the same market. The market share for vehicle $j$ comes from integrating over individual choices:

$$s_j = \int \frac{exp(\delta_j + \mu_{ij})}{\sum_{j'} exp(\delta_{j'} + \mu_{ij'})} \mathrm{d}\nu_i. \tag{14}$$

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 unobserved vehicle quality $\xi_j$. Our model considers strategic choices of the DEF tank size. We are less concerned about the correlation between $\xi_j$ and trunk space through the DEF tank size. The DEF tank size is a design choice that is not easily adjustable after market entry, and automakers design vehicles years ahead of market launch. For robustness, we allow for this potential correlation of $\xi_j$ and trunk space due to the DEF tank size choice. Our instrumental variables below correct the potential bias in the taste parameter for trunk space stemming from that correlation.

We instrument for prices and trunk space with three groups of instrumental variables. First, we include BLP instruments constructed from exogenous vehicle characteristics. The BLP instruments are the sums of each of the 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 net trunk space after space is taken up by the DEF tank (when a DEF tank is present in the vehicle). However, for vehicles without DEF tanks, the gross trunk space equals the net trunk space. The gross trunk space of a vehicle without a DEF tank strongly correlates with the trunk space of a vehicle with a DEF tank in the same series.[26] Gross trunk space is also a valid instrument because gross trunk space is chosen in the earliest stages of vehicle design and remains fixed throughout the whole design process.[27]

We estimate the demand model with a general method of moments estimator. We invert the market shares using contraction mapping to obtain $\xi(\theta)$ for every parameter guess. Define $Z$ to be the matrix of instruments and $A$ a weighting matrix. We estimate $\theta$ by:

$$\min_{\theta} \xi(\theta)' Z A Z' \xi(\theta). \tag{15}$$

[26]Series are distinguished by body styles (e.g., Audi A3 Cabriolet versus Audi A4 Limousine), and vehicles within a series have very similar dimensions and gross trunk space.

[27]For a detailed discussion on the timing of vehicle design, see Whitefoot et al. (2017).

## 5.2 Profits and Marginal Costs

Firms earn variable profits given by:

$$\pi_f(\boldsymbol{a}, \boldsymbol{p}) = \sum_{j \in J_f} [p_j - mc_j(a_j)]\, q_j(\boldsymbol{a}, \boldsymbol{p}), \tag{16}$$

where $J_f$ is the set of products of firm $f$, $mc_j$ is the marginal cost of vehicle $j$, and $q_j$ is sales quantity, or the market size multiplied by the market share $s_j$. Abatement actions $a_j$ may impact variable profits in two ways. First, larger DEF tanks may reduce the willingness to pay for the vehicle because it compromises trunk space, an attribute that buyers potentially value. Second, abatement actions may increase the marginal cost of production. Larger DEF tanks may be costlier to install. Our demand and marginal cost estimates inform us of the degree to which variable profits are decreasing in DEF tank size. Likewise, cross-price and cross-trunk-space derivatives of the estimated demand model determine the degree to which a firm's variable profit depends on competitors' abatement actions.

Assuming Nash Bertrand competition in prices, we back out marginal costs from the first-order conditions of the variable profit function. Let $\Omega$ be the ownership matrix, where the element $\Omega_{jh}$ indicates whether the same firm sells product $j$ and product $h$. 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 $j$, $p_j$; that is, $S_{jh} = -\frac{\partial s_h(\boldsymbol{a}, \boldsymbol{p})}{\partial p_j}$. The market share of a vehicle depends 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 implies the following vector of marginal costs:

$$\boldsymbol{mc} = \boldsymbol{p} + (\Omega \odot S(\boldsymbol{a}, \boldsymbol{p}))^{-1} \boldsymbol{s}, \tag{17}$$

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

We regress these marginal costs on product attributes and an indicator for members of the working group to estimate the implications of abatement choices and collusion on marginal costs:

$$mc_j = \eta_x x_j + \eta_a a_j + \eta_{wg} a_j I(F_j \in \mathcal{F}^{WG}) + \omega_j, \tag{18}$$

where $I(F_j \in \mathcal{F}^{WG})$ equals one whenever the producer of vehicle $j$, $F_j$, is in the working group and zero otherwise, and $\omega_j$ is the unobserved marginal cost. If the working group achieved cost savings relative to other firms, we would expect the parameter $\eta_{wg}$ to be negative. We estimate marginal costs with a rich set of fixed effects. The cost parameters are identified from variations between almost identical vehicles in the same series generation produced on the same platform and plant, among other fixed effects. Because of the rich set of fixed effects and the short-term immutability of DEF tank sizes, we assume that there is no concern for any remaining endogeneity of DEF tank sizes.

### 5.3 Bounds on Expected Noncompliance Penalties

Proposition 1 shows how colluding on low abatement must be motivated by a reduction in expected noncompliance 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 would unilaterally choose the same level of low abatement as in the working-group proposal. Rearranging Inequality (2), we have:

$$\mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) \geq \pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \pi_f(\boldsymbol{a^{NC}}) + \mathbb{E}K_f(\boldsymbol{a^{NC}}), \tag{19}$$

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

Second, we obtain an upper bound on the expected noncompliance penalties faced by each working-group firm from the participation constraint in Inequality (1):

$$\mathbb{E}K_f(\boldsymbol{a^C}) \leq \pi_f(\boldsymbol{a^C}) - \pi_f(\boldsymbol{a^{NC}}) + \mathbb{E}K_f(\boldsymbol{a^{NC}}). \tag{20}$$

The expected noncompliance penalty for a working-group firm $f$ under the collusive proposal must be smaller than the variable profit gain from the collusion, plus any applicable penalty at the non-collusive profile.

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

$$\underbrace{\mathbb{E}K_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \mathbb{E}K_f(\boldsymbol{a^C})}_{\text{Reduction in Expected Noncompliance Penalties}} \geq \underbrace{\pi_f(a_f^C, \boldsymbol{a_{-f}^{NC}}) - \pi_f(\boldsymbol{a^C})}_{\text{Reduction in Variable Profit}}, \tag{21}$$

which provides a lower bound on the *reduction* in the expected noncompliance penalties from joint low abatement relative to unilateral low abatement. Unlike the lower bound in Inequality (19) and the upper bound in Inequality (20), this combined lower bound on the reduction in expected noncompliance penalties does not depend on $\mathbb{E}K_f(\boldsymbol{a^{NC}})$, which cancels out. Inequality (21) can also be derived directly from Inequality (3) in Section 2.

### 5.4 Non-Collusive Equilibria

To quantify the bounds on expected noncompliance penalties characterized by Inequalities (19)–(21), 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 term from observed quantities and Nash-Bertrand markups defined in Equation (17). To estimate the remaining terms, we need to know what tank sizes would have been chosen in a non-collusive equilibrium, which is not observed in the data. Using the competitive DEF tank choices from non-working-group firms to inform identification (in a first-order condition approach, for example) would require strong functional form assumptions on the expected noncompliance penalties.[28] Instead, we approximate the non-collusive equilibrium outcome with 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.

