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ENVIRONMENTAL POLICIES IN INTERNATIONAL MARKETS

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"*You must do the things you think you cannot do.*"
Eleanor Roosvelt

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FAIG CONSTAR que aquest treball, titulat *Environmental Policies in International Markets*, que presenta Françeska Tomori per a l'obtenció del títol de Doctor, ha estat realitzat sota la meva direcció al Departament d'Economia d'aquesta universitat.

HAGO CONSTAR que el presente trabajo, titulado *Environmental Policies in International Markets*, que presenta Françeska Tomori para la obtención del título de Doctor, ha sido realizado bajo mi dirección en el Departamento de Economía de esta universidad.

I STATE that the present study, entitled *Environmental Policies in International Markets*, presented by Françeska Tomori for the award of the degree of Doctor, has been carried out under my supervision at the Department of Economics of this university.

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Els directors de la tesi doctoral
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Françeska Tomori
June 2021, Reus

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Foreword

During the industrialisation boom in the 1960s, pollution from industrial activity became an increasing concern for many developed economies. This period is considered by economists as the beginning of the new field of specialisation in economics named environmental economics. Since those early years, environmental economists have been aware of rapid economic growth and its consequences to the environment. Environmental economics focuses mainly on the efficient allocation of environmental and natural resources, and how alternative environmental policies deal with environmental damage, such as air pollution, water quality, solid waste, toxic substances, and global warming. In this context, it has become a major objective for policymakers and economists around the world that have to deal with issues such as inefficient natural resource allocation, market failure, negative externalities, and management of public goods. All this has led to the establishment of new environmental bodies among world economies in 1972, named the United Nations Environment Programme (UNEP).

The literature on the environmental economics' studies dates back to the pioneering works of Adam Smith (1776), Nicolas de Condorcet (1785), Thomas Robert Malthus (1798), David Ricardo (1817), and John Stuart Mill (1848) that use externality arguments in the context of the policy analysis of environmental issues. This thesis contributes to the literature of environmental economics with three studies organised as independent chapters identifying several environmental economics issues. The remainder of the current document is as follows:[1]

Chapter 1 studies the market power in Californian's water market.[2] In California the water market is thin. Thus, we provide an estimation of this thin water market. The main hypothesis is that market frictions may distort the potential welfare gains from water marketing. By using a Nash-Cournot model, we derive a closed-form solution for the extent of market power in a typical water market setting. This solution is used to estimate market power in a newly assembled dataset on California's water economy. The results of this study indicate that under the assumptions of the Cournot model, market power in this thin water market is limited. The robustness tests prove the same result.

[1]Note that each chapter is independent of the others, so each chapter has an introduction and a conclusion. Due to the fact that each chapter corresponds to a completely independent article, some repetitions are generated mainly in the definitions.

[2]This Chapter is derived from the article: "Market power in California's water market." (2021), joint with Ansink, E., Houba, H., Hagerty, N., and Bos, C. S.

Chapter 2 analyses the impact of environmental regulatory capture on innovation and emissions for the case of the automobile industry.[3] The hypothesis states that in the light of the Volkswagen emissions scandal, a common belief that has formed is that regulatory capture in the control and setting of emission standards has led to lower pollution abatement and less environmental innovation in gasoline and diesel combustion engines. Under a multi-product monopoly, the results indicate that regulatory capture only leads to more emissions and less innovation effort. The opposite is true under oligopoly competition. These results differ due to a competition intensifying effect, which is only present with at least two firms in the market. This effect comes from the fact that a consumer-orientated regulator sets higher emission standards for diesel cars, which leads to higher output and more intensive competition among car producers. Consequently, because emission standards and environmental innovation are strategic substitutes, car producers reduce their innovation effort. This result means that the hypothesis is false.

Chapter 3 provides a comparison of two policy instruments such as emission standards and acquisition taxes for the automobile market.[4] We investigate under which situation and instrument the adoption of electric vehicles, innovation effort and social welfare is higher. A Cournot oligopoly model with multi-product firms that vertically differentiate their products is used to derive the equilibrium results. The results indicate that emission standards offer greater innovation incentives, total output, firms' profits, and social welfare as compared to acquisition taxes. Acquisition taxes allow a major adoption of electric vehicles than emission standards. However, as long as environmental damages are not too large and when the tax revenues are redistributed, consumers prefer an acquisition tax. Otherwise, they are better off under an emission standard.

[3]This Chapter is derived from the article: "The impact of environmental regulatory capture on innovation and emissions: The case of the automobile industry." (2021), joint with Theilen, B.

[4]This Chapter is derived from the article: "Taxes versus emission standards: Welfare consequences and innovation incentives of electric vehicle adoption policies." (2021), joint with Theilen, B.

Chapter 1

Market power in California's water market

Overview. We estimate market power in California's thin water market. Market frictions may distort the potential welfare gains from water marketing. We use a Nash-Cournot model and derive a closed-form solution for the extent of market power in a typical water market setting. We then use this solution to estimate market power in a newly assembled dataset on California's water economy. We show that under the assumptions of the Cournot model, market power in this thin market is limited.

JEL classification: C72; D43; Q25.

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1.1 Introduction

We estimate the extent and impact of market power in California's thin water market. In this water market, both water leases and permanent sales of water rights reallocate water from lower to higher value uses. Such reallocation is known to substantially increase the efficiency of water use (see e.g., Vaux Jr. and Howitt, 1984; Jenkins et al., 2004), but it may be obstructed by various market frictions. There is ample evidence, both from California and other regions, and both for ground- and surface water trading, that market power may be an important source of friction in water markets (Rosegrant and Binswanger, 1994; Easter et al., 1999; Jacoby et al., 2004; Holland, 2006; Chakravorty et al., 2009; Bruno and Sexton, 2020). Under the premise that market frictions may distort the potential welfare gains from water marketing, we seek to identify the extent and impact of such market power in California.

Inspired by the model set-up of Ansink and Houba (2012), we introduce a Nash-Cournot model of water transactions. Under two main assumptions, discussed below, this model allows us to derive a closed-form solution for the extent of market power in a typical water market setting. One novelty is that we write this solution in terms of willingness-to-pay and -accept. We subsequently apply our model to a newly assembled dataset on California's water economy by Hagerty (2019). The data that we use is a 1993-2015 panel data on water transactions in California, with detailed information on quantities and prices at the water district-level, combined with detailed spatial data on locations of buying and selling districts as well as geographical factors that may affect market power. The data allows us to control, amongst others, for main water uses of buying and selling districts, and various types of associated transaction costs. The results of our estimation allow us, ultimately, to estimate Lerner indices for California's water market.

Our main approach starts with two main assumptions, both of which will be relaxed later on. One assumption is that we fix the side of the market where market power resides. Our base model assumes buyer market power, a belief held by many stakeholders and supported by previous literature (see e.g., Tomkins and Weber, 2010; Hansen et al., 2014; Hagerty, 2019). To check the relevance of this assumption, we also employ a model specification where we allow for market power on both sides; we find support for buyer power only. The second main assumption is that we use linear demand, originating from a quadratic benefit function of water use. This functional form is commonplace in the water economics literature and allows for a straightforward empirical strategy to derive our results. Constant linear demand across selling districts may not be realistic, however, and therefore, we relax this assumption in an alternative specification where, instead, we impose constant price elasticity. This alternative specification, with constant price elasticity, is presented as part of a larger class of model specifications featuring homogeneous demand, for which we present a closed-form solution as well.

An important methodological advantage of our model is that we do not rely on a conjectural variations approach that employs consistent conjectures (Bresnahan, 1989). This approach is not compatible with standard notions of rational behaviour since the game theory revolution (see e.g., Lindh, 1992).[1] In addition, the model that we propose can be adapted and applied to other endowment economies, including permit markets.

Our results show that market power in the Californian water market is limited. Our main specification implies that buyer power yields an average mark-down of 6% of the transaction price. This result is obtained for the linear model, but continues to hold for the non-linear specification and is robust to other model modifications. Our result is surprising in the sense that the thinness of water markets, including California's, is conventionally associated with higher possibilities of exploiting market power. It is also important in the sense that water market reform need not take into account market power but can focus on other factors instead, most notably transaction costs (Carey et al., 2002; Regnacq et al., 2016; Hagerty, 2019; Leonard et al., 2019).

We first introduce the model and our main model specification in Section 1.2. Next, we present the data in Section 1.3 and our empirical strategy in Section 1.4. Subsequently, we present model results in Section 1.5, focusing on our estimation of Lerner indices for California's water market. This main result is compared with a conjectural variations approach in Section 1.6 and checked for robustness in Section 1.7. In Section 1.8, we conclude.

1.2 Model

1.2.1 A model of market power in water markets

We develop a Nash-Cournot model of water transactions in order to derive an index for the extent of market power in a typical water market setting. Consider a water market with water transactions between sellers at origins $o = 1, 2, \ldots, N_o$ and buyers at destinations $d = 1, 2, \ldots, N_d$. Water is a homogeneous good and purchases from different sellers are perfect substitutes. Both sellers and buyers have entitlements of water, denoted either $e_o > 0$ or $e_d \geq 0$, depending upon their role. Although variation in rainfall and snow-melt may cause endowments to change over time, we suppress time subscripts in this section to keep notation simple. The amount of water sold by seller o to buyer d is denoted $q_{od} \geq 0$. Obviously, sellers cannot sell more water than their entitlements, i.e., $\sum_{d=1}^{N_d} q_{od} \leq e_o$.

Water use by buyers consists of their own entitlement plus purchased water: $Q_d \equiv e_d + \sum_{o=1}^{N_o} q_{od}$. Buyers' benefit from using this total sum of water equals $f_d(Q_d)$, which

[1] In Hagerty (2019), the same dataset is analysed, but the focus is on the impact of transaction costs in obstructing water markets. As a robustness check, the potential impact of market power as an alternative explanation for market frictions is explored, using an approach that employs consistent conjectures. Other papers, including Bruno and Sexton (2020), use this same approach.

is increasing in the neighbourhood of e_d (buyers are unsatiated at e_d), strictly concave, and twice continuously differentiable in Q_d. For later reference, we introduce the buyer's willingness-to-pay, denoted WTP, which is defined as the partial derivative of net benefits w.r.t. water use. Formally,

$$\mathrm{WTP}_d\left(Q_d\right) = f_d'\left(Q_d\right). \tag{1.1}$$

In any bilateral trade, buyers do not pay more than their WTP_d through the transaction-specific price $p_{od} \leq f_d'\left(Q_d\right)$.

