WORKING PAPERS

N° 1204

October 2024

"Colluding Against Environmental Regulation"

Jorge Ale-Chilet, Cuicui, Jing Li and Mathias Reynaert

Toulouse School of Economics

Colluding against Environmental Regulation

Jorge Alé-Chilet Cuicui Chen Jing Li Mathias Reynaert *

October 29, 2024

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 emissions control technology. By estimating a structural model of the European automobile industry from 2007 to 2018, we find that collusion lowers expected noncompliance penalties substantially and increases buyer and producer surplus. Due to increased pollution, welfare decreases by €1.57–5.57 billion. 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

*Alé-Chilet: Universidad de Los Andes, Chile, jale@uandes.cl. Chen: State University of New York at Albany, cchen27@albany.edu. Li: Tufts University, j.li@tufts.edu. Reynaert: Toulouse School of Economics, University of Toulouse Capitole and CEPR, mathias.reynaert@tse-fr.eu. We thank the editor and three referees for their helpful and constructive comments and Mike Abito, Charles Angelucci, Megan Bailey, Ying Fan, Matt Gentzkow, Bob Gibbons, Gautam Gowrisankaran, Ginger Jin, Karam Kang, Ashley Langer, Ignacia Mercadal, Kostas Metaxoglou, Nate Miller, Juan-Pablo Montero, Stef Proost, Mar Reguant, Patrick Rey, François Salanié, Chris Sullivan, Frank Verboven and seminar and conference participants for useful discussions and suggestions. Chunyu Guo provided excellent research assistance. Alé-Chilet acknowledges funding from NSF-BSF grant number 2020690. Chen acknowledges support from the University at Albany Faculty Research Award Category A. Chen and Li acknowledge support from the NSF under grants SES-2049446 and SES-2049263, respectively. Reynaert acknowledges funding from ANR under grant ANR-17-EURE-0010 (Investissements d'Avenir program) and grant ANR-CAREGUL-18-CE03-0004-01. Legal disclaimer: This work analyzes an antitrust case strictly from an economic point of view. Our statements are based on the European Commission statements, media articles, and economic data. We do not discuss the legality of the firms' actions.

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 an antitrust case. In July 2021, the European Commission found that German automakers BMW, Daimler, and Volkswagen (the "working group") colluded to restrict the effectiveness of diesel emissions 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 could result in noncompliance penalties, including fines, legal costs, and reputation damages. However, abatement increases firms' marginal costs and compromises product attributes that consumers value. Variable profits thus 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 firms' abatement choices. We provide three reasons why coordinated noncompliance may reduce expected penalties. First, penalties may decrease through the 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 choice compares with other firms. The first and third reasons can be at play when a regulator considers multiple violators too big to fail and becomes reluctant to prosecute or impose steep penalties. Our model shows that antitrust can complement regulation by counteracting the reduction in the expected penalties and making coordinated noncompliance unattractive.

We apply our model to the EU antitrust case on diesel emissions control. In 2007, the EU announced a much stricter diesel NO_x emission limit, the EU6 standard, to take effect in 2014. We take the EU emissions standards as given and study automakers' compliance decisions.[1] The compliance option for large diesel vehicles is a NO_x control technology called Selective Catalytic Reduction (SCR). SCR requires a Diesel Exhaust Fluid (DEF) tank to neutralize 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" to limit 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 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, emissions control systems, and trunk space, among other variables. On-road emissions test results reveal that diesel vehicles exceed the NO_x standard by a factor of three on average, and more than 70% of the diesel vehicles are out of compliance. We observe an average DEF tank size 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, incorporating abatement costs through DEF tank size choices. Large DEF tanks reduce variable profits by increasing marginal costs and taking up trunk space. Our demand estimates show that consumers are willing to pay €231 to avoid the trunk space shrinkage from larger, compliant DEF tanks.[2] Our marginal cost estimates show that the SCR system costs €687, consistent with SCR system cost estimates from the engineering literature. Increasing the volume of the DEF tank by one liter is estimated to cost €42. We do not find significant differences in DEF costs between the working group and other firms, which suggests that the collusive scheme did not induce cost efficiencies for the working group. The antitrust case and supportive documents did not mention cost efficiencies either, nor were upstream DEF suppliers involved in the case.

[1] We abstract from two dynamic issues: firms can lobby ex-ante to change the stringency of standards, and policymakers can base regulation on past compliance. Our framework focuses on coordinated compliance choices to a regulation. We summarize all the effects of regulatory enforcement on future payoffs in the expected penalty term.

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

The estimated variable profit functions and the participation constraints of collusion provide bounds for the expected noncompliance penalties of the working group. Estimating these bounds requires information on the DEF tank sizes 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 estimate the marginal expected noncompliance penalty function. Based on the estimated function, we compute the counterfactual equilibrium of DEF choices, where both non-working-group and working-group firms choose DEF sizes non-cooperatively. This procedure shows that the non-cooperative industry equilibrium would have been compliant. Collusion thus brings the whole industry into noncompliance. In a 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. In this scenario, 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 the structural and descriptive approaches, we estimate that the expected noncompliance penalties for the working group are at least €69–345 million lower due to coordinated noncompliance.

We discuss how the working group achieves such substantial expected penalty reductions in the EU automobile market. The EU sets the emissions standards, and member states enforce them. Enforcement at a lower level of government generates a too-big-to-fail setting. The German automobile industry is important for the German economy; for example, it employs 11% of manufacturing workers (ACEA, 2024). The working group may expect a national authority to be unwilling to punish widespread noncompliance. Furthermore, we find that coordinated noncompliance would diffuse 22–43% of reputation damages when working-group firms are caught together, give skin in the game to competitors whose stolen business would contribute to 25–47% of a 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 the emissions standards were too stringent.[3] In our empirical case, 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

[3]The EU emissions standards have become increasingly stringent over time, and industry experts stated the EU 6 standards would be too demanding for manufacturers.

consider, collusion against regulation reduced social welfare by €1.57–5.57 billion. The Commission fined the cartel €2.7 billion, which, based on our estimates, is sufficient to repair welfare.

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 when making the proposal to reduce abatement, the working group expected to pay at most 11% of the penalties specified in a collusion-proof policy. Second, antitrust may have a complementary role in regulatory enforcement. To play this role in practice, antitrust would need 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 consider the possibility that enforcement might create incentives for coordinated 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 collusion among firms against the regulator has not been considered. We show that accounting for the possibility of collusion has important implications for environmental policy design 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 regulation generates sufficiently strong negative spillovers from firms' compliance choices on other firms, a regulation becomes vulnerable to collusion.

We also contribute to the empirical literature on collusion. Most of this literature studies collusion in prices (e.g., Bresnahan, 1987) and quantities (e.g., Porter, 1983, and more recent work that structurally estimates incentives for such collusion Igami and Sugaya, 2022). Instead, we study collusion in a dimension other than prices and quantities, as in Alé-Chilet and Atal (2020), Gross (2020), Sullivan (2020), and Bourreau et al. (2021) (also see Nocke (2007) for a theoretical analysis).[4] The unique aspect of our paper is that firms collude on a product characteristic that is key to compliance with environmental regulation. Our focus on regulation adds complexity to the analysis because collusion interacts with expected noncompliance penalties and produces pollution 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. Section 2 presents a model of coordinated noncompliance. Section 3 describes our data. Section 4 describes the empirical context and shows descriptive evidence for collusion and widespread noncompliance in the industry. Section 5 describes our empirical strategy for estimating vehicle demand and marginal costs and for bounding expected noncompliance penalties. Section 6 presents estimation results. Section 7 presents the welfare effects of 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 of participating in coordinated noncompliance and complements environmental regulation. The model provides estimable bounds that inform the structure of the expected noncompliance penalties. Finally, we describe the enforcement of coordinated noncompliance and the implications of coordination by a subgroup of firms on other firms.

[4] 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 price collusion. Explicit 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.

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 those 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.[5] As a result, a noncompliant firm probabilistically incurs penalties (such as regulatory fines and reputation damages). The regulator inspects firm f with probability $P_f(\boldsymbol{a})$ to reveal its compliance status. If inspected, the firm incurs a noncompliance penalty $K_f(\boldsymbol{a}) \geq 0$. 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 $\mathbb{E}K_f(\boldsymbol{a}) \equiv P_f(\boldsymbol{a})K_f(\boldsymbol{a})$ and use $\mathbb{E}K_f(a_f, \boldsymbol{a_{-f}})$ to define the expected penalty when firm f would play a_f while the other firms are at a profile $\boldsymbol{a_{-f}}$.

Firm f's payoff at the industry abatement profile $\boldsymbol{a}$ is $\pi_f(\boldsymbol{a}) - \mathbb{E}K_f(\boldsymbol{a})$. We define the abatement profile $\boldsymbol{a^N}$ as the non-cooperative equilibrium. We denote $\boldsymbol{a^*}$ as the profile where each firm exactly complies with the standard. Noncompliance penalties are zero when firms comply or overcomply: $\mathbb{E}K_f(a_f, \cdot) = 0$ for $a_f \geq a_f^*$. Because variable profits are decreasing in abatement, it follows that overcompliance is a dominated action, and hence, there is no overcompliance in the non-cooperative

[5] One can conceptualize this as each firm having a pollution type θ_f and abatement a_f. Emissions 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).

equilibrium $\boldsymbol{a^N} \leq \boldsymbol{a^*}$.

2.2 Coordinated Abatement Choices

A working group proposes a profile of abatement actions $\boldsymbol{a^J}$.[6] 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 $\mathbb{E}A_f \geq 0$ as the expected antitrust penalty a firm assigns to participating. The expected antitrust penalty $\mathbb{E}A_f$ is separate from $\mathbb{E}K_f(\boldsymbol{a})$, because $\mathbb{E}A_f$ applies only when firms coordinate to play $\boldsymbol{a} = \boldsymbol{a^J}$, while $\mathbb{E}K_f(\boldsymbol{a})$ applies whenever firms are noncompliant. Additionally, antitrust and regulatory penalties are usually determined by different governmental agencies.

Firm f considers whether to accept the joint proposal based on its participation constraint:

$$\pi_f(\boldsymbol{a^J}) - \mathbb{E}K_f(\boldsymbol{a^J}) - \mathbb{E}A_f(\boldsymbol{a^J}) \geq \pi_f(\boldsymbol{a^N}) - \mathbb{E}K_f(\boldsymbol{a^N}), \tag{1}$$

showing that the profits from coordinating need to be higher than the non-cooperative profits to achieve participation. The participation constraint reveals a complementary role for antitrust in enforcing regulation. When firms expect higher antitrust penalties, $\mathbb{E}A_f$, a working group is less likely to be able to make a profitable proposal that would reduce abatement and increase pollution.

Without the joint proposal, firms would play $\boldsymbol{a^N}$, the non-cooperative equilibrium. By the definition of a non-cooperative equilibrium, firm f would obtain a lower payoff by unilaterally deviating from a_f^N to a_f^J:

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

Together (1) and (2) reveal that if a proposal is accepted, it must be that coordinating is more profitable than not coordinating, which in turn is more profitable than abating a_f^J unilaterally.

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

Proposition 1. If firm f chooses to participate in a joint proposal that decreases compliance ($\boldsymbol{a^J} < \boldsymbol{a^N}$), then $\mathbb{E}K_f(\boldsymbol{a^J}) < \mathbb{E}K_f(a_f^J, \boldsymbol{a^N_{-f}})$. The difference between these expected penalties is bounded below by the difference in the firm's variable profit:

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

[6] 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.