We find suggestive evidence for our assumption that compliance is a competitive outcome in Figure 3. Working-group firms released vehicles approved for Euro 6 before the regulation became binding in 2016. The early DEF dosages are comparable to what firms chose in 2016–2018. We see the working group's early DEF dosage choices as communicating their low compliance choices to the industry. When Euro 6 standards took effect, the non-working-group firms could comply or follow the working group into noncompliance. If non-working-group firms choose to follow into noncompliance, it implies that doing so must be more profitable than compliance. In this way,

[28] 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 because it would require assumptions about continuity of noncompliance penalties with respect to DEF tank sizes.

the collusion led not only the working group to adopt small DEF tanks, but also the rest of the industry to shade their pollution. With this interpretation, the industry would likely have moved into compliance in the absence of collusion.

For robustness to alternative assumptions on the degree of compliance in the non-collusive equilibrium, we also compute results under a more conservative view of what the collusion achieved. The working group could have achieved a reduction of DEF dosages just below what we observe for non-working-group firms, rather than leading the industry to noncompliance. The competitive equilibrium would then consist of abatement choices that are comparable across the industry. We compute such a counterfactual by increasing the distribution of working-group DEF dosages to have the same median as those of non-working-group firms. Appendix Table A6 reports welfare effects of the collusion in this alternative scenario. Results are close to the 2 % compliance scenario and within the range of effects of our three compliance scenarios. Hereafter, we focus on the three compliance scenarios defined in Section 4.

# 6 Estimation Results

We first present our demand and marginal costs estimates. We then quantify the benefit of collusion by computing bounds on the reduction of expected noncompliance penalties achieved by joint noncompliance relative to unilateral noncompliance. We show empirical evidence of the presence of the possible mechanisms behind that reduction, discussed in Section 2. This section concludes with a description of how the collusive scheme affects the compliance choices of firms outside the working group.

## 6.1 Demand Estimates

We report the demand estimates in Table 4. A comparison of the logit OLS results in Column (1) with the logit IV results in Column (2) shows that the instrumental variables for price (BLP instruments and cost shifters) correct for the upward bias in the price coefficient from endogeneity. Column (2) also tests for consumer demand for DEF by including an indicator variable of whether the vehicle has an SCR system with a DEF tank, and if so, the DEF tank size. We find coefficients statistically indistinguishable from zero. This confirms our assumption that consumers do not value the DEF tank size on its own. In Appendix Table A3, we report more specifications involving the DEF tank size, and similarly find no statistically significant consumer demand for DEF tank sizes.

Column (3) of Table 4 instruments for both the trunk space and the price. The instrument set

Table 4: Demand Estimates

| | (1) Logit OLS | | (2) Logit IV | | (3) Logit IV | | (4) Rand Coeff Logit | |
|---|---|---|---|---|---|---|---|---|
| | Param. | St. Err. | Param. | St. Err. | Param. | St. Err. | Param. | St. Err. |
| | | | | | | | Mean Valuation | |
| Retail Price/Per Capita GDP | -0.23 | (0.04) | -3.03 | (0.09) | -2.79 | (0.10) | -3.44 | (0.40) |
| Trunk Space (cubic m) | 1.25 | (0.55) | 1.52 | (0.13) | 1.50 | (0.14) | 1.56 | (0.15) |
| Power (100kw) | -0.53 | (0.10) | 0.71 | (0.05) | 0.60 | (0.05) | 0.71 | (0.11) |
| Engine Size (L) | 0.08 | (0.05) | 0.19 | (0.02) | 0.19 | (0.02) | 0.20 | (0.02) |
| Curb Weight (ton) | -1.81 | (0.26) | -1.48 | (0.08) | -1.50 | (0.08) | -1.37 | (0.10) |
| Footprint (sq m) | 1.73 | (0.16) | 1.98 | (0.04) | 1.95 | (0.04) | 1.97 | (0.04) |
| Fuel Cost/Per Capita GDP | -65.19 | (3.26) | -30.23 | (1.65) | -33.33 | (1.67) | -42.84 | (2.97) |
| Foreign | -0.89 | (0.05) | -0.66 | (0.02) | -0.68 | (0.02) | -0.67 | (0.02) |
| Range (100 km) | 0.07 | (0.02) | 0.12 | (0.01) | 0.12 | (0.01) | 0.05 | (0.02) |
| SCR | | | -0.002 | (0.059) | | | | |
| DEF Size (L) | | | 0.004 | (0.003) | | | | |
| | | | | | | | Standard Deviation | |
| 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) |
| IV for Price | | | X | | X | | X | |
| IV for Trunk | | | | | X | | X | |
| N | 200067 | | 200067 | | 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 Column (2), we instrument for retail price using BLP instruments (constructed from power, engine size, range, curb weight, footprint, and fuel cost divided by per capita GDP) and cost shifters (number of vehicles on the same platform, number of vehicles in the same plant, and change in production platform). In Columns (3)-(4), we instrument for both retail price and trunk space and add the gross trunk space of similar vehicles as an instrument. Column (4) 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.

now includes the trunk IV based on gross trunk space as well as BLP instruments and cost shifters. The trunk space coefficient is statistically the same as in Column (2), providing additional evidence that DEF tanks are likely uncorrelated with the unobserved vehicle quality. The magnitude of the trunk space coefficient implies that the willingness to pay for a 15-liter increase in the trunk space, or equivalently having an average-sized DEF tank removed, is 283 euros.[29]

The random coefficient logit specification in Column (4) 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 (4) in all the subsequent estimates. The random coefficient model is important because it results in higher cross-price elasticities for more similar vehicles relative to the logit model. In Appendix Table A4, we report the price diversion ratios. The results show that due to the random coefficients, the products of the collusive firms are closer substitutes, and more so for vehicles with DEF tanks. These substitution patterns play an important role in

[29]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.

our analysis of the diffusion of responsibility and skin in the game mechanisms below, as well as in our counterfactual analysis.

## 6.2 Marginal Cost Estimates

Table 5 reports the marginal cost estimates for diesel vehicles.[30,31] 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 cost 494 dollars (for large vehicles) and LNT to cost 320 dollars (for small vehicles). To estimate how the marginal cost 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.

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 are clustered at the series generation level. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

[30] We allow the marginal cost function to be specific for diesel and gasoline. We do not report the results for gasoline vehicles because they never have a DEF tank and their marginal costs remain constant in the counterfactual simulations.

[31] The reported standard errors do not correct for variability from the demand estimation stage. A bootstrapped 95% confidence interval for the DEF tank size coefficient in Column (2) which takes into account demand variability is [17, 55], see Appendix A3.

Columns (3)-(4) add interaction terms with the working group indicator to the previous two specifications. All the interaction terms have statistically imprecise parameters. We do not find statistically significant evidence that the working group achieved cost savings relative to the rest of the industry, although we cannot exclude the possibility that the whole industry benefited from cost efficiencies. The European Commission's documents and the working group's responses did not mention cost efficiencies, nor were upstream DEF suppliers involved in the case.