Water use by sellers consists of their own entitlement minus sold water: $Q_o \equiv e_o - \sum_{d=1}^{N_d} q_{od}$. Sellers' benefit from using the unsold amount of water equals $f_o\left(Q_o\right)$, which is increasing in the neighbourhood of e_o (sellers are unsatiated at e_o), strictly concave, and twice continuously differentiable in Q_o. Sellers' net benefits of water use are now given by $f_o\left(Q_o\right)$ plus revenues from selling water, introduced below. For later reference, we introduce the seller's willingness-to-accept, denoted WTA, which is defined as the partial derivative of net benefits w.r.t. water use. Formally,

$$\mathrm{WTA}_o\left(Q_o\right) = f_o'\left(Q_o\right). \tag{1.2}$$

In any bilateral trade, sellers must be financially compensated for these opportunity costs through the transaction-specific price $p_{od} \geq f_o'\left(Q_o\right)$.

Recall that we consider the case where buyers hold all market power. In this case, the market clearing price must equal the seller's WTA:

$$p_{od} = \mathrm{WTA}_o\left(Q_o\right). \tag{1.3}$$

Buyer d's expenditure on buying water from seller o is then given by $q_{od} \cdot \mathrm{WTA}_o\left(Q_o\right)$. Buyers maximise over all potential sellers to purchase their water. Formally,

$$\max_{q_{1d},\ldots,q_{N_o d}} f_d\left(Q_d\right) - \sum_{o=1}^{N_o} q_{od} \cdot \mathrm{WTA}_o\left(Q_o\right). \tag{1.4}$$

Using the positive relation between Q_d and q_{od} as well as the negative relation between Q_o and q_{od}, a buyer's first-order condition w.r.t. Q_d (implicitly, q_{od}) for an interior solution is given by[2]

$$f_d'\left(Q_d\right) - \mathrm{WTA}_o\left(Q_o\right) + q_{od} \cdot \mathrm{WTA}_o'\left(Q_o\right) = 0. \tag{1.5}$$

Substituting (1.1) into (1.5) and rewriting yields

$$\begin{aligned} \mathrm{WTP}_d\left(Q_d\right) &= \mathrm{WTA}_o\left(Q_o\right) - q_{od} \cdot \mathrm{WTA}_o'\left(Q_o\right) \\ &\geq \mathrm{WTA}_o\left(Q_o\right). \end{aligned} \tag{1.6}$$

[2]The first-order conditions for the boundary solution $q_{od} = 0$ have the weak inequality $\leq$ replacing the equality.

Substituting (1.3) into (1.6), we now have the following system that we will use in Section 1.4:

$$p_{od} = \mathrm{WTA}_o(Q_o), \tag{1.7a}$$
$$p_{od} = \mathrm{WTP}_d(Q_d) + q_{od} \cdot \mathrm{WTA}_o'(Q_o). \tag{1.7b}$$

Recall that $\mathrm{WTA}_o'(Q_o) < 0$, so that the last term of (1.7b) is negative.

The wedge between buyers' WTP and sellers' WTA reflects the possible price range for each transaction. Under our assumption of buyer power, the realised price equals the seller's WTA, the lowest possible price. We therefore use the wedge to construct our measure of market power, which can be interpreted as the Lerner index applied to our model (note the multiplication of the inverse price elasticity of sellers' WTA by the ratio of transaction volume to water use):

$$\frac{\mathrm{WTP}_d(Q_d) - \mathrm{WTA}_o(Q_o)}{\mathrm{WTA}_o(Q_o)} = -\frac{q_{od}}{Q_o} \cdot \frac{Q_o \mathrm{WTA}_o'(Q_o)}{\mathrm{WTA}_o(Q_o)}. \tag{1.8}$$

This Lerner index is the main result of our theoretical model. In Section 1.4, we will use the system of equations (1.7) to estimate $\mathrm{WTA}_o'(Q_o)$ which we then use in (1.8) to measure market power in California's water market.

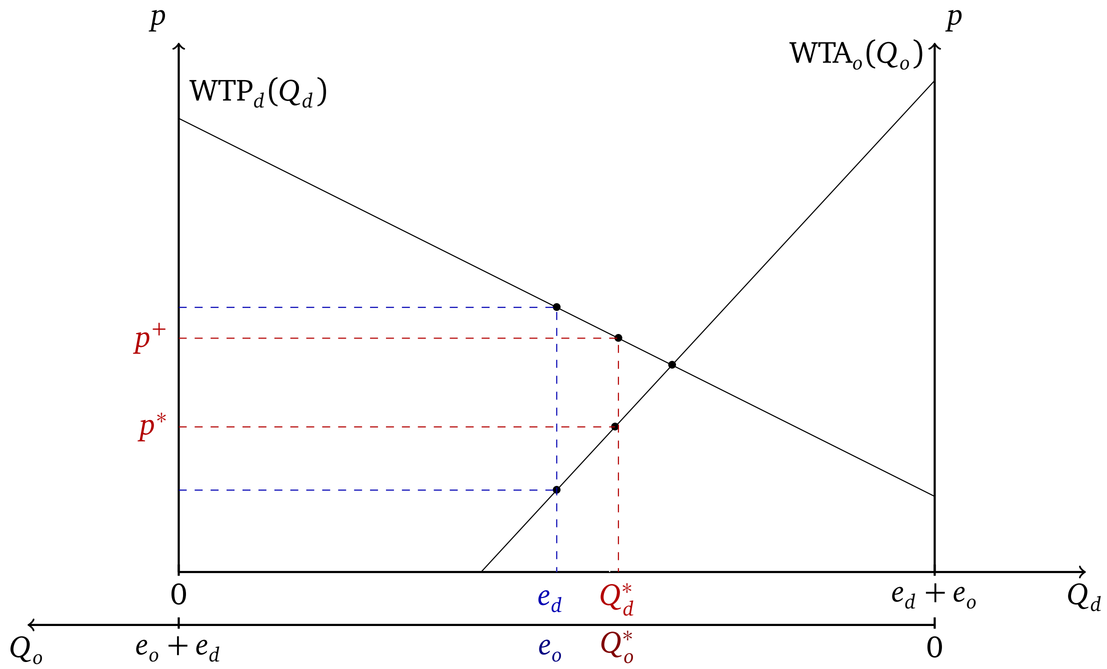
Our model is illustrated in Figure 1.1. With two types of districts (buyers and sellers) and one good (water), whose supply is given, our model is an endowment economy and so we can visualise it in a chart with a secondary mirrored primary axis, while total available water is on the horizontal axis. Demand for water is displayed using the $\mathrm{WTA}_o(Q_o)$ curve for sellers and the $\mathrm{WTP}_d(Q_d)$ curve for buyers. Starting from water endowments e_o and e_d in Figure 1.1, water transactions increase buyers' water consumption and decrease sellers' water consumption, while closing the wedge between buyers' WTP and sellers' WTA. Compared with the competitive equilibrium, buyer power implies a lower transaction volume, which leaves a positive wedge, as discussed in this section and as illustrated in the figure.

1.2.2 Main specification

The preferred specification of our model uses quadratic benefit functions for both buyers and sellers. This specification allows to estimate a linear model, as explained in Section 1.4. Our proposed benefit functions allow for heterogeneity across buyers and sellers as well as over time, which is why we add time subscripts from here on.

For each origin we have $f_{ot}(Q_{ot}) = Q_{ot}(\alpha_{ot} - \frac{1}{2}\delta Q_{ot})$, where $\alpha_{ot} = \phi_o + \beta_t + \nu_{ot}$ captures heterogeneity between different sellers and time periods, while parameter δ is kept constant. This benefit function implies that $f_{ot}'(Q_{ot}) = \alpha_{ot} - \delta Q_{ot}$, which is the sellers' WTA in (1.2). Similarly, for each destination we have $f_{dt}(Q_{dt}) = Q_{dt}(a_{dt} - \frac{1}{2}\gamma Q_{dt})$, with $a_{dt} = \psi_d + \beta_t + u_{dt}$, and therefore $f_{dt}'(Q_{dt}) = a_{dt} - \gamma Q_{dt}$, which is the buyers' WTP in

Figure 1.1: Endowments and Nash-Cournot equilibrium.



Stylised visualisation of endowments (blue) and Nash-Cournot equilibrium (red), where p^+ equals p^* plus the wedge $\mathrm{WTP}_d(Q_d^*) - \mathrm{WTA}_o(Q_o^*)$.

(1.1). Note that in Appendix 1.9, we generalise our main model specification to allow for asymmetry in terms of benefit parameters γ and δ. We do so after presenting the solution to the symmetric version of our main specification in Appendix 1.9.

The sufficient and necessary condition for positive quantities in the symmetric Nash equilibrium is that $f'_{dt}(e_{dt}) > f'_{ot}(e_{ot})$, which implies

$$a_{dt} - \gamma e_{dt} > \alpha_{ot} - \delta e_{ot}. \tag{1.9}$$

The interpretation is that the marginal benefit of water use at the initial entitlement of each destination exceeds the marginal benefit of water use at the initial entitlement of each origin. In other words, trade is (marginally) beneficial at the initial entitlement levels.

1.3 Data

We apply our model using newly assembled data on California's water economy, first described by Hagerty (2019). We mainly use three datasets. The first is a proprietary dataset compiled by WestWater Research, LLC, listing prices, volumes, and other information related to

Californian water transactions. The second is a dataset compiled from the archives of the California Department of Water Resources, the U.S. Bureau of Reclamation, and the State Water Resources Control Board, that combines the universe of yearly surface water entitlements and deliveries in California. The third is a geo-spatial dataset that identifies locations of buying and selling districts, and is used to estimate distances and identify other parameters related to transaction costs. Full details on each dataset, its cleaning and processing, is provided in Hagerty (2019, Section 4 and Appendix G).

