Colluding against Environmental Regulation

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Abstract

We study collusion among firms against imperfectly monitored environmental regulation. Firms increase variable profits by violating regulation and reduce expected noncompliance penalties by violating jointly. We consider a case of three German automakers colluding to reduce the effectiveness of emission control technology. By estimating a structural model of the European automobile industry from 2007 to 2018, we find that the collusion lowers expected noncompliance penalties substantially and increases buyer and producer surplus. Welfare decreases by €0.73–2.51 billion because of increased pollution. We show how environmental policy design and antitrust play complementary roles in preventing noncompliance.

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

JEL codes: L4, L5, L6, Q5

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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. This paper considers firms colluding over compliance strategies to undermine regulation.

Why may firms collude on noncompliance, and what are the welfare effects of such collusion? We study these questions in the context of a recent antitrust case. In July 2021, the European Commission found that German automakers BMW, Daimler, and Volkswagen (or the "working group") colluded to restrict the effectiveness of diesel emission control technology (European Commission, 2021). Although the case did not involve collusive pricing, the Commission concluded for the first time that coordinating to limit technical development violates competition law.

Our analysis begins with a model that explores what firms can gain from participating in a coordinated scheme to reduce compliance. Firms face a pollution standard that is imperfectly enforced because of monitoring costs. Insufficient pollution abatement incurs noncompliance penalties in expectation, consisting of fines, legal costs, and reputation damages. However, abatement increases firms' marginal costs and compromises product attributes that consumers value. The resulting variable profits decrease with a firm's own abatement and increase with competitors' abatement. A firm's payoff is its variable profit minus the expected noncompliance penalty. Firms choose their pollution abatement either non-cooperatively or following a joint scheme.

The model shows that coordination on low abatement is only profitable when the expected penalties increase with other firm's abatement choices. The incentives to collude are generated by the enforcement of regulation and stem from positive externalities that firms' abatement actions impose on each other's expected penalties. We provide three reasons why expected penalties might decrease through coordinated noncompliance. First, penalties may decrease through diffusion of responsibility: A penalty for a noncompliant firm may be lower when multiple violators are caught. Second, coordination gives all participants "skin in the game," which lowers the risk of a compliant competitor reporting the violation. Third, the probability of the regulator inspecting a firm can depend on how that firm's abatement choices compares with other firms'. The first and third reasons can both be at play when a regulator considers multiple violators that are too big to fail and becomes reluctant to prosecute or impose steep penalties. Our model also shows that antitrust can complement regulation by counteracting the reductions in the expected penalty and making coordinated noncompliance unattractive.

We apply our model to the EU antitrust case on diesel emission control. The case involves a $\mathrm{NO_x}$ control technology called Selective Catalytic Reduction (SCR). Larger diesel vehicles need SCR to comply with increasingly stringent EU emission standards. SCR requires a tank of Diesel Exhaust Fluid (DEF) to neutralize $\mathrm{NO_x}$ emissions. The DEF tank takes up trunk space, which consumers value. The three German automakers communicated extensively through meetings and emails to agree on a "coordinated approach" of limiting the 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 $\mathrm{NO_x}$ pollution.

Our data cover vehicle registrations, characteristics, and on-road emissions from the European automobile market between 2007 and 2018. We observe detailed information on DEF tank sizes, emission control systems, and trunk space, among other variables. On-road emission test results reveal that diesel vehicles exceed the $\mathrm{NO_x}$ standard by a factor of three on average, and more than 70% of the diesel vehicles are out of compliance. We observe average DEF tank sizes of 16 liters. Based on the on-road emissions and engineering estimates, we compute the observed DEF tanks to be 13 liters smaller than what is required for 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 variable profits because they increase marginal costs and take up trunk space. Our demand estimates show that consumers would be willing to pay €230 to avoid the trunk space shrinkage from larger, compliant DEF tanks.[1] Our marginal cost estimates show that the SCR system costs €543, or €36 per liter of the DEF tank, 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 and the participation constraints of the collusion bound the expected noncompliance penalties faced by the working group. Estimating the bounds requires

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

knowledge of the DEF tank size that firms would have chosen without colluding. We present two approaches to quantifying this counterfactual non-cooperative equilibrium. First, we rely on the observation that non-working-group firms are not in the collusive scheme. Their non-cooperative choices imply first-order conditions that allow us to learn about the marginal expected noncompliance penalty function. With knowledge of this marginal expected noncompliance penalty function, we compute the counterfactual equilibrium of DEF choices, where both non-working-group and working-group firms choose DEF sizes non-cooperatively. We find from this procedure that the industry equilibrium would have been compliant in the absence of collusion. Collusion thus brings the whole industry into noncompliance. In the second approach, we use the descriptive evidence from our case to present a scenario in which the industry would be noncompliant in the non-cooperative equilibrium. Collusion merely allows the working group to reduce their DEF tank sizes further below non-working-group firms' choices. Given the range of non-cooperative scenarios derived from both structural and descriptive approaches, we estimate that the expected noncompliance penalties for the working group are at least €150–571 million lower due to coordinated noncompliance.

We discuss how the working group achieves such substantial reductions of expected penalties in the EU automobile market. The EU sets the emission standards and member states enforce them. Enforcement at a lower level of government generates a too-big-to-fail setting, where the working group may expect a national authority to be unwilling to punish widespread noncompliance. Furthermore, we find quantitative evidence that coordinated noncompliance would diffuse 16–81% of reputation damages when working-group firms are caught together, give skin in the game to competitors whose stolen business would contribute to 12–39% of the single violator's variable profit gain, and help mask otherwise suspiciously small DEF tanks.

The welfare effects of collusion against regulation are theoretically ambiguous. Environmental regulation weighs market surplus against pollution externalities. Collusion could improve social welfare if, for example, the regulation were too stringent.[2] In our empirical case, we find that collusion against regulation harms social welfare. Our results show that the collusion increases industry profits and car buyer surplus due to larger trunk space and lower marginal costs. However, these benefits are outweighed by the cost of increased NO_x pollution. Across the scenarios we consider, the collusion reduces social welfare by €0.73–2.51 billion. The Commission fined the cartel €2.7 billion, which we estimate to be sufficient to repair welfare damages.

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[2] The EU emission standard has become increasingly stringent over time and industry experts stated the EU 6 standard would be too demanding for manufacturers, reducing already low levels of pollution.

Our work has three policy implications. First, we evaluate how the existing EU policy environment compares to a "collusion-proof" environment, where welfare-reducing collusion does not occur. Che and Kim (2006) argue that policymakers can make firms the residual claimant of the total surplus to achieve collusion-proofness. We find that the working group expected to pay at most 55% of penalties from the collusion-proof policy. Second, antitrust has a complementary role in regulatory enforcement. To play this role in practice, antitrust needs to broaden its scope to be able to evaluate coordinated noncompliance and incorporate externality damages. Third, in the absence of antitrust, environmental policy design could take into account the possibility that enforcement can generate incentives to coordinate on noncompliance.

This paper contributes to the regulatory enforcement literature by providing a theoretical and empirical framework for understanding coordinated noncompliance. The literature 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. We show that 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 Shleifer (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. Whenever the enforcement of a regulation generates sufficiently strong positive externalities of firms' abatement choices on other firm's expected penalties, a regulation becomes vulnerable to collusion.

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 environmental regulation. Our focus on regulation adds complexity to the analysis because

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

collusion interacts with expected noncompliance penalties and produces 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 (2022) and Holland et al. (2016) on health outcomes, Bachmann et al. (2022) on reputation spillovers among German automakers, and Ater and Yoseph (2022) 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 coordinated noncompliance. Section 3 describes our data. Section 4 describes the empirical context and 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 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 provide a model to understand firms' regulatory compliance choices. The model shows that gains from coordinating on noncompliance stem from reductions in expected penalties. Antitrust reduces the benefits from participating in coordinated noncompliance and complements environmental regulation. The model provides bounds that inform the structure of the expected noncompliance penalties. We estimate these bounds in our empirical case. Finally, we describe the enforcement of coordinated noncompliance and implications of coordination by a subgroup of firms on other firms.

2.1 Individual Abatement Choices

Firms, indexed by $f \in \{1, 2, \cdots, n\}$, face a regulation that aims to correct a negative externality. In response to the regulation, firms take abatement actions to reduce externalities. Let $\boldsymbol{a} \equiv (a_1, a_2, \ldots, a_n)$ represent the profile of those abatement actions in the industry. We do not model entry and assume that the regulation does not drive firms out of the market.

Each firm f receives a variable profit of $\pi_f(\boldsymbol{a})$. We assume that the variable profit is strictly decreasing in a firm's own abatement action and strictly increasing in a competitor's abatement action. This assumption rationalizes regulation: no firm would abate absent the regulation. Abatement typically increases marginal costs or reduces quality by compromising product characteristics desirable to consumers. Firms who abate little therefore steal business from those who abate more.

For each firm f, let a_f^* denote the minimal abatement action that would be sufficient for it to comply with the regulation. If firm f chooses an abatement action below a_f^*, the firm is out of compliance. We assume away information asymmetry among firms. The regulator is at an information disadvantage relative to the firms. The regulator observes firms' abatement actions but not the degree to which those abatement actions reduce externalities towards compliance.[4] As a result, a noncompliant firm incurs penalties (such as regulatory fines and reputation damages) probabilistically. The regulator decides to inspect firm f with probability $P_f(\boldsymbol{a})$ to reveal its compliance status. If inspected, the firm incurs a noncompliance penalty $K_f(\boldsymbol{a})$, with $K_f(a_f, \cdot) = 0$ for $a_f \geq a_f^*$. We allow the probability and the penalty to depend on other firms' abatement choices. We discuss multiple reasons for this dependency below. We denote firm f's expected noncompliance penalty as $\mathbb{E}K_f(\boldsymbol{a}) \equiv P_f(\boldsymbol{a})K_f(\boldsymbol{a})$.

Firm f's payoff at the industry abatement profile $\boldsymbol{a}$ is $\pi_f(\boldsymbol{a}) - \mathbb{E}K_f(\boldsymbol{a})$. We denote the non-cooperative abatement profile as $\boldsymbol{a^N}$ and the fully compliant profile as $\boldsymbol{a^*}$. Because variable profits are decreasing in abatement and noncompliance penalties are zero when firms comply, over-compliance is a dominated action and hence $\boldsymbol{a^N} \leq \boldsymbol{a^*}$.

2.2 Coordinated Abatement Choices

A working group proposes a profile of abatement actions $\boldsymbol{a^J}$.[5] The proposal is accepted if and only if all firms agree to it. The working group can enforce the joint decision – we discuss this below in Section 2.3. Firms participating in the scheme may risk antitrust scrutiny. We define $\mathbb{E}A_f$ as the expected antitrust penalty a firm assigns to participating. If the proposal is not accepted, firms take non-cooperative abatement actions $\boldsymbol{a^N}$.

A working group may propose abatement actions that can be lower or higher than the non-cooperative abatement choices. Proposition 1 states that if firms accept a coordinated profile that

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[4] One can conceptualize this as each firm having a pollution type θ_f and abatement a_f. Emission are determined by $e_f = \theta_f - a_f$. The regulator sets an emission standard e^*. The regulator observes a_f but not θ_f. Firms can misreport emissions to the regulator and enter the market with $e_f > e^*$. We assume that misreporting in itself is not costly, but noncompliant firms risk penalties. Putting the regulator at an information disadvantage relative to the industry is consistent with the regulation literature, e.g., Weitzman (1974) and Baron and Myerson (1982).