### 6.3 Estimates of Expected Noncompliance Penalties

To estimate the bounds on the expected noncompliance penalties, we simulate the variable profits at DEF tank size choices according to Inequalities (19)–(21). 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 4: 2% dosage, 3% dosage, and 3% dosage with 30% higher fuel consumption. For each scenario, we recompute marginal costs and trunk space with compliant DEF tank sizes and find new equilibrium prices and quantities.

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

| | Unilateral Noncompliance | Joint Noncompliance | Reduction by Collusion |
|---|---|---|---|
| | Lower bound on $EK_f(a_f^C, \boldsymbol{a_{-f}^{NC}})$ | Upper bound on $EK_f(\boldsymbol{a^C})$ | Lower bound on the difference |
| Panel A: 2% Dosage for Compliance | | | |
| BMW | 83 | 28 | 54 |
| Daimler | 179 | 141 | 38 |
| Volkswagen | 602 | 506 | 96 |
| Working Group Total | 864 | 675 | 188 |
| Panel B: 3% Dosage for Compliance | | | |
| BMW | 194 | 31 | 162 |
| Daimler | 521 | 412 | 109 |
| Volkswagen | 1629 | 1330 | 299 |
| Working Group Total | 2344 | 1774 | 571 |
| Panel C: 3% dosage for Compliance with Higher Fuel Consumption | | | |
| 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. A conservative 95% confidence interval for the lower bound on the reduction in the expected noncompliance penalties under the 3% dosage scenario is [94, 226] for BMW, [62, 151] for Daimler, [176, 412] for Volkswagen, and [334, 796] for the working group total, see Appendix A3.

Table 6 reports three bounds: a lower bound on the expected noncompliance penalty under unilateral noncompliance, an upper bound on the expected noncompliance penalty under joint noncompliance, and a lower bound on their difference under the three compliance scenarios. Compared to unilateral noncompliance, joint noncompliance reduces the expected noncompliance penalties by at least 54–272 million euros for BMW, 38–177 million euros for Daimler, and 96–528 million euros for Volkswagen. In sum, the collusion brings down the expected noncompliance penalties faced by the working group by at least 188–976 million euros across the three scenarios. We bootstrap the computation of the bounds to obtain a confidence interval, see Appendix A3. A conservative 95% confidence interval for the 3% dosage scenario on the lower bound on the reduction in the expected noncompliance penalty is [94, 226] for BMW, [62, 151] for Daimler, [176, 412] for Volkswagen, and [334, 796] for the working group total.

Our findings are economically important. In the 3% compliance scenario, the upper bound on the joint expected noncompliance penalty is 1.7 billion euros. This number is the variable profit gain the cartel achieves from low abatement and implies that the working group reduces the expected noncompliance penalties by at least 570 million euros to gain 1.7 billion euros in variable profits. These numbers represent the reduction in the expected, or ex ante, noncompliance penalties.

## 6.4 Mechanisms for Expected Penalty Reduction

The previous subsection shows that joint noncompliance reduces the expected noncompliance penalties of the working group substantially. In this subsection, we provide quantitative evidence of the three mechanisms introduced in Section 2 that can explain this reduction: diffusion of responsibility, skin in the game, and reduction in the detection probability. The evidence presented here suggests the extent to which the economic forces behind the mechanisms are potentially present in the industry. With a single case of collusion, we are unable to separately identify the importance of each mechanism.

**Diffusion of responsibility.** We quantify the degree to which noncompliance penalties, including potential reputation damages, could diffuse when multiple violators are caught. When one firm is caught noncompliant and receives a reputation shock that lowers consumer utility for its products, consumers can substitute to other firms with unaffected reputations. When all firms are caught noncompliant, all firms' reputations are affected. The relative position of a firm compared to its competitors does not change as much with a joint shock as with a unilateral shock. With a joint shock, the position of the industry relative to the outside option decreases. Joint reputation shocks diffuse the damage that unilateral reputation shocks would inflict on individual firms. The degree of diffusion depends on the substitution patterns. When a firm has many close competitors, a unilateral reputation shock starkly decreases sales, while a joint reputation shock diffuses much of that damage.[32]

To simulate the degree of diffusion in the industry, 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.[33] We calibrate the joint reputation shocks by introducing firm-specific additive shocks $t_f$ to buyers' indirect utility such that each firm gets the same variable profit (after reaching a new price equilibrium) as under the 3% compliant dosage scenario. This vector of reputation shocks would exactly undo the variable profit gains from joint noncompliance.

Next, we introduce the reputation shock $t_f$ to each firm $f$ one at a time, and compute prices and profits when all other firms receive no reputation shock, $t_{-f} = 0$. Our results in Table 7 show the extent to which reputation damage to a single working-group firm diffuses with joint reputation shocks. The reputation damage would be 16% smaller for Daimler, 17% for Volkswagen, and 81% for BMW when other firms also receive reputation shocks. To explain the strong diffusion effect for BMW, note that the degree of diffusion in this exercise depends on the relative magnitude of calibrated reputation shocks and the substitution patterns. We find that the reputation shocks to undo the collusive profit would be much larger for Daimler and Volkswagen than BMW, due to their larger shares of SCR vehicles with small DEF tanks. Those large reputation shocks to Daimler and Volkswagen would diffuse much of BMW's unilateral reputation damages. We interpret these results as evidence that noncompliance penalties could be lower when firms are caught jointly, especially when penalties include reputation damages.

**Skin in the game.** We compute the extent to which a unilateral violator would reduce the variable profits of its compliant competitors. The degree to which unilateral noncompliance leads to business stealing depends on the substitution patterns in the industry. Suppose that the competitors can legally recoup the variable profit damages inflicted by the violator. The violating firm may then want to reduce such risks by including its competitors in a collusive scheme.

Table 8 shows that whenever a working-group firm violates unilaterally, between 12% to 39% of the variable profit gains from unilateral violation stem from stealing business from other firms

[32] A further argument for the diffusion of responsibility could come from the political economy of national economic concerns. According to an EU parliamentary report (Gieseke and Gerbandy, 2017), member states were aware of noncompliance but were reluctant to intervene. A group of firms or an entire industry might be too big to prosecute.

[33] Bachmann et al. (2021) study collective reputation; we shock reputations of individual firms.

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

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

Notes: Reputation shock $t_f$ 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., $100 \times 141/172 = 81\%$).

in the working group. The collusion reduces the risk of being reported by a competitor to the regulator. When every member of the working group violates the regulation, every member has skin in the game and is less likely to expose the noncompliance.

Table 8: 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 reports 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., $100 \times (4.4 + 17.5)/55.6 = 39\%$).

**Reduction in the detection probability.** We show that each working-group firm's DEF tank sizes would have stood out had the firm been the sole violator. Joint noncompliance can reduce the probability of each working-group firm being detected noncompliant by the regulator.