The combined dataset provides panel data on, amongst others, water deliveries and transaction prices in California over the 23-year period 1993-2015. The panel data is unbalanced since districts can be involved in more than one transaction per year. Our unit of observation is the water district-level. This is the lowest possible level where (a) we can unambiguously match transactions to units, and (b) we have sufficient information on the units' entitlements and deliveries. It turns out that roughly 75% of all transactions in our transaction dataset can be matched to districts with complete information on entitlements and deliveries.[3]

The WestWater transactions database includes a total of 6,309 transactions over the period 1990–2015. Since we will assess transactions both from the sellers' and from the buyers' perspective, we duplicate each transaction and split the dataset into two, one for buyers and one for sellers. A minority of transactions involve more than one district on each side of the transaction. We split up such transactions such that each observation contains one selling and one buying district. Because of our focus on market power, we choose to include in our dataset only freely-negotiated transactions of surface water in the spot market. We therefore drop transactions by excluding (1) transactions whose price is set administratively (or missing), (2) groundwater transactions, (3) transactions of permanent water rights, and (4) transactions executed before 1993 (since data on water deliveries is only available from 1993 onward). Applying these exclusion criteria, we drop 88% of our observations. We subsequently lose another 28% of our remaining observations (slightly more for buyers than for sellers) when merging our transactions dataset with our dataset on districts' entitlements and deliveries. Our final dataset contains 1,131 observations, 592 for sellers and 539 for buyers.

Summary statistics (mean, standard deviation, and number of observations) on transaction for both buyers and sellers are shown in Table 1.1. In addition to transaction volumes and prices, this table lists statistics on six different factors that were found by Hagerty (2019) to be costly to buyers or sellers, and thereby generate transaction costs. The first three are costly to sellers: (S1) transactions that cross the Sacramento-San Joaquin Delta, (S2) transactions where the buyer is primarily using water for agricultural purposes, and (S3) the

[3]The alternative to districts as units of observation would be to either use planning areas or DAU-county areas (both are hydro-geographical areas defined by the California Department of Water Resources). Doing so would facilitate the matching with entitlements and deliveries. The downside, however, is that it would severely reduce the number of observations in our final dataset since transactions would be lumped into fewer units.

total distance if water is conveyed along a river. The next three are costly to buyers: (B1) the virtual distance between buyer and seller if water is transferred against the direction of flow, and (B2) transactions that are subject to a State Water Boards review, and (B3) transactions that export water from a federal or state water project. Two factors cause differences in the data between buyers and sellers. One is that, in merging transactions with entitlements, we lose more observations for buyers than for sellers, and this difference is apparently not a random draw. The second factor is that the buyer observations include a substantial share, 24%, where water is acquired for instream use, while for sellers this is only 1%. Such transactions tend to have much lower prices, roughly half of those where buyers are purchasing water for consumptive use. We will check whether inclusion of these transactions affects our results in Section 1.5.

Table 1.1: Summary statistics on transactions by sellers/buyers.

	Sellers			Buyers		
	Mean	SD	Obs	Mean	SD	Obs
Price (2010$/AF)	237.49	296.79	592	185.50	173.75	539
Volume (AF)	8.74	24.70	583	8.93	26.67	530
S1: Delta crossing (1=yes)	0.33	0.47	568	.	.	0
S2: Agricultural buyer (1=yes)	0.47	0.50	592	.	.	0
S3: River distance (km)	0.09	0.10	568	.	.	0
B1: Virtual distance (km)	.	.	0	0.08	0.11	534
B2: State Water Boards review (1=yes)	.	.	0	0.42	0.49	539
B3: Export from project (1=yes)	.	.	0	0.05	0.22	539

Transactions mostly occur in a limited number of hydrologic regions. Sellers are mostly located in the Sacramento River and San Joaquin River regions, while buyers are mostly located in the Tulare Lake, San Joaquin River, and South Coast regions. We find only few instances of districts that both sell and buy, suggesting that we can assume fixed roles for districts as sellers or buyers. Transactions in our database cover a total of 161 districts, which implies a mean number of $592/161 = 3.7$ transactions per district over our 23-year period from the sellers' perspective and $539/161 = 3.3$ for buyers. This low number illustrates that California's water market is thin.[4]

1.4 Empirical strategy

The objective of our empirical exercise is to measure market power in California's water market. We do so using the Lerner index (1.8). Calculation of this index requires an estimate

[4] One could argue that our data suffers from selection bias since we only observe realised transactions and these are typically from seller-buyer pairs with low transaction costs. Note, however, that we only observe equilibrium transactions and any non-observed transaction price would be 'out-of-equilibrium'.

of $\text{WTA}'_{ot}(Q_{ot})$. For the linear model specification introduced in Section 1.2.2, we have $\text{WTA}'_{ot}(Q_{ot}) = f''_{ot}(Q_{ot}) = -\delta$, which we will estimate using the system of equations (1.7). Note that this parameter δ is the only estimate that we need to measure market power using the Lerner index (1.8). To see this, note that our linear model specification with buyer power allows us to write this index in terms of δ as well as transaction prices and quantities p_{odt} and q_{odt}, which are present in our transaction data:

$$\begin{aligned}\frac{\text{WTP}_{dt}(Q_{dt}) - \text{WTA}_{ot}(Q_{ot})}{\text{WTA}_{ot}(Q_{ot})} &= -\frac{q_{odt}}{Q_{ot}} \cdot \frac{Q_{ot}\text{WTA}'_{ot}(Q_t)}{\text{WTA}_{ot}(Q_{ot})} \\ &= \delta \cdot \frac{q_{odt}}{p_{odt}}. \qquad (1.10)\end{aligned}$$

Below, we present our empirical strategy to estimate parameter δ.

Given our panel data on transaction prices and quantities, we construct a fixed effects model, which exploits variation in observed transaction prices, WTA, and WTP across trading districts and across time. This approach rests on two requirements. The first is that we have sufficient variation in WTA and WTP over time. In our data, such variation over time is caused by variation in water entitlements over time, which imply movements along the benefit function of water use, thereby changing districts' marginal benefits of water use. Water entitlements are determined by the interaction of weather fluctuations with historically-determined allocation rules, which are markedly different across regions of California. The second requirement is that WTA and WTP are exogenous, conditional on unobserved district characteristics (as captured by the fixed effects). We meet this requirement by assumption, since our model dictates that WTA (and, implicitly, WTP) determines transaction prices.

There are two possible sources of endogeneity in our data, one of which is that omitted variables may cause biases. Ideally, we would control for these using both year fixed effects as well as time-invariant district-by-counterparty fixed effects. The latter would capture any variation in prices caused by unobserved heterogeneity across pairs of trading districts. Unfortunately, we do not have sufficient observations per trading district-pair to estimate such fixed effects. We resort to separate seller- and buyer fixed effects instead. The second possible source of endogeneity is reverse causality, which we discuss at the end of this section.

We substitute the linear specification of our model into the system of equations (1.7):

$$p_{odt} = -\delta Q_{ot} + \phi_o + \beta_t + \nu_{ot}, \qquad (1.11a)$$

$$p_{odt} = -\gamma Q_{dt} - \delta q_{odt} + \psi_d + \beta_t + u_{dt}. \qquad (1.11b)$$

An implicit assumption underlying the regression of *individual* transaction prices on (some function of) *total* water use levels is that districts face no uncertainty on their water entitlements or future prices, which may give them an incentive to hedge the risk of water shortage within each year. One example would be that districts buy 'too much' water and will try to re-sell later that same year. We find, however, that only a handful of districts in our dataset have ever been active on both sides of the market within one year. Hence, this assumption of no uncertainty seems warranted. It is also consistent with the situation in many Western US watersheds, where predictions on water availability in early spring provide 'reasonably accurate forecasts' of actual availability (Draper, 2001).

Without uncertainty, price differences across transactions for a particular district and year should not occur, except in the case of transaction costs. In model variations, we therefore control for various types of transaction costs, as introduced in Section 1.3. Transaction costs are pair-specific and time-invariant, and they apply to either the seller or the buyer in a specific transaction, as summarised in Table 1.1. In the regressions below, transaction costs are included as $T_{odr} = \tau_r C_{odr} + \tau_o + \tau_d + \varepsilon_{odr}$, where vector C_{odr} includes seller-, buyer-, and pair-specific transaction costs, with units (mostly dummies) as presented in Table 1.1, while τ_o and τ_d represent district fixed costs. Since each transaction is assessed twice in this system, we add r to indicate whether the transaction is assessed from the seller's perspective ($r = 0$) or the buyer's perspective ($r = 1$). We expect $\tau_r \geq 0$ if $r = 0$ and $\tau_r \leq 0$ if $r = 1$. That is, transaction costs enter sellers' WTA positively, because these have to be compensated for sellers on top of the sellers' net benefits, while transaction costs enter the buyers' WTP negatively, because these decrease sellers' net benefits.

We add transaction costs to (1.11), and re-order and re-label terms:

$$\begin{aligned} p_{odrt} &= -\delta Q_{ot} + (\phi_o + \tau_o) + \tau_d + \beta_t + \tau_r C_{odr} + (\nu_{ot} + \varepsilon_{odr}) \\ &= -\delta Q_{ot} + \phi_o + \psi_d + \beta_t + \tau_r C_{odr} + \epsilon_{odrt} \qquad (1.12a) \\ p_{odrt} &= -\gamma Q_{dt} - \delta q_{odt} + \tau_o + (\psi_d + \tau_d) + \beta_t + \tau_r C_{odr} + (u_{dt} + \varepsilon_{odr}) \\ &= -\gamma Q_{dt} - \delta q_{odt} + \phi_o + \psi_d + \beta_t + \tau_r C_{odr} + \epsilon_{odrt} \qquad (1.12b) \end{aligned}$$

Note that coefficient δ appears in both equations. We estimate both equations simultaneously by constructing two variables, R^o_{odtk} and R^d_{odtk}, that combine the coefficients on water use from (1.12). We also add a counter k, since there can be multiple transactions between one origin o and one destination d within one year t:

$$R^o_{odtk} = \begin{cases} Q_{ot} & \text{if } r = 0 \\ q_{odtk} & \text{if } r = 1, \end{cases} \quad \text{and} \quad R^d_{odtk} = \begin{cases} 0 & \text{if } r = 0 \\ Q_{dt} & \text{if } r = 1. \end{cases}$$

The combined regression equation, which also suppresses the intercept, is:

$$p_{odrtk} = -\delta R^o_{odtk} - \gamma R^d_{odtk} + \phi_o + \psi_d + \beta_t + \tau_r C_{odr} + \epsilon_{odrtk}. \qquad (1.13)$$

In the next section, we will estimate variations of (1.13) using linear regression.

Unlike standard models of supply and demand, we are estimating a system with two demand functions (with slopes given by parameters γ and δ), while the annual supply of water is determined by rainfall and snow-melt. With hydrological variation between years, the total amount of water in the system changes exogenously each year. Summed over all districts, annual supply cannot respond to changes in price. Despite this exogeneity in supply, individual districts may still respond to price changes by changing the volume of water bought or sold. We therefore also estimate (1.13), while instrumenting for water use with districts' entitlements, in line with Hagerty (2019).