[5] Not all firms may receive the working group's proposal. In Section 2.4, we discuss the incentives of firms not included in the proposal.

lowers abatement, this must imply that the expected penalty increases with other firms' abatement:

Proposition 1. If firm f participates in a joint proposal $\boldsymbol{a^J} < \boldsymbol{a^N}$, its expected penalty under $\boldsymbol{a^J}$ must be strictly lower than if it adopts a_f^J unilaterally: $\mathbb{E}K_f(\boldsymbol{a^J}) < \mathbb{E}K_f(a_f^J, \boldsymbol{a^N_{-f}})$. The reduction in the expected penalty is bounded below by the difference in variable profits:

$$\mathbb{E}K_f(a_f^J, \boldsymbol{a^N_{-f}}) - \mathbb{E}K_f(\boldsymbol{a^J}) \geq \pi_f(a_f^J, \boldsymbol{a^N_{-f}}) - \pi_f(\boldsymbol{a^J}). \tag{1}$$

Proof. In the non-cooperative profile $\boldsymbol{a^N}$ that firms would have chosen in the absence of collusion, a firm f could consider a unilateral deviation to action a_f^J. However, since a_f^J is an abatement action available to firm f but is not played in the profile $\boldsymbol{a^N}$, it would yield a payoff no higher than the firm's non-cooperative payoff:

$$\pi_f(a_f^J, \boldsymbol{a^N_{-f}}) - \mathbb{E}K_f(a_f^J, \boldsymbol{a^N_{-f}}) \leq \pi_f(\boldsymbol{a^N}) - \mathbb{E}K_f(\boldsymbol{a^N}). \tag{2}$$

Because firm f participates in the joint proposal, its participation constraint is:

$$\pi_f(\boldsymbol{a^J}) - \mathbb{E}K_f(\boldsymbol{a^J}) - \mathbb{E}A_f(\boldsymbol{a^J}) \geq \pi_f(\boldsymbol{a^N}) - \mathbb{E}K_f(\boldsymbol{a^N}). \tag{3}$$

Combining (2) and (3), we have:

$$\pi_f(\boldsymbol{a^J}) - \mathbb{E}K_f(\boldsymbol{a^J}) - \mathbb{E}A_f(\boldsymbol{a^J}) \geq \pi_f(a_f^J, \boldsymbol{a^N_{-f}}) - \mathbb{E}K_f(a_f^J, \boldsymbol{a^N_{-f}}). \tag{4}$$

Because $\mathbb{E}A_f(\boldsymbol{a^J}) \geq 0$ and after rearranging, this implies that $\mathbb{E}K_f(a_f^J, \boldsymbol{a^N_{-f}}) - \mathbb{E}K_f(\boldsymbol{a^J}) \geq \pi_f(a_f^J, \boldsymbol{a^N_{-f}}) - \pi_f(\boldsymbol{a^J})$. Because $\boldsymbol{a^J_{-f}} < \boldsymbol{a^N_{-f}}$, the assumption on the variable profits further implies that the right hand side of this inequality is strictly positive. $\square$

Coordination on lower abatement can only be profitable when firms' abatement choices impose negative externalities on other firms' payoffs. A firm's payoff is the variable profit minus the expected penalty. Abatement generates positive externalities across firms' payoffs through the variable profits, providing incentives for firms to coordinate on more abatement. Therefore, the negative externalities necessary to rationalize coordinating on *lower* abatement must stem from the expected noncompliance penalties.[6] The enforcement of the regulation itself can provide the required interdependencies in the expected penalties, which we discuss below. Our empirical case involves firms coordinating to limit emission control technology, we rely on the insight that the expected penalties are bounded below by a difference in variable profits to estimate a lower bound for the reduction in the expected penalties.

The proof of Proposition 1 reveals a complementary role for antitrust in enforcing regulation.

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[6] Appendix A3 formalizes how the direction of the coordinated proposal depends on the externalities in the payoff function.

When firms expect high antitrust penalties, $\mathbb{E}A_f$, it is less likely that a working group can make a profitable proposal:

Corollary 1. A larger expected antitrust penalty necessitate larger reductions in expected noncompliance penalties to rationalize $\boldsymbol{a^J} < \boldsymbol{a^N}$.

Proof. Inequality (4) implies that $\mathbb{E}K_f(a_f^J, \boldsymbol{a^N_{-f}}) - \mathbb{E}K_f(\boldsymbol{a^J}) \geq \pi_f(a_f^J, \boldsymbol{a^N_{-f}}) - \pi_f(\boldsymbol{a^J}) + \mathbb{E}A_f$, so an increase in $\mathbb{E}A_f$ lifts the lower bound on the $\mathbb{E}K_f$ reduction needed for a working group proposal to be accepted. □

We now discuss three reasons why coordinated noncompliance can reduce expected noncompliance penalties.[7] First, reputation damages included in the noncompliance penalty K_f can decrease when several firms are caught noncompliant. Such "diffusion of responsibility" can also arise from a too-big-to-fail argument. Upon detection of widespread noncompliance, enforcing the regulation would result in industry-wide fines, which the regulator might be reluctant to impose because of adverse economic effects. Second, when a firm violates the regulation by choosing noncompliance, our variable profit assumption implies that the firm will steal profits from compliant firms. This business-stealing effect creates a risk that honest competitors may call out the noncompliance to the regulator. By jointly choosing noncompliance, competitors get "skin in the game:" noncompliant competitors have less incentive to call out noncompliance of firm f, thereby reducing P_f. Third, the probability of detecting a firm's noncompliance can decrease when other firms are noncompliant. The regulator may infer the sufficiency of a firm's abatement action by comparing it to other firms' abatement actions.[8] If the regulator uses yardstick competition Shleifer (1985) and makes inspection decisions based on the observations of firms' abatement actions, firms can manipulate the regulator's information by coordinating abatement actions (Tangerås, 2002). This "reduction in the detection probability" channel can also arise from the too-big-to-fail argument. A regulator might be disinclined to start investigating when an investigation would reveal industry-wide noncompliance.[9]

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[7] Appendix A2 presents a simple two-by-two example to illustrate each reason. These reasons do not need to be present simultaneously to reduce expected penalties.

[8] 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.

[9] Firms may also have the power to affect the regulation directly through successful lobbying. Analyzing this possibility is beyond the scope of this paper.

2.3 Enforcement of Joint Decisions

Our model has so far been agnostic about how the working group enforces the joint abatement decisions. Documentary evidence about deviation incentives, together with the conviction of the cartel, suggests that coordinated noncompliance in our empirical case was achieved through collusion. Deviation incentives arise if a colluding firm wants to unilaterally increase abatement when the reduction in the expected noncompliance penalty from such deviation is greater than the reduction in the variable profit. Yet, firms in the working group have long-standing engineering cooperation in many vehicle technologies that allows for potential exclusion of the deviant firm as a way of punishment and of dynamic enforcement.[10] Appendix A1 contains the technical details that rationalize the joint noncompliance profile as a collusive outcome, including dynamic cartel enforcement and whistle-blower incentives.

In contrast to collusion on prices, deviation from the collusive noncompliance scheme leads to lower variable profits. Furthermore, while collusion on prices allows firms to avoid negative externalities on each other's variable profit, collusion on noncompliance enables firms to avoid negative externalities on each other's expected noncompliance penalty. We compare the welfare implications between price collusion and noncompliance collusion in Section 7.

2.4 Coordination by a Subgroup of Firms

Not all firms in the market may receive a joint noncompliance proposal from the working group. We now discuss the incentives of firms that are not part of the scheme.[11] We assume that non-working-group firms observe whether the proposal is accepted before making abatement choices.[12] If the proposal is accepted, the non-working-group firms condition on the proposal while choosing non-cooperative abatement actions. For notational convenience, we include those actions in the profile $\boldsymbol{a^J}$. If the proposal is not accepted, all firms choose actions non-cooperatively, $\boldsymbol{a^N}$.

Observing a noncompliant choice by a non-working-group firm g, $a_g^J < a_g^*$, implies that increas-

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[10] A recent empirical contribution by Igami and Sugaya (2022) estimates incentives to collude in the context of collusion on prices. Their setting allows quantification of the punishment from a reversal to Nash pricing. In our setting, the punishment could occur in future working group meetings by, for example, excluding a deviator from new technology. Because we do not observe the data to quantify such punishment, our framework focuses on the participation decision of working group members.

[11] We take the membership in the working group as exogenous. In our empirical context, the firms included in the working group are all German and have long established cooperation on engineering and R&D choices.

[12] Section 3 reports that the working group had introduced a small number of noncompliant vehicles in the years before the emission standard took effect. We interpret this as the working group communicating their acceptance of a proposal to non-working-group firms.

ing a_g^J to a_g^* would make the firm worse off:

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

where we have used $K_g(a_g^*, \cdot) = 0$. This inequality implies that firm g's expected noncompliance penalty at $\boldsymbol{a^J}$ is at most $\pi_g(\boldsymbol{a^J}) - \pi_g(a_g^*, \boldsymbol{a^J_{-g}})$. By following the working group into noncompliance, a non-working-group firm increases its variable profit more than it increases the expected noncompliance penalty. The same three reasons outlined above can explain why the non-working-group firms expect penalty reductions when they follow suit. We estimate the upper bound on non-working-group firms' expected noncompliance penalties in our empirical case in Section 6.

3 Data

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 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 for Euro 6 emission standards under the New European Driving Cycle (NEDC) and before the Volkswagen Dieselgate scandal began to affect vehicle designs.[13]

We augment the JATO data with data from ADAC, a German automobile association.[14] The ADAC data provide information on 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, trunk space, emission control technology, 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 testing and data company. The company conducted a thousand tests on on-road NO_x emissions between 2011 and 2020.

In our sample period 2007–2018, the EU automobile industry consists of the working-group

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[13] We describe the details of the Euro 6 emission standards, the NEDC, and the Volkswagen Dieselgate scandal in Section 4.

[14] 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.

firms—BMW, Daimler, and Volkswagen—and 17 other firms.[15] 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. In 2017, the working group generated €81 billion in revenue from diesel vehicles and €55 billion from gasoline vehicles, compared with €78 billion and €72 billion for non-working-group firms, respectively.

4 Empirical Context

4.1 EU Regulation of Automobile NO_x Emissions

Road transport generates about 40% of Nitrogen oxide (NO_x) emissions in the EU, of which 80% come from diesel vehicles (European Environment Agency, 2015). NO_x is a family of poisonous gases with adverse effects on the environment and human health.[16] Vehicle emission standards are a common tool for governments to reduce tailpipe emissions.[17]

Since 2000, the EU has adopted increasingly stringent NO_x emission standards for diesel vehicles. The EU implements the standards using a "type approval" procedure. A vehicle "type" can only enter the market if it passes the emissions test conducted by a third-party testing company. The EU sets the emission standards and member states enforce them. Figure 1 compares the NO_x emission standards in the EU and US. The depicted emission limits reflect the implementation date for automakers to obtain type approval. The emission standards bind for all new registrations typically one year later, providing a year for automakers to type approve their fleet. For example, type approval requires Euro 6 from September 2014 onward and new vehicle registrations require Euro 6 from September 2015 onward.

The emission standard relevant to our analysis is Euro 6 (2014–). The Euro 6 emission limit was announced in 2007. Given the long gap between the announcement and the implementation of the regulation, our framework focuses on firm behavior in response to a fixed regulation. The vehicles affected by the collusion were tested under the New European Driving Cycle (NEDC) procedure.

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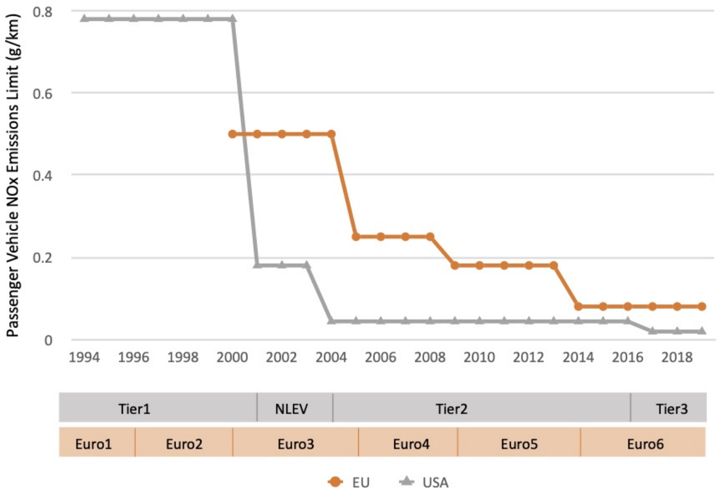
[15] The working-group firms own multiple brands: BMW owns BMW, MINI, and Rolls-Royce; Daimler owns Maybach, Mercedes, and Smart; and Volkswagen owns Audi, Bentley, Cupra, Lamborghini, Porsche, SEAT, Skoda, and VW.

[16] NO_x combines with atmospheric chemicals to form fine particulate matter (PM2.5). NO_x 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, 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 productivity, leading to more CO_2 in the atmosphere and interacts with water to form acid rain.

[17] Jacobsen et al. (2022) show that emission standards have caused substantial reductions in air pollution from transport in the US.

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



Starting in 2017, the EU changed the testing procedure several times to better reflect real driving emissions (RDE). The current testing procedure is the Worldwide Harmonized Light Vehicle Test Procedure (WLTP). We end our study in 2018 when the majority of new vehicles registered were still approved under NEDC.