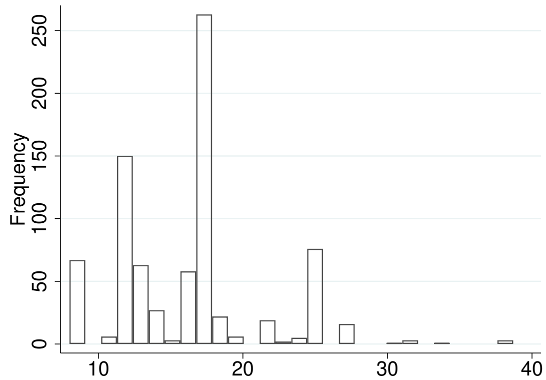
Figure 4(a) shows the distribution of DEF tank sizes as observed under the collusive scheme. Figure 4(b) plots the observed DEF tank sizes of each working-group firm against the 3% compliant distribution for the rest of the industry. These plots suggest that vehicles released by BMW, Daimler, and Volkswagen would likely appear suspicious relative to a compliant rest-of-industry.[34] The working group, therefore, potentially benefits from reduced scrutiny by moving into noncompliance jointly.[35]

[34] Dohmen and Hawranek (2017) write that "[i]f one manufacturer had installed larger [DEF] tanks, licensing and regulatory authorities would probably have become suspicious. The obvious question would have been why that one company's vehicles needed so much more urea to clean the exhaust gases, while the other manufacturers' cars supposedly managed with significantly less [DEF]".

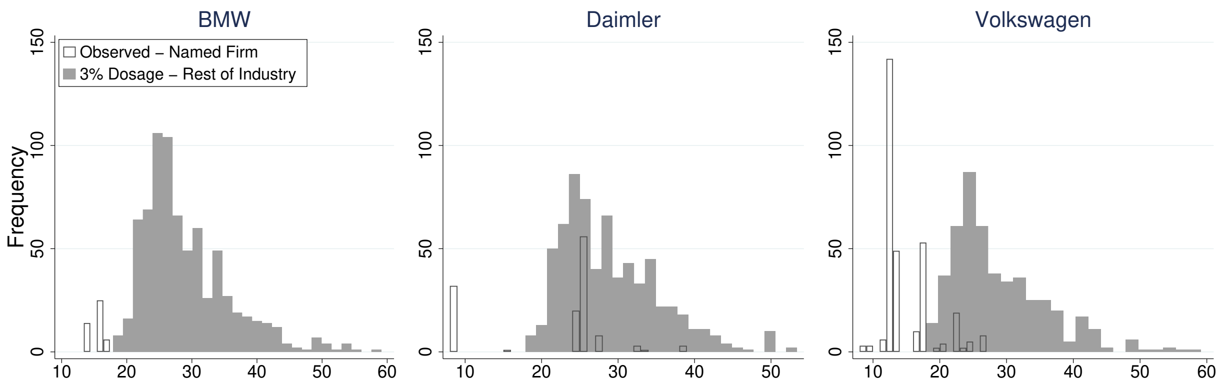
[35] One could make an opposite case: given that all firms are noncompliant, any single investigation would be more likely to expose all the firms. The probability of detection may then increase. It is interesting to consider the

Figure 4: 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.

In sum, we find empirical support for the potential existence of the three mechanisms. Our estimated demand shows that the working-group firms are close competitors, especially in the high-end diesel segment; this leads to strong diffusion of responsibility and skin in the game. Furthermore, by adopting similarly small DEF tanks, the working group masks their otherwise suspiciously low abatement choices.

## 6.5 Estimated Incentives of the Non-Working-Group Firms

Our empirical analysis of the non-working-group firms' variable profits shows that non-working-group firms would prefer the competitive compliant equilibrium. The non-working-group firms

Volkswagen scandal. The scandal was exposed in the US by independent investigators who wanted to understand how Volkswagen succeeded in bringing clean diesel vehicles to the market while US automakers did not. This event matches the argument here about a noncompliant firm standing out relative to other presumably compliant firms. In the EU, almost all automakers released noncompliant diesel vehicles. The regulator never investigated even while third parties, such as the ICCT, questioned compliance before the Volkswagen scandal.

would gain a total of 27 million euros in variable profits if the industry were to move to full compliance from the observed equilibrium.

Conditional on the collusive equilibrium being chosen, the non-working-group firms as a group gain 677 million euros in variable profits by following the working group into noncompliance in our 3% scenario. We obtain this number based on Inequality (5), by comparing non-working group profits under the observed noncompliant equilibrium with those under a counterfactual equilibrium where only the working-group firms would be noncompliant. This variable profit gain is also an estimate of the upper bound on the noncompliance penalties that the non-working-group firms expect. The three mechanisms that reduce expected noncompliance penalties may have also applied apply to non-working-group firms.

# 7 Welfare Effects of Collusion

This section explains how we compute welfare in counterfactual simulations, discusses the welfare effects of the collusion, and offers policy implications by comparing the existing regulatory environment with a collusion-proof mechanism.

## 7.1 Welfare Computation

To compute how collusion changes welfare, we calculate the difference in welfare between the observed collusive market and the compliant scenarios. We use the estimated demand and marginal costs from Section 5. For each diesel vehicle approved under Euro 6 NEDC with a DEF tank, we compute corresponding changes in marginal production costs and trunk space from enlarging the DEF tank to be compliant. Given these new marginal production costs and trunk spaces, we solve for a new Bertrand Nash equilibrium in prices. We compute quantities, firm profits, and buyer surplus represented by the inclusive value of the choice sets.

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

$$\sum_{\tau=0}^{T} \delta^{\tau} \left[ q_{jt} \underbrace{(e^* + (a_j^* - a_j) RemovalRate)}_{\text{On-road emissions}} - q_{jt}^* e^* \right] \times AnnualMileage \times \phi, \tag{22}$$

where $T$ is the lifetime of a vehicle, $\delta$ 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, and $\phi$ is the marginal damage of a unit of $NO_x$ emissions.

To parameterize these $NO_x$ damages, we use $\delta = 0.943$ (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.[36] We emphasize that these are only the health damages from $NO_x$-induced PM 2.5. They do not include 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.

### 7.2 Welfare Results

Table 9 reports the welfare effects of the collusion. The table shows that the working group's extra variable profits due to the collusion are substantial—1.77 billion euros in the 3% dosage scenario—while the aggregate profits of other firms change little. The buyer surplus greatly increases, reaching 3.26 billion euros in the 3% scenario. Across the three scenarios, the health damages of excess $NO_x$ reach 2.43 to 12.86 billion euros, outweighing the gains in firm profits and buyer surplus.[37]

We find that the collusion enables both the working-group and non-working-group firms to charge higher prices for Euro 6 NEDC SCR vehicles and also sell more of them. Compared with the competitive scenario of 3% dosage, the working group sells 6% more Euro 6 NEDC SCR vehicles featuring 8% larger trunk space and 5% higher prices (we weight the trunk space and price changes by sales quantity). Likewise, other firms sell vehicles with 6% larger trunk space and 4% higher prices. The prices and quantities of other diesel and gasoline vehicles experience only slight decreases. Appendix Table A5 reports these market outcome changes due to the collusion.