1.5 Results

The estimates of regression equation (1.13) are shown in Table 1.2. Recall that the aim of this regression is to estimate the impact of market power on transaction prices via the wedge $\text{WTP}_{dt}(Q_{dt}) - \text{WTA}_{ot}(Q_{ot})$. Applying a model with quadratic benefit functions implies that *Seller water use* (i.e., R^{O}_{odtk}) is one of the independent variables, whose coefficient gives the slope of the sellers' benefit function, parameter δ. Multiplied by transaction volume, this parameter gives the wedge for each transaction.

Table 1.2: Estimating WTA and WTP: Linear model.

Price (2010$/AF)	(1)	(2)	(3)	(4)
	OLS	OLS	IV	IV
Seller water use (1,000 AF)	-0.0183^{**}	-0.0280^{**}	-0.580^{***}	-0.932^{**}
(coefficient $-\delta$)	(0.00821)	(0.0130)	(0.208)	(0.445)
Buyer water use (1,000 AF)	-0.00757^{**}	-0.0144^{**}	-0.309^{**}	-0.311^{**}
(coefficient $-\gamma$)	(0.00336)	(0.00612)	(0.132)	(0.156)
Seller fixed effects	✓	✓	✓	✓
Buyer fixed effects	✓	✓	✓	✓
Year fixed effects	✓			
Quadratic time trend		✓	✓	✓
Transaction costs				✓
# Observations	1034	1034	879	877
# Clusters	543	337	308	307
# FE dummies	212	190	164	163
Cragg-Donald F-statistic			9.936	8.681

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Coefficient estimates from fixed effects models using OLS and IV. Standard errors in parentheses, clustered by seller, buyer, and year (but only by seller and buyer in models (2)–(4) where year fixed effects are replaced by a quadratic time trend).

In model (1), estimated using OLS, we model water use as our only explanatory variable, combined with seller-, buyer-, role-, and year fixed effects. The coefficient on *Seller water use* implies that $\delta = 0.0183$, which is more than double the size of $\gamma = 0.00757$, implied by the coefficient on *Buyer water use*. The difference indicates that selling districts have steeper demand curves than buying districts. In model (2) we attempt to improve efficiency of these estimates. Given the large number of clusters compared to observations, we replace year fixed effects by a time trend. No comparable simplification was found feasible for the other fixed effects. Particularly, there is no obvious possibility to replace seller- and buyer fixed effects with a coarser set of dummy variables. As a result of replacing the year fixed effect by the time trend, the number of clusters decreases sharply. Compared to model (1), the model (2) estimates for both δ and γ increase significantly. In model (3), we instrument water use by districts' water entitlements. The resulting estimations of δ and γ increase sharply, in absolute terms, compared to those of models (2) and (3). Finally, in model (4), we add seller- and buyer-specific transaction costs, which do not appear to improve the model results, decreasing the F-statistic and increasing the standard error of our main coefficient of interest. The Cragg-Donald F-statistics for the first stages of the IV models (not presented here) are both higher than their critical values, as reported by Stock and Yogo (2005), suggesting that models (3) and (4) do not suffer from weak instruments.

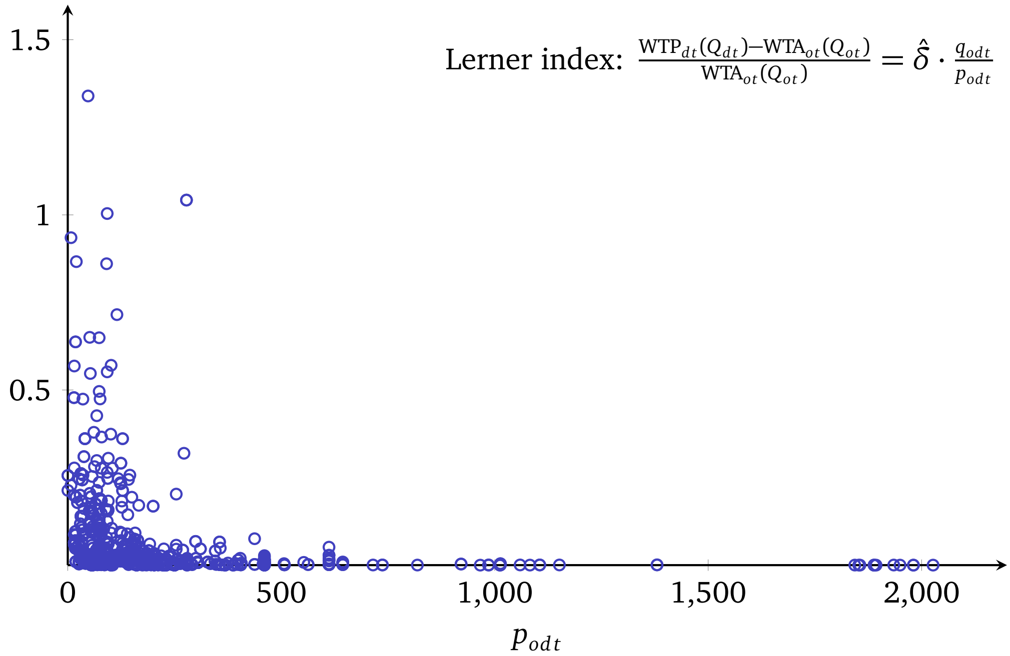
Based on these model results and interpretation, our preferred model is model (3) and we use the main coefficient of interest from this specification, $\delta = 0.580$, in the remainder of this section. The interpretation of δ is that sellers' WTA, which equals the water price in our model, increases by \$0.58/AF for each 1,000 AF sold.[5] More important for our analysis, however, is that δ is used to calculate the wedge $\text{WTP}_{dt}(Q_{dt}) - \text{WTA}_{ot}(Q_{ot}) = \delta q_{od}$. Doing so we find that the average wedge, after removing one outlier, equals \$4.60/AF (SD=8.66). This wedge corresponds to about 6.4% of the transaction price, on average, with markedly higher wedges (both in absolute and relative terms) for transactions with low prices. We use transaction-specific wedges to compute the Lerner index of (1.10) and plot these in Figure 1.2. This figure shows that the Lerner index is relatively low. It is markedly higher, though, for a small set of transactions with low prices, which also tend to have the highest transaction volumes. All in all, we find that market power is relatively low in Californias' water market.

1.6 A conjectural variations approach

We proceed to compare our results to those obtained using a conjectural variations approach in order to verify whether our assumption of buyer power is warranted. In this approach, the term expressing market power is multiplied by some weight that dampens this term. A recent example that employs this approach and analyses Californian groundwater is Bruno and Sexton (2020). Accordingly, we introduce conjectural variations using parameter $\theta \in [0, 1]$ that measures the degree of buyer power, while $\xi \in [0, 1]$ measures the degree of seller power. Allowing for both buyer- and seller power, we rewrite (1.7) to include these market

[5] AF: acre-foot. One acre-foot equals 1,233 m^3.

Figure 1.2: Transaction prices and the Lerner index.



Scatter-plot of transaction prices and the Lerner index as given by (1.10) (one outlier removed).

power weights:

$$p_{odt} = \mathrm{WTA}_{ot}(Q_{ot}) - \xi \cdot q_{odt} \cdot \mathrm{WTP}'_{dt}(Q_{dt}), \tag{1.14a}$$
$$p_{odt} = \mathrm{WTP}_{dt}(Q_{dt}) + \theta \cdot q_{odt} \cdot \mathrm{WTA}'_{ot}(Q_{ot}). \tag{1.14b}$$

The new terms capture districts' expectations about other districts' reactions to a change in transaction quantities. These expectations are convex combinations of expected reactions under perfect competition vs. settings with buyer or seller power. As a result, the maximum possible markups or markdowns are dampened by, respectively, θ or ξ. In our analysis so far we have assumed $(\theta, \xi) = (1, 0)$, i.e., only buyer power. Two other special cases of the model are seller power – which would imply $(\theta, \xi) = (0, 1)$ – and perfect competition, which would imply $(\theta, \xi) = (0, 0)$.

We proceed to estimate this system of equations. The resulting values of θ and ξ will verify whether our assumption of buyer power is warranted using this conjectural variations approach. Taking similar steps as before, we first substitute the linear model specification:

$$\begin{aligned} p_{odrt} = \alpha - \delta Q_{ot} + \gamma q_{odtk} &- (1-\xi)\gamma q_{odt} \\ &+ \phi_o + \psi_d + \beta_t + \tau_r C_{odr} + \epsilon_{odrt}, \end{aligned} \tag{1.15a}$$
$$\begin{aligned} p_{odrt} = a - \delta q_{odt} - \gamma Q_{dt} &+ (1-\theta)\delta q_{odtk} \\ &+ \phi_o + \psi_d + \beta_t + \tau_r C_{odr} + \epsilon_{odrt}. \end{aligned} \tag{1.15b}$$

The combined regression equation becomes:

$$p_{odrtk} = -\delta R^o_{odtk} - \gamma \tilde{R}^d_{odtk} + (1-\theta)\delta \hat{R}^o_{odtk} - (1-\xi)\gamma \hat{R}^d_{odtk} + \phi_o + \psi_d + \beta_t + \tau_r C_{odr} + \epsilon_{odrtk} \quad (1.16)$$

with R^o_{odtk} as defined in Section 1.4, while $\tilde{R}^d_{odtk}$, $\hat{R}^o_{odtk}$ and $\hat{R}^d_{odtk}$ are defined as follows:

$$\tilde{R}^d_{odtk} = \begin{cases} -q_{odtk} & \text{if } r = 0 \\ Q_{dt} & \text{if } r = 1, \end{cases}, \quad \hat{R}^o_{odtk} = \begin{cases} 0 & \text{if } r = 0 \\ q_{odtk} & \text{if } r = 1, \end{cases}, \quad \hat{R}^d_{odtk} = \begin{cases} q_{odtk} & \text{if } r = 0 \\ 0 & \text{if } r = 1. \end{cases}$$

In order to get a clear view on the parameters of interest, we apply extremum estimation of the IV criterion function, transformed such that we optimise our parameters δ, γ, θ and ξ. Table 1.3 reports the results for the case where no restrictions were imposed on the parameters in the IV criterion function. We present three models. In model (1) we allow only buyer power, in model (2) only seller power, while model (3) allows for both. In addition to the coefficients on seller and buyer water use, $-\delta$ and $-\gamma$, we report coefficients on both market power weights, θ and ξ, while suppressing the coefficients on the terms $\hat{R}^o_{odtk}$ and $\hat{R}^d_{odtk}$, since these coefficients are combinations of the four parameters that are already reported.