4.2 Abatement Responses to NO_x Emission Standards

To meet Euro 6 emission standards, automakers adopted Selective Catalytic Reduction (SCR), a technology already used for trucks, in passenger diesel vehicles. SCR has virtually no performance penalty on vehicles and is suitable for larger vehicles. SCR requires a tank to hold Diesel Exhaust Fluid (DEF), a urea solution sprayed into engine-out emissions. DEF neutralizes NO_x into harmless water and nitrogen. Another emission control technology is Lean NO_x Trap (LNT). It reduces fuel efficiency and is more suitable for small vehicles. SCR and LNT can be combined to achieve more effective emissions control, but this option is less common.

While trucks refill their DEF tanks frequently, automakers designed DEF tanks in passenger cars to have annual refills. A full tank of DEF was supposed to last for a year of driving for two reasons. First, automakers were wary of burdening consumers with the hassle costs of refilling the DEF tank more frequently than annual check-ups to avoid making diesel cars less attractive than gasoline cars.[18] Second, passenger car owners found it challenging to refill DEF tanks themselves.

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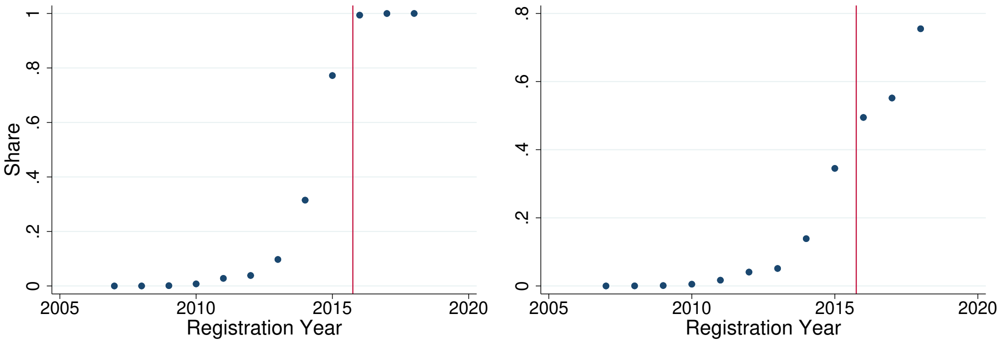
[18] Dohmen and Hawranek (2017) report that the manufacturers' internal records show that DEF tanks are "designed so that customers would not have to refill them." and the U.S. Environmental Protection Agency explicitly "demanded that the tanks contain enough urea to ensure that they would only have 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 refilling infrastructure had been designed for trucks and tune-ups would be needed after refills.[19]

Figure 2 depicts the adoption of Euro 6 emission standards and DEF tanks in new large diesel vehicle registrations.[20] The reference line marks September 2015, the Euro 6 implementation date for registrations. Subfigure (a) depicts the share of large diesels with Euro 6 type approval. The share of Euro 6 vehicles increases gradually in the years leading up to the Euro 6 implementation deadline, reaching 100% after the deadline. Subfigure (b) depicts the share of large diesel registrations with a DEF tank; it increases leading up to the Euro 6 implementation deadline as vehicle models with Euro 6 type approval enter. DEF market shares continue to increase after the Euro 6 implementation deadline, as more DEF models enter and non-DEF models exit. The specific adoption of DEF tanks in response to Euro 6 shows that firms respond to the regulation and at least signal compliance steps to the regulator.

Figure 2: Adoption of Euro 6 and Diesel Exhaust Fluid Tanks in Large Diesel Vehicles


(a) Euro 6 share

(b) DEF share

Notes: Panel (a) presents the share of large diesel vehicle registrations with Euro 6 type approval; Panel (b) presents the share of large diesel vehicles registrations with a DEF tank. The reference lines mark September 2015, after which all new registrations must abide by Euro 6.

Figure 3 shows the distribution of DEF tank sizes on SCR-only vehicles in the industry.[21] The observed tank sizes are dispersed, ranging from 8 liters to 38 liters. This provides evidence against standardization in DEF tank sizes.

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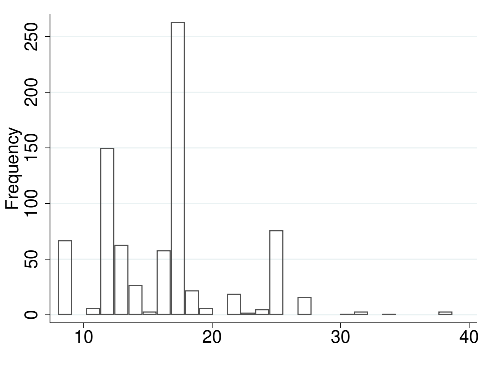
the owner, a potential turnoff for prospective customers," and that "Volkswagen wanted the fluid to last long enough to be refilled by dealers during regularly scheduled oil changes, so there would be no inconvenience to owners."

[19] 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.

[20] We define large diesel vehicles as having engines of at least 1.8 liters. Appendix Table A2 shows that DEF tanks are installed on larger and more powerful vehicles, consistent with Yang et al. (2015).

[21] Because LNT reduces emissions, DEF tank sizes on vehicles with both SCR and LNT are not comparable to those with SCR only.

Figure 3: Distribution of DEF Tank Sizes in SCR-only Vehicles, 2007-2018



Notes: Figure plots the frequency distribution of the DEF tank sizes in Liters observed in vehicles registered between 2007-2018.

4.3 Imperfect Enforcement and Widespread Noncompliance

It is difficult for a regulator to understand precisely how much DEF a vehicle needs 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 regulator does not observe engine-out emissions or the efficacy of the SCR system that result in tailpipe emissions. Accurate measurement of tailpipe emissions requires testing vehicles on the road. The NEDC testing procedure did not incorporate such on-road testing but relied exclusively on lab measurement.[22]

The absence of on-road testing further complicates enforcement when firms use defeat devices. Investigation and regulatory action in the US against Volkswagen revealed the use of defeat devices to circumvent US emission standards. These devices consist of sensors that identify test conditions and software that changes the vehicle's operation to emit less during lab testing than on the road. The Volkswagen scandal exposed industry-wide circumvention of emission standards in the EU (Reynaert and Sallee, 2021). An EU parliament inquiry on the inadequacy of the enforcement of emission standards blamed the unwillingness of EU member states with large automobile industries to properly enforce the standards (Gieseke and Gerbandy, 2017).

With defeat devices, automakers were able to obtain type approval for vehicles not fully compliant with emission standards.[23] The discovery of defeat devices and resulting attention on on-road emissions has negative consequences for automakers. First, automakers face a series of ongoing

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[22] On-road testing with portable emissions measurement systems attached to the vehicle accurately reflects emissions from the driving conditions of each individual test. However, on-road tests are difficult and costly to incorporate into regulation because of uncontrolled variability from the driver, traffic, and weather. In-lab tests, in contrast, are generally reproducible. The EU implemented on-road testing only with the change from NEDC to WLTP in 2018, when on-road testing technology became more mature and available.

[23] Although vehicles are "compliant" on paper based on in-lab measurement, they are not compliant on the road in the spirit of the EU regulation. In this paper, we define compliance as actual emission reductions on the road.

lawsuits by consumer groups and shareholders for dishonesty. Second, the discovery of high diesel pollution causes reputation damages for the diesel segment and the brands that engage in dishonest behavior. Third, the use of defeat devices is legally dubious in the EU, and several countries have started legal investigations into the practice.

Using our data, we assess the extent to which the observed DEF choices are compliant with Euro 6 emission standards. We first use the RDE data to estimate the relationship between DEF choices and on-road $\mathrm{NO_x}$ emissions. The on-road emission for vehicle j, measured in mg/km, is:

$$e_j = \kappa_j - \mathit{RemovalRate} \times a_j + \upsilon_j, \tag{6}$$

where κ_j are the engine-out emissions, which depend on vehicle characteristics such as fuel consumption and the presence of a supplementary LNT system, a_j is the DEF tank size, and υ_j is an i.i.d. idiosyncratic error. The parameter of interest is *RemovalRate*, describing how much a liter of DEF neutralizes $\mathrm{NO_x}$.

Table 1: 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. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

Table 1 reports the regression results using Equation (6) based on the RDE test results of Euro 6 SCR. Column (1) shows that emissions decrease with the DEF tank size and the presence of a supplementary LNT system, and they increase with fuel consumption. Because the collusion affected NEDC vehicles, we restrict to this subsample in Column (2) and estimate the DEF removal rate to be 7.71 mg/km per liter of DEF.

We then use the estimated relationship in (6) to calculate a counterfactual DEF size for each

Table 2: 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.

vehicle such that it is compliant with the emission limit of 80 mg/km. We convert the tank size to "dosages". Dosage is the ratio of the DEF tank size to the annual fuel consumption and is used in the engineering literature to measure the effectiveness of SCR systems.[24] To obtain the annual fuel consumption for each vehicle, we multiply an annual average mileage of 20,000 km with the vehicle-specific fuel consumption (liter per km driven).[25] 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% and exceeds the 75th percentile of observed dosages shown in the top panel of Table 2. 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 on 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%.[26] Similarly, Op De Beeck et al. (2013) report a compliant dosage of 3%, and Sala et al. (2018) report 3–5%. Based on all this evidence, we adopt 3% as the dosage needed for compliance.[27]

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[24] 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.

[25] 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."

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

[27] In appendix, we replicate all outcomes for a 2%-scenario in favor of automakers and a "3% plus"-scenario that increases the fuel consumption ratings by 30% to account for on-road fuel consumption for EU vehicles being higher than official fuel consumption (Reynaert and Sallee, 2021).

We apply the compliant dosages informed by the RDE dataset to our main dataset that covers the universe of NEDC SCR models available in the seven representative European markets. Comparing the actual choices of DEF tank sizes with our computed compliant sizes shows widespread noncompliance in the industry. Panel B in Table 2 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. At least 66.1% models have insufficient DEF tank sizes.

4.4 The Antitrust Case

The European Commission fined BMW, Daimler, and Volkswagen in July 2021 for forming a cartel that restricted emission control technology (European Commission, 2021). Since the 1990s, engineers of the leading German automakers have met regularly to discuss different technologies and engine specifications (Dohmen and Hawranek, 2017). The working group consists of BMW, Daimler, and Volkswagen, with Volkswagen also owning Audi and Porsche. The antitrust case is the first concluded case that has ruled technology coordination in violation of EU competition law.

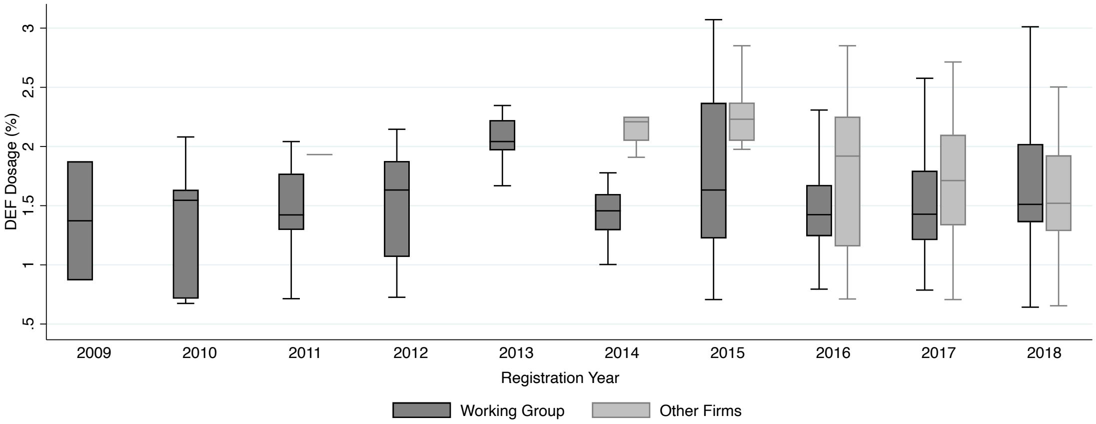
As early as 2006, the working group discussed fitting a DEF tank in future models. According to an internal working-group report, after the failure of an initial agreement to effectively limit the DEF tank sizes, the automakers sensed the "urgent need for cooperation". They applied pressure on their managers to hold additional meetings and reach an agreement. Although larger DEF tanks reduce more $\mathrm{NO_x}$, 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). Moreover, none of the companies wanted to make customers refill DEF tanks more than once a year. The firms thus coordinated to limit tank sizes and refill ranges.