In Table 9, the net welfare change, $\Delta W$, is -2.51 billion euros in our main 3% dosage scenario (with a conservative 95% confidence interval of [-4.42, -0.47]), and ranges between -0.78 to -4.44 billion euros across scenarios. We estimate the residual claim $\Re = \Delta W - \Delta \pi$, capturing the welfare effect that the collusion incurs on the rest of the society, to be -4.28 billion euros in our main scenario (with a conservative 95% confidence interval of [-5.48, -3.03]) and ranges between -1.46 to

[36] This number is comparable to the current VSL recommended by the U.S. Environmental Protection Agency at 7.4 million in 2006 dollars. The VSL would need to be as low as 5 million to undo the net welfare damage we find below across the three scenarios. All monetary values in the results are reported 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 dollars.

[37] The excess $NO_x$ emissions are 34, 106, and 180 kton in the three scenarios respectively.

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

| | Competitive Scenario | | |
|---|---|---|---|
| | I | II | III |
| *changes in billion euros* | 2% dosage | 3% dosage | 3% dosage plus |
| Working Group's Profit $\Delta\pi$ | 0.68 | 1.77 | 2.83 |
| Residual Claim $\Re$ | -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 $\Delta\pi + \Re$ | -0.78 | -2.51 | -4.44 |
| Ratio $\lambda = \Delta\pi/(-\Re)$ | 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. In the 3% dosage scenario, a conservative 95% confidence interval is [-5.48,-3.03] for the residual claim and [-4.42,-0.47] for the net welfare, see Appendix A3.

-7.37 billion euros across scenarios. This entails that noncompliance penalties would need to reach 1.46 to 7.37 billion euros to repair the harms of the collusion ex post. This range is consistent with the antitrust fines that the European Commission imposed on the working group, which amount to 2.7 billion without leniency, novelty, and settlement discounts (European Commission, 2021). Our central estimate of $\lambda$, the ratio of the working group's profit gains and the harm to the rest of the society, is 0.41 in our main scenario, and ranges between 0.39 and 0.46 across scenarios.

The ratio $\lambda$ falls between 0 and 1. This means that the working group profits less than it harms the rest of the society. One way to interpret this number is an upper bound on the probability that firms perceive of incurring a noncompliance penalty equal to the residual claim. The firms would participate in the collusive proposal as long as the probability of being made the residual claimant is lower than 0.41. An alternative interpretation of $\lambda = 0.41$ is a lower bound on the distance from a residual claim policy, where $\lambda \geq 1$.

Our reading of $\lambda \in (0, 1)$ is twofold. First, the European Commission's antitrust division partly complements weakly enforced environmental regulation. The intervention of the European Commission's antitrust division makes the regulatory environment more robust to collusive incentives stemming from reductions in expected noncompliance penalties. Without firms considering antitrust intervention, collusion would be profitable every time it decreases expected compliance penalties enough to make noncompliance the optimal choice. Our results indicate how vital this antitrust case is for future environmental regulation in Europe. Environmental regulation often requires technology deployment. The European Commission made a clear case that collusive decisions to reduce externality abatement constitute an infringement of competition law, thereby bringing European policy closer to a residual claim policy.

Second, the antitrust fines imposed on the working group are not sufficient. Although we estimate the level of the antitrust fines to be high enough to repair damages to society ex post, they fall short of deterring future welfare-decreasing collusion on technology adoption ex ante. This is because the detection of noncompliance will unlikely be perfect. This suggests room for environmental regulators to improve the structure of the expected noncompliance penalties to be less vulnerable to collusion, with or without antitrust enforcement.

# 8 Conclusion

We study the causes and welfare effects of firms colluding on insufficient pollution abatement in response to imperfectly monitored environmental regulation. We examine the 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 the incentive to collude on noncompliance stems from the ability to reduce expected penalties. This reduction can arise from three mechanisms: diffusion of responsibility, skin in the game, and the reduction of detection probability under joint noncompliance.

Our welfare analysis reveals that the collusive benefits to automakers and car buyers come at the greater cost of $NO_x$ damages. Collusion reduces social welfare by between 0.78 and 4.44 billion euros. The magnitude of the residual claim, or the welfare damages the cartel inflicts on the rest of the society, reaches between 1.46 billion and 7.37 billion euros. The ex post noncompliance penalty needs to reach the residual claim to remedy the welfare damages of this collusion. Furthermore, imposing the residual claim ex ante achieves a collusion-proof regulatory environment, by perfectly aligning the incentives of the cartel and the regulator.

In a world where firms' compliance behavior is hardly perfectly observed by the regulator, our study warns of the possibility of collusion on noncompliance and demonstrates the empirical harms of one such case. To forestall those collusive harms, environmental policy design and antitrust can have complementary roles in imposing the residual claim. Where antitrust is insufficient or does not have jurisdiction, environmental policy should be made robust against the three mechanisms that reward firms for colluding against the regulator.

## References


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

Alexander, D. and Schwandt, H. (forthcoming). The Impact of Car Pollution on Infant and Child Health: Evidence from Emissions Cheating. *Review of Economic Studies*.

Ater, I. and Yoseph, N. (forthcoming). The Impact of Environmental Fraud on the Used Car Market: Evidence from Dieselgate. *Journal of Industrial Economics*.

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

Bachmann, R., Ehrlich, G., Fan, Y., and Ruzic, D. (2021). Firms and Collective Reputation: a Study of the Volkswagen Emissions Scandal. *NBER Working Paper No. 26117*.

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

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

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

Bourreau, M., Sun, Y., and Verboven, F. (2021). Market Entry, Fighting Brands and Tacit Collusion: Evidence from the French Mobile Telecommunications Market. *American Economic Review*, 111(11):3459–3499.

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

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

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

Earnhart, D. and Friesen, L. (2021). Use of Competitive Endogenous Audit Mechanisms by Federal and State Inspectors within Environmental Protection Agencies. *Journal of Environmental Economics and Management*, 109.

European Commission (2019). Antitrust: Commission sends Statement of Objections to BMW, Daimler and VW for restricting competition on emission cleaning technology. Accessed at `https://ec.europa.eu/commission/presscorner/detail/en/IP_19_2008` on September 21, 2021.

European Commission (2021). Antitrust: Commission fines car manufacturers 875 million for restricting competition in emission cleaning for new diesel passenger cars. Accessed at `https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3581` on September 21, 2021.

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

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

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

Gieseke, J. and Gerbandy, G.-J. (2017). Report on the inquiry into emission measurements in the automotive sector. Technical Report 2016/2215(INI), European Parliament.

Gross, D. P. (2020). Collusive Investments in Technological Compatibility: Lessons from U.S. Railroads in the Late 19th Century. *Management Science*, 66(12):5485–6064.

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

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

Holland, S. P., Mansur, E. T., Muller, N. Z., and Yates, A. J. (2016). Damages and Expected Deaths Due to Excess NOx Emissions from 2009 to 2015 Volkswagen Diesel Vehicles. *Environmental Science and Technology*, 50(3):1111–1117.

Kang, K. and Silveira, B. S. (2021). Understanding disparities in punishment: Regulator preferences and expertise. *Journal of Political Economy*, 129(10):2947–2992.