Proof. Since firm f chooses to participate in the joint proposal, its participation constraint defined in (1) must hold. Without the joint proposal, firms would play $\boldsymbol{a^N}$, the non-cooperative equilibrium defined in (2). Combining (1) and (2) yields:

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

Rearranging the terms, we have $\mathbb{E}K_f(a_f^J, \boldsymbol{a_{-f}^N}) - \mathbb{E}K_f(\boldsymbol{a^J}) \geq \pi_f(a_f^J, \boldsymbol{a_{-f}^N}) - \pi_f(\boldsymbol{a^J}) + \mathbb{E}A_f(\boldsymbol{a^J}) \geq \pi_f(a_f^J, \boldsymbol{a_{-f}^N}) - \pi_f(\boldsymbol{a^J})$ because $\mathbb{E}A_f(\boldsymbol{a^J}) \geq 0$. We have thus established Inequality (3). Since the variable profit is strictly increasing in a competitor's abatement action, $\boldsymbol{a_{-f}^N} > \boldsymbol{a_{-f}^J}$ implies that $\pi_f(a_f^J, \boldsymbol{a_{-f}^N}) - \pi_f(\boldsymbol{a^J}) > 0$. Therefore, $\mathbb{E}K_f(a_f^J, \boldsymbol{a_{-f}^N}) - \mathbb{E}K_f(\boldsymbol{a^J}) > 0$. □

To gain intuition behind Proposition 1, observe that the acceptance of a collusive proposal to lower abatement reveals that abatement imposes negative spillovers on other firms. Collusion increases payoffs by limiting these negative spillovers from abatement. A firm's payoff is the variable profit minus the expected noncompliance penalty. Because variable profits increase with competitors' abatement, the source of negative spillovers must be the expected noncompliance penalty.[7] This is what Proposition 1 concludes: the expected penalty that a firm incurs must increase (and the firm's total payoff decrease) as other firms increase their abatement.[8] In our empirical analysis of the case where automakers coordinated to limit emissions control technology, we quantify the strength of these negative spillovers in expected penalties by bounding them from below with the estimated positive spillovers in variable profits.

We now discuss three reasons why coordinated noncompliance can reduce expected noncompliance penalties.[9] 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 might report the noncompliance to

[7] Appendix A3 formalizes how the direction of the joint proposal depends on the signs of spillovers in the variable profit and expected penalty functions.

[8] We compare $\mathbb{E}K_f(\boldsymbol{a^J})$ and $\mathbb{E}K_f(a_f^J, \boldsymbol{a_{-f}^N})$, but it is important to note the comparison does not follow from having firms other than f strategically change their choices from $\boldsymbol{a_{-f}^J}$ to $\boldsymbol{a_{-f}^N}$. Proposition 1 is a statement about spillovers between firms' expected noncompliance penalty function revealed by collusion. The proof relies on the participation constraint and the definition of the non-cooperative Nash profile from firm f's perspective.

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

the regulator. By jointly choosing noncompliance, competitors get "skin in the game:" noncompliant competitors have less incentive to report noncompliance, 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.[10] 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.[11]

2.3 Enforcement of Joint Decisions

Our model has so far been agnostic about how the working group enforces the joint abatement decisions. In contrast to collusion on prices, deviation from the collusive noncompliance scheme leads to lower variable profits. Deviation incentives arise if a colluding firm, by unilaterally increasing abatement, reduces its expected noncompliance penalty by more than the reduction in its variable profit. Because we do not observe the data to quantify cartel enforcement in response to deviations, our framework focuses on the participation decision of working group members and is, therefore, not explicitly dynamic.[12] Appendix A1 elaborates on the dynamic cartel enforcement and whistle-blower incentives.

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.[13] We assume that non-working-group firms observe whether the proposal is accepted before making abatement choices.[14] If the proposal is accepted, the non-working-group firms condition on the proposal while choosing

[10] 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 similar regulated firms are subject to more intensive audits.

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

[12] 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.

[13] 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.

[14] 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.

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 a unilateral deviation from 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 price 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.[15]

We augment the JATO data with data from ADAC, a German automobile association.[16] 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, emissions 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

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

[16] 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.

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 firms—BMW, Daimler, and Volkswagen—and 21 other firms.[17] The working group accounts for about half of the sales revenue 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 environmental and human health effects.[18] Vehicle emission standards are a common government tool to reduce tailpipe emissions.[19]

Since 2000, the EU has adopted increasingly stringent NO_x emission standards for diesel vehicles. The emission standards relevant to our analysis are Euro 6 (2014–). The change from the Euro 5 to the Euro 6 standards required carmakers to more than halve NO_x emissions for diesel vehicles from 0.18 g/km to 0.08 g/km. Appendix Figure A2 shows this change brought the EU NO_x emission standard closer to the more stringent one of the US. The EU implements the standards using a "type approval" procedure. Automakers typically receive one year to type-approve vehicles before the standard binds. For example, type approval requires Euro 6 from September 2014 onward, and new vehicle registrations require Euro 6 from September 2015 onward. A vehicle "type" can only enter the market if it passes the emissions test conducted by a third-party testing company. While the EU sets the emission standards, the member states oversee the type approval procedure and enforce the emission standards.

[17] In our study period, BMW owns BMW and MINI, and Volkswagen owns Audi, Bentley, Lamborghini, Porsche, SEAT, Skoda, and VW.

[18] 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, leads to more CO_2 in the atmosphere, and interacts with water to form acid rain.

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

The Euro 6 emissions limits were 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. Starting in 2017, the EU changed the testing procedure several times to better reflect real driving emissions (RDE). The Worldwide Harmonized Light Vehicle Test Procedure (WLTP) is the current testing procedure. We end our study in 2018 when most 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) in passenger diesel vehicles, a technology already used in trucks. 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. An alternative to SCR is Lean NO_x Trap (LNT), which reduces fuel efficiency and is more suitable for small vehicles. Further, 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 of refilling the DEF tank more frequently than annual check-ups. They wanted to avoid making diesel cars less attractive than gasoline cars.[20] Second, during the years of our study, passenger car owners found it challenging to refill DEF tanks themselves. The refilling infrastructure had been designed for trucks, and tune-ups would be needed after refills.[21] Because each DEF tank provides DEF for a year of driving, we can convert the tank size to "dosage," defined as the ratio of the DEF tank size to the amount of diesel that sustains one year of driving. The term dosage is used in the

[20] Dohmen and Hawranek (2017) report that the manufacturers' internal records show that DEF tanks are "designed so that customers would not have to refill them." and the U.S. Environmental Protection Agency explicitly "demanded that the tanks contain enough urea to ensure that they would only have to be refilled during an inspection after about 16,000 kilometers. They were unwilling to accept the possibility that the tanks could be refilled between inspection dates[...]". Ewing and Granville (2019) write that "refilling the tank would become an extra chore and expense for the owner, a potential turnoff for prospective customers," and that "Volkswagen wanted the fluid to last long enough to be refilled by dealers during regularly scheduled oil changes, so there would be no inconvenience to owners."

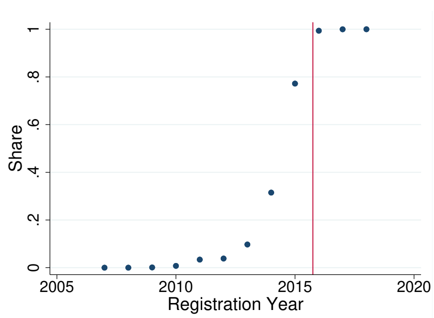
[21] Total, a fuel station brand, advises consumers against refilling themselves, pointing out that the DEF filler neck on the vehicle may be hard to access, that DEF pumps at gas stations are designed specifically for trucks but not passenger vehicles, and that many vehicles need a technical reset by a mechanic after the DEF refill. Likewise, on their website, Jaguar asks consumers to book a refill with an authorized repairer when the vehicle alerts that DEF levels are critically low. Persistent URLs in Appendix.

engineering literature to measure the effectiveness of SCR systems. The amount of diesel a vehicle consumes annually depends on a vehicle's fuel efficiency and a driver's mileage. Increasing dosage corresponds to increased DEF tank size when considering a specific vehicle, mileage, and refill frequency. Therefore, we focus on DEF tank size and dosages as measures of the efficiency of the DEF system for a given vehicle.

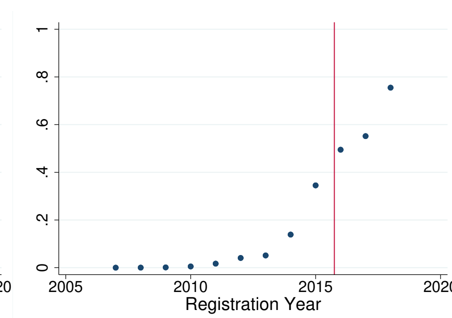
Figure 1 depicts the adoption of Euro 6 emission standards and DEF tanks in new large diesel vehicle registrations.[22] The reference line marks September 2015, the Euro 6 implementation date for registrations. Subfigure (a) depicts the share of large diesel registrations with Euro 6 type approval. The share of Euro 6 registrations 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. The firms choose DEF as their primary compliance technology in response to Euro 6. However, despite widespread DEF adoption, low dosages might still lead to insufficient compliance. Below, we discuss the dosages and efficiency of the DEF systems.

Figure 1: Adoption of Euro 6 and DEF Tanks in Large Diesel Vehicles

(a) Euro 6 share



(b) DEF share



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

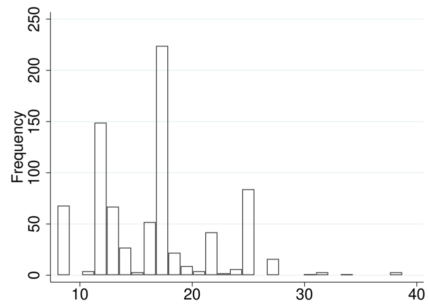
Figure 2 shows the distribution of DEF tank sizes on SCR-only vehicles in the industry.[23] The

[22]We define large diesel vehicles as having at least 1.8 liters engines. The sample median is 1.97 liters. Appendix Table A2 shows that DEF tanks are installed on larger and more powerful vehicles, consistent with Yang et al. (2015).

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

observed tank sizes are dispersed, ranging from 8 liters to 38 liters, showing the automakers did not coordinate on a uniform DEF tank size.

Figure 2: 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

It is difficult for a regulator to know the precise DEF dosage a vehicle needs to comply with the Euro 6 standards. Automakers have proprietary engine tuning technologies that manage the combustion process and determine engine-out emissions. Those engine-out emissions then interact with the SCR system. Tailpipe emissions are determined by a complex process involving a catalyst and its temperature, engine load, altitude, speed, and driving dynamics (European Commission, 2021).

The regulator does not observe engine-out emissions directly and has to measure tailpipe emissions. In our sample period, the EU relied on NEDC tests, consisting exclusively of lab measurement, to monitor Euro 6 compliance.[24]

Monitoring is further complicated due to defeat devices. The 2015 Volkswagen Dieselgate scandal in the US revealed the use of defeat devices to circumvent emission standards. These devices consist of sensors to identify testing conditions and software that artificially reduces vehicle emissions in lab testing. With defeat devices, automakers could obtain type approval for vehicles that were not compliant with emission standards on the road.