It is striking that coordination took place in documented meetings of the firms. We think this potentially means that firms were not expecting to be subject to antitrust investigation, so that firms' expected antitrust penalty ($\mathbb{E}A$ in our model in Section 2) may be zero. The documented coordination is about limiting tank sizes but never explicitly about noncompliance and the use of defeat devices. The firms were allegedly aware that smaller tanks did not contain enough DEF to reduce $\mathrm{NO_x}$ emissions to levels compliant with Euro 6; a 2011 internal report stated that the introduction of Euro 6 would require an increase in DEF consumption of up to 50 percent (Ewing, 2018). This suggests that firm were expecting noncompliance penalties ($\mathbb{E}K$ in our model) with their insufficiently-sized DEF tanks.

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 lead to costly adoption of larger DEF tanks. 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 the incentive to unilaterally deviate to larger DEF tanks absent cartel enforcement. The long-term R&D relationship among the cartel members allows the cartel to punish deviant firms by excluding them from future R&D collaborations. Because R&D collaboration is not public information, we do not empirically estimate cartel enforcement and instead focus on the economic benefits of participation in the cartel.

Using our data, we plot in Figure 4 the evolution of DEF dosage distributions adopted by the working group compared to other firms' choices. The working group sold SCR vehicles as early as 2009 before the Euro 6 emission standards took effect. The number of these early SCR vehicles was 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 introduce SCR vehicles after Euro 6. The interquartile values of the working group's dosages are between 0.7% and 2.4%. The interquartile ranges of their dosages are consistently below those of other firms until 2018. Appendix Table A3 reports regressions of log DEF dosages on the working group indicator and finds that the working group adopts on average 8% lower dosages than other firms for SCR vehicles approved under NEDC. For vehicles approved under the new WLTP, the dosage difference is statistically insignificant. This explains the narrowing of the dosage gap towards 2018 shown in Figure 4 as the share of WLTP vehicles starts to increase.

Figure 4: 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.

In October 2017, the European Commission began initial inquiries into possible collusion by inspecting the premises of BMW, Daimler, and Volkswagen in Germany. Daimler blew the whistle on the cartel, and Volkswagen closely followed. Both firms rushed to blow the whistle because the inquiry into documents related to the ongoing Volkswagen emission scandal in the US was likely to uncover their agreement. Our framework focuses on quantifying the ex-ante risk firms placed on the exposure of their collusion at the time of the participation decision. The escalation in antitrust risk following the exposure of the Volkswagen scandal is beyond the scope of this paper.[28]

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 decision, (European Commission, 2021), does not explicitly mention noncompliance with the Euro 6 emission standards. The European Commission is restricted to implementing EU antitrust law and cannot make statements about environmental compliance.[29]

The investigation concluded in July 2021 and the European Commission set a fine of €2.7 billion for limiting the sizes of their DEF tanks in the diesel cars and coordinating on their ranges until the next refill. The automakers received lower fines in practice after a 20% novelty discount and a 10% settlement discount. The novelty discount was given because this is the first case of technology cooperation being ruled a cartel. BMW received a 373 million fine, and Volkswagen received a 502 million fine (including an additional leniency discount of 45% for cooperating with the investigation). Daimler avoided a total fine of €727 million for being the first whistle-blower.

4.5 Summary

We summarize this section with four important takeaways for our empirical model. First, the EU member states enforce the EU 6 emission standards imperfectly and are at an information disadvantage about actual emissions and the amount of abatement needed for compliance. Firms can therefore enter the market with noncompliant vehicles. Second, the fact that firms install costly SCR systems in response to the regulation and express concern about insufficiently-sized DEF tanks in internal communications shows that firms consider possible noncompliance penalties when

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[28] An EU antitrust expert shared the view that the whistle-blowing status was misused in this case because the firms would have been exposed anyway. The whistle-blowing was still useful in enabling the European Commission to close the case in a settlement.

[29] Formally, the EC argued that automakers colluded not to provide abatement beyond regulatory requirements. One interpretation of this statement could be that the non-cooperative equilibrium would be one of over compliance and collusion limited the industry to compliance. This is at odds with evidence on noncompliance presented below. We interpret this statement as the EC arguing that emission cleaning technology has been limited without making any statement about the public law that regulates emissions and is outside the EC's scope.

making noncompliant abatement choices. In the language of our theoretical model, $\mathbb{E}K_f(\boldsymbol{a}) > 0$ when $a_f < a_f^*$. Third, the German automakers settled a cartel case with the European Commission and admitted to coordinating to restrict DEF tank sizes. In the data, we thus observe a coordinated equilibrium with less abatement than in the absence of coordination: $\boldsymbol{a}^J < \boldsymbol{a}^N$. Fourth, our data confirms widespread noncompliance in the industry, $\boldsymbol{a}^J < \boldsymbol{a}^*$, and that the working group choose smaller DEF tanks than the rest of the industry. These facts inform non-cooperative counterfactuals we construct below.

5 Estimation

We specify a demand and supply model to estimate consumer preferences, substitution patterns, and firm variable profits. We are particularly interested in how firms' abatement choices affect vehicle demand and marginal costs. Next, we combine the estimated variable profit functions with the inequalities from Proposition 1 to estimate a lower bound on the reduction in the expected noncompliance penalties. Finally, we discuss how we construct non-cooperative abatement choices to estimate this lower bound.

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:

$$U_{ij} = \delta_j + \mu_{ij} + \varepsilon_{ij}, \tag{7}$$

where δ_j is the mean utility of vehicle j that is the same for every consumer, and μ_{ij} is the individual deviation from the mean utility. Consumer-vehicle specific taste shocks, ε_{ij}, are assumed to be i.i.d. Type-I extreme value distributed. The outside option is not purchasing a vehicle, with its indirect utility normalized to $u_{i0} = \varepsilon_{i0}$.[30]

The mean utility δ_j of vehicle j is:

$$\delta_j = \alpha p_j + x_j(a_j)\beta + \xi_j, \tag{8}$$

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 ξ_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

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[30] We assume that households are in the market for a new vehicle every 7 years. The implied outside good share varies between 30% and 77%.

x_j, such as trunk space.[31] Pollution reduction is considered to be an externality and does not enter the indirect utility independently.[32] We empirically verify this assumption in Section 6.

The individual deviation μ_{ij} from the mean utility is:

$$\mu_{ij} = \sigma_p p_j \nu_{ip} + \sum_k \sigma_k x_{jk}(a_{jk}) \nu_{ik}, \tag{9}$$

where ν_{ip}, ν_{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.

Consumer i chooses vehicle j if $U_{ij} \geq U_{ij'}$ for all $j' \neq j$. The market share for vehicle j comes from integrating over individual choices:

$$s_j = \int \frac{exp(\delta_j + \mu_{ij})}{\sum_{j'} exp(\delta_{j'} + \mu_{ij'})} \mathrm{d}\nu_i. \tag{10}$$

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 ξ_j. Our model considers strategic choices of the DEF tank size. We are less concerned about the correlation between ξ_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 potential correlations of ξ_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.[33] Third, we instrument for trunk space using

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[31] Appendix Table A4 reports that a one-liter increase in the DEF tank size reduces the trunk space by 0.91 liters. An average DEF tank of 16 liters then takes up 3.6% of the average trunk space of a diesel vehicle. 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) reports only the trade-off with trunk space.

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

[33] A typical manufacturing plant consists of several production lines. A production line consists of several stations at which workers or machines perform various assembly steps. Our data includes the name of each production line. A change in production line means that the vehicle assembly process moves to another line within the same or another plant.

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.[34] 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.[35]

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 θ by:

$$\min_{\theta} \xi(\theta)' Z A Z' \xi(\theta). \tag{11}$$

Our estimation algorithm takes into account the recent improvements in demand estimation.[36]

5.2 Profits and Marginal Costs

Firms earn variable profits given by:

$$\pi_f(\boldsymbol{a}, \boldsymbol{p}) = \sum_{j \in J_f} \left[p_j - mc_j(a_j)\right] q_j(\boldsymbol{a}, \boldsymbol{p}), \tag{12}$$

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. 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 Ω be the ownership matrix, where the element Ω_{jh} indicates whether the same firm sells product j and product h. Let $S(\boldsymbol{a}, \boldsymbol{p})$ be a matrix whose

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[34] 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.

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

[36] We use the Knitro solver with an analytic gradient, approximate the market share integral with 1000 Modified Latin Hypercube Sampling (MLHS) draws, use a tight convergence criterion for the contraction mapping (1e-12), estimate variances of the random coefficients and not standard deviations, use approximate optimal instruments for the random coefficients, start from 10 different starting values to avoid local minima, estimate two-step GMM with optimal weighting matrix, and check first and second-order conditions at the obtained minimum. See Conlon and Gortmaker (2020) for an overview of methodological improvements in demand estimation.

element $S_{jh} = -\frac{\partial s_h(\boldsymbol{a},\boldsymbol{p})}{\partial p_j}$. Then, the first-order condition of the firms' maximization problem implies the following vector of marginal costs:

$$\boldsymbol{mc} = \boldsymbol{p} + (\Omega \odot S(\boldsymbol{a}, \boldsymbol{p}))^{-1}\boldsymbol{s}, \tag{13}$$

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:

$$mc_j = \eta_x x_j + \eta_a a_j + \eta_{wg} a_j I(F_j \in WG) + \omega_j, \tag{14}$$

where $I(F_j \in WG)$ equals one whenever the producer of vehicle j, F_j, is in the working group and zero otherwise, and ω_j is the unobserved marginal cost. If the working group achieved cost savings relative to other firms, we would expect the parameter η_{wg} to be negative. We estimate marginal costs with a rich set of fixed effects. The cost parameters are identified from variations between almost identical vehicles in the same series generation produced on the same platform and plant. 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

We estimate a bound on the reduction in expected penalties formulated in Proposition 1 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 were to unilaterally choose the same level of low abatement as in the working-group proposal. Rearranging Inequality (2), we have:

$$\mathbb{E}K_f(a_f^J, \boldsymbol{a}_{-\boldsymbol{f}}^{\boldsymbol{N}}) \geq \pi_f(a_f^J, \boldsymbol{a}_{-\boldsymbol{f}}^{\boldsymbol{N}}) - \pi_f(\boldsymbol{a}^{\boldsymbol{N}}) + \mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{N}}), \tag{15}$$

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 noncooperative profile. A conservative lower bound on the expected noncompliance penalty of this unilateral low abatement is $\pi_f(a_f^J, \boldsymbol{a}_{-\boldsymbol{f}}^{\boldsymbol{N}}) - \pi_f(\boldsymbol{a}^{\boldsymbol{N}})$, because $\mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{N}}) \geq 0$.

Second, we obtain an upper bound on the expected noncompliance penalties faced by each working-group firm from the participation constraint in Inequality (3):

$$\mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{J}}) \leq \pi_f(\boldsymbol{a}^{\boldsymbol{J}}) - \pi_f(\boldsymbol{a}^{\boldsymbol{N}}) + \mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{N}}) - \mathbb{E}A_f(\boldsymbol{a}^{\boldsymbol{J}}). \tag{16}$$

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 penalties at the non-cooperative profile. A conservative upper bound is $\pi_f(\boldsymbol{a^J}) - \pi_f(\boldsymbol{a^N}) + \mathbb{E}K_f(\boldsymbol{a^N})$, because $\mathbb{E}A_f(\boldsymbol{a^J}) \geq 0$.

Third, we combine the lower and upper bounds from above to obtain a rearranged Inequality (4):

$$\underbrace{\mathbb{E}K_f(a_f^J, \boldsymbol{a^N_{-f}}) - \mathbb{E}K_f(\boldsymbol{a^J})}_{\text{Reduction in Expected Noncompliance Penalties}} \geq \underbrace{\pi_f(a_f^J, \boldsymbol{a^N_{-f}}) - \pi_f(\boldsymbol{a^J})}_{\text{Reduction in Variable Profit}} + \mathbb{E}A_f(\boldsymbol{a^J}), \tag{17}$$

which provides a lower bound on the *reduction* in the expected noncompliance penalties from joint low abatement relative to unilateral low abatement. A conservative lower bound is $\pi_f(a_f^J, \boldsymbol{a^N_{-f}}) - \pi_f(\boldsymbol{a^J})$, because $\mathbb{E}A_f(\boldsymbol{a^J}) \geq 0$. Unlike the lower bound in Inequality (15) and the upper bound in Inequality (16), this combined lower bound on the reduction in expected noncompliance penalties does not depend on $\mathbb{E}K_f(\boldsymbol{a^N})$, which cancels out.