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

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

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

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

Nocke, V. (2007). Collusion and Dynamic (Under-)Investment in Quality. *The RAND Journal of Economics*, 38(1):227–249.

Oldenkamp, R., Van Zelm, R., and Huijbregts, M. A. (2016). Valuing the Human Health Damage Caused by the Fraud of Volkswagen. *Environmental Pollution*, 212:121–127.

Op De Beeck, J., Thompson, J., and Booth, N. (2013). Upcoming Emission Regulations for Passenger Cars: Impact on SCR System Requirements and Developments. *SAE Technical Papers*, 2.

Rai, A. S. and Sjöström, T. (2004). Is Grameen Lending Efficient? Repayment Incentives and Insurance in Village Economies. *Review of Economic Studies*, 71(1):217–234.

Reynaert, M. (2021). Abatement Strategies and the Cost of Environmental Regulation: Emission Standards on the European Car Market. *The Review of Economic Studies*, 88(1):454–488.

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

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

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

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

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

Sullivan, C. (2020). Split Apart: Differentiation, Diversion, and Coordination in the Market for Superpremium Ice Cream. *AEA Papers and Proceedings*, 110:573–78.

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

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

Whitefoot, K. S., Fowlie, M. L., and Skerlos, S. J. (2017). Compliance by design: Influence of acceleration trade-offs on co2 emissions and costs of fuel economy and greenhouse gas regulations. *Environmental Science & Technology*, 51(18):10307–10315. PMID: 28825797.

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

# Online 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: diffusion of responsibility, skin in the game, and reduction in the detection probability. We first discuss how these mechanisms create benefits from coordination. We 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. For illustrating purposes, consider the stage-game payoff matrix below. 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, as consistent with the assumptions in Section 2. Variable profits are higher at $(C, C)$ than at $(H, H)$, consistent with our empirical finding. A firm has the highest variable profit of 7 when it chooses C and the other player chooses H. We have also set $EK_{(H,H)} = 0$.

| | | Firm 2 | |
|---|---|---|---|
| | | $C$ | $H$ |
| Firm 1 | $C$ | $5 - \mathbb{E}K_{(C,C)}, 5 - \mathbb{E}K_{(C,C)}$ | $7 - \mathbb{E}K_{(C,H)}, 1$ |
| | $H$ | $1, 7 - \mathbb{E}K_{(H,C)}$ | $4, 4$ |

We start by analyzing the game when the expected noncompliance penalties are constant across action profiles: $\mathbb{E}K_{(C,C)} = \mathbb{E}K_{(C,H)} = \mathbb{E}K_{(H,C)} \geq 0$. In this case, there exists no $\mathbb{E}K$ that generates benefits from coordinating on $(C, C)$. To see this, (1) when $0 \leq \mathbb{E}K \leq 3$, $(C, C)$ itself is the only Nash equilibrium, obviating the need to coordinate; (2) when $3 < \mathbb{E}K \leq 4$, both $(C, C)$ and $(H, H)$ are Nash equilibria, but $(H, H)$ yields higher payoffs than $(C, C)$, and (3), when $\mathbb{E}K > 4$, $(H, H)$ 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 $(C, C)$.

Now we 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: Diffusion of responsibility.** When part of the noncompliance penalties involve reputation damages, those penalties might be lower when multiple firms are caught cheating. 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 create a game where there are benefits to reaching $(C, C)$ in a coordinated manner. We fix the probability of detection at $P_{(C,H)} = P_{(H,C)} = P_{(C,C)}$, and diffusion of responsibility implies that the ex-post noncompliance penalty satisfy $K_{(C,H)} = K_{(H,C)} > K_{(C,C)}$. A diffusion of responsibility leading to $\mathbb{E}K_{(C,C)} < 1$ and $\mathbb{E}K_{(H,C)} > 3$ generates a payoff matrix where coordinating on $(C, C)$ is beneficial. This is because, (1) for $(H, H)$ to be a competitive outcome, we need $\mathbb{E}K_{(H,C)} = \mathbb{E}K_{(C,H)} > 3$; and (2) for firms to prefer $(C, C)$ over the competitive outcome $(H, H)$, we need $\mathbb{E}K_{(C,C)} < 1$.[38]

**Mechanism 2: 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. When both firms are in noncompliance, they have skin in the game and will be less likely to call out each other. This increases $P_{(C,H)}$ for the $C$ firm above $P_{(C,C)}$. Furthermore, in an asymmetric profile, if the honest firm does call out on the noncompliant firm, the honest firm can sue the latter for damages. This raises the $K_{(C,H)}$ for the $C$ firm above $K_{(C,C)}$. These two effects combine to yield $\mathbb{E}K_{(C,H)} > \mathbb{E}K_{(C,C)}$. As before, if $\mathbb{E}K_{(C,H)} > 3$ and $\mathbb{E}K_{(C,C)} < 1$, firms will have the incentive to coordinate on $(C, C)$.

**Mechanism 3: 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 $\mathbb{E}K_{(C,H)} = \mathbb{E}K_{(H,C)} > \mathbb{E}K_{(C,C)}$. 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. Cases where the reduction in the detection probability leads to $\mathbb{E}K_{(C,C)} < 1$ and $\mathbb{E}K_{(H,C)} = \mathbb{E}K_{(C,H)} > 3$ will generate the incentive to coordinate on $(C, C)$.

**Turning coordination into collusion.** The first and third mechanisms both lead to a co-

[38] $(C, C)$ will also lead to the highest total payoff because $10 - 2\mathbb{E}K_{(C,C)} > 8 > 8 - \mathbb{E}K_{(H,C)}$.

ordination 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 firms' abatement. As long as $\mathbb{E}K_{C,H} = \mathbb{E}K_{H,C} \geq \mathbb{E}K_{C,C}$ 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 $(C, C)$.[39] We need to explain why the working group needed collusion with inter-temporal punishment, and not just coordination.

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.

In the skin in the game mechanism, the damages that the honest firm can obtain after suing the violator provide the temptation to deviate.

Under the third 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 $\pi_{(C,C)} - \mathbb{E}K_{(C,C)} < \pi_{(M,C)} - \mathbb{E}K_{(M,C)}$ where $\pi_{(M,C)} - \mathbb{E}K_{(M,C)} \geq \pi_{(H,H)}$. 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.

## A2 Sufficient Conditions for the Direction of Collusion

We provide sufficient conditions for the collusive abatement actions to be higher or lower than competitive abatement actions. Those sufficient conditions are derived by assuming smoothness of the variable profit function and the expected noncompliance penalty function and comparing their first-order derivatives.

The following proposition establishes the existence of a lower-than-competitive collusive profile, if reducing own abatement below the competitive profile increases the expected noncompliance penalty more than it increases the variable profit, and reducing rival abatement reduces the expected noncompliance penalty more than it reduces variable profit. The reverse conditions are sufficient for the existence of a higher-than-competitive collusive profile.