An inquiry by the EU Parliament (Gieseke and Gerbandy, 2017) revealed deficiencies in the enforcement of EU emission standards. First, the inquiry describes the inconsistent application

[24] Accurate measurement of tailpipe emissions would require testing vehicles on the road. On-road testing with portable emissions measurement systems attached to the vehicle accurately reflects emissions from the driving conditions of each individual test. However, while in-lab tests are generally reproducible, on-road tests were difficult and costly to incorporate into regulation due to uncontrolled variability from the driver, traffic, and weather. 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.

of EU law across member states regarding exemptions for defeat devices (Art. 33). Second, it points out that member states contravened their legal obligation to monitor the ban on defeat devices (Art. 34). Third, the inquiry blames the member states and the European Commission for maladministration and failing to understand the discrepancy between lab and on-road emissions (Art. 36-42).

The Parliamentary inquiry also calls upon member states to impose the EU rules on their domestic automobile industry. However, given the national importance of these industries, a "too-big-to-fail" mechanism might be at play, whereby the member states are reluctant to enforce EU standards strictly to avoid damaging their domestic industry.[25]

The regulatory environment is thus characterized by weak monitoring and legal uncertainty about what constitutes a defeat device, making it possible for firms to risk a noncompliance strategy without the certainty of getting caught. Although vehicles may be legally compliant based on in-lab tests, they exceed emissions limits on the road. This paper defines compliance as actual emission reductions on the road, in line with the goal of the EU regulation to reduce pollution.

Despite imperfect enforcement, automakers still may face consequences for noncompliance. The discovery of defeat devices and the resulting attention on on-road emissions negatively affected automakers for several reasons. First, automakers face a series of ongoing lawsuits by consumer groups and shareholders for dishonesty. Second, the discovery of high diesel pollution causes reputation damage for the diesel segment and for 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.

4.4 The Antitrust Case

The European Commission found guilty and 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 firms in the working group have met regularly to discuss different technologies and engine specifications (Dohmen and Hawranek, 2017).

The decision of the antitrust case documents the coordination from internal meeting notes. It is striking that the firms recorded their coordination; we think this behavior might mean that firms were not expecting to be the subject of an antitrust investigation, so that the firms' expected

[25] The German industry employs 11% of the German manufacturing workforce (ACEA, 2024), there is strong evidence of revolving doors between the German government and the automotive industry (Joshua Posaner, 2017), and German policymakers have openly tried to delay and reduce the stringency of EU emission regulations during the legislative process (Gearino, 2020).

antitrust penalty ($\mathbb{E}A$ in our model in Section 2) may be zero. The antitrust case is the first concluded case that has ruled technology coordination violated EU competition law.

As early as 2006, the working group discussed fitting a DEF tank in future models.[26] 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 pressured their managers to hold additional meetings and reach an agreement. Although larger DEF tanks reduce more NO_x, the chassis managers preferred smaller tanks because they were "lightweight, did not cost much, and left enough space for golf bags in the trunk" (Dohmen and Hawranek, 2017). 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. There is no evidence for explicit coordination on noncompliance and defeat devices. However, the firms allegedly knew smaller tanks would not contain enough DEF to reduce NO_x emissions and be compliant with Euro 6. A 2011 internal report stated that Euro 6 would require large DEF tanks to increase DEF consumption by 50 percent (Ewing, 2018). By explicitly coordinating on DEF tank size and refill frequency, the firms implicitly coordinated on noncompliance.

In May 2014, Audi sent an email warning that the increased DEF injection required by Euro 6 could necessitate the costly adoption of larger DEF tanks. Such communication and the initially stated need for cooperation in 2007 show that individual automakers seem to have had the incentive to deviate to larger DEF tanks unilaterally. The firms communicate that DEF tanks should increase in size to attain compliance.

The cartel potentially had to enforce their proposal to limit tank sizes. 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 punishment and instead focus on participation in the cartel.

In October 2017, the European Commission began initial inquiries into possible collusion by inspecting the premises of BMW, Daimler, and Volkswagen in Germany. After the initial inquiry, Daimler and, soon afterward, Volkswagen applied for leniency to become whistle-blowers. Both firms blew 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

[26] Note that the coordination took place well before the 2015 Volkswagen Dieselgate scandal.

scandal is beyond the scope of this paper.[27]

In April 2019, the Commission sent a statement of objections to the working group with the preliminary view that the working group "participated in a collusive scheme, in breach of EU competition rules, to limit the development and roll-out of emission cleaning technology [. . .]" (European Commission, 2019). The investigation concluded in July 2021, and the EC found the working group guilty of violating Article 101(1) of the Treaty and Article 53(1) of the EEA Agreement, (European Commission, 2021). The firms were convicted of forming a cartel that restricted competition in the EU by coordinating their emissions control technology. The Commission argues that automakers colluded not to provide abatement beyond regulatory requirements, which could be interpreted as if the non-cooperative equilibrium would be one with over-compliance and that collusion limited the industry to compliance. This is at odds with the evidence of on-road noncompliance we present below. The Commission is restricted to implementing EU antitrust law and does not have jurisdiction over environmental regulation. The authority to determine noncompliance lies within the purview of individual member states. We interpret the Commission's argumentation as sufficient to show a violation of EU competition law without adjudicating on behalf of member states what constitutes environmental compliance.

The European Commission set a fine of €2.7 billion for limiting the sizes of their DEF tanks in diesel cars and coordinating their refill ranges. 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 Evidence for Widespread Noncompliance

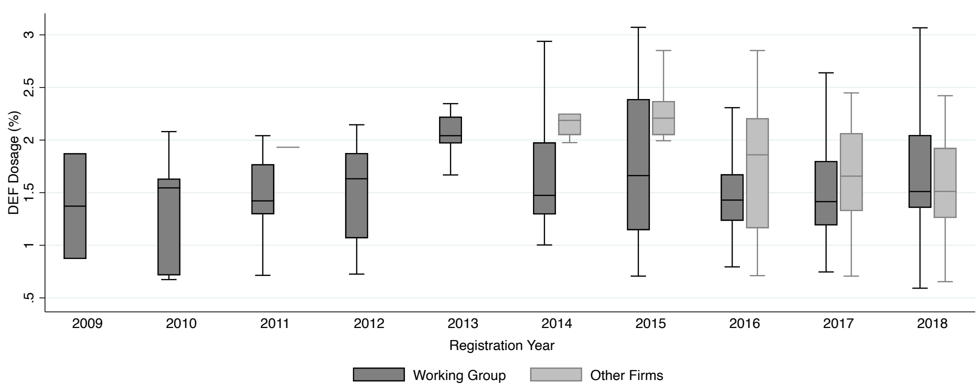
The EC closed its case based on the proven communication among the firms to attempt to reduce the size of the DEF tanks, but it did not make statements about the actual market effects of the coordination. We study DEF dosages to investigate if carmakers restricted the emissions control systems below the EU standards.

Using our data, we plot in Figure 3 the distributions of DEF dosages adopted by the working

[27] 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.

group and other firms. We convert DEF tank sizes to dosages by dividing the former by the annual fuel consumption. 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).[28] Figure 3 shows that 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 137 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. Contrarily, the working group has a higher dosage for WLTP-approved vehicles. This explains the narrowing of the dosage gap towards 2018, shown in Figure 3 as the share of WLTP vehicles starts to increase.

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



Notes: Box plot based on all diesel SCR vehicles (NEDC and WLTP) approved for Euro 6. Dosage equals DEF tank size divided by the fuel consumption for an annual mileage of 20,000km. Lines within the box plot indicate the median. Box edges represent the 25th and 75th percentiles. End points represent the lower and upper adjacent values. Outside values are omitted.

We now assess whether those dosage choices are sufficient for Euro 6 compliance under NEDC. To do so, we first use the RDE data to estimate the relationship between DEF choices and on-road NO_x emissions. The on-road emission for vehicle j, measured in mg/km, is:

$$e_j = n_j \kappa - RemovalRate \times a_j + \upsilon_j, \tag{6}$$

[28]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."

where $n_j\kappa$ is the part of vehicle j's engine-out emission that is explained by a large set of control variables n_j including fuel consumption and the presence of a supplementary LNT system, υ_j is the i.i.d. idiosyncratic part of j's engine-out emission, and a_j is the DEF tank size. The parameter of interest is $RemovalRate$, describing how much a liter of DEF neutralizes NO_x.[29]

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.

Table 1 reports the regression results using Equation (6) based on the RDE test results. Column (1) shows that emissions decrease with the DEF tank size and the presence of a supplementary LNT system and 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 vehicle such that it is compliant with the emission limit of 80 mg/km. 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.[30] Following these studies, we adopt 3% as the dosage needed for compliance. Our

[29] We use a linear relationship between emission and DEF tank size. In our sample, we have no observations with zero emissions after SCR treatment (at which point additional DEF cannot abate because emissions cannot be negative), and we find no statistical evidence for a nonlinear relationship between a_j and e_j.

[30] Holderbaum et al. (2015) test a vehicle with different NO_x treatment systems and conclude that compliance in real

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	2.99	2.62	0.12	0.99	3.88	13.76	73.8
Panel B: Main Dataset							
Observed DEF tank size (L)	16.27	5.22	8.00	12.00	17.00	38.70	
Implied dosage (%)	1.70	0.57	0.59	1.28	2.15	3.25	
Compliant DEF size (L)							
2% dosage	19.78	4.46	11.92	16.45	22.49	39.40	66.8
3% dosage	29.68	6.69	17.89	24.68	33.74	59.09	99.2
3% dosage plus	38.58	8.69	23.25	32.08	43.86	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 744.

appendix reports robustness using 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 16.3 liters to 29.7 liters in the 3% compliance scenario. At least 66.1% of vehicle models have insufficient DEF tank sizes in the conservative 2% scenario. Overall, Table 2 provides evidence that the automakers did not comply with the Euro 6 emission standards under the NEDC.

We also find that the working group increased dosages and became more compliant from 2018 onwards under the WLTP. In Appendix Table A5 Column (1), we report results from regressing the working group’s DEF dosage choices on the test cycle indicator with vehicle series fixed effects. We find that the average working-group vehicle increases its DEF dosage by 0.21 percentage points as the test cycle changed from NEDC to WLTP (the mean dosage was 1.6% under NEDC). In Column (2), using the RDE dataset, we find the working group substantially reduced NO_x emissions. The NO_x exceedance factor decreases by 1.35 from a mean of 2.8 when the test procedure changed from NEDC to WLTP. Therefore, the working group could have achieved compliance but chose not to

driving conditions requires DEF dosages between 2.9% and 3.6%. The study tested vehicles with fuel consumption of 6.8 liters/100km and reports DEF usage of 2 to 2.5 liters/1000km to obtain compliance. Similarly, Op De Beeck et al. (2013) report a compliant dosage of 3%, and Sala et al. (2018) report 3–5%.

use the SCR technology to its full potential under NEDC between 2014 and 2018.

We conclude that there is clear evidence of noncompliance in the period 2014-2018 when NEDC type-approved Euro 6 vehicles were sold. The firms communicated about reducing DEF tank sizes, and the DEF emission control systems were upgraded in response to regulatory changes after the VW scandal.

4.6 Summary

We summarize this section with four important takeaways for our empirical model. First, 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 potential noncompliance penalties when making noncompliant abatement choices. In the language of our theoretical model, $\mathbb{E}K_f(\boldsymbol{a}) > 0$ when $a_f < a_f^*$. Second, the EU member states enforce the Euro 6 emissions 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. Third, the working group 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 without coordination: $\boldsymbol{a}^J < \boldsymbol{a}^N$. Fourth, our data confirm widespread noncompliance in the industry, $\boldsymbol{a}^J < \boldsymbol{a}^*$, and we find the working group chooses smaller DEF tanks than the rest of the industry, and we observe tank sizes increase after the revelation of noncompliance. These facts inform the non-cooperative counterfactuals we construct below.