5.4 Non-Cooperative Equilibria

To quantify the bounds on expected noncompliance penalties characterized by Inequalities (15)–(17), we need to estimate variable profits $\pi_f(\boldsymbol{a^J})$, $\pi_f(a_f^J, \boldsymbol{a^N_{-f}})$, and $\pi_f(\boldsymbol{a^N})$. We estimate the first term from observed quantities and Nash-Bertrand markups defined in Equation (13). To estimate the remaining terms, we need to know DEF tank sizes in a non-cooperative equilibrium, $\boldsymbol{a^N}$, which is not observed in the data. The position of $\boldsymbol{a^N}$ between $\boldsymbol{a^J}$ and $\boldsymbol{a^*}$ determines the degree of additional noncompliance achieved by the working group. We present results for two cases of the non-cooperative equilibrium. First, a structural estimation of the marginal expected noncompliance penalty function shows that the industry would move to a compliant equilibrium $\boldsymbol{a^N} = \boldsymbol{a^*}$ in the absence of collusion. Second, we simulate a noncompliant $\boldsymbol{a^N} \in (\boldsymbol{a^J}, \boldsymbol{a^*})$ that plausibly captures the minimal effect of collusion without relying on assumptions about the expected noncompliance penalty function.

In the first case, we use our structural framework to estimate $\boldsymbol{a^N}$. We rely on the non-working-group firms' first-order conditions associated with their non-cooperative abatement choices conditional on the working-group collusion:

$$\frac{\partial \mathbb{E}\pi_g(\boldsymbol{a^J})}{\partial a_j} = \frac{\partial \mathbb{E}K_g(\boldsymbol{a^J})}{\partial a_j}. \tag{18}$$

Our estimated demand and marginal cost equations allow us to construct the left-hand side of this equation. By making a functional-form assumption on the right-hand side, we can use variations in the marginal profits to estimate the marginal expected noncompliance penalty. We assume that the marginal expected noncompliance penalty is a linear function of a firm's own abatement choice, average abatement levels of other firms, and a firm's historical sales revenue. Once we estimate the right-hand side of equation (18), we can use this system of first-order conditions to solve for the counterfactual $\boldsymbol{a^N}$, where all firms choose abatement non-cooperatively. We detail the assumptions and computational steps for this approach in Appendix A4. We find that all firms have the incentive to increase abatement in the absence of collusion. Since the expected noncompliance penalty is zero at compliance, our estimates imply that the non-cooperative equilibrium is the corner solution with industry-wide compliance, $\boldsymbol{a^N} = \boldsymbol{a^*}$.

A compliant non-cooperative equilibrium corresponds to the maximal amount of additional noncompliance achieved by the working group proposal. It not only allows the working group to choose lower dosages than the rest of the industry, but it also leads to widespread noncompliance in the industry.[37] We construct this $\boldsymbol{a^N}$ by increasing the DEF tank sizes of all firms in the industry to compliance. We show results for the 3% dosage scenario defined in Section 3 and report robustness results for the 2% dosage and 3% dosage plus (with real-world fuel consumption) in Appendix Table A8. These scenarios span a comprehensive range of what it takes to comply, with average DEF tank sizes ranging from 19 to 38 liters and average increases of 3 to 22 liters.

In the second case, we focus on a scenario where the working group achieves a minimal amount of additional noncompliance beyond non-cooperative choices: $\boldsymbol{a^N} \in (\boldsymbol{a^J}, \boldsymbol{a^*})$. To approximate this $\boldsymbol{a^N}$, we rely on the difference in the observed dosages between the working and non-working group firms, as shown in Figure 4. The collusion may have merely enabled the working-group firms to adopt lower dosages than the non-working-group firms. In this case, absent the collusion, the working group may have chosen dosages comparable to the rest of the industry. We implement this approach by moving the distribution of dosages of the working group so that their median dosage in each year equals that of the median of non-working-group firms.[38] Across years, this corresponds to an increase in the working group median dosages from 1.5% to 2.1%, or a 5-liter increase in median tank sizes.

To sum up, the collusion succeeded in reducing tank sizes, and we compute two non-cooperative

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[37] Figure 4 shows that working-group firms released vehicles approved for Euro 6 before the regulation became binding in 2014. The early DEF dosages are comparable to what firms chose in 2014–2018. The working group may have thus signaled their low DEF dosage choices to non-working group firms. When Euro 6 standards take effect, the non-working groups follow the working group into noncompliance.

[38] We ignore a potential strategic response of non-working-group firms to the change in the DEF tank sizes of the working group. Such strategic responses are of second-order importance for the welfare results because the non-working group firms sell much fewer vehicles with DEF tanks.

scenarios that correspond to a minimal and a maximal collusion-enabled reduction. We use these scenarios to quantify the possible outcomes of interest in the next two sections.

6 Estimation Results

We first present our demand and marginal costs estimates. We then quantify bounds on the reduction of expected noncompliance penalties that the collusion achieves. We show empirical evidence of the presence of the possible reasons behind such a reduction, discussed in Section 2. The 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 3. 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 no statistically significant demand for DEF. In Appendix Table A5, we report more specifications involving the DEF tank size, and similarly find no statistically significant coefficients. While those imprecise estimates do not statistically rule out a positive demand for DEF, several arguments indicate that consumer demand for DEF is unlikely. First, had consumers valued specifications of emission control technology, automakers could have offered SCR much earlier. Engine variants and interior choices are omnipresent in this market. In contrast, SCR was deployed as a response to Euro 6, as shown in Figure 2. Second, consumers are likely uninformed about the DEF tank size. DEF tank sizes are not usually listed in owner's manuals or displayed at dealerships. Third, as described in Section 4, during the study period, DEF refills are designed to coincide with annual check-ups without intervention from consumers.

Column (3) instruments for both the trunk space and the price. The instrument set 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 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.[39]

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

Table 3: 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 emission 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. The logit standard errors are clustered at the series-body level, the random coefficient logit is estimated by optimal two-step GMM.

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. The median own-price elasticity is -3.26. The median firm-level price elasticity is -2.55. The median market-level price elasticity is -1.24. The median margin is 33%. In Appendix Table A6, 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 our analysis of the diffusion of responsibility and skin in the game mechanisms below, as well as in our counterfactual analysis.

€35,091.

6.2 Marginal Cost Estimates

Table 4 reports the marginal cost estimates for diesel vehicles.[40,41] Column (1) estimates that the Selective Catalytic Reduction (SCR) technology costs €543 and the LNT technology costs €357. These estimates are roughly consistent with the engineering estimates in Sanchez et al. (2012), who report SCR to cost $494 (for large vehicles) and LNT to cost $320 (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 per liter. We use this estimate in our counterfactual analysis when we change DEF tank sizes.

Table 4: Marginal Cost Estimates

	(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: Reported in million 2018 euros. 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. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

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

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[40] 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.

[41] 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 A5.

statistical evidence that the working group achieved cost savings relative to the rest of the industry. 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 (15)–(17). We take the collusive choices a_f^J as the observed DEF tank sizes, and the non-cooperative choices a_f^N as the DEF tank sizes consistent with the two scenarios discussed in Section 5: one where the non-cooperative equilibrium is noncompliant and the other where it is compliant. For each scenario, we recompute marginal costs and trunk space with counterfactual DEF tank sizes and find new equilibrium prices and quantities.

Table 5: Bounds on the Expected Noncompliance Penalties

	Lower bound on $\mathbb{E}K_f(a_f^{\boldsymbol{J}}, \boldsymbol{a_{-f}^N})$	Upper bound on $\mathbb{E}K_f(\boldsymbol{a^J})$	Lower bound on the reduction
Panel A: Observed $\boldsymbol{a^J}$ *vs.* Noncompliant $\boldsymbol{a^N}$			
BMW	-	-	54
			[31, 80]
Daimler	-	-	29
			[16, 43]
Volkswagen	-	-	67
			[40, 97]
Working Group Total	-	-	188
			[87, 220]
Panel B: Observed $\boldsymbol{a^J}$ *vs.* Compliant $\boldsymbol{a^N} = \boldsymbol{a^*}$			
BMW	194	31	162
	[116, 276]	[11, 52]	[94, 237]
Daimler	521	412	109
	[309, 747]	[243, 591]	[62, 164]
Volkswagen	1629	1330	299
	[970, 2335]	[790, 1902]	[176, 425]
Working Group Total	2344	1774	571
	[1395, 3357]	[1048, 2541]	[334, 829]

Notes: Reported in million 2018 euros. Bootstrapped 95% confidence intervals for the lower bound on the reduction in the expected noncompliance penalties are in brackets. See Appendix A5 for details.

Table 5 reports three bounds: a lower bound on the expected noncompliance penalty under unilateral low abatement, an upper bound on the expected noncompliance penalty under coordinated low abatement, and a lower bound on their difference. The first two bounds cannot be computed when the non-cooperative equilibrium involves noncompliance because the expected penalty $\mathbb{E}K_f(\boldsymbol{a^N})$ is not zero when $\boldsymbol{a^N} < \boldsymbol{a^*}$. However, the term $\mathbb{E}K_f(\boldsymbol{a^N})$ cancels out when taking the difference between the first two bounds. Compared to unilateral low abatement, coordinated low abatement reduces the expected penalties by at least €54–162 million for BMW, €29–109 million for Daimler, and €67–299 million for Volkswagen. The estimated reductions in penalties differ between firms because the size of the change in the counterfactual trunks is asymmetric and because each firm sells different products associated with different own- and cross- price elasticities. In sum, the collusion reduces the expected noncompliance penalties faced by the working group by at least €150–571 million across the three scenarios. Appendix Table A8 reports results under additional compliance scenarios.

The reductions in expected penalties are economically significant. In the compliant non-cooperative scenario, the working group increases variable profits by €1.77 billion relative to compliance (see Table 8). The €571 million reduction in penalties is large relative to the additional variable profit gains from collusion. This number represents the reduction in the expected, or ex ante, noncompliance penalties.

6.4 Reasons for Expected Penalty Reduction

We provide quantitative evidence for the three reasons that potentially reduce expected penalties: diffusion of responsibility, skin in the game, and probability of detection. The evidence presented here, illustrated with compliance as the non-cooperative scenario, suggests the extent to which these economic forces are potentially present in the industry. With a single case of collusion, we are unable to identify their importance separately.

Diffusion of responsibility. We quantify the degree to which noncompliance penalties, including potential reputation damages, could diffuse when multiple violators are caught noncompliant. When one firm is caught and receives a reputation shock, consumers experience utility loss for that firms' products and can substitute to other firms with unaffected reputations. When all firms are caught, 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.[42]

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[42] 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.

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.[43] 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 in the compliant non-cooperative scenario. This vector of reputation shocks would exactly undo the variable profit gains from coordinated 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 6 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 diffuse much of BMW's 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.

Table 6: Diffusion of Responsibility with Reputation Shocks

	Joint Shock Effect	Unilateral Shock Effect	Effect Difference	% Diffused
	$\pi_f(t_f, t_{-f}) - \pi_f$	$\pi_f(t_f, 0) - \pi_f$	$\pi_f(t_f, t_{-f}) - \pi_f(t_f, 0)$	
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 (in million 2018 euros), 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., $100 \times 141/172 = 81\%$).

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

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[43] Bachmann et al. (2022) study collective reputation; we shock reputations of individual firms.

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 7 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 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 7: Skin in the Game with Business Stealing

	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 (in million 2018 euros) when a firm in a row is the unilateral violator of the regulation: the firm chooses tank sizes a_f^J 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., $100 \times (4.4+17.5)/55.6 = 39\%$).