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

**Proposition 2.** There exists a collusive abatement profile with $a_f^C < a_f^{NC}$ for each firm $f$, if for all $\boldsymbol{a} < \boldsymbol{a^{NC}}$, the variable profit and the expected noncompliance penalty functions are smooth and satisfy:

1. $\frac{\partial \pi_f(\boldsymbol{a})}{\partial a_f} > \frac{\partial \mathbb{E}K_f(\boldsymbol{a})}{\partial a_f}$; and
2. $\frac{\partial \pi_f(\boldsymbol{a})}{\partial a_g} < \frac{\partial \mathbb{E}K_f(\boldsymbol{a})}{\partial a_g}$ for all $g \neq f$

*Proof.* We prove the case with two firms in the cartel; the extension to more than two firms is straightforward. An indifference curve at level $U$ for Firm 1 consists of all $(a_1, a_2)$'s such that $\pi_1(a_1, a_2) - \mathbb{E}K_1(a_1, a_2) = U$. To derive the slope of the indifference curve, we take the total differentiation:

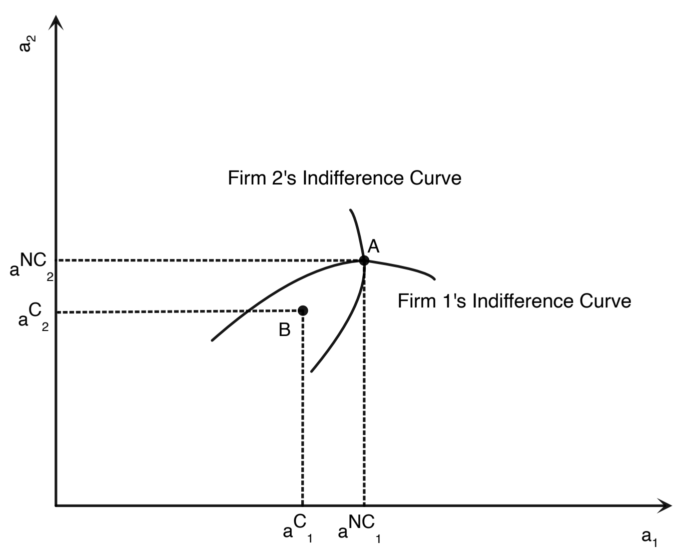
$$0 = \mathrm{d}U = (\frac{\partial \pi_1}{\partial a_1} - \frac{\partial \mathbb{E}K_1}{\partial a_1})\mathrm{d}a_1 + (\frac{\partial \pi_1}{\partial a_2} - \frac{\partial \mathbb{E}K_1}{\partial a_2})\mathrm{d}a_2,$$

which implies that:

$$\frac{\mathrm{d}a_2}{\mathrm{d}a_1} = -(\frac{\partial \pi_1}{\partial a_1} - \frac{\partial \mathbb{E}K_1}{\partial a_1})/(\frac{\partial \pi_1}{\partial a_2} - \frac{\partial \mathbb{E}K_1}{\partial a_2}).$$

At the competitive profile $\boldsymbol{a^{NC}}$, Firm 1's competitive first-order condition that $\frac{\partial \pi_1(\boldsymbol{a^{NC}})}{\partial a_1} = \frac{\partial \mathbb{E}K_1(\boldsymbol{a^{NC}})}{\partial a_1}$ implies that the slope of the indifference curve $\frac{\mathrm{d}a_2}{\mathrm{d}a_1}$ at $\boldsymbol{a^{NC}}$ is 0. At any $\boldsymbol{a} < \boldsymbol{a^{NC}}$, Conditions 1 and 2 imply that the slope is positive. Figure A1 illustrates the indifference curves going through the competitive profile that satisfy those slope constraints: each firm's indifference curve has a zero slope at the competitive point $A$ and positive slopes below.

Figure A1: Indifference Curves Going Through the Competitive Abatement Profile



Because of smoothness, there exists some point $B$ between the two indifference curves. Condition 2 implies that at holding fixed $a_f$, a lower rival abatement $a_g$ increases firm $f$'s payoff. Therefore, $B$ lies on the higher-payoff indifference curves than those going through the competitive profile. Hence, both firms prefer $B$ to $A$, and will have the incentive to reach $B$ jointly. What turns this into collusion is that each firm would have the temptation to deviate upwards from $B$ unilaterally. This is ensured by Condition 1, which says that holding fixed rival abatement, a higher own abatement increases the payoff. Therefore, $B$ is a collusive profile with lower-than-competitive abatement actions. □

## A3 Computation of Confidence Intervals

To compute a confidence interval for the lower bounds on the reduction in the expected noncompliance penalties in Section 6 and the welfare effects in Section 7 we take the following steps:

1. We draw $N$ vectors of demand coefficients using the estimated variance-covariance matrix of the demand parameters of the random coefficient logit demand specification, Column (4) in Table 4.

2. For each of the $N$ draws, we back out $N$ vectors of vehicle-specific marginal costs using the Nash-Bertrand competitive pricing conditions.

3. We project the $N$ marginal cost vectors on the cost covariates and obtain $N$ sets of marginal cost coefficients, as in Column (2) in Table 5. We save the estimated DEF cost coefficients and their estimated variances.

4. For each DEF coefficient we draw the 2.5th and 97.5th percentiles from a normal distribution with the estimated mean and variance of the DEF cost coefficient. We now have $2N$ sets of demand and DEF cost coefficients (two DEF cost coefficients for each set of demand coefficients).

5. We compute each of the market and welfare outcomes for the $2N$ sets of parameters. Our outcomes are monotonic in the DEF cost coefficient.

6. We construct a conservative 95% confidence interval by taking the 2.5th percentile of the $N$ outcomes with low DEF cost parameter and the 97.5th percentile of the $N$ outcomes with high DEF cost parameter.

We choose $N = 100$.

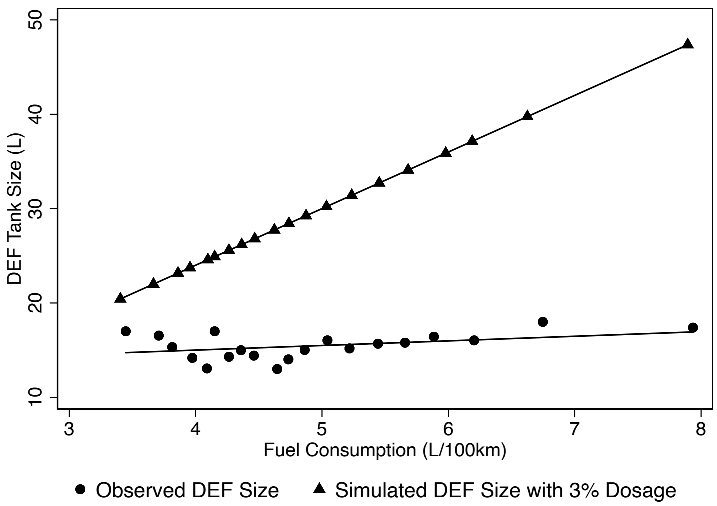
## A4 Additional Figures and Tables

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 A2: 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)<br>Trunk Space (L) | (2)<br>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: Additional Demand Specifications