5 Estimation

5.1 Demand

The demand model is a random coefficients nested logit model (RCNL), which combines the nested logit as in Cardell (1997) and Berry (1994), and the random coefficients logit as in BLP (Berry et al., 1995). See Miller and Weinberg (2017) for a recent application and Grigolon and Verboven (2014) for comparing different demand models. We define a market as a country-year and suppress the market subscript for notational ease. Each consumer i has conditional indirect utility from purchasing vehicle j:

$$U_{ij} = \delta_j + \mu_{ij} + \bar{\varepsilon}_{ij}, \tag{7}$$

where δ_j is the mean utility of vehicle j that is the same for every consumer, μ_{ij} is the individual deviation from the mean utility, and $\bar{\varepsilon}_{ij}$ is a stochastic term described below. The outside option

($j = 0$) is not purchasing a vehicle, with its indirect utility normalized to $u_{i0} = \bar{\varepsilon}_{i0}$.[31]

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 x_j, such as trunk space.[32] Pollution reduction is considered an externality and does not enter the indirect utility independently.[33] In Section 6, we empirically test whether consumers value DEF tanks sizes.

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-vehicle-specific taste shocks, $\bar{\varepsilon}_{ij}$, follow the distributional assumptions of the nested logit model in Cardell (1997). We define ten size classes, $c = 0, 1, ..., 9$, such that class 0 includes the outside good, and the other nine classes are based on the EU vehicle size classification: subcompact, compact, intermediate, standard, luxury, MPV, SUV, compact van, and sports. We have $\bar{\varepsilon}_{ij} = \zeta_{ic}(\rho) + (1-\rho)\varepsilon_{ij}$, with ε_{ij} i.i.d. extreme value, and $\zeta_{ic}(\rho)$, which depends on the parameter ρ, having the unique distribution such that $\bar{\varepsilon}_{ij}$ is extreme value. The nesting parameter ρ has a value, $0 \leq \rho \leq 1$. When $\rho = 0$, the model becomes a standard random coefficient logit model. When the nesting parameter is larger than 0, consumer preferences for goods in the same nest correlate more strongly.

Consumer i chooses vehicle j if $U_{ij} \geq U_{ij'}$ for all $j' \neq j$. The market share for vehicle j comes

[31] 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%.

[32] 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.

[33] 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. The impact of collusion on buyer surplus would be ambiguous because collusion (which decreases abatement) would increase buyer surplus through increased trunk space but decrease it through increased pollution.

from integrating over individual choices:

$$s_j = \int \frac{\exp\{(\delta_j + \mu_{ij})/(1-\rho)\}}{\exp\{I_{ic}/(1-\rho)\}} \frac{\exp\{I_{ic}\}}{\exp\{I_i\}} \mathrm{d}\nu_i, \tag{10}$$

with the inclusive value terms defined as: $I_{i0} = 0$, $I_{ic} = (1-\rho)log \sum_{j'=1}^{J_c} \exp\{(\delta_{j'} + \mu_{ij'})/(1-\rho)\}$, and $I_i = log(1 + \sum_{c=1}^{C} \exp\{I_{ic}\})$, where the first sum is over the products J_c within class c and the second sum over all inside nests C. The parameters from the demand model to be estimated are $\theta = (\alpha, \beta, \rho, \sigma)$.

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, trunk space, random coefficients, and the nesting parameter with five 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 those 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.[34] Third, we instrument for trunk space using *gross* trunk space. In the data, we observe net trunk space after space is taken up by the DEF tank (when a DEF tank is present in the vehicle). However, the gross trunk space equals the net trunk space for vehicles without DEF tanks. 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.[35] Gross trunk space is a valid instrument because it is chosen in the earliest stages of vehicle design and remains fixed throughout the whole design process (Whitefoot et al., 2017). Fourth, we construct approximate optimal instruments to identify the variances of the random coefficients (Reynaert and Verboven, 2014; Conlon and Gortmaker, 2020). Fifth, we

[34] A typical manufacturing plant consists of several production lines. A production line consists of several stations where 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.

[35] 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.

include the number of products in each nest and market to instrument for the nesting parameter.

We estimate the demand model with a general method of moments estimator. We invert the market shares using a 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 Supply

In the supply model, firms joining the working group make coordinated decisions in response to the EU emissions standard. The timing is as follows. First, the firms observe the emission standard and the penalty function for noncompliance. Second, selected firms receive an invitation to join the working group. If all invited firms accept, then they form the working group. Third, all firms make simultaneous abatement choices (DEF dosages) for vehicles with an SCR system. The working group coordinates their abatement choices, and non-working group firms make non-coordinated choices. This ends the vehicle design phase for the EU6 production period 2014-2018. Fourth, vehicle-by-market-specific demand and cost shocks materialize. Fifth, all firms make simultaneous price decisions for all vehicles (gasoline and diesel) in a Nash Bertrand game and collect variable profits. Sixth, the regulator might discover noncompliance; noncompliant firms pay penalties when caught. The difficulty of the empirical setting is that we do not observe the penalty function associated with noncompliance and that our application only contains a single noncompliance event. Yet, we present an approach to estimate reductions in the penalty function obtained by the working group and the market equilibrium effects of the collusive agreement.

Firms' payoffs at the end of the game are the sum of variable profits and expected penalties. Many of our results focus on the participation decision to join the working group, a decision made before the demand and cost shocks materialize. Therefore, we use the terms expected penalty $\mathbb{E}K_f$ and expected profit $\mathbb{E}\pi_f$ to quantify the firms' expectations about penalties and variable profits at the time of the participation decision. We draw from the estimated cost and demand shock distributions to obtain the expected profit $\mathbb{E}\pi$.

[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.

5.2.1 Variable Profits

Firms earn variable profits given by:

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

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 indicate how much variable profits decrease with 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.

5.2.2 Marginal Costs

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 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:

$$mc_j = \eta_x x_j + \eta_a a_j + \eta_{wg} a_j WG_j + \omega_j, \tag{14}$$

where WG_j is a dummy variable, taking the value of one whenever the producer of vehicle 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 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 our timing assumptions, we assume that there is no concern for any remaining endogeneity of DEF tank sizes.

5.2.3 Bounds on Expected Noncompliance Penalties

We estimate a bound on the reduction in expected penalties formulated in Proposition 1 by simulating automakers' expected variable profits at different abatement action profiles. We estimate 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. We do so by rearranging Inequality (2):

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

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 $\mathbb{E}\pi_f(a_f^J, \boldsymbol{a}_{-\boldsymbol{f}}^{\boldsymbol{N}}) - \mathbb{E}\pi_f(\boldsymbol{a}^{\boldsymbol{N}})$, because $\mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{N}}) \geq 0$.

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

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

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

Third, we combine the lower and upper bounds from above to obtain a rearranged version of Inequality (4) from Proposition 1:

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

which provides a lower bound on the reduction in the expected penalties from joint low abatement relative to unilateral low abatement. The inequality also gives a conservative lower bound for the reduction in expected *noncompliance* penalties, $\mathbb{E}K_f(a_f^J, \boldsymbol{a}_{-\boldsymbol{f}}^{\boldsymbol{N}}) - \mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{J}})$, because $\mathbb{E}A_f(\boldsymbol{a}^{\boldsymbol{J}}) \geq 0$. Although this lower bound is a direct derivation from the lower bound in Inequality (15) and the upper bound in Inequality (16), it has the advantage of not relying on $\mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{N}})$; we only need information on variable profits at different abatement profiles.

5.2.4 Non-Cooperative Equilibria

To quantify the bounds on expected noncompliance penalties characterized by Inequalities (15)–(17), we need to estimate variable profits $\mathbb{E}\pi_f(\boldsymbol{a^J})$, $\mathbb{E}\pi_f(a_f^J, \boldsymbol{a^N_{-f}})$, and $\mathbb{E}\pi_f(\boldsymbol{a^N})$. We estimate the first term from observed quantities and Nash-Bertrand markups defined in Equation (13).[37] To estimate the remaining terms, we need to know DEF tank size choices in a non-cooperative equilibrium, $\boldsymbol{a^N}$, which is not observed in the data.

The relative 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, which shows that the industry would move to a compliant equilibrium $\boldsymbol{a^N} = \boldsymbol{a^*}$ without 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 estimate $\boldsymbol{a^N}$ from the optimal abatement choices of non-working-group firms. We assume firms make abatement choices at the series-generation level r.[38] This modeling choice is based on the observation that there is no variation in the DEF tank size within a series generation. The first-order condition associated with the non-cooperative abatement choices of non-working group firms balances the marginal profit of changing abatement for all DEF vehicles in series r with the marginal change in the expected profit. Thus, the first-order condition for series r by a non-working-group firm g, conditional on the working-group collusion, is:

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

The estimated model of demand and supply allows us to construct the left-hand side of this equation. Following the analytical method of Villas-Boas (2007), we compute the marginal changes in expected profits by summing up the marginal changes due to increased marginal production cost, decreased demand from smaller trunk space, and an adjustment of equilibrium prices (see Appendix Section A4.1). We use variations in the marginal expected profits to estimate the marginal expected noncompliance penalty of the non-working group firms by specifying the right-hand side of (18) as

[37] Firms make decisions before demand and cost shocks materialize. In simulations, we take 100 draws with replacement from the estimated demand and cost shock distributions, ξ and ω, respectively.

[38] A series generation is a firm-designated collection of models of the same style and dimensions within 3-5 years. For example, the series generation "BMW Series 3 Limousine (07/15 - 10/18)" contains models 316, 318, 320, 325, 330, 335, 340 and runs from 2015 to 2018.

follows:

$$\frac{\partial \mathbb{E} K_g(\boldsymbol{a})}{\partial a_r} = -\exp\{\gamma_0 + \gamma_1 a_r + \gamma_2 a_{-g} + \gamma_3 \log(size_g) + \epsilon_r\}, \tag{19}$$

where the marginal expected noncompliance penalty is an exponential function of a firm's own abatement choice, the average abatement levels of other firms, and its historical sales revenue. We assume an i.i.d. error term ϵ_r. We present estimation results in Appendix Section A4.3.

With the estimation results of (19), we expand the set of equations (18) to include the first-order conditions that working group firms would use to choose DEF dosage non-cooperatively. The system has $\boldsymbol{a^N}$ as unknowns, equal to the total number of series generations with SCR. We recompute the equilibrium prices while solving for the counterfactual $\boldsymbol{a^N}$. We detail the computation in Appendix A4.3. We find that all firms have the incentive to increase abatement in the absence of collusion: the decrease in variable profits is smaller than the decrease in the expected penalty. 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.[39] 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 A9. 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 3. Collusion may have merely enabled the working-group firms to adopt lower dosages than the non-working-group firms. In this case, absent 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. Across years, this corresponds to an increase

[39] Figure 3 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.

in the working group median dosages from 1.5% to 2.1%, or a 5-liter increase in median tank sizes. 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.

To sum up, collusion succeeded in reducing tank sizes, and we compute two non-cooperative scenarios corresponding 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 cost estimates. We then quantify the bounds of the reduction in expected noncompliance penalties achieved by collusion. We show empirical evidence for the possible reasons behind such a reduction, discussed in Section 2. We conclude by describing 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. Column (1) presents a logit OLS. In column (2), we expand the model to the nested logit, and we instrument for prices, trunk space, and the nesting term. The instrumental variables for price correct the upward bias in the price coefficient in Column (1). The trunk IV based on gross trunk does not change the trunk space coefficient relative to the OLS, 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 14-liter increase in the trunk space, or equivalently having an average-sized DEF tank removed, is €291.[40] The nesting parameter is 0.33, meaning there is more substitution between vehicles in the same size class than between vehicles in different size classes.