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

While Figure 3 shows the DEF tank size distribution observed under the collusive scheme, Figure 5 plots the observed DEF tank sizes of each working-group firm against the 3% compliant distribution for the rest of the industry. Figure 5 suggests that vehicles released by BMW, Daimler, and Volkswagen would likely appear suspicious relative to a compliant rest-of-industry.[44] The working group thus potentially benefits from reduced scrutiny by moving into noncompliance jointly.[45]

In sum, we find empirical support for an economic environment that is susceptible to reductions

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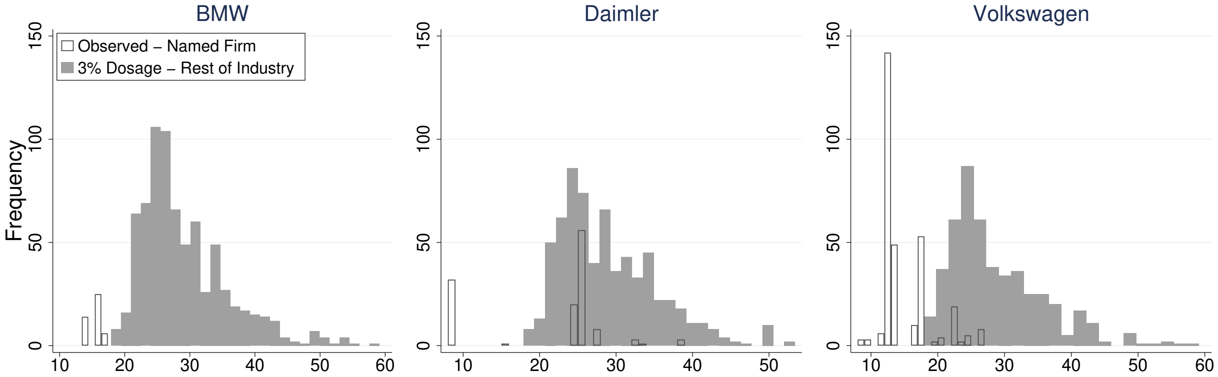
[44] Dohmen and Hawranek (2017) write that "[i]f one manufacturer had installed larger [DEF] tanks, licensing and regulatory authorities would probably have become suspicious. The obvious question would have been why that one company's vehicles needed so much more urea to clean the exhaust gases, while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

[45] 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 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.

Figure 5: Unilateral Noncompliance Stands Out



Notes: This figure plots the distribution of DEF tank sizes of each working-group firm against a counterfactual distribution of compliant DEF tank sizes (at 3% dosage) for the rest of the industry.

in expected penalties under coordinated noncompliance. Our demand estimates show that the working-group firms are close competitors, especially in the large 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. Finally, the working group involves all major German automakers, creating a situation where the national enforcer might find the working group too big to fail, an explanation that can be nested under diffusion of responsibility and reduction in the detection probability. As described in Section 4, member states were reluctant to enforce strict emission testing.[46]

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 prefer the non-cooperative equilibrium. Relative to the *noncompliant* non-cooperative scenario, collusion causes the non-working-group firms to lose €320 million in variable profits because they compete with more attractive diesel vehicles of the working group. However, moving from the *compliant* non-cooperative scenario to the observed collusion only reduces the non-working-group firms' variable profits by €27 million. Relative to the *compliant* non-cooperative scenario, collusion enables noncompliance for the entire industry. The non-working group's loss from competing with more attractive diesel vehicles of the working group is almost completely offset by gains from also being able to move into noncompliance.

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[46] When firms succeed in capturing an enforcer, one might question their power to influence the level of the standards as well. Our framework keeps the emission standards fixed for two reasons described in Section 4. First, the standards are set at the EU level, and the German firms may have less power to lobby at the EU level. Second, the standards are set seven years in advance of implementation.

Conditional on the working group colluding, the non-working-group firms as a group gain €983 million in variable profits by following the working group into noncompliance from 3% dosage compliance. We obtain this number based on Inequality (5), by comparing each non-working-group firm's observed variable profits with what it would receive as the only compliant firm. 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 reasons that explain the reduction in expected noncompliance penalties may also apply to non-working-group firms.

7 Welfare and Policy Implications

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

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

$$W(\boldsymbol{a}) = BS(\boldsymbol{a}) + \sum_f \pi_f(\boldsymbol{a}) - \sum_j \rho e_j(a_j) q_j(\boldsymbol{a}), \tag{19}$$

which includes buyer surplus BS, the sum of firm profits π_f, and the externality damages given by the marginal damage of a unit of $\mathrm{NO_x}$ emissions, ρ, times emissions and sales. The social welfare change caused by collusion relative to competition equals:

$$\Delta W = W(\boldsymbol{a}^{\boldsymbol{J}}) - W(\boldsymbol{a}^{\boldsymbol{N}}). \tag{20}$$

To find changes in buyer surplus BS and variable profits π_f, 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.[47] 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.

For changes in externality damages, we sum the changes in $\mathrm{NO_x}$ damages from each of firm f's

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[47] One concern with our pollution effect measure is that buyers of NEDC DEF vehicles would substitute to other vehicles or the outside good in the absence of collusion. The outside good includes the option to keep their current polluting old diesel vehicle. We abstract away from this channel because we find collusion increases the total quantity of vehicles sold by only 0.12%, non-NEDC-DEF diesels have a very small market share, and gasoline vehicles emit very low levels of $\mathrm{NO_x}$. See Appendix Table A7. Jacobsen et al. (2022) model how the efficiency of US pollution standards is affected by scrappage.

Euro 6 NEDC SCR vehicle j registered in year t as follows:

$$\sum_{\tau=0}^{T} \delta^{\tau} \left[q_j (e^* + (a_j^* - a_j) RemovalRate) - q_j^* e^* \right] \times AnnualMileage \times \rho, \tag{21}$$

where T is the lifetime of a vehicle, δ is the discount factor, e^* is the compliant emission, a_j is the DEF tank size, and q_j^* and a_j^* are the counterfactual sales quantity and compliant 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. The term $(e^* + (a_j^* - a_j)RemovalRate)$ represents the on-road emissions of vehicle j. 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.[48] 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 3.

7.2 Welfare Results

Table 8 reports the welfare effects of the collusion. The table shows that the working group's extra variable profits due to the collusion are substantial: €0.9 billion relative to the noncompliant non-cooperative scenario and €1.77 billion relative to the compliant scenario. The aggregate profits of other firms decrease by a much smaller extent, as we explained in Section 6.5. Buyer surplus also increases substantially with as much as €3.26 billion relative to compliance. We find the health damages of excess NO_x to reach €2.32-7.52 billion, outweighing the sum of the gains in firm profits and buyer surplus.[49]

The collusion enables both the working-group and non-working-group firms to charge higher prices for Euro 6 NEDC DEF vehicles and also sell more of them. Compared to the compliant non-cooperative scenario, Appendix Table A7 reports that the working group sells 6% more Euro 6 NEDC DEF vehicles featuring 8% larger trunk space and 5% higher prices (trunk space and price

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[48] 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 to \$1.18.

[49] The excess NO_x emissions due to collusion are 106 kton relative to compliance.

Table 8: Welfare Effects of the Collusion, 2007-2018

	Non-Cooperative Scenario	
	Noncompliant	Compliant
Working Group's Profit $\Delta\pi$	0.90	1.77
	[0.53, 1.30]	[1.05, 2.54]
Residual Claim $\Re$	-1.63	-4.28
	[-1.87, -1.37]	[-5.48, -3.03]
NO_x health impact	-2.32	-7.52
	[-2.38, -2.27]	[-7.70, -7.36]
Buyer surplus	1.01	3.26
	[0.58, 1.44]	[1.90, 4.63]
Other firms' profit	-0.32	-0.03
	[-0.46, -0.19]	[-0.07, -0.01]
Net Welfare $\Delta\pi + \Re$	-0.73	-2.51
	[-1.34, -0.08]	[-4.42, -0.47]
Ratio $\lambda = \Delta\pi/(-\Re)$	0.55	0.41
	[0.28, 0.95]	[0.19, 0.84]

Notes: Reported in million 2018 euros. Bootstrapped 95% confidence intervals are in brackets, see Appendix A5.

changes are weighted by sales quantity). Likewise, other firms sell SCR vehicles with 6% larger trunk space and 4% higher prices. The prices and quantities of non-NEDC-DEF diesel and gasoline vehicles experience only slight decreases.

Taking together buyer surplus, firm profits, and NO_x damages, we find that the net welfare change as defined in Equation (20) is -€2.51 billion relative to the compliant non-cooperative scenario with a 95% confidence interval of [-4.42, -0.47]. Relative to all the non-cooperative scenarios we consider in Table 8 and Appendix Table A9 we estimate welfare changes to be between -€0.78 and -€4.44 billion.

The welfare consequence of this collusion case is very different from that of price collusion. While price collusion typically results in a transfer from consumers to producers, this collusion on noncompliance results in benefits to both participating firms and buyers at the expense of population-wide externality damages.

7.3 Policy Implications

Our welfare results allow us to evaluate the existing regulatory environment. We do this by comparing firms' expectations about their punishment with a penalty that would allow for welfare-increasing cooperation on technology but prevent welfare-reducing collusion. Following Che and Kim (2006), we compute the penalty that prevents welfare-reducing collusion by making the cartel the residual claimant of the welfare effect of the collusion on the rest of the society:

$$\Re = \Delta W - \Delta\pi, \tag{22}$$

where $\Delta\pi$ is the working group's profit gain from collusion, $\sum_{f\in WG}[\pi_f(\boldsymbol{a^J}) - \pi_f(\boldsymbol{a^N})]$. A residual-claim penalty transforms the sum of the participation constraints (3) into $\Delta\pi + \Re = \Delta W \geq 0$,[50] so that the working group's objective becomes perfectly aligned with that of a regulator who seeks to maximize social welfare. Firms accept the collusive proposal $\boldsymbol{a}^J$ only when collusion is not welfare-reducing.

Focusing on cases when $\Re < 0$, we construct the following measure that relates collusive profits to the residual claim:

$$\lambda = \frac{\Delta\pi}{-\Re}. \tag{23}$$

Under a collusion-proof policy, we should only observe collusion if $\Delta W \geq 0$, or $\lambda \geq 1$. In this case, colluding increases the working group's profits more than it harms the rest of the society. Making the working group the residual claimant has a redistributive role, but the working group would still collude as it generates enough profits to pay the claim. Such welfare-increasing collusion could indicate that the emission standard is too stringent; collusion increases efficiency but does so by harming other market participants.

However, the actual policy environment is not necessarily collusion-proof. If $\lambda \in (0, 1)$, then the collusion increases the working group profits less than it harms the rest of the society. This is where our empirical case falls. The residual claim, as reported in Table 8, is -€1.63 billion when we compare the collusive outcome to a noncompliant non-cooperative scenario and -€4.28 billion when the comparison is with compliance. We estimate λ to be between 0.41 and 0.55. We can interpret this range for λ in three different ways. First, firms would participate in the collusive proposal as long as the probability of being made the residual claimant is lower than 0.41. Second, firms would participate in the collusive proposal if they expect to be caught and pay at most 0.41 of the residual claim. Third, $1 - \lambda = 0.45$ gives the lower bound on the distance of the existing regulatory environment from the residual claim policy.

Antitrust complements weakly enforced environmental regulation and brings the EU regulatory environment closer to a residual-claim policy. However, the antitrust fines imposed on the working group are not sufficient. While the antitrust fines are sufficient to repair welfare damages ex post,

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[50] 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).

they fall short of deterring welfare-decreasing collusion on noncompliance ex ante.

8 Conclusion

We study the causes and welfare effects of firms coordinating 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 abatement choices, in which the incentive to coordinate on noncompliance stems from the ability to reduce expected penalties. 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 €0.73–2.51 billion. The magnitude of the welfare damages the cartel inflicts on the rest of the society reaches between €1.63–4.28 billion.

Although our analysis shows that antitrust is not stringent enough to prevent welfare-reducing collusion in the EU, we find an important complementary role of antitrust in enforcing regulation. Antitrust counteracts the reduction in the expected noncompliance penalty and reduces the benefits from collusion. However, using antitrust to complement environmental regulation has practical challenges. Unlike price collusion where the degree of overcharging provides the basis for fines and damages, coordinated noncompliance leads to overselling rather than overcharging. Prices are too low or product quality too high from a social perspective, which increases sales as well as pollution per unit sold. As such, the quantity sold and the additional pollution could form the basis of antitrust fines. The European Commission based fines on revenues from the relevant segment. There were no claims about the pollution, and the actual fines do not directly relate to a relevant welfare statistic (European Commission, 2021). As discussed in Section 4, the European Commission has no legal authority to make statements about environmental compliance. This makes it challenging to set fines based on relevant welfare measures such as the residual claim and to rely on antitrust to complement environmental regulation in the case of profitable coordination on noncompliance. In practice, the scope of antitrust needs to be broadened to allow explicit evaluation of noncompliance in order to have antitrust complement regulation.