The unrestricted estimates for seller and buyer power weight, ξ and θ, are found to lie outside the bounds $[0,1]$. All three models find estimates for $-\delta$ and $-\gamma$ that are very close to those obtained in our preferred model (3) of Table 1.2. Looking at the estimated coefficients for ξ and θ, we find that the seller power weight ξ is negative in model (2) while it is not significantly different from zero in model (3). The buyer power weight θ has the correct sign, though the present estimates seems to be larger than 1, both in model (1) and (3). These results point to absence of seller power while they support buyer power.

Imposing the restrictions that $\xi \in [0,1]$ and $\theta \in [0,1]$ leads to the expected result estimates at the boundaries of these intervals. Given that the amount of observations in the dataset is relatively low compared to the number of parameters and fixed effects, and hence both estimates and standard deviations cannot be extracted with too great precision, we take these results as an indication that buyer power is the most reasonable assumption.

1.7 Robustness

In this section, we report on five robustness checks. First, we check robustness when we focus on relevant sub-samples of the data. Second, we apply an alternative model specification featuring non-linear benefit functions. Third, we alter the calculation of districts' water use to account for timing of transactions within one year. Fourth, we check whether selling and buying districts can be reasonably assumed to have similar benefit functions. Finally, despite the results of our conjectural variations approach, we estimate a model with seller power.

Note that this list of robustness checks is not exhaustive. Importantly, we also checked for differential levels of market power. One such example would be differential market

Table 1.3: Estimating WTA and WTP: Conjectural variations.

Price (2010$/AF)	(1)	(2)	(3)
	IV Buyer power ($\xi = 0$)	IV Seller power ($\theta = 0$)	IV Both
Seller total water use (1,000 AF) (coefficient $-\delta$)	-0.577^{***} (0.162)	-0.610^{***} (0.180)	-0.573^{***} (0.162)
Buyer total water use (1,000 AF) (coefficient $-\gamma$)	-0.242^{***} (0.070)	-0.282^{***} (0.082)	-0.241^{***} (0.070)
Seller power weight (coefficient ξ)		-8.581^{**} (3.570)	1.251 (2.422)
Buyer power weight (coefficient θ)	5.664^{***} (0.658)		6.155^{***} (1.237)
Seller fixed effects	✓	✓	✓
Buyer fixed effects	✓	✓	✓
Year fixed effects			
Quadratic time trend	✓	✓	✓
Transaction costs			
# Observations	879	879	879
# FE dummies	164	164	164

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Coefficient estimates from fixed effects models using extremum estimation. The covariance matrix is computed as a robust sandwich covariance matrix, following the theory of extremum estimation (Cameron and Trivedi, 2005, Section 6.3.4). Standard errors in parentheses. Models (1)–(3) correspond to model (3) of Table 1.2, but using the conjectural variations approach.

power occurs in wet versus dry years. In wet years, one could imagine that buyers have better opportunities to exercise market power. Using the Sacramento Valley Water Year Hydrological Classification Index to classify years, we fail to find such differences. Another option is differential market power depending on the location of buyers and sellers. The argument would be that buyers that are more central would have more opportunities to switch to another seller and could therefore achieve higher markdowns. This argument ignores, however, that the Californian water market features an almost complete hydrological network enabling water transfers between nearly any two districts. As a result, while central buyers would probably face lower transaction costs, they do not have increased opportunities to exercise market power compared to buyers at the periphery.

1.7.1 Sub-sample analysis

We repeat our preferred model (3) of Table 1.2 for three sub-samples of interest. Table 1.4 shows the results of these additional regressions. For reference, we include the preferred model as model (1). In model (2), we drop all observations that involve water for environmental use, for instance buy-backs by the government. Arguably, such transactions are markedly different from transactions between districts that intend to use the water for consumptive purposes. In model (3), we include only transactions where agricultural districts are selling, which seem to represent the smaller, weaker actors in the market. Unfortunately, our sample size does not allow us to focus only on water sales from agricultural to urban districts (slightly more than 100 transactions), which seem to represent the larger, stronger actors capable of exercising market power (see e.g., Isaaks and Colby, 2020). By focusing on all sales from agricultural districts, we may still capture the fact that agricultural districts may have less market power than the other types of districts. Note that half of these sales are to other agricultural districts, while the other half is shared roughly equally between buying urban districts and environmental projects. In model (4), we drop outlier transactions. We exclude the 5% transactions with lowest and 5% transactions with highest transaction prices, and similarly for transaction volumes.

Table 1.4: Estimating WTA and WTP: Sub-samples

Price (2010$/AF)	(1)	(2)	(3)	(4)
	IV preferred	IV no env	IV ag sellers	IV no outliers
Seller water use (1,000 AF)	-0.580^{***}	-0.520^{**}	-0.570^{***}	-0.442^{***}
(coefficient $-\delta$)	(0.208)	(0.201)	(0.179)	(0.142)
Buyer water use (1,000 AF)	-0.309^{**}	-0.278^{**}	-0.284^{***}	-0.232^{**}
(coefficient $-\gamma$)	(0.132)	(0.127)	(0.108)	(0.0906)
Seller fixed effects	✓	✓	✓	✓
Buyer fixed effects	✓	✓	✓	✓
Quadratic time trend	✓	✓	✓	✓
# Observations	879	728	778	737
# Clusters	308	248	261	250
# FE dummies	164	149	133	132
Cragg-Donald F-statistic	9.936	7.057	14.01	10.82

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Coefficient estimates from fixed effects models using IV. Standard errors in parentheses, clustered by seller and buyer. Model (1) corresponds to our preferred model (3) of Table 1.2. In model (2), we drop transactions from or to environmental use. In model (3), we keep only transactions where agricultural districts are selling. In model (4), we drop transactions that are outliers in terms of price or volume.

Coefficients of sub-sample Models (2)–(4) are not statistically different from those of the preferred model. Model (2), which discards 17% of the observations, performs similarly in terms of precision and slightly worse in terms of the F-statistic. Unexpectedly, Model (3) does not show a higher coefficient (in absolute terms). Hence, there is no indication of more buyer power when buying from an agricultural district. Model (4) suggests that some of the market power we find is driven by outlier transactions in terms of price or volume, as one could expect. Combined, these additional regressions show that our main results are robust to including only specific sub-samples of interest.

1.7.2 Constant price elasticity

In the main specification of our model, we have imposed a constant slope of the benefit functions and a variable price elasticity. In this section, we impose instead that these functions have a constant price elasticity and, consequently, a variable slope. In particular, we consider the class of non-linear WTA functions that are homogeneous[6]. Given our earlier assumption of differentiability, we have that Euler's Homogeneous Function Theorem[7] applies to the equilibrium conditions and Lerner index.

For arbitrary homogeneous $\text{WTA}_{ot}(Q_{ot})$ of order $-\kappa_o$, we can rewrite the wedge $\text{WTP}_{dt}(Q_{dt}) - \text{WTA}_{ot}(Q_{ot})$ as

$$-q_{odt} \cdot \text{WTA}'_{ot}(Q_{ot}) = -\frac{q_{odt}}{Q_{ot}} \cdot \left[Q_{ot} \cdot \text{WTA}'_{ot}(Q_{ot})\right] = \frac{q_{odt}}{Q_{ot}} \cdot \left[\kappa_o \cdot \text{WTA}_{ot}(Q_{ot})\right]. \tag{1.17}$$

This implies that the Lerner index of (1.8) can be updated to

$$\frac{\text{WTP}_{dt}(Q_{dt}) - \text{WTA}_{ot}(Q_{ot})}{\text{WTA}_{ot}(Q_{ot})} = \frac{q_{odt}}{Q_{ot}} \cdot \kappa_o. \tag{1.18}$$

The empirical strategy to estimate κ_o has many similarities to the empirical strategy proposed in Section 1.4, and we refer to Appendix 1.9 for details. The resulting regression equation becomes:

$$\ln p_{odrtk} = -\kappa_o \overline{R}^o_{odtk} - \kappa_d \overline{R}^d_{odrtk} + \phi_o + \psi_d + \beta_t + \ln \tau_r C_{odr} + \epsilon_{odrtk}, \tag{1.19}$$

where $\overline{R}^o_{odtk}$ and $\overline{R}^d_{odtk}$ are modifications of R^o_{odtk}, respectively, R^d_{odtk} that are defined in Appendix 1.9.

We estimate variations of (1.19) using linear regression, similar to Table 1.2 for our main model specification. Table 1.5 shows the estimates of four models that are similar to models (1)–(4) of Table 1.2. Despite allowing for non-linear benefit functions, the models of Table 1.5 do not perform better than those of our linear model specification in Table 1.2 in terms of the Cragg-Donald F-statistic, nor the precision of our coefficient of interest, the coefficient on *Seller water use*.

Again, we use model (3) to derive the main coefficient of interest for this model specification, $\kappa_o = 0.370$. Similar as before, we use this coefficient to calculate the wedge

[6] The function $f : R \to R$ is homogeneous of order $\kappa \in R$ if $f(\mu x) = \mu^k f(x)$, for all x and $\mu > 0$.
[7] Let the function $f : R \to R$ be homogeneous of order $\kappa \in R$. Euler's Homogeneous Function Theorem states that $x \cdot f'(x) = \kappa \cdot f(x)$.

Table 1.5: Estimating WTA and WTP: Constant price elasticity.

Log price (2010$/AF)	(1)	(2)	(3)	(4)
	OLS	OLS	IV	IV
Log (seller water use, 1,000 AF)	−0.0000147	−0.000660	−0.370**	−0.623*
(coefficient $-\kappa_o$)	(0.000224)	(0.000670)	(0.173)	(0.357)
Log (buyer water use, 1,000 AF)	−0.000576	−0.00185*	−0.402**	−0.458
(coefficient $-\kappa_d$)	(0.000568)	(0.00106)	(0.194)	(0.279)
Seller fixed effects	✓	✓	✓	✓
Buyer fixed effects	✓	✓	✓	✓
Year fixed effects	✓			
Quadratic time trend		✓	✓	✓
Transaction costs				✓
# Observations	942	942	827	825
# Clusters	465	292	274	273
# FE dummies	188	166	148	147
Cragg-Donald F-statistic			7.808	5.954

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Coefficient estimates from fixed effects models using OLS and IV. Standard errors in parentheses, clustered by seller and buyer, and year (but only by seller and buyer in models (2)–(4), where year fixed effects are replaced by a quadratic time trend). Models (1)–(4) correspond to models (1)–(4) of Table 1.2, but now with a non-linear model specification.