The nested random coefficient logit specification in Column (3) shows significant heterogeneity in the price and range coefficients but not in the trunk space or power coefficient.[41] We use the RCNL model from Column (3) in all the subsequent estimates. The nesting coefficient is precisely estimated to be 0.47, and together with the random coefficients, the demand model estimates higher cross-price elasticities for more similar vehicles in terms of prices, power, and size class relative to

[40] To obtain this number, we compute: $0.87/1000 \times 14/1.47 \times 35091 = 283$ using the average GDP per capita of €35,091.

[41] We estimate a normal distribution for the random coefficient on price. In theory, this could be inconsistent because firms would set infinite prices if some consumers have a positive price coefficient. In practice, we use a truncated normal distribution so that no simulated individuals ever have a positive taste for the price. We truncate the 1% most extreme positive and negative MLHS draws for the price random coefficient.

Table 3: Demand Estimates

	(1) Logit OLS		(2) Nested Logit IV		(3) RC Nested Logit		(4) RC Nested Logit	
	Param.	St. Err.	Param.	St. Err.	Param.	St. Err.	Param.	St. Err.
					Mean Valuation		Mean Valuation	
Retail Price / Per Capita GDP	-0.21	(0.02)	-1.47	(0.08)	-2.04	(0.31)	-2.04	(0.31)
Trunk Space (cubic m)	0.90	(0.13)	0.87	(0.09)	0.83	(0.13)	0.83	(0.13)
Power (100 kw)	-0.54	(0.02)	0.25	(0.03)	0.13	(0.09)	0.13	(0.09)
Engine Size (L)	0.08	(0.02)	0.15	(0.01)	0.13	(0.02)	0.12	(0.01)
Curb Weight (ton)	-1.70	(0.07)	-1.10	(0.05)	-0.81	(0.01)	-0.81	(0.06)
Footprint (sq m)	1.77	(0.03)	1.28	(0.04)	1.04	(0.04)	1.05	(0.04)
Fuel Cost / Per Capita GDP	-64.73	(1.14)	-36.54	(1.12)	-52.80	(1.23)	-52.92	(1.23)
Foreign	-0.90	(0.01)	-0.56	(0.01)	-0.54	(0.01)	-0.54	(0.01)
Range (1000 km)	0.82	(0.04)	0.60	(0.04)	0.07	(0.04)	0.07	(0.04)
Having SCR							-0.01	(0.04)
DEF Tank Size (cubic m)							3.67	(2.30)
					Standard Deviation		Standard Deviation	
Retail Price / Per Capita GDP					0.78	(0.20)	0.78	(0.20)
Trunk Space					0.04	(0.19)	0.04	(0.19)
Power					0.18	(0.04)	0.19	(0.04)
Range					0.00	(0.00)	0.00	(0.00)
Nesting Parameter			0.33	(0.01)	0.47	(0.01)	0.46	(0.01)
IV for Price			X		X		X	
IV for Trunk			X		X		X	
N	212661		212661		212661		212661	

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. The random coefficient nested logit is estimated by optimal two-step GMM.

the logit model. The outside good is in a separate nest, so there is also more substitution between inside goods than between the outside good and inside goods.

The median own-price elasticity is -3.06. The median firm-level price elasticity is -2.44. The median market-level price elasticity is -0.74. The median margin is 37%. These price elasticities are of the same magnitude as recent other applications in the Spanish (Miravete et al., 2018) and German (Remmy, 2022) automobile markets, but somewhat lower than estimates in the US market (Grieco et al., 2023). Appendix Table A7 reports 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 and in our counterfactual analysis.

Column (4) also tests 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 A6, 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, if consumers value SCR emissions 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 1. 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, DEF refills are designed to coincide with annual check-ups without consumer intervention during the study period.

6.2 Marginal Cost Estimates

Table 4 reports the marginal cost estimates for diesel vehicles. We allow the marginal cost function to be specific for diesel and gasoline.[42] Column (1) estimates that the SCR technology costs €687 and the LNT technology costs €437. The estimates are statistically consistent with the engineering estimates in Sanchez et al. (2012), who report SCR to cost $494 (for large vehicles) and LNT $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 €42 per liter. We use this estimate in our counterfactual analysis when we change DEF tank sizes.

Columns (3)–(4) add interaction terms with the working group indicator to the previous two specifications. All the interaction terms have statistically imprecise parameters. We do not find 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 expected variable profits at DEF tank size choices according to Inequalities (15)–(17). We consider the observed DEF tank sizes as the collusive choices a_f^J. For the non-cooperative tank size choices a_f^N, we use the two scenarios discussed in Section 5: one where the non-cooperative equilibrium is noncompliant and the other where it is compliant. We recompute marginal costs and trunk space with counterfactual DEF tank sizes for each scenario and find new equilibrium prices and quantities.

Table 5 quantifies the bound from Inequality 17. For the noncompliant counterfactual scenario,

[42] 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.

Table 4: Marginal Cost Estimates

	(1)	(2)	(3)	(4)
LNT	437.18	405.08	450.89	430.01
	(84.57)	(81.12)	(132.15)	(130.83)
SCR	686.88		941.76	
	(115.72)		(200.14)	
DEF Size (L)		42.09		62.28
		(6.61)		(13.87)
LNT × Working Group			−18.17	−23.51
			(168.88)	(165.08)
SCR × Working Group			−378.65	
			(247.60)	
DEF Size × Working Group				−26.98
				(15.94)
Controls	X	X	X	X
Fixed Effects	X	X	X	X
N	97228	97228	97228	97228
Adjusted R^2	0.631	0.631	0.631	0.631

Notes: Reported in 2018 euros. Diesel vehicles only. Fixed effects are at the series generation level. Control variables include engine size, horsepower, torque, wheelbase, footprint, height, fuel consumption, curb weight, country-specific year trend, and dummies of 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.

Table 5: Bounds on the Reduction in Expected Noncompliance Penalties

	Non-Cooperative Scenario	
	Noncompliant	Compliant
BMW	30	109
Daimler	18	83
Volkswagen	21	153
Working Group Total	69	345

Notes: Reported in million 2018 euros. This table quantifies Inequality (17) under two non-cooperative scenarios.

the bounds for (15) and (16) cannot be computed 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, so that the reduction in the expected penalty can be computed without having to take a stance on the level of expected penalties in the non-cooperative profile. Compared to unilateral low abatement, coordinated low abatement reduces the expected penalties by at least €30–109 million for BMW, €18–83 million for Daimler, and €21–153 million for Volkswagen. The estimated penalty reductions 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, collusion reduces the expected noncompliance penalties the working group faces by at least €69–345 million across the two scenarios. Appendix Table A9 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 €410 million relative to compliance (see Table 8). The €345 million reduction in expected penalties is large relative to the additional realized variable profit gain from collusion.

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 collusion case, we cannot identify their importance separately.

Diffusion of responsibility. We quantify the degree to which a single firm's noncompliance penalty could decrease when caught along with other violators compared to being caught alone. To do so, we compute a hypothetical example where firms receive reputation damages alone or jointly. We proceed in two steps. First, we apply joint reputation shocks that reduce the profits of the working group firms. We reduce buyers' indirect utilities with firm-specific additive shocks t_f until each firm's profits decrease by one-third of the working group gains. Second, we apply the same reputation shock to one firm at a time without shocking the reputation of the other working group firms (firm f receives t_f and $t_{-f} = 0$ for other firms $-f$).[43]

When a firm's profit from a joint shock is smaller than that from a shock received alone, we interpret this as evidence of the presence of diffusion in this industry. When only one firm is caught and receives a reputation shock, other firms' reputations are unaffected, so consumers can substitute for the undamaged firms or the outside good. When multiple firms are caught noncompliant, all firms' reputations are affected. The joint reputation shock shifts the industry's position relative to the outside option but not the relative position between firms. Joint reputation shocks thus potentially diffuse the damage that unilateral reputation shocks inflict on single firms.[44]

Table 6 shows the extent to which reputation damage to a single working-group firm diffuses with joint reputation shocks. The reputation damage would be 26% smaller for BMW, 22% for

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

[44] 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.

Daimler, and 43% for Volkswagen when other firms also receive reputation shocks. To explain the strong diffusion effect for Volkswagen, note that the degree of diffusion in this exercise depends on the estimated substitution patterns and number of affected vehicles. Since each working-group firm loses less when other firms' reputations are also damaged, we interpret this as evidence that noncompliance penalties could diffuse in this sector.

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	-137	-186	49	26%
Daimler	-137	-175	38	22%
Volkswagen	-137	-242	105	43%

Notes: Reputation shock t_f is the reduction in the indirect consumer utility for each firm f in the working group that reduces the working group's variable profit (in million 2018 euros) to that under the 3% dosage compliance. The last column computes the percentage of reputation damages that are diffused by the joint shocks relative to the unilateral shocks (e.g., $100 \times 49/186 = 26\%$).

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

Table 7 shows that whenever a working-group firm violates unilaterally, between 25% to 47% of the variable profit gains from unilateral violation stem from stealing business from other firms in the working group. Collusion reduces the risk of being reported by a competitor to the regulator. When every working group member 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

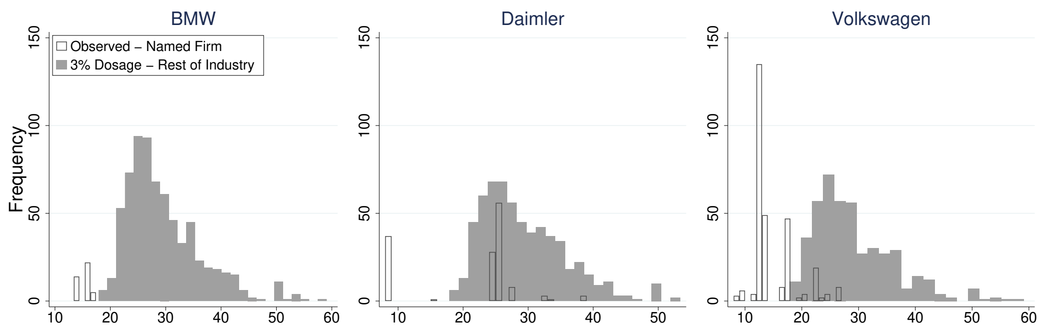
	Variable Profit Change			% Variable Profit Change Stolen
	BMW	Daimler	Volkswagen	from the Rest of the Working Group
BMW	100	-12	-28	39%
Daimler	-31	177	-53	47%
Volkswagen	-65	-59	498	25%

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., $(31 + 53)/177 = 47\%$).

Probability of detection. We show that DEF tank sizes of each working-group firm 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 2 shows the DEF tank size distribution observed under the collusive scheme, Figure 4 plots the observed DEF tank sizes of each working-group firm against the 3% compliant distribution for the rest of the industry. It suggests that vehicles released by BMW, Daimler, and Volkswagen would likely appear suspicious relative to a compliant rest-of-industry.[45] The working group thus potentially benefits from reduced scrutiny by moving into noncompliance jointly.[46]

Figure 4: Unilateral Noncompliance Stands out



Notes: This figure plots the distribution of DEF tank sizes (in SCR-only vehicles approved for Euro 6 NEDC) of each working-group firm against a counterfactual distribution of compliant DEF tank sizes (at 3% dosage) for the rest of the industry.