| | (1) IV | (2) IV | (3) IV |
|---|---|---|---|
| Retail Price/Per Capita GDP | −3.038*** | −2.781*** | −2.797*** |
| | (0.092) | (0.094) | (0.096) |
| Trunk Space (cubic m) | 1.512*** | 1.503*** | 1.468*** |
| | (0.134) | (0.136) | (0.138) |
| Power (100kw) | 0.707*** | 0.600*** | 0.608*** |
| | (0.048) | (0.049) | (0.049) |
| Engine Size (L) | 0.194*** | 0.183*** | 0.165*** |
| | (0.018) | (0.018) | (0.019) |
| Curb Weight (ton) | −1.468*** | −1.507*** | −1.462*** |
| | (0.078) | (0.077) | (0.081) |
| Footprint (sq m) | 1.971*** | 1.954*** | 1.944*** |
| | (0.036) | (0.036) | (0.036) |
| Fuel Cost/Per Capita GDP | −30.172*** | −33.359*** | −33.081*** |
| | (1.655) | (1.668) | (1.693) |
| Foreign | −0.662*** | −0.683*** | −0.683*** |
| | (0.016) | (0.016) | (0.016) |
| Range (100km) | 0.119*** | 0.115*** | 0.118*** |
| | (0.005) | (0.005) | (0.005) |
| Has a DEF Tank | | −0.002 | 1.039 |
| | | (0.058) | (0.542) |
| DEF Tank Size (L) | | 0.004 | −0.059 |
| | | (0.003) | (0.033) |
| IV for Price | X | X | X |
| IV for Trunk | | X | X |
| IV for DEF Size | | | X |
| N | 220067 | 220067 | 220067 |
| Adjusted $R^2$ | 0.214 | 0.231 | 0.229 |

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 Column (1), we do not include DEF and instrument for retail price using BLP instruments (constructed from power, engine size, range, curb weight, footprint, and fuel cost divided by per capita GDP) and cost shifters (number of vehicles on the same platform, number of vehicles in the same plant, and change in production platform). In Column (2), we include DEF and instrument for both retail price and trunk space using additionally the trunk IV as discussed in Section 5. In Column (3), we include DEF and instrument also for the DEF tank size using additionally the sum of the trunk IV of vehicles from competing firms in the same market. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

Table A4: Price Diversion Ratios

| Price Increase from: | Market Share Loss | Market Share Gain (%) | | | |
|---|---|---|---|---|---|
| | | BMW | Daimler | Volkswagen | Average NWG |
| Panel A: Logit IV | | | | | |
| BMW | -1 | 3.09 | 1.97 | 10.04 | 1.66 |
| Daimler | -1 | 3.10 | 1.96 | 10.04 | 1.66 |
| Volkswagen | -1 | 3.10 | 1.97 | 10.02 | 1.66 |
| Average NWG | -1 | 3.10 | 1.97 | 10.04 | 1.64 |
| Panel B: Random Coefficient Logit IV | | | | | |
| BMW | -1 | 3.93 | 2.53 | 12.40 | 1.99 |
| Daimler | -1 | 4.11 | 2.67 | 12.64 | 2.00 |
| Volkswagen | -1 | 3.88 | 2.49 | 12.33 | 1.99 |
| Average NWG | -1 | 3.81 | 2.45 | 12.07 | 1.98 |
| Panel C: Random Coefficient Logit IV, Price Increase on DEF Vehicles Only | | | | | |
| BMW | -1 | 4.71 | 3.22 | 14.40 | 2.17 |
| Daimler | -1 | 4.31 | 2.83 | 13.34 | 2.08 |
| Volkswagen | -1 | 4.29 | 2.75 | 13.65 | 2.12 |
| Average NWG | -1 | 4.52 | 3.03 | 13.97 | 5.50 |

Notes: The diversion ratios measure, for a unit of price increase from an average vehicle produced by a row firm in an average market, the proportion of the lost market share that goes to each column firm. When the column firm is the same as the row firm, the entry measures the market share gains to other vehicles produced by that firm. Average NWG stands for an average non-working-group firm.

Table A5: Percentage Changes in Market Outcomes by the Collusion, 2007-2018

| | Competitive Scenario | | |
|---|---|---|---|
| | I | II | III |
| | 2% dosage | 3% dosage | 3% dosage plus |
| Quantity-Weighted Trunk | 0.09 | 0.25 | 0.41 |
| WG Euro 6 NEDC DEF | 2.97 | 8.41 | 14.33 |
| NWG Euro 6 NEDC DEF | 1.51 | 6.22 | 11.56 |
| | | | |
| Quantity-Weighted Price | 0.05 | 0.13 | 0.21 |
| WG Euro 6 NEDC DEF | 1.70 | 4.90 | 8.36 |
| NWG Euro 6 NEDC DEF | 1.19 | 4.12 | 7.05 |
| WG other diesel | -0.09 | -0.26 | -0.44 |
| NWG other diesel | -0.08 | -0.25 | -0.42 |
| WG gasoline | -0.12 | -0.34 | -0.56 |
| NWG gasoline | -0.09 | -0.27 | -0.46 |
| | | | |
| Quantity | 0.04 | 0.12 | 0.20 |
| WG Euro 6 NEDC DEF | 2.18 | 6.10 | 10.27 |
| NWG Euro 6 NEDC DEF | 0.84 | 3.93 | 7.52 |
| WG other diesel | -0.05 | -0.16 | -0.26 |
| NWG other diesel | -0.04 | -0.12 | -0.20 |
| WG gasoline | -0.08 | -0.23 | -0.37 |
| NWG 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. WG stands for working group, and NWG for non-working group.

Table A6: Welfare and Market Effects with an Alternative Competitive Scenario, 2007-2018

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

| Market Changes, % | Q.-Weighted Trunk | Q.-Weighted Price | Quantity |
|---|---|---|---|
| WG Euro 6 NEDC DEF | 3.55 | 2.61 | 2.12 |
| NWG Euro 6 NEDC DEF | -0.14 | -0.10 | -0.15 |
| WG other diesel | | -0.08 | -0.05 |
| NWG other diesel | | -0.07 | -0.03 |
| WG gasoline | | -0.11 | -0.08 |
| NWG gasoline | | -0.08 | -0.04 |

Notes: In this table, we take the more conservative stance that the collusion merely allowed the working group to adopt lower dosages than the rest of the industry. The competitive outcome would have the working group adopt DEF tanks of the same median size as the observed median size from other firms in the same series-generation start year. Trunk space and price changes are weighted by sales quantity. WG stands for working group, and NWG for non-working group.

## A5 Internet Archive Persistent URLs

1. Total Energies Adblue FAQ: https://web.archive.org/save/https://lubricants.totalenergies.com/business/distributorreseller/products/adbluer-faqs
2. Jaguar DEF and Euro 6 Emissions: https://web.archive.org/web/20211023025618/https://www.jaguar.com/owners_international/choose-your-engine/jaguar-diesel-exhaust-fluid.html
3. European Commission (2019): https://web.archive.org/web/20200205062247/https://ec.europa.eu/commission/presscorner/detail/en/IP_19_2008
4. European Commission (2021): https://web.archive.org/web/20210708090823/https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3581