Where antitrust is insufficient or has limited jurisdiction, welfare can be improved by environmental policy that is robust against forces that reduce expected penalties for joint action. First, fines could increase with the number of noncompliant firms to undo the diffusion of reputation damages. This can be justified from a legal perspective with a proof of explicit conspiracy. Second, policymakers could provide incentives for firms to reveal noncompliance, similar to leniency programs for price collusion, to reduce skin in the game. Third, inspection decisions could incorporate the possibility that seemingly consistent abatement choices in the industry result from a joint scheme. Further research needs to investigate potential solutions to coordinated noncompliance, especially when regulation targets imperfectly competitive industries.

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Online Appendix

A1 Using Collusion to Achieve Joint Noncompliance

We provide the technical details of how our model can rationalize the use of collusion to achieve coordinated noncompliance, to complement Section 2.3.

A colluding firm has the temptation to unilaterally deviate from the collusive scheme. The reduction in the expected penalties provides the incentive to deviate to a higher abatement action. To see why, for a deviant action a_f^D to be statically profitable for firm f, we need:

$$\pi_f(a_f^D, \boldsymbol{a_{-f}^J}) - \mathbb{E}K_f(a_f^D, \boldsymbol{a_{-f}^J}) - \mathbb{E}A_f(a_f^D, \boldsymbol{a_{-f}^J}) > \pi_f(\boldsymbol{a^J}) - \mathbb{E}K_f(\boldsymbol{a^J}) - \mathbb{E}A_f(\boldsymbol{a^J}) \tag{A1}$$

Our assumption that the variable profit is decreasing in the firm's own abatement action implies that $\pi_f(a_f^D, \boldsymbol{a_{-f}^J}) < \pi_f(\boldsymbol{a^J})$ for $a_f^D > a_J^C$. Inequality (A1) then implies that firm f's expected combined penalties must be lower under deviation than collusion: $\mathbb{E}K_f(a_f^D, \boldsymbol{a_{-f}^J}) + \mathbb{E}A_f(a_f^D, \boldsymbol{a_{-f}^J}) < \mathbb{E}K_f(\boldsymbol{a^J}) + \mathbb{E}A_f(\boldsymbol{a^J})$.

To counteract this incentive to deviate, the cartel need to design a continuation payoff following collusion relative to deviation, $G_f(\boldsymbol{a^J}) > 0$, such that:

$$\pi_f(a_f^D, \boldsymbol{a_{-f}^J}) - \mathbb{E}K_f(a_f^D, \boldsymbol{a_{-f}^J}) - \mathbb{E}A_f(a_f^D, \boldsymbol{a_{-f}^J}) \leq \pi_f(\boldsymbol{a^J}) - \mathbb{E}K_f(\boldsymbol{a^J}) - \mathbb{E}A_f(\boldsymbol{a^J}) + G_f(\boldsymbol{a^J}) \tag{A2}$$

One example of G_f in price-collusion models is the discounted sum of collusive profits minus the discounted sum of Nash payoffs. In our empirical context, G_f can be the reward of future R&D collaborations in other aspects of vehicle designs.

A whistle-blower would avoid the expected antitrust penalty $\mathbb{E}A_f(\boldsymbol{a^J})$ but also forgo the continuation payoff $G_f(\boldsymbol{a^J})$ (assuming that this continuation payoff is relative to both deviation and competition). To guard against this incentive, we have for all f:

$$G_f(\boldsymbol{a^J}) \geq A_f(\boldsymbol{a^J}) \tag{A3}$$

where we have assumed that the revelation of the collusion does not lead to changes in the expected noncompliance penalty $\mathbb{E}K_f(\boldsymbol{a^J})$. An increase in the antitrust risk increases $A_f(\boldsymbol{a^J})$ and can therefore overturn this inequality and increase a firm's incentive to blow the whistle. If the revelation of the cartel also leads to the detection of noncompliance, then to prevent whistle-blowing, the cartel needs to have:

$$G_f(\boldsymbol{a}^{\boldsymbol{J}}) \geq \mathbb{E}A_f(\boldsymbol{a}^{\boldsymbol{J}}) - (1 - P_f(\boldsymbol{a}^{\boldsymbol{J}}))K_f(\boldsymbol{a}^{\boldsymbol{J}}) \tag{A4}$$

When whistle-blowing entails the collateral damage of having the violation discovered, the continuation payoff to collusion can be lower while still sustaining the collusion on noncompliance. However, an increase in the probability of detecting noncompliance can potentially overturn this inequality as well as an increase in the antitrust risk.

A2 Illustration of Reasons 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 static Nash equilibrium. We ignore the expected antitrust penalty in this illustration for notational convenience.

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 illustration 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 our 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 $\mathbb{E}K_{(H,H)} = 0$.

		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, note that (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 static *competitive* outcome, leading to the use of intertemporal incentives to support (C,C) as a *collusive* outcome.

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 $\mathbb{E}K_{(H,C)} = K_{(C,H)} > 3$ 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 $\mathbb{E}K_{(C,C)} < 1$.[51]

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 firms coordinate on 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).

The probability of detection. 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

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

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. In the diffusion of responsibility mechanism, an honest firm can benefit from the reputation loss of its cheating rival. This increases the deviation payoff from playing H when the rival plays C. In the skin in the game mechanism, the damages that the honest firm can obtain after suing the violator provide the temptation to deviate. In the detection probability mechanism, the simple example has restricted the action set to be binary, and firms do not have the unilateral incentive to deviate to H from (C, C). But deviation does not necessarily have to be deviating to honest compliance. If there exists a third action, D, such that $\pi_{(C,C)} - \mathbb{E}K_{(C,C)} < \pi_{(D,C)} - \mathbb{E}K_{(D,C)}$ where $\pi_{(D,C)} - \mathbb{E}K_{(D,C)} \geq \pi_{(H,H)}$, a firm would have an incentive to unilaterally deviate to D.

A3 Sufficient Conditions for the Direction of Collusion

We provide sufficient conditions for the existence of collusive abatement actions above or below non-cooperative levels, assuming that the variable profit function and the expected noncompliance penalty function are twice continuously differentiable. These sufficient conditions complement Proposition 1, which provides necessary conditions on selected points of those functions implied by the existence of a collusive profile.

We start with a result under a payoff structure that features cross-firm externalities only in variable profits:

Proposition 2. If $\frac{\partial \pi_f}{\partial a_g} > (<) 0$ and $\frac{\partial \mathbb{E}K_f}{\partial a_g} = 0$ for all $f \neq g$ and $\boldsymbol{a} > (<) \boldsymbol{a^N}$, then there exists a collusive abatement profile with $a_f^J > (<) a_f^N$ for each firm f.

Proof. We prove with two firms; the extension to more than two firms is straightforward. An indifference curve at level U for Firm f consists of all (a_1, a_2)'s such that $\pi_f(a_1, a_2) - \mathbb{E}K_f(a_1, a_2) = U$. To derive the slope of Firm 1's 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:

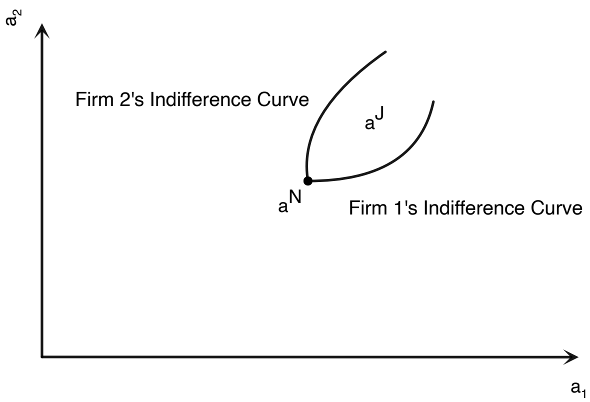
$$\frac{\mathrm{d}a_2}{\mathrm{d}a_1} = -(\frac{\partial \pi_1}{\partial a_1} - \frac{\partial \mathbb{E}K_1}{\partial a_1})/(\frac{\partial \pi_1}{\partial a_2} - \frac{\partial \mathbb{E}K_1}{\partial a_2}). \tag{A5}$$

Because there is no cross-firm externality in the expected noncompliance penalty function, the slope simplifies to:

$$\frac{\mathrm{d}a_2}{\mathrm{d}a_1} = -\frac{\partial \pi_1}{\partial a_1}/\frac{\partial \pi_1}{\partial a_2}.$$

At the non-cooperative profile $\boldsymbol{a^N}$, Firm 1's competitive first-order condition that $\frac{\partial \pi_1(\boldsymbol{a^N})}{\partial a_1} = 0$ implies that the slope of the indifference curve $\frac{\mathrm{d}a_2}{\mathrm{d}a_1}$ at $\boldsymbol{a^N}$ is 0. Because of the second-order condition and the continuity of first-order derivatives, for abatement profiles just above $\boldsymbol{a^N}$, Firm 1 has $\frac{\partial \pi_1(\boldsymbol{a})}{\partial a_1} \leq 0$. Combined with the stated condition that $\frac{\partial \pi_1(\boldsymbol{a})}{\partial a_2} > 0$, this implies that Firm 1's slope is positive at $\boldsymbol{a} > \boldsymbol{a^N}$. The same reasoning applies to Firm 2. Figure A1 plots the indifference curves going through the non-cooperative profile that satisfy those slope constraints: each firm's indifference curve has a zero slope at the non-cooperative profile $\boldsymbol{a^N}$ and positive slopes above.

Figure A1: Indifference Curves Going Through the Non-Cooperative Abatement Profile



Because the continuity of second-order derivatives, there exists an area between the two indifference curves. The stated condition implies that at holding fixed a_f, a higher rival abatement a_g increases firm f's payoff. Therefore, the area between the two indifference curves yields higher payoffs than at the non-cooperative profile. This is where $\boldsymbol{a^J}$ lies, where both firms prefer $\boldsymbol{a^J}$ to $\boldsymbol{a^N}$. Each firm also would have the temptation to deviate downwards from $\boldsymbol{a^J}$ unilaterally, because $\frac{\partial \pi_1(\boldsymbol{a})}{\partial a_1} \leq 0$. This establishes the existence of a collusive profile above the non-cooperative level. The result in parentheses can be similarly proved. □

The intuition is as follows. The stated condition means that firms' abatement actions generate positive externalities on each other. When abatement actions have positive externalities, a firm choosing the abatement action independently does not consider the positive externalities and will abate “too little”. Firms would therefore like to collude on increasing their abatement actions. Technically, as a firm increases its abatement above a_f^N, it reduces its own payoff only slightly (because of the first-order condition) but yields a non-negligible increase in rival's payoff (because of the positive externality). Hence, there exists a profile above the non-cooperative profile that would benefit every firm.

This is akin to price/quantity collusion. In a price collusion, firms' prices generate positive externalities on each other; a higher price from a rival firm improves other firms' profits. As a result, firms, when left alone, price too low, and the price collusion would be about fixing higher prices. In a quantity collusion, firms' quantities generate negative externalities. Firms, when left alone, produce too much, and the collusion would be about restricting output jointly.

When the expected noncompliance penalty function also features cross-firm externalities, Equation (A5) shows that the sign of the net externality effect determines the existence of a collusive profile above or below the non-cooperative level:

Corollary 2. If $\frac{\partial \pi_f}{\partial a_g} < (>) \frac{\partial \mathbb{E} K_f(\boldsymbol{a})}{\partial a_g}$ for all $f \neq g$ and $\boldsymbol{a} < (>) \boldsymbol{a^N}$, then there exists a collusive abatement profile with $a_f^J < (>) a_f^N$ for each firm f.

Intuitively, when the positive externality in the expected noncompliance penalty exceeds the positive externality in the variable profit, the net effect of one firm's increased abatement on others will be negative. Thus, when that firm reduces abatement below the non-cooperative level, it will marginally reduce its own payoff but non-marginally increase others' payoffs - this non-marginal effect comes from a reduction in $\mathbb{E}K$ that more than offsets the reduction in π.