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

[45] 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]".

[46] 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 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.

diffusion of responsibility and reduction in the detection probability.

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 €109 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 €66 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.

Conditional on the working group colluding, the non-working-group firms collectively gain €327 million in variable profits by following the working group into noncompliance from 3% dosage compliance.[47] We obtain this number from Inequality (5), which compares each non-working-group firm's observed variable profits with what it would earn 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 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 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:

$$W(\boldsymbol{a}) = BS(\boldsymbol{a}) + \sum_{f} \pi_f(\boldsymbol{a}) - \sum_{j} \phi e_j(a_j) q_j(\boldsymbol{a}), \tag{20}$$

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 NO_x emissions, ϕ, times emissions and sales. Regulatory penalties

[47] We obtain this number using the realized demand and cost shocks instead of taking expectations (as we do for the working group firm's bounds) due to computation burden.

are considered a transfer and cancel out. The social welfare change caused by collusion relative to competition equals:

$$\Delta W = W(\boldsymbol{a^J}) - W(\boldsymbol{a^N}). \tag{21}$$

To find changes in buyer surplus BS and variable profits π_f, we use the estimated demand and marginal cost parameters 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.[48] Given these new marginal production costs and trunk spaces, we solve for a new Bertrand Nash price equilibrium. 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 NO_x damages from each of firm f's Euro 6 NEDC SCR vehicle j registered in year t as follows:

$$\sum_{\tau=0}^{T} \delta^{\tau} \left[q_j(e^* + (a_j^* - a_j)RemovalRate) - q_j^* e^* \right] \times AnnualMileage \times \phi, \tag{22}$$

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.[49] $RemovalRate$ 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.[50] 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

[48] We do not include a scenario where automakers change the DEF refill frequency because it is not feasible to estimate the costs of refills for consumers in our empirical context. If increasing the refill frequency is less costly than increasing the tank size, we will overestimate the collusive benefits to firms and car buyers.

[49] We assume the outside good and vehicles without DEF cause no NO_x emissions. We ignore outside good emissions because we find collusion increases the total quantity of vehicles sold by only 0.02%. See Appendix Table A8. Diesel vehicles without DEF have a very small market share, and gasoline vehicles emit low levels of NO_x. See Jacobsen et al. (2022) for an example of how scrappage affects US pollution standards' efficiency.

[50] 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.

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 collusion. The table shows that the working group's extra variable profits due to collusion are 200 million relative to the noncompliant non-cooperative scenario and 410 million relative to the compliant scenario. The aggregate profits of other firms decrease by a smaller extent. Buyer surplus increases substantially with as much as €1.97 billion relative to compliance, which amounts to €332 per DEF vehicle sold. We find the health damages of excess NO_x to reach €2.18-7.89 billion, outweighing the sum of the gains in firm profits and buyer surplus.[51]

Collusion enables both the working-group and non-working-group firms to increase prices and sales of Euro 6 NEDC DEF vehicles. Compared to the compliant non-cooperative scenario, Appendix Table A8 reports that the working group sells 1.4% more Euro 6 NEDC DEF vehicles featuring 3.6% larger trunk space and 1.4% higher prices (trunk space and price changes are weighted by sales quantity). Likewise, other firms sell SCR vehicles with 2.5% larger trunk space and 1.17% 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 (21) is -€5.57 billion relative to the compliant non-cooperative scenario with a 95% confidence interval of [-6.63, -3.80]. Relative to all the non-cooperative scenarios in Table 8 and Appendix Table A10, we estimate welfare changes between -€1.57 and -€9.57 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 benefits both participating firms and buyers at the expense of population-wide externality damages.

7.3 Policy Implications

Although our welfare results show the collusion decreased welfare, simply banning all cooperation is not an optimal policy. The optimal policy would aim to prevent welfare-reducing collusion. Cooperation on abatement decisions could enhance welfare if there is over-regulation (e.g., a too stringent standard) or when coordination reduces the cost of technology development. Our model does not include technology cost reductions from coordination, which is consistent with the case

[51] The excess NO_x emissions due to collusion are 111kton relative to compliance.

Table 8: Welfare Effects of Collusion, 2007-2018

	Non-Cooperative Scenario	
	Noncompliant	Compliant
Working Group's Profit $\Delta\pi$	0.20	0.41
	[0.14, 0.29]	[0.29, 0.60]
Residual Claim $\Re$	-1.77	-5.98
	[-2.03, -1.29]	[-7.00 -4.26]
NO_x health impact	-2.18	-7.89
	[-2.40, -1.52]	[-8.78, -5.45]
Buyer surplus	0.52	1.97
	[0.25, 0.76]	[0.88, 2.87]
Other firms' profit	-0.11	-0.07
	[-0.16, -0.07]	[-0.10, -0.05]
Net Welfare $\Delta\pi + \Re$	-1.57	-5.57
	[-1.85, -1.05]	[-6.63, -3.80]
Ratio $\lambda = \Delta\pi/(-\Re)$	0.11	0.07
	[0.09, 0.20]	[0.05, 0.13]

Notes: Reported in billion 2018 euros. The 95% confidence intervals are in brackets. See Appendix A5 for details on the computation of those confidence intervals.

document and our empirical findings. However, in other contexts, cost reductions could be the reason for firms' coordinated responses to regulation.

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 collusion on the rest of the society:

$$\Re = \Delta W - \Delta\pi, \tag{23}$$

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 (1) into $\Delta\pi + \Re = \Delta W \geq 0$,[52] so that the working group's objective becomes perfectly aligned with that of a welfare-maximizing regulator. Firms accept the collusive proposal $\boldsymbol{a}^J$ only when collusion is not welfare-reducing.

We construct a benchmark to evaluate the actual policy environment firms used to make their participation decision:

$$\lambda = \frac{\Delta\pi}{-\Re}. \tag{24}$$

Under a collusion-proof policy, we should only observe collusion if $\Delta W \geq 0$, or $\lambda \geq 1$ when we focus on cases where $\Re < 0$. In this case, collusion 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 standards are too stringent; collusion

[52]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).

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 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 -€1.77 billion when we compare the collusive outcome to a noncompliant non-cooperative scenario and -€5.98 billion when the comparison is with compliance. We estimate λ to be 0.11 and 0.07 in the two scenarios. We can interpret this 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 λ. Second, firms would participate in the collusive proposal if they expect to be caught and pay at most λ of the residual claim. Third, $(1 - \lambda)$ 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, 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 €1.57–5.57 billion. The magnitude of the welfare damages the cartel inflicts on the rest of the society reaches between €1.77–5.98 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 against regulation. 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 would need 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 an 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 proof of explicit conspiracy. Second, policymakers could incentivize 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.

References

ACEA (2024). The automobile industry pocket guide 2023/2024.

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

Alexander, D. and Schwandt, H. (2022). The Impact of Car Pollution on Infant and Child Health: Evidence from Emissions Cheating. *Review of Economic Studies*.

Ater, I. and Yoseph, N. (2022). The Impact of Environmental Fraud on the Used Car Market: Evidence from Dieselgate. *Journal of Industrial Economics*, 70(2):463–491.

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

Bachmann, R., Ehrlich, G., Fan, Y., Ruzic, D., and Leard, B. (2022). Firms and collective reputation: a study of the volkswagen emissions scandal. *Journal of the European Economic Association*, page jvac046.

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

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

Berry, S. T. (1994). Estimating discrete-choice models of product differentiation. *The RAND Journal of Economics*, pages 242–262.

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

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

Bresnahan, T. F. (1987). Competition and Collusion in the American Automobile Industry: The 1955 Price War. *Journal of Industrial Economics*, 35(4):457–482.

Cardell, N. S. (1997). Variance components structures for the extreme-value and logistic distributions with application to models of heterogeneity. *Econometric Theory*, 13(2):185–213.

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

Conlon, C. and Gortmaker, J. (2020). Best practices for differentiated products demand estimation with PyBLP. *RAND Journal of Economics*, 51(4):1108–1161.

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

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

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

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

European Commission (2021). Case AT.40178 - Car Emissions - Commission Decision of 8.7.2021.

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

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

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

Gearino, D. (2020). Love is blind: How germany's long romance with cars led to the nation's biggest clean energy failure. *Inside Climate News*.

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

Grieco, P. L. E., Murry, C., and Yurukoglu, A. (2023). The Evolution of Market Power in the U.S. Automobile Industry*. *The Quarterly Journal of Economics*, 139(2):1201–1253.

Grigolon, L. and Verboven, F. (2014). Nested logit or random coefficients logit? a comparison of alternative discrete choice models of product differentiation. *The Review of Economics and Statistics*, 96(5):916–935.

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

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

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

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

Igami, M. and Sugaya, T. (2022). Measuring the Incentive to Collude: The Vitamin Cartels, 1990–99. *Review of Economic Studies*, 89(3):1460–1494.

Jacobsen, M. R., Sallee, J. M., Shapiro, J., and van Benthem, A. (2022). Regulating untaxable externalities: Are vehicle air pollution standards effective and efficient?

Joshua Posaner, Florian Muller, G. H. (2017). Too big to fail: Why germany's autostate keeps winning. *Politico*.

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

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

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

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

Mansley, R., Miller, N., Ryan, C., and Weinberg, M. (2019). Notes on the nested logit demand model.

Miller, N. H. and Weinberg, M. C. (2017). Understanding the Price Effects of the MillerCoors Joint Venture. *Econometrica*, 85(6):1763–1791.

Miravete, E. J., Moral, M. J., and Thurk, J. (2018). Fuel taxation, emissions policy, and competitive advantage in the diffusion of european diesel automobiles. *The RAND Journal of Economics*, 49(3):504–540.

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

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

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

Porter, R. H. (1983). A study of cartel stability: the joint executive committee, 1880-1886. *The Bell Journal of Economics*, pages 301–314.

Rai, A. S. and Sjöström, T. (2004). Is Grameen Lending Efficient? Repayment Incentives and Insurance in

Village Economies. *Review of Economic Studies*, 71(1):217–234.

Remmy, K. (2022). Adjustable product attributes, indirect network effects, and subsidy design: The case of electric vehicles. *University of Bonn and University of Mannheim, Germany.*

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

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

Reynaert, M. and Verboven, F. (2014). Improving the performance of random coefficients demand models: The role of optimal instruments. *Journal of Econometrics*, 179(1):83–98.

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

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

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

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

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

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

Villas-Boas, S. B. (2007). Vertical relationships between manufacturers and retailers: Inference with limited data. *Review of Economic Studies*, 74(2):625–652.

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

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

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

Online Appendix

A1 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:

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

Our assumption that the variable profit is decreasing in the firm's own abatement action implies that $\pi_f(a_f^D, \boldsymbol{a}^{\boldsymbol{J}}_{-\boldsymbol{f}}) < \pi_f(\boldsymbol{a}^{\boldsymbol{J}})$ 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: $\mathbb{E}K_f(a_f^D, \boldsymbol{a}^{\boldsymbol{J}}_{-\boldsymbol{f}}) + \mathbb{E}A_f(a_f^D, \boldsymbol{a}^{\boldsymbol{J}}_{-\boldsymbol{f}}) < \mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{J}}) + \mathbb{E}A_f(\boldsymbol{a}^{\boldsymbol{J}})$.