$\mathrm{WTP}_{dt}(Q_{dt}) - \mathrm{WTA}_{ot}(Q_{ot}) = \frac{q_{odt}}{Q_{ot}} \cdot [\kappa_o \cdot \mathrm{WTA}_{ot}(Q_{ot})]$, which now also depends on the ratio $\frac{q_{odt}}{Q_{ot}}$. We find that the mean value of this ratio is heavily skewed by 15 districts that sell the majority of their entitlements at least once. After removing these outlier observations, we have $\frac{q_{odt}}{Q_{ot}} = 0.10$ and the corresponding average wedge equals \$ 6.97/AF (SD=14.05), which is about 50% larger than the wedge found for the linear model specification, but still small in percentage terms.

Note that we do not attach much weight to the results from this specification, both because of its sensitivity to removing outliers, and also since the functional form of regression equation (1.19) depends on the specific implementation of a first-order Taylor expansion (see Appendix 1.9 for details), which may not be warranted. With these caveats in mind, the results of a model specification with constant price elasticity are largely consistent with those from the linear model specification.

1.7.3 Transaction timing

So far we have ignored information on the timing of transactions. As a result, in case of multiple transactions per district per year, each district's water use—as captured by variables R^i_{odtk}, $i = o, d$, in (1.13)—is identical for each of these transactions within one year. This approach is consistent with the assumption of no uncertainty with respect to districts' water entitlements, such that districts can foresee how much water they are going to sell or buy within a year. In this section, we take the alternative approach and update Q_{dt} and Q_{ot} after each transaction. This implies that we use counter k to calculate water use (just) after transaction $j = 1, 2, \ldots$ as $Q_{otj} = e_{ot} - \sum_{k=1}^{j} q_{od(j)tk}$ and $Q_{dtj} = e_{dt} + \sum_{k=1}^{j} q_{o(j)dtk}$, where $d(j)$ is the j^{th} counterparty of o and $o(j)$ is the j^{th} counterparty of d. When multiple transactions happen to occur within the same month, we order them by transaction volume such that smaller transactions go first. In an alternative specification, we reverse this order.

Table 1.6 shows the results. For reference, we include the preferred model from

Table 1.6: Estimating WTA and WTP: Dynamic updating

Price (2010$/AF)	(1)	(2)	(3)
	IV preferred	IV dynamic	IV dynamic reversed
Seller water use (1,000 AF)	-0.580^{***}	-0.530^{***}	-0.551^{***}
(coefficient $-\delta$)	(0.208)	(0.186)	(0.195)
Buyer water use (1,000 AF)	-0.309^{**}	-0.306^{**}	-0.305^{**}
(coefficient $-\gamma$)	(0.132)	(0.127)	(0.128)
Seller fixed effects	✓	✓	✓
Buyer fixed effects	✓	✓	✓
Quadratic time trend	✓	✓	✓
# Observations	879	879	879
# Clusters	308	308	308
# FE dummies	164	164	164
Cragg-Donald F-statistic	9.936	11.15	10.58

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Coefficient estimates from fixed effects models using IV. Standard errors in parentheses, clustered by seller and buyer. Model (1) corresponds to our preferred model (3) of Table 1.2. In models (2) and (3), water use is updated dynamically in case of multiple transactions per district per year. In model (2), multiple transactions in one month are ordered from small to large volume, in model (3) this is reversed.

Table 1.2 as model (1). In models (2) and (3), we repeat this model using our dynamically updating measure of water use. The results shows that the effect of transaction timing on prices is negligible.

1.7.4 Sellers and buyers on one demand curve

So far we have estimated buyers' and sellers' demand curves separately rather than estimating a combined curve. We reject this possibility with multiple arguments. First, we test for equivalence of coefficients using our preferred model (3) of Table 1.2. Based on a Wald test (F(1,356)=4.92, $p = 0.027$), we reject equality of these coefficients. Second, we use theory and data to argue that selling and buying water districts differ in key characteristics, implying that buying districts cannot be on the same demand curve as selling districts, and hence our approach of modelling two distinct curves is correct.

Table 1.7 compares selling and buying districts in terms of their main type of water use (urban, agriculture, environment), levels of water entitlements and water use as well as whether or not a district trades with more than one counterparty in any given year. Clearly,

Table 1.7: Key differences between sellers/buyers.

	Sellers		Buyers	
	Mean	SD	Mean	SD
District: urban (share)	0.08	0.28	0.29	0.45
District: agriculture (share)	0.91	0.29	0.47	0.50
District: environment (share)	0.01	0.09	0.24	0.43
Water entitlements (1,000 AF)	193.72	298.63	207.97	570.51
Total water use (1,000 AF)	176.22	280.61	251.65	578.29
More than one counterparty (yes=1)	0.36	0.48	0.55	0.50

selling and buying districts differ in their types of water use. Sellers are more likely to use water for agriculture, while buyers are more likely to use water for urban or environmental uses. The key variable that underlines our argument that sellers and buyers are on different demand curves for water is *Water entitlements*. Table 1.7 shows that buying districts have higher water entitlements than selling districts, and by purchasing water they end up with even higher levels of water use compared with selling districts. If selling and buying districts would have identical demand curves for water, then districts with higher water use would be selling water, rather than buying. In Figure 1.1, this implies that e_d would be located to the right of the competitive Q_d. This location implies that $\mathrm{WTP}_d(Q_d) < \mathrm{WTA}_o(Q_o)$, which is inconsistent with the occurrence of observed water transactions. It follows that sellers and buyers are not on one demand curve.

A final difference between selling and buying districts is related to the dummy variable that measures whether a district has *More than one counterparty*. Comparison indicates that buyers have 53% more transactions with multiple counter-parties than sellers do. This statistic points to buyer power, with sellers being on the long side of the market.

1.7.5 Seller power

Our main result is that buyer power is relatively low. Going against previous literature, stakeholder beliefs, and the results of our conjectural variations approach of Section 1.6, we now reverse our model to estimate seller power. This allows us to check if rather counter-intuitively, a model with seller power would better explain our data than our model with buyer power. We start by adapting (1.7) as follows:

$$p_{od} = \mathrm{WTA}_o(Q_o) - q_{od} \cdot \mathrm{WTP}'(Q_d), \tag{1.20a}$$

$$p_{od} = \mathrm{WTP}_d(Q_d). \tag{1.20b}$$

Taking similar steps as in Section 1.4, the resulting regression equation becomes:

$$p_{odrtk} = -\delta \tilde{R}^o_{odtk} - \gamma \tilde{R}^d_{odtk} + \tau_r C_{odr} + \phi_o + \psi_d + \beta_t + \varepsilon_{odrtk}, \tag{1.21}$$

where $\tilde{R}^o_{odtk}$ and $\tilde{R}^d_{odtk}$ are modifications of R^o_{odtk}, respectively, R^d_{odtk} that are defined as follows:

$$\tilde{R}^o_{odtk} = \begin{cases} Q_{ot} & \text{if } r = 0 \\ 0 & \text{if } r = 1, \end{cases} \quad \text{and} \quad \tilde{R}^d_{odtk} = \begin{cases} -q_{odtk} & \text{if } r = 0 \\ Q_{dt} & \text{if } r = 1. \end{cases}$$

Table 1.8: Estimating WTA and WTP: Seller power.

Price (2010\$/AF)	(1)	(2)	(3)	(4)
	OLS	OLS	IV	IV
Seller water use (1,000 AF)	−0.0162**	−0.0251**	−0.576***	−0.867**
(coefficient $-\delta$)	(0.00786)	(0.0126)	(0.212)	(0.435)
Buyer water use (1,000 AF)	−0.00764**	−0.0145**	−0.329**	−0.324**
(coefficient $-\gamma$)	(0.00341)	(0.00620)	(0.147)	(0.159)
Seller fixed effects	✓	✓	✓	✓
Buyer fixed effects	✓	✓	✓	✓
Year fixed effects	✓			
Quadratic time trend		✓	✓	✓
Transaction costs				✓
# Observations	1034	1034	879	877
# Clusters	543	337	308	307
# FE dummies	212	190	164	163
Cragg-Donald F-statistic			8.507	8.231

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Coefficient estimates from fixed effects models using OLS and IV. Standard errors in parentheses, clustered by seller, buyer, and year (but only by seller and buyer in models (2)–(4), where year fixed effects are replaced by a quadratic time trend). Models (1)–(4) correspond to models (1)–(4) of Table 1.2, but now with seller power.

Results of this regression are displayed in Table 1.8. The resulting coefficients are very similar to those of models (1)–(4) of our main specification with buyer power in Table 1.2. Importantly, with seller power our measure of market power is now based on the coefficient on *Buyer water use*, i.e., γ rather than δ. Restricting the comparison to our preferred model (3), we find that model (3) of Table 1.8 does not perform better than model (3) of Table 1.2 when comparing either the Cragg-Donald F-statistic, or the precision of our coefficient of interest. In case one would still assume seller power, we obtain from model (3) of Table 1.8 that $\gamma = 0.329$, which is lower than $\delta = 0.580$ from model (3) of Table 1.2. This difference would imply Lerner indices to be about 50% lower under seller power than under buyer power.

1.8 Conclusions

Using a Nash-Cournot model, we derive a closed-form solution for the extent of market power in a typical water market setting and we construct related Lerner indices. Applying our model to surface water transactions in California over the period 1993-2015, we find only limited market power in California's water market, despite the thinness of this market. Our main specification implies that buyer power yields an average mark-down of 6% of the transaction price. This result is important in the context of current discussions on Californian water market reform (see e.g., Maples et al., 2018) which, perhaps, should focus on other distorting factors, most notably transaction costs (Carey et al., 2002; Regnacq et al., 2016; Hagerty, 2019; Leonard et al., 2019).

Our model has three main assets: (1) it features a closed-form solution, (2) it does not rely on conjectural variations, and (3) it is sufficiently flexible that it can be applied to other types of endowment economies, including permit markets. On the downside, our model requires choosing a specific functional form for WTP and WTA that may not be warranted. In addition, while our current application is quite clear in terms of the side of the market where market power resides, this may not be the case in other applications.