A4 Estimation of the Non-Cooperative DEF Tank Size Choices

A4.1 Estimation Procedure

We explain how we estimate the counterfactual non-cooperative equilibrium from the first-order conditions of non-working-group firms. At the observed abatement profile $\boldsymbol{a^J}$, a non-working-group firm g's choices imply the following first-order conditions for every product j:

$$\frac{\partial \mathbb{E} \pi_g(\boldsymbol{a^J})}{\partial a_j} - \frac{\partial \mathbb{E} K_g(\boldsymbol{a^J})}{\partial a_j} = 0 \tag{A6}$$

Our goal is to estimate the slope of the expected noncompliance penalty function from variations in the slope of the profit function. To restrict the sign of the derivatives in line with our economic model, we take the following transformation of (A6):

$$\log(-\frac{\partial \mathbb{E}\pi_g(\boldsymbol{a^J})}{\partial a_j}) = \log(-\frac{\partial \mathbb{E}K_g(\boldsymbol{a^J})}{\partial a_j}) \tag{A7}$$

We can compute the realized $\frac{\partial \pi_g(\boldsymbol{a^J})}{\partial a_j}$ from our estimated demand and marginal cost functions following the methodology outlined in Villas-Boas (2007). The marginal profit change from a marginal increase in the DEF size of product j for firm g comes from three sources: increased marginal production cost, decreased demand due to decreased quality from smaller trunk space, and an adjustment of equilibrium prices. Our estimates give us the marginal profits computed at realized demand and cost shocks, while the firms choose abatement before these shocks realize. There may be a difference between the firms' expected and realized marginal profits. We define this expectation error as:

$$\epsilon_j \equiv \log(-\frac{\partial \pi_g(\boldsymbol{a^J})}{\partial a_j}) - \log(-\frac{\partial \mathbb{E}\pi_g(\boldsymbol{a^J})}{\partial a_j}). \tag{A8}$$

We assume that this expectation error is mean-independent of abatement choices, which follows from the timing assumption when the abatement choices are made in the vehicle design stage before firms know demand and cost realizations.

Next, we parameterize the marginal expected noncompliance penalty function as follows:

$$\frac{\partial \mathbb{E}K_g(\boldsymbol{a})}{\partial a_j} = -\exp(\gamma_0 + \gamma_1 a_j + \gamma_2 a_{-g} + \gamma_3 \log(size_g)), \tag{A9}$$

where g is a firm, j is a series generation that contains NEDC DEF models produced by firm g, a_j is the average DEF dosage of those models in series generation j, a_{-g} is the average DEF dosage of NEDC DEF models from other firms, and $size_g$ is the size of firm g measured by historical annual average sales revenue between 2007 and 2013.[52,53] We assume that firms choose DEF sizes for each series generation, rather than each individual vehicle. A series generation is a firm-designated collection of models of the same style and dimensions within 3-5 years.[54] Our data show that DEF

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[52] This function is a 'reduced form' approximation of an expected penalty function that would include cross-firm externalities in the inspection probability and penalty terms. Our data are not rich enough to separately estimate parameters affecting the probability and the penalty.

[53] We introduce firm size and not exact quantity. If firms would consider that the expected penalty scales with the quantity sold, this would affect our marginal cost specification. We assume that penalties are based on firm size and not exact quantity. This is in line with the European Commission's practice to scale fines with firm revenues.

[54] For example, BMW's Series 3 Limousine (07/15 - 10/18) contains models 316, 318, 320, 325, 330, 335, 340 and runs from 2015 to 2018.

models in a series generation almost always have the same DEF size, consistent with our knowledge of car design and manufacturing practices.

Substituting (A8) and (A9) into (A7), we obtain the following estimable equation:

$$\log(-\frac{\partial \pi_g(\boldsymbol{a}^{\boldsymbol{J}})}{\partial a_j}) = \gamma_0 + \gamma_1 a_j + \gamma_2 a_{-g} + \gamma_3 \log(size_g) + \epsilon_j. \tag{A10}$$

We estimate this equation with data from the non-working group firms to obtain $\hat{\boldsymbol{\gamma}}$ and $\hat{\epsilon}_j^{NWG}$.

The first-order condition (A6) does not hold for the working-group firms. We rewrite the participation constraint for a working-group firm f from Inequality (3):

$$\pi_f(\boldsymbol{a}^{\boldsymbol{J}}) = \mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{J}}) + \mathbb{E}A_f(\boldsymbol{a}^{\boldsymbol{J}}) + \Delta_f,$$

where Δ_f is a term capturing the slackness of the participation constraint. Taking the derivative with respect to a_j, we have $\frac{\partial \pi_f(\boldsymbol{a}^{\boldsymbol{N}})}{\partial a_j} = \frac{\partial \mathbb{E}K(\boldsymbol{a}^{\boldsymbol{J}})}{\partial a_j} + \frac{\partial \mathbb{E}A(\boldsymbol{a}^{\boldsymbol{J}})}{\partial a_j} + \frac{\partial \Delta_f}{\partial a_j}$. If we run a similar regression as (A10) for the choices of the working group, we have:

$$\log(-\frac{\partial \pi_f(\boldsymbol{a}^{\boldsymbol{J}})}{\partial a_j}) = \phi_0 + \phi_1 a_j + \phi_2 a_{-f} + \phi_3 \log(size_f) + \epsilon_j. \tag{A11}$$

The estimated working-group coefficients from this regression, $\hat{\boldsymbol{\phi}}$, capture the combined slopes of the expected noncompliance penalty, the slackness of the participation constraint, and the expected antitrust penalty. These coefficients are impossible to interpret without a formal cartel formation and antitrust enforcement model. However, we obtain residuals $\hat{\epsilon}_j^{WG}$ from estimating (A11) on the working group sample. These residuals are useful in the next step.

In the counterfactual non-cooperative equilibrium $\boldsymbol{a}^{\boldsymbol{N}}$, (A7) determines all firms' optimal abatement choices instead of only the choices of the non-working group firms. As such, we obtain a system of J equations for J unknown elements of $\boldsymbol{a}^{\boldsymbol{N}}$, where J is the number of series generations:

$$\log(-\frac{\partial \pi_g(\boldsymbol{a}^{\boldsymbol{N}})}{\partial a_j}) - (\gamma_0 + \gamma_1 a_j + \gamma_2 a_{-g} + \gamma_3 \log(size_g) + \epsilon_j) = 0. \tag{A12}$$

Plugging in $\hat{\boldsymbol{\gamma}}$, $\epsilon_j^{N\hat{W}G}$, and $\epsilon_j^{\hat{W}G}$ allows us to solve for the J elements of $\boldsymbol{a}^{\boldsymbol{N}}$. Importantly, we assume that every firm faces the same expected penalty function. This is crucial because it allows us to use the information about the penalty function inferred from the non-working group firms to solve for the equilibrium when all firms would choose non-cooperatively.

A4.2 Estimation Results

We discuss three results. First, we discuss the regression results of estimating (A10). Second, we evaluate the first-order conditions of working-group firms at their collusive choices. This reveals the direction of the deviation incentives of the working group firms. Third, we solve the system of equations in (A12) to obtain the counterfactual non-cooperative equilibrium $\boldsymbol{a^N}$.

Table A1: Regression Results of Equation (A10)

	(1) Non Working Group
DEF dosage (%)	0.953*
	(0.553)
Average DEF dosage from other firms (%)	24.294***
	(9.040)
log(Historical firm revenue (2018 euros))	0.590**
	(0.290)
Constant	−40.841*
	(21.994)
N	71

Notes: An observation is a series generation that contains NEDC DEF vehicles. Historical firm revenue is the annual average sales revenue between 2007 and 2013. Robust standard errors in parentheses. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

Table A1 reports the regression results of Equation (A10) for non-working-group series generations. Using Equation (A9), the estimated coefficients imply that the slope of the expected noncompliance is decreasing (more negative) in DEF dosage and firm size, and strongly decreasing in other firms' dosages. Note that these coefficients capture the derivative of the expected noncompliance penalty with respect to own dosage. In the main text, we discuss that the derivative of the expected noncompliance penalty with respect to other firms' dosage is relevant to a working-group firm's collusive incentive (see Proposition 1). Furthermore, the regression in Table A1 does not allow us to identify the level of the expected penalty; only the slope is relevant to the first-order conditions of non-cooperative choices.

Next, we predict the working group's deviation incentive at the observed collusive profile $\boldsymbol{a^J}$. We do this by comparing the marginal profits at $\boldsymbol{a^J}$ with the slope of the expected penalty function.[55] We find that the marginal profits are larger (or less negative) than marginal expected penalties for almost all working-group series generations, indicating an incentive to increase abatement beyond

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[55] Conceptually, we change the ϕ coefficients with the γ coefficients from Table A1 in (A11) while keeping the estimated residuals fixed at $\epsilon_j^{\hat{W}G}$.

the observed level. This provides evidence that the working group colludes on low abatement, with the temptation to deviate to more abatement unilaterally.

Finally, we try to solve the system of equations in (A12). We replace the observed abatement profile with profiles featuring more abatement, gradually leading up to industry-wide compliance.[56] For each guess of $\boldsymbol{a^N}$, we compute a new price equilibrium and the corresponding marginal variable profits that enter the first term in the system of equations. We also evaluate the second term with the estimated coefficients from Table A1, the estimated residuals, and the associated abatement levels. We find their difference to be consistently negative, indicating that firms face an incentive to increase abatement in the absence of collusion. Furthermore, this gap widens as the industry approaches compliance. This means we find a corner solution for $\boldsymbol{a^N}$: all firms would choose compliance under non-cooperative incentives.

A5 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 3.

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 4. 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.

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[56] Solving the system exactly with a nonlinear equation solver is too costly computationally. Therefore, we resort to a grid search of $\boldsymbol{a^N}$).

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 $N = 100$.

A6 Additional Figures and Tables

Table A2: 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.

Table A3: DEF Dosages of the Working Group

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

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

Table A4: DEF Trade-off with Trunk Space and Weight

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

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

Table A5: 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 emission 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 A6: 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 A7: Percentage Changes in Market Outcomes by the Collusion, 2007-2018

	Non-Cooperative Scenario			
	Noncompliant	2% dosage	3% dosage	3% dosage plus
Quantity–Weighted Trunk	0.08	0.09	0.25	0.41
WG Euro 6 NEDC DEF	3.55	2.97	8.41	14.33
NWG Euro 6 NEDC DEF	-0.14	1.51	6.22	11.56
Quantity–Weighted Price	0.04	0.05	0.13	0.21
WG Euro 6 NEDC DEF	2.61	1.70	4.90	8.36
NWG Euro 6 NEDC DEF	-0.10	1.19	4.12	7.05
WG other diesel	-0.08	-0.09	-0.26	-0.44
NWG other diesel	-0.07	-0.08	-0.25	-0.42
WG gasoline	-0.11	-0.12	-0.34	-0.56
NWG gasoline	-0.08	-0.09	-0.27	-0.46
Quantity of Vehicles Sold	0.04	0.04	0.12	0.20
WG Euro 6 NEDC DEF	2.12	2.18	6.10	10.27
NWG Euro 6 NEDC DEF	-0.15	0.84	3.93	7.52
WG other diesel	-0.05	-0.05	-0.16	-0.26
NWG other diesel	-0.03	-0.04	-0.12	-0.20
WG gasoline	-0.08	-0.08	-0.23	-0.37
NWG gasoline	-0.04	-0.04	-0.14	-0.24

Notes: The percentage change in each row is relative to the corresponding row-value in non-cooperative scenarios. WG - working group, and NWG - non-working group. The first row ("Quantity...") of each group of numbers is the percentage change for all inside goods relative to the non-cooperative scenario.

Table A8: Bounds on the Expected Noncompliance Penalties under Alternative Non-Cooperative Scenarios in Million 2018 Euros, 2007-2018

	Lower bound on $EK_f(a_f^J, \boldsymbol{a}^{\boldsymbol{N}}_{\boldsymbol{-f}})$	Upper bound on $EK_f(\boldsymbol{a}^{\boldsymbol{J}})$	Lower bound on the reduction
Observed $\boldsymbol{a}^{\boldsymbol{J}}$ *vs.* $\boldsymbol{a}^{\boldsymbol{N}}$ as 2% dosage			
BMW	83	28	54
Daimler	179	141	38
Volkswagen	602	506	96
Working Group Total	864	675	188
Observed $\boldsymbol{a}^{\boldsymbol{J}}$ *vs.* $\boldsymbol{a}^{\boldsymbol{N}}$ as 3% dosage plus			
BMW	305	33	272
Daimler	974	798	177
Volkswagen	2532	2004	528
Working Group Total	3811	2835	976

Table A9: Welfare and Market Effects with Alternative Non-Cooperative Scenarios in Billion 2018 Euros, 2007-2018

	Non-Cooperative Scenario	
	2% dosage	3% dosage plus
Working Group's Profit $\Delta\pi$	0.68	2.83
Residual Claim $\Re$	-1.46	-7.37
NO_x health impact	-2.43	-12.86
Buyer surplus	1.08	5.49
Other firms' profit	-0.10	0.09
Net Welfare $\Delta\pi + \Re$	-0.78	-4.44
Ratio $\lambda = \Delta\pi/(-\Re)$	0.46	0.39

A7 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`