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

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

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

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

where we have assumed that the revelation of collusion does not lead to changes in the expected noncompliance penalty $\mathbb{E}K_f(\boldsymbol{a}^{\boldsymbol{J}})$. An increase in the antitrust risk increases $A_f(\boldsymbol{a}^{\boldsymbol{J}})$ 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:

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

When whistle-blowing entails the collateral damage of having the violation discovered, the continuation payoff to collusion can be lower while still sustaining 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 $\mathbb{E}K_{(C,C)} < 1$.[53]

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

[53] (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:

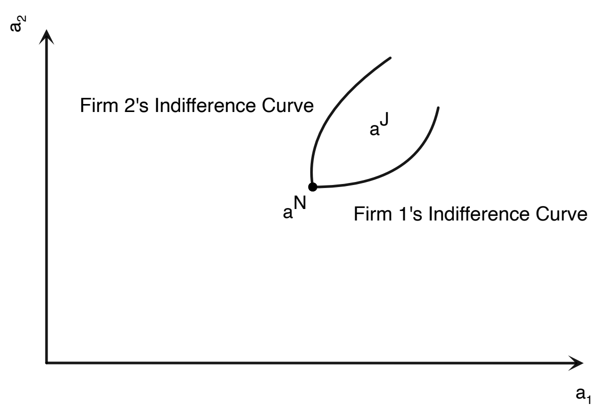
$$\frac{\mathrm{d}a_2}{\mathrm{d}a_1} = -(\frac{\partial \pi_1}{\partial a_1} - \frac{\partial \mathbb{E}K_1}{\partial a_1})/(\frac{\partial \pi_1}{\partial a_2} - \frac{\partial \mathbb{E}K_1}{\partial a_2}). \tag{A5}$$

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 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 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 1. 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

We provide details on the computation of the counterfactual non-cooperative equilibrium. Equation 18 gives the first-order conditions of non-working-group firms at the observed abatement profile $\boldsymbol{a^J}$. Our goal is to estimate the slope of the expected noncompliance penalty function from variations in the slope of the expected profit function. To restrict the sign of the derivatives in line with our economic model, we take the following transformation of (18):

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

We describe how we compute marginal profits and estimate the slope of the penalty function.

A4.1 Marginal Profits

We adapt the method outlined in Villas-Boas (2007) to compute the marginal profits. Firms optimize profits in two stages. First, they choose the DEF tank size for each series generation that has DEF vehicles. Second, firms price all vehicles in the market after observing demand and marginal cost shocks. Therefore, we simulate over the estimated demand and cost shocks, by drawing with replacement, to compute the derivative of profits with respect to the DEF tank choices. The derivative incorporates the firms' expected effect of DEF tank size on equilibrium prices in the second stage. We define the set of DEF vehicles in series generation r as $J_r \subset J_f$, with vehicles in a series generation having identical DEF tank sizes: $a_j = a_r, \forall j \in J_r$.

The first-order derivative of firm f's expected profit with respect to its series generation r's DEF tank size is the sum across all j's in J_r:

$$\frac{\partial \mathbb{E}\pi_f}{\partial a_r} \equiv \sum_{j \in J_r} \frac{\partial \mathbb{E}\pi_f}{\partial a_j} = \mathbb{E}(\sum_{j \in J_r} \frac{\partial \pi_f}{\partial a_j}),$$

where the second equation is due to the Dominated Convergence Theorem (that the marginal expected profit is equal to the expected marginal profit as long as the marginal profit is bounded), and:

$$\frac{\partial \pi_f}{\partial a_j} = -\frac{\partial mc_j}{\partial a_j} q_j + \sum_{j' \in J_f} (p_{j'} - mc_{j'})(\frac{\partial q_{j'}}{\partial x_j}\frac{\partial x_j}{\partial a_j} + \sum_{k \notin J_f} \frac{\partial q_{j'}}{\partial p_k}\frac{\partial p_k}{\partial a_j}), \quad \text{(A7)}$$

where mc is the marginal cost, q is the quantity, J_f is the set of all vehicles (with or without DEF tanks) from firm f, p is the equilibrium price, x is the vehicle characteristic affected by the DEF size, which is trunk space.

The first term on the right-hand side of Equation (A7) captures the marginal cost effect coming from firm f's DEF vehicles only. Larger DEF tanks in a series generation increase the marginal cost of DEF vehicles, which reduces the profit.

The second term on the right-hand side captures the market share effect coming from all vehicles of firm f, regardless of whether they have DEF tanks or not. An increase in the DEF tank size has two effects on the market share of all vehicles of firm f. First, a larger DEF tank reduces the trunk space (and thus the quality) of the DEF vehicle, which *directly* changes the market share of each of the firm's vehicles. Second, a larger DEF tank *indirectly* changes the market shares through the re-pricing of vehicles by other firms. The envelope theorem allows us to eliminate the terms containing the partial price derivatives of firm f's own vehicles with respect to the DEF tank size.

We further derive $\frac{\partial p_k}{\partial a_j}$ in the re-pricing effect using the total differentiation approach in Villas-Boas (2007). Firm f's pricing first-order condition for vehicle j' is:

$$q_{j'} + \sum_{j'' \in J_f} (p_{j''} - mc_{j''}) \frac{\partial q_{j''}}{\partial p_{j'}} = 0 \tag{A8}$$

We then totally differentiate Equation (A8) with respect to the prices of all vehicles (including other firms' vehicles), p_k, $k = 1, \ldots, N$, and to DEF vehicle j's DEF tank size, a_j:

$$\begin{aligned}
&\sum_{k=1}^{N} \underbrace{[\frac{\partial q_{j'}}{\partial p_k} + \sum_{j'' \in J_f} (p_{j''} - mc_{j''})) \frac{\partial^2 q_{j''}}{\partial p_{j'} \partial p_k} + T_f(k, j') \frac{\partial q_k}{\partial p_{j'}}]}_{G(j',k)} \mathrm{d}p_k \\
&+ \underbrace{[\frac{\partial q_{j'}}{\partial x_j} \frac{\partial x_j}{\partial a_j} + \sum_{j'' \in J_f} (p_{j''} - mc_{j''}) \frac{\partial^2 q_{j''}}{\partial p_{j'} \partial x_j} \frac{\partial x_j}{\partial a_j} + (-\frac{\partial mc_{j'}}{\partial a_j}) \frac{\partial q_j}{\partial p_{j'}}]}_{H(j')} \mathrm{d}a_j = 0,
\end{aligned} \tag{A9}$$

where $T_f(k, j') = 1$ if models k and j' are produced by firm f and 0 otherwise. Stacking all vehicles produced by all firms, we let G be an $N \times N$ matrix whose (j', k)-th element is $G(j', k)$, and H be an $N \times 1$ vector whose j'-th element is $H(j')$. Equation (A9) becomes $G\mathrm{d}p + H\mathrm{d}a_j = 0$, which implies that $\frac{\mathrm{d}p}{\mathrm{d}a_j} = -G^{-1}H$, a $N \times 1$ vector whose k-th element is $\frac{\mathrm{d}p_k}{\mathrm{d}a_j}$.

In Equation (A9), computing the second-order cross derivatives $\frac{\partial^2 q_{j''}}{\partial p_{j'} \partial p_k}$ and $\frac{\partial^2 q_{j''}}{\partial p_{j'} \partial x_j}$ for the random-coefficient nested logit model is not straightforward. We rely on Mansley et al. (2019) to compute 9 types of derivatives before combining them into an N by N matrix for each k and each j.

Finally, because the marginal cost and demand shocks have not realized when firms choose DEF tank size, we compute the marginal profit in Equation (A7) for each simulated draw of marginal cost and demand shocks (including solving for the corresponding price equilibrium) and then take the average.

A4.2 Estimation of Derivative of Penalty Function with respect to Abatement

To estimate equation 19, we substitute (A6) for a non-working-group firm g and obtain the following estimable equation:

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

where r is a series generation that contains NEDC DEF vehicles produced by firm g, a_r is the DEF dosage of series generation r, a_{-g} is the average DEF dosage of NEDC DEF vehicles from other firms, and $size_g$ is the size of firm g measured by historical annual average sales revenue between 2007 and 2013.[54] 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 estimate parameters affecting the probability and penalty separately. We estimate this equation with data from the non-working group firms to obtain $\hat{\boldsymbol{\gamma}}$ and $\hat{\epsilon}_r^{NWG}$, where the superscript NWG refers to these being the residuals for the non-working group sample.

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 (1):

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

where Δ_f is a term capturing the slackness of the participation constraint. Taking the derivative with respect to a_r, we have $\frac{\partial \pi_f(\boldsymbol{a^J})}{\partial a_r} = \frac{\partial \mathbb{E}K(\boldsymbol{a^J})}{\partial a_r} + \frac{\partial \mathbb{E}A(\boldsymbol{a^J})}{\partial a_r} + \frac{\partial \Delta_f}{\partial a_r}$. We estimate:

$$\log(-\frac{\partial \pi_f(\boldsymbol{a^J})}{\partial a_r}) = m(a_r, a_{-f}) + \epsilon_r, \tag{A11}$$

where the function m captures the slopes of the slackness condition, the penalty function, and the antitrust penalty. We parameterize $m(a_r, a_{-f})$ to include own DEF tank size and its square, other firms' average DEF tank size, own firm's other series generations' average DEF tank size, and log firm size.[55] The function m is impossible to interpret without a formal cartel formation and antitrust enforcement model. However, we obtain residuals $\hat{\epsilon}_r^{WG}$ from estimating (A11) on the working group sample. These residuals are useful in the next step.

In the counterfactual non-cooperative equilibrium $\boldsymbol{a^N}$, the conditions in (A6) determine all firms' optimal abatement choices instead of only the choices of the non-working group firms. As such, we obtain a system of R equations for the R unknown elements of $\boldsymbol{a^N}$, where R is the number of series generations:

$$\log(-\frac{\partial \pi_f(\boldsymbol{a^N})}{\partial a_r}) - (\gamma_0 + \gamma_1 a_r + \gamma_2 a_{-f} + \gamma_3 \log(size_g) + \epsilon_r) = 0. \tag{A12}$$

[54] 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.

[55] The results reported below remain the same when we use the same functional form as in (A10) for this regression.

Plugging in $\hat{\boldsymbol{\gamma}}$, $\hat{\epsilon}_r^{NWG}$, and $\hat{\epsilon}_r^{WG}$ allows us to solve for the R elements of $\boldsymbol{a^N}$. 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 choose non-cooperatively.

A4.3 Estimation Results

We discuss three results. First, we discuss the regression results of estimating (19) by (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 (19)

	(1) $\log(-\frac{\partial \mathbb{E} K_f}{\partial a_r})$
DEF dosage (%)	0.842 (0.388)
Others firms' DEF dosage	17.468 (8.326)
log(Historical firm revenue)	0.362 (0.278)
Constant	−19.592 (19.888)
N	69

Notes: An observation is a non-working-group series generation that contains NEDC DEF vehicles. Historical firm revenue is the annual average sales revenue between 2007 and 2013 in 2018 euros. The omitted origin is France. Germany does not have non-working-group series generations with NEDC DEF vehicles. Robust standard errors in parentheses.

Table A1 reports the regression results of Equation (A10) for non-working-group series generations. The estimated coefficients imply that the slope of the expected noncompliance penalty is decreasing in DEF dosage and other firms' dosages. We have also conducted robustness checks with additional specifications that include a quadratic term in the DEF dosage of the series generation, the average dosage of the firm's other series generations, and/or origin country fixed effects. The results of those additional specifications are statistically imprecise due to the limited number of SCR series generations in the sample.