One explanation for the limited extent of market power in California is that transaction quantities are, generally, small. These quantities enter our Lerner index linearly such that small quantities imply low mark-downs. By the same line of reasoning, high prices also imply low mark-downs. This effect was illustrated clearly in Figure 1.2. Another explanation for the limited extent of market power is that, although California's water market is 'thin' in trades, it is 'thick' in possibilities to trade. Recall from Section 1.7 that California features an almost complete hydrological network such that nearly any two districts can trade water. The fact that many do not trade does not imply that such trades are not feasible. Rather, it implies that such districts have high pair-specific transaction costs, which causes a relatively low WTP or a relatively high WTA. The threat of a counterparty switching to a competing district limits the possibility to exercise market power (Funaki et al., 2020). The extent to which such threats affect equilibrium outcomes is an avenue for future research.

1.9 Appendix

Solution for the symmetric model

In this appendix, we provide a solution to this main specification of our model in terms of quantities and prices, assuming $\alpha_{ot} = \alpha$ for all o and $a_{dt} = a$ for all d to keep the analysis simple. We maintain condition (1.9) which, suppressing time subscripts, can now be written as $a - \gamma e_d > \alpha - \delta e_o$.

For each individual buyer, we can write the maximand of equation (1.4), i.e., the buyer's profit function as

$$\begin{aligned}\pi_d &= f_d(Q_d) - \sum_{o=1}^{N_o} q_{od} \cdot \left[\mathrm{WTA}(Q_o)\right] \\ &= \left(e_d + \sum_{o=1}^{N_o} q_{od}\right)\left(a - \frac{1}{2}\gamma\left(e_d + \sum_{o=1}^{N_o} q_{od}\right)\right) - \sum_{o=1}^{N_o} q_{od} \cdot \left[\alpha - \delta\left(e_o - \sum_{d=1}^{N_d} q_{od}\right)\right]. \quad (1.22)\end{aligned}$$

Applying (1.5), we take the derivative of the buyer's profit function (1.22) with respect to q_{od} and, by symmetry, simplify the resulting condition by writing $q_{od} = q$:

$$a - \gamma(e_d + N_o q) - \alpha + \delta(e_o - N_d q) - \delta q = 0, \quad (1.23)$$

This condition implies $a - \gamma e_d - \alpha + \delta e_o = [N_o\gamma + (N_d + 1)\delta]q > 0$. Thus, the equilibrium quantity from seller to buyer q_{od} equals

$$q^* = q^*_{od} = \frac{a - \gamma e_d - \alpha + \delta e_o}{N_o\gamma + (N_d + 1)\delta}, \quad (1.24)$$

which is positive for all o and d by (1.9).

In case the number of available buyers N_d and/or the number of available sellers N_o increases, then each buyer would buy less water from each individual seller. The quantity in equilibrium can be expressed differently by substituting $S = \alpha - \delta e_o$ and $B = a - \gamma e_d$. Thus, $q^* = (B - S)/(N_o\gamma + (N_d + 1)\delta)$. The numerator of this expression consists of the marginal benefits of water use at the initial entitlements. If the buyers' marginal benefit B increases, trade will increase. In contrast, if the sellers' marginal benefit S increases, trade will decrease. The effects on trade of parameters a, α, γ, δ and initial entitlements e_d and e_o follow immediately through their effects on either B or S. For example, an increase in the initial entitlement e_d of individual buyers implies that individual buyers buy less. Similarly, an increase of the initial entitlement e_o of individual sellers implies that individual sellers sell more.

We use equilibrium quantities as in (1.24) to derive the sellers' and buyers' equilibrium (marginal) benefits as well as prices. Using (1.2), we have that $\text{WTP}(Q_d) = a - \gamma Q_d$ and $\text{WTA}(Q_o) = \alpha - \delta Q_o$. By symmetry, we can therefore write the marginal benefit for, respectively, each buyer and each seller in equilibrium:

$$\text{WTP}(Q_d^*) = a - \gamma\left(e_d + N_o q_{od}^*\right) = \frac{(N_d+1)\delta B + N_o\gamma S}{N_o\gamma + (N_d+1)\delta}, \tag{1.25a}$$

$$\text{WTA}(Q_o^*) = \alpha - \delta(e_o - N_d q_{od}^*) = \frac{(N_o\gamma+\delta)S + N_d\delta B}{N_o\gamma + (N_d+1)\delta}. \tag{1.25b}$$

From the WTP function, we directly obtain $Q_d = (a - \text{WTP}(Q_d))/\gamma$. The other component of benefit function f_d is $(a - \frac{1}{2}\gamma Q_d)$ and it can also be expressed in terms of this WTP: $\left(a - \frac{1}{2}\gamma Q_d\right) = \frac{1}{2}(a + a - \gamma Q_d) = \frac{1}{2}(a + \text{WTP}(Q_d))$. Combining these expressions yields the buyers' benefit function

$$\begin{aligned} f_d(Q_d^*) = Q_d^*(a - \frac{1}{2}\gamma Q_d^*) &= \frac{1}{2\gamma}\left[a^2 - (\text{WTP}(Q_d^*))^2\right] \\ &= \frac{1}{2\gamma}\left[a^2 - \left(\frac{(N_d+1)\delta B + N_o\gamma S}{N_o\gamma + (N_d+1)\delta}\right)^2\right]. \end{aligned} \tag{1.26a}$$

Similar steps are applied to obtain the sellers' benefit function

$$\begin{aligned} f_o(Q_o^*) = Q_o^*\left(\alpha - \frac{1}{2}\delta Q_o^*\right) &= \frac{1}{2\delta}\left[\alpha^2 - \left(\text{WTA}(Q_o^*)\right)^2\right] \\ &= \frac{1}{2\delta}\left[\alpha^2 - \left(\frac{(N_o\gamma+\delta)S + N_d\delta B}{N_o\gamma + (N_d+1)\delta}\right)^2\right]. \end{aligned} \tag{1.26b}$$

Given buyer power, equilibrium price equals the marginal willingness to accept. Using (1.25b), we have

$$p^* = \text{WTA}(Q_o^*) = \frac{(N_o\gamma+\delta)S + N_d\delta B}{N_o\gamma + (N_d+1)\delta}. \tag{1.27}$$

This completes the derivation of the symmetric version of the main specification of our model.

For completeness, we also verify that equation (1.6) holds. This equation states that the difference between WTP and WTA equals $-q_{od}\text{WTA}_o'(Q_o) = \delta q_{od}^* > 0$. Substitution of our equilibrium expressions (1.25b) and (1.25a) gives

$$\begin{aligned} \text{WTP}(Q_d^*) - \text{WTA}(Q_o^*) &= \frac{(N_d+1)\delta B + N_o\gamma S}{N_o\gamma + (N_d+1)\delta} - \frac{(N_o\gamma+\delta)S + N_d\delta B}{N_o\gamma + (N_d+1)\delta} \\ &= \delta\frac{B - S}{N_o\gamma + (N_d+1)\delta} \\ &= \delta q_{od}^*. \end{aligned} \tag{1.28}$$

Therefore, equation (1.6) holds, as it should.

Main specification with asymmetry

In this appendix, we generalise the linear model specification introduced in Section 1.2.2 to allow for asymmetry in terms of benefit parameters γ and δ.

Consider a setting where all buyers are asymmetric, all sellers are asymmetric and buyers are on the short side of the market. We update our benefit functions to allow for asymmetry in terms of benefit parameters γ and δ, while suppressing time subscripts to keep notation simple. For each destination we now have $f_d(Q_d) = Q_d(a_d - \frac{1}{2}\gamma_d Q_d)$, and for each origin we now have $f_o(Q_o) = Q_o(\alpha_o - \frac{1}{2}\delta_o Q_o)$. Therefore $f_d'(Q_d) = a_d - \gamma_d Q_d$, which is the WTP in (1.1), while $f_o'(Q_o) = \alpha_o - \delta_o Q_o$, which is the WTA in (1.2). We number sellers as $o = 1, 2, 3, \ldots$ and buyers as $d = -1, -2, -3 \ldots$. Subscript $od = 2-1$ implies that seller 2 delivers to buyer 1.

Three simplified settings are representative for almost all transactions that occur in the data, as introduced in Section 1.3: (a) 1 seller–1 buyer, (b) 1 seller–y buyers with $y \geq 2$, and (c) x sellers–1 buyer with $x \geq 2$. Transaction networks with x sellers and y buyers pertain to only 3% of transactions in our database, illustrating again that California's water market is thin.

Consider setting (a) of a single seller and a single buyer who only trade with each other and non-traders in the background as potential alternative trading partners. The simplest situation consists of one non-trader on each side of the market. If we number seller 1 and buyer -1 as the trading parties with $q_{1-1} > 0$, then seller 2 and buyer -2 do not trade, i.e., $q_{1-2} = q_{2-1} = q_{2-2} = 0$. The equilibrium conditions are derived from buyer -1 who maximises over quantities q_{1-1} and q_{2-1} and from buyer -2 who maximises over quantities q_{1-2} and q_{2-2}. After adding subscripts d and o, we take the derivative of the buyer's profit function (1.22) with respect to q_{od} and obtain:

$$a_d - \gamma_d(e_d + q_{1d} + q_{2d}) - \alpha_o + \delta_o(e_o - q_{o-1} - q_{o-2}) + \delta_o q_{od} \leq 0. \tag{1.29}$$

For $o = 1, 2$ and $d = -1, -2$, we have $q_{1-1} > 0$ and $q_{1-2} = q_{2-1} = q_{2-2} = 0$, so we obtain four equilibrium conditions:

$$\begin{aligned}
&a_{-1} - \gamma_{-1}(e_{-1} + q_{1-1}) - \alpha_1 + \delta_1(e_1 - q_{1-1}) + \delta_1 \cdot q_{1-1} = 0, && \text{(1.30a)}\\
&a_{-1} - \gamma_{-1}(e_{-1} + q_{1-1}) - \alpha_2 + \delta_2 e_2 \leq 0, && \text{(1.30b)}\\
&a_{-2} - \gamma_{-2}e_{-2} - \alpha_1 + \delta_1(e_1 - q_{1-1}) \leq 0, && \text{(1.30c)}\\
&a_{-2} - \gamma_{-2}e_{-2} - \alpha_2 + \delta_2 e_2 \leq 0. && \text{(1.30d)}
\end{aligned}$$