The coefficients in Table A1 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 based on Specification (1) of Table A1.[56] We find that the marginal profits are larger than the marginal expected penalties for 69 out of 71 working-group series generations, indicating an incentive to increase abatement beyond 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 evaluate the system of equations in (A12). We replace the observed abatement profile with profiles featuring more abatement, gradually leading up to industry-wide compliance.[57] 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 the equations in (A12) to be consistently negative, indicating that firms face an incentive to increase abatement in the absence of collusion. This is also true at the compliant vector $\boldsymbol{a^*}$, which means we find a corner solution for $\boldsymbol{a^N}$: all firms would choose compliance under non-cooperative incentives.

A5 Computation of Confidence Intervals for Welfare

To compute confidence intervals for the welfare effects in Section 7, we follow the procedure described in Conlon and Gortmaker (2020) and take the following steps:

1. We draw 100 sets of the demand and marginal cost coefficients using the estimated variance-covariance matrix associated with specification Table 1 (3) and Table 2 (2).

2. For each set of parameter draws, we update the marginal costs and indirect utility and solve for the implied Nash-Bertrand equilibrium in prices and shares.

3. For each set of parameter draws, we also compute the counterfactual prices and shares in the

[56]Conceptually, we replace the function $m(a_r, a_{-f})$ with the predicted relation from (A11) while keeping the estimated residuals fixed at $\hat{\epsilon_r^{WG}}$.

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

absence of collusion.

4. We calculate the welfare statistics in Table 8 by taking the difference between the counterfactual equilibrium in Step 3 and the equilibrium in Step 2.

5. We construct the 95% confidence interval by taking the 2.5th and 97.5th percentile of each welfare statistic across parameter draws.

A6 Additional Figures and Tables

Figure A2: Diesel Passenger Vehicle NO_x Emission Standards in the EU and US

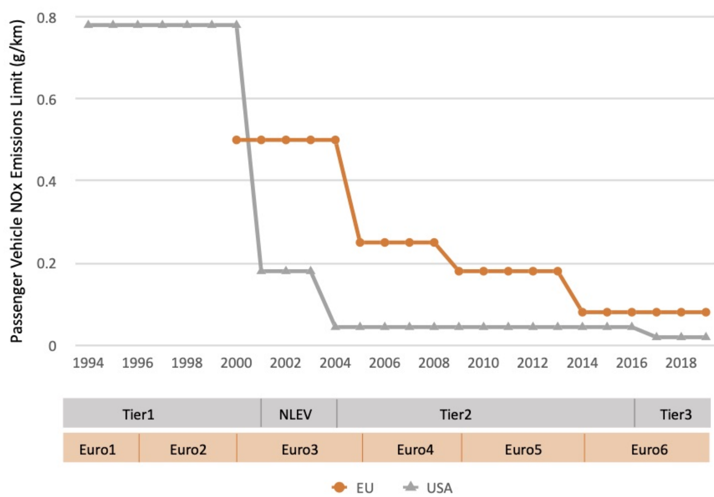


Table A2: Summary Statistics of Selected Characteristics by NO_x Control Technology

	Basic (EGR only)	LNT	SCR
Retail Price (10,000 euro)	3.90	3.64	5.10
	(1.70)	(1.35)	(2.16)
Trunk Space (cubic m)	0.45	0.45	0.53
	(0.13)	(0.11)	(0.12)
Footprint (sq. m)	8.22	8.14	8.74
	(0.76)	(0.66)	(0.68)
Range (100 km)	11.26	12.67	12.55
	(1.89)	(1.80)	(2.21)
Curb Weight (ton)	1.57	1.49	1.70
	(0.26)	(0.21)	(0.28)
Fuel Cost (euro per 100 km)	7.67	5.79	6.57
	(2.02)	(1.28)	(1.76)
Power (kW)	113.81	110.98	136.76
	(36.68)	(36.17)	(45.20)
Engine Size (L)	2.07	1.87	2.18
	(0.51)	(0.37)	(0.55)
Foreign Share	0.87	0.88	0.83
	(0.33)	(0.33)	(0.38)
N	59542	18482	12924

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 1,745 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	−0.022	−0.146	−0.085	0.128
	(0.017)	(0.026)	(0.024)	(0.022)
Euro 6 Cycle	Both	NEDC	NEDC	WLTP
Controls			X	X
N	1352	744	744	607
Adjusted R^2	0.000	0.040	0.179	0.286

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.

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

	(1) Trunk Space (L)	(2) Curb Weight (kg)
DEF Tank Size (L)	−0.83	0.03
	(0.23)	(0.57)
Control	X	X
Sample	SCR only	SCR only
N	1361	1361
Adjusted R^2	0.965	0.965

Notes: An observation is a diesel SCR vehicle. Controls include series body fixed effects, model start year fixed effects, drive type, transmission type, power, engine size, height, and fuel tank size. Robust standard errors are in parentheses.

Table A5: Working Group Abatement Choices and Outcomes From NEDC to WLTP

	(1) Dosage (%)	(2) NOx Exceedance Factor
From NEDC to WLTP	0.208	−1.354
	(0.050)	(0.643)
Dataset	Main	RDE
N	746	68
Adjusted R^2	0.544	0.327

Notes: An observation is a diesel SCR vehicle from the working group approved for Euro 6. Fixed effects are at the vehicle series level. Robust standard errors are in parentheses.

Table A6: Additional Demand Specifications

	(1) RC Logit		(2) Nested Logit		(3) RC Nested Logit		(4) RC Nested Logit	
	Param.	St. Err.	Param.	St. Err.	Param.	St. Err.	Param.	St. Err.
	Mean Valuation						Mean Valuation	
Retail Price / Per Capita GDP	-3.45	(0.67)	-1.47	(0.08)	-1.44	(0.08)	-1.95	(0.25)
Trunk Space (cubic m)	1.12	(0.37)	0.88	(0.09)	0.89	(0.09)	0.79	(0.10)
Power (100 kw)	0.42	(0.24)	0.25	(0.03)	0.24	(0.04)	0.14	(0.05)
Engine Size (L)	0.15	(0.03)	0.14	(0.01)	0.15	(0.01)	0.13	(0.01)
Curb Weight (ton)	-1.22	(0.10)	-1.11	(0.05)	-1.13	(0.06)	-0.85	(0.06)
Footprint (sq m)	1.97	(0.05)	1.29	(0.04)	1.29	(0.04)	1.06	(0.03)
Fuel Cost / Per Capita GDP	-51.28	(2.88)	-36.57	(1.12)	-36.94	(1.13)	-53.49	(1.48)
Foreign	-0.71	(0.02)	-0.56	(0.01)	-0.56	(0.01)	-0.55	(0.01)
Range (1000 km)	0.49	(0.19)	0.61	(0.04)	0.59	(0.04)	0.08	(0.04)
Having SCR			-0.01	(0.04)	-0.41	(0.36)	-0.01	(0.04)
DEF Tank Size (cubic m)			2.96	(2.23)	27.51	(22.16)	3.30	(2.78)
	Standard Deviation						Standard Deviation	
Retail Price / Per Capita GDP	0.65	(0.37)					0.78	(0.18)
Trunk Space	0.03	(0.84)					0.02	(0.22)
Power	0.40	(0.15)					0.00	(0.00)
Range	0.87	(0.04)						
DEF Tank Size (cubic m)							0.36	(0.20)
Nesting Parameter			0.33	(0.01)	0.33	(0.01)	0.46	(0.01)
IV for Price	X		X		X		X	
IV for Trunk	X		X		X		X	
IV for DEF					X			
N	212661		212661		212661		212661	

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.

Table A7: Price Diversion Ratios

Price Increase from:	Market Share Gain (%)				
	BMW	Daimler	Volkswagen	Average NWG	Outside Good
Panel A: Nested Logit IV					
BMW	9.58	6.09	15.59	1.89	37.21
Daimler	9.74	6.92	15.96	1.81	37.23
Volkswagen	6.49	4.43	15.83	2.16	37.21
Average NWG	5.42	3.36	15.14	2.95	29.60
Panel B: RC Nested Logit					
BMW	12.44	7.76	18.47	2.07	26.82
Daimler	13.10	9.40	19.67	1.97	25.10
Volkswagen	7.92	5.40	18.45	2.39	28.35
Average NWG	6.42	4.04	17.39	3.67	22.69
Panel C: RC Nested Logit, Price Increase on DEF Vehicles Only					
BMW	13.91	11.12	19.42	1.95	14.87
Daimler	13.07	9.11	18.53	2.06	21.96
Volkswagen	11.51	7.49	19.43	2.10	22.10
Average NWG	6.66	4.73	18.23	7.30	2.76

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 A8: Percentage Changes in Market Outcomes under Collusion, 2007-2018

	Non-Cooperative Scenario			
	Noncompliant	2% dosage	3% dosage	3% dosage plus
Quantity–Weighted Trunk	0.04	0.05	0.16	0.27
WG Euro 6 NEDC DEF	1.37	1.28	3.59	5.99
NWG Euro 6 NEDC DEF	-0.05	0.58	2.52	4.72
Quantity–Weighted Price	0.01	0.01	0.03	0.06
WG Euro 6 NEDC DEF	0.54	0.49	1.40	2.34
NWG Euro 6 NEDC DEF	-0.06	0.32	1.17	2.04
WG other diesel	-0.03	-0.03	-0.09	-0.14
NWG other diesel	-0.02	-0.03	-0.08	-0.14
WG gasoline	-0.03	-0.04	-0.12	-0.19
NWG gasoline	-0.02	-0.02	-0.08	-0.13
Quantity of Vehicles Sold	0.01	0.01	0.02	0.04
WG Euro 6 NEDC DEF	0.55	0.51	1.42	2.34
NWG Euro 6 NEDC DEF	-0.04	0.18	0.89	1.70
WG other diesel	-0.01	-0.02	-0.05	-0.08
NWG other diesel	-0.01	-0.01	-0.04	-0.07
WG gasoline	-0.02	-0.02	-0.06	-0.10
NWG gasoline	-0.01	-0.01	-0.04	-0.07

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 A9: Bounds on the Reduction in Expected Noncompliance Penalties under Alternative Non-Cooperative Scenarios, 2007-2018

	Non-Cooperative Scenario	
	2% dosage	3% dosage plus
BMW	34	186
Daimler	27	135
Volkswagen	43	275
Working Group Total	103	596

Notes: Reported in million 2018 euros. This table quantifies Inequality (17) under two additional non-cooperative scenarios.

Table A10: Welfare Effects of Collusion under Alternative Non-Cooperative Scenarios, 2007-2018

	Non-Cooperative Scenario	
	2% dosage	3% dosage plus
Working Group's Profit $\Delta\pi$	0.15	0.67
	[0.11, 0.23]	[0.46, 0.96]
Residual Claim $\Re$	-1.92	-10.23
	[-2.26, -1.40]	[-11.94 -7.26]
NO_x health impact	-2.54	-13.43
	[-2.85, -1.76]	[-14.93, -9.32]
Buyer surplus	0.66	3.30
	[0.29, 0.97]	[1.50, 4.79]
Other firms' profit	-0.04	-0.08
	[-0.07, -0.03]	[-0.13, -0.06]
Net Welfare $\Delta\pi + \Re$	-1.77	-9.57
	[-2.12, -1.21]	[-11.33, -6.52]
Ratio $\lambda = \Delta\pi/(-\Re)$	0.08	0.07
	[0.06, 0.16]	[0.05, 0.13]

Notes: Reported in billion 2018 euros. The 95% confidence intervals are in brackets, see Appendix A5 for details on the computation of those confidence intervals.

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