Before solving, we combine and rewrite these four equilibrium conditions in terms of equilibrium WTP or WTA. In doing so, note that because $q_{1-1} \geq 0$, we can rewrite the first condition as a weak inequality: $a_{-1} - \gamma_{-1}(e_{-1} + q_{1-1}) - \alpha_1 + \delta_1(e_1 - q_{1-1}) = -\delta_1 q_{1-1} \leq 0$. We obtain

$$\begin{aligned}
\alpha_1 - \delta_1(e_1 - q_{1-1}) &\geq \max\{a_{-1} - \gamma_{-1}(e_{-1} + q_{1-1}), a_{-2} - \gamma_{-2}e_{-2}\},\\
\alpha_2 - \delta_2 e_2 &\geq \max\{a_{-1} - \gamma_{-1}(e_{-1} + q_{1-1}), a_{-2} - \gamma_{-2}e_{-2}\},\\
a_{-1} - \gamma_{-1}(e_{-1} + q_{1-1}) &\leq \min\{\alpha_1 - \delta_1(e_1 - q_{1-1}), \alpha_2 - \delta_2 e_2\},\\
a_{-2} - \gamma_{-2}e_{-2} &\leq \min\{\alpha_1 - \delta_1(e_1 - q_{1-1}), \alpha_2 - \delta_2 e_2\}.
\end{aligned}$$

The first two conditions indicate that, *in equilibrium*, the seller's WTA must be equal to or larger than the highest WTP for all buyers in the market, independent whether these sellers trade or not. The last two lines indicate that, *in equilibrium*, the buyers' WTP must be equal to or lower than the highest WTA from sellers in the market, independent whether these buyers trade or not. These insights generalise to any market with N_o sellers and N_d buyers, independent whether these trade or not. These conditions imply that none of the buyer-seller pairs has incentives to expand equilibrium trade.

We now check each of the equilibrium conditions in (1.30). Solving condition (1.30a) gives equilibrium trade between seller $o = 1$ and buyer $d = -1$. We obtain

$$q^*_{1-1} = \frac{a_{-1} - \gamma_{-1}e_{-1} - \alpha_1 + \delta_1 e_1}{\gamma_{-1}}. \tag{1.31}$$

Under $a_{-1} - \gamma_{-1}e_{-1} > \alpha_1 - \delta_1 e_1$, which is a straightforward modification of (1.9), this quantity is positive. Substitution of q^*_{1-1} into condition (1.30b) yields $\alpha_1 - \delta_1 e_1 \leq \alpha_2 - \delta_2 e_2$. Evaluated at the initial entitlements, seller 1's WTA is lower than that of seller 2, making seller 1 more efficient in supplying water. Rewriting after substitution of q^*_{1-1} into condition (1.30c) yields

$$a_{-2} - \gamma_{-2}e_{-2} \leq \left(1 - \frac{\delta_1}{\gamma_{-1}}\right)(\alpha_1 - \delta_1 e_1) + \frac{\delta_1}{\gamma_{-1}}(a_{-1} - \gamma_{-1}e_{-1}). \tag{1.32}$$

For $\frac{\delta_1}{\gamma_{-1}} \in [0, 1]$, the right-hand side is the convex combination of seller 1's WTA and buyer 1's WTP, both evaluated at the initial entitlements. For the boundary case $\delta_1 = \gamma_{-1}$, the right-hand side simplifies to $a_{-1} - \gamma_{-1}e_{-1}$. Evaluated at the initial entitlements, buyer -1's WTP is higher than that of buyer -2, making buyer -1 more efficient in purchasing water. If the gap in WTP between the two buyers is positive, then condition (1.32) also holds for δ_1 almost equal to γ_{-1}. Finally, condition (1.30d) specifies the condition that non-trading seller $o = 2$ and non-trading buyer $d = -2$ do not want to trade with each other. If rewritten as $a_{-2} - \gamma_{-2}e_{-2} \leq \alpha_2 - \delta_2 e_2$, it is the complement of modified condition (1.9).

To summarise, the configuration in which seller 1 exclusively trades with buyer -1 arises naturally in case seller 1 has a substantially lower WTA than competing seller 2, while buyer -1 has a substantially larger WTP than competing buyer -2. By the preceding discussion of the equilibrium conditions in (1.30), a sufficient condition for water trade between seller 1 and buyer -1 is the following:

$$\alpha_2 - \delta_2 e_2 > a_{-1} - \gamma_{-1}e_{-1} > \alpha_1 - \delta_1 e_1 > a_{-2} - \gamma_{-2}e_{-2}. \tag{1.33}$$

Equilibrium (marginal) benefits and prices for the asymmetric case can be determined similarly to the symmetric case as was done in Appendix–1.9.

Cases (b) and (c) can be analysed in a similar way when trading buyers are symmetric and trading sellers are symmetric. This involves a lot of repetition of case (a) without generating new insights. Asymmetry within the groups of trading buyers and sellers can also be included. This requires solving a linear system of equations in order to obtain the unique equilibrium quantities, which is cumbersome for the general case of x asymmetric sellers and y asymmetric buyers.

Non-linear demand

In this appendix, we present our empirical strategy for the model of Section 1.7.2 featuring a non-linear WTA function that is homogeneous. Our aim is to estimate κ_o, so that we can measure the Lerner index for this model specification.

The strategy is largely similar to that of Section 1.4 for the linear model specification. We start with the following system of regression equations, based on (1.7), and substitute (1.17) to obtain

$$\begin{aligned} p_{od} &= \mathrm{WTA}(Q_o), && (1.34a) \\ p_{od} &= \mathrm{WTP}(Q_d) - \kappa_o \cdot \frac{q_{od}}{Q_o} \cdot \mathrm{WTA}(Q_o). && (1.34b) \end{aligned}$$

Substituting p_{od} for $\mathrm{WTA}_o(Q_o)$, we solve the last equation for p_{od}, which yields the non-linear system

$$\begin{aligned} p_{od} &= \mathrm{WTA}(Q_o), && (1.35a) \\ p_{od} &= \left(1 + \frac{q_{od}}{Q_o} \cdot \kappa_o\right)^{-1} \mathrm{WTP}_d(Q_d). && (1.35b) \end{aligned}$$

This system can be written in logarithmic form as

$$\begin{aligned} \ln p_{od} &= \ln \mathrm{WTA}(Q_o), && (1.36a) \\ \ln p_{od} &= \ln \mathrm{WTP}(Q_d) - \ln\left(1 + \frac{q_{od}}{Q_o} \cdot \kappa_o\right). && (1.36b) \end{aligned}$$

To extract parameter κ out of the last term, we approximate it by the first-order Taylor expansion of the logarithmic function around 1.[8] This yields the following non-linear system:

$$\begin{aligned} \ln p_{od} &= \ln \mathrm{WTA}(Q_o), && (1.37a) \\ \ln p_{od} &= \ln \mathrm{WTP}(Q_d) - \kappa_o \cdot \frac{q_{od}}{Q_o}. && (1.37b) \end{aligned}$$

[8]The first-order Taylor expansion of $\ln(1+x)$ around $x_0 = 0$ is given by $\ln(1+x_0) + \frac{1}{1+x_0}(x - x_0) = x$. In our case $x = \frac{q_{od}}{Q_o} \cdot \kappa$.

We proceed to estimate (1.37) for the specification $A_i(Q_i)^{-\kappa_i}$, $i = o, d$ and $\kappa_i > 0$, that features constant price elasticity equal to $-1/\kappa_i$. Substitution, rewriting and including multiplicative transaction costs in the factor A_i, $i = o, d$ as well as seller-, buyer-, and year fixed effects, yields

$$\ln p_{odrtk} = -\kappa_o \ln Q_{ot} \qquad\qquad + \ln \tau_r C_{odr} + \phi_o + \psi_d + \beta_t + \varepsilon_{odrtk}, \tag{1.38a}$$

$$\ln p_{odrtk} = -\kappa_o \frac{q_{odtk}}{Q_{ot}} - \kappa_d \ln Q_{dt} + \ln \tau_r C_{odr} + \phi_o + \psi_d + \beta_t + \varepsilon_{odrtk}. \tag{1.38b}$$

Similar to the procedure used in deriving the regression equation for our linear model specification, we combine both equations. This combination requires the construction of two new variables that are defined by

$$\overline{R}^o_{odtk} = \begin{cases} \ln Q_{ot} & \text{if } r = 0 \\ q_{odtk}/Q_{ot} & \text{if } r = 1, \end{cases} \quad \text{and} \quad \overline{R}^d_{odtk} = \begin{cases} 0 & \text{if } r = 0 \\ \ln Q_{dt} & \text{if } r = 1. \end{cases}$$

The combined regression equation is:

$$\ln p_{odrtk} = -\kappa_o \overline{R}^o_{odtk} - \kappa_d \overline{R}^d_{odrtk} + \ln \tau_r C_{odr} + \phi_o + \psi_d + \beta_t + \varepsilon_{odtk}. \tag{1.39}$$

Results of the estimation of this regression equation are presented in Table 1.5 and discussed in Section 1.7.2.

Chapter 2

The impact of environmental regulatory capture on innovation and emissions: The case of the automobile industry

Overview. In the light of the Volkswagen emissions scandal, a common belief that has formed is that regulatory capture in the control and setting of emission standards has led to lower pollution abatement and less environmental innovation in gasoline and diesel combustion engines. This chapter analyses whether this indeed is the case. Our results indicate that regulatory capture only leads to more emissions and less innovation effort under a multi-product monopoly, while the opposite is true under oligopoly competition. These different results are due to a competition intensifying effect which is only present with at least two firms in the market. This effect results from the fact that a consumer-orientated regulator sets higher emission standards for diesel cars, which leads to higher output and more intensive competition among car producers. Consequently, because emission standards and environmental innovation are strategic substitutes, car producers reduce their innovation effort. The result means that the common belief that regulatory capture in the control and setting of environmental standards necessarily leads to more emissions and less environmental innovation is false.

JEL classification: Q52; Q55; Q58; L51.

Keywords: Environmental regulation, Emission standards, Innovation, Abatement technology, Regulatory capture, Automobile industry.

2.1 Introduction

Environmental concerns about diesel cars have intensified since the Volkswagen emissions scandal in 2015, when the United States Environmental Protection Agency (EPA) discovered that Volkswagen used a specific technology in its diesel motor cars to reduce emissions during the testing period. A major consequence of the Volkswagen emissions scandal was that it raised awareness among the population that diesel car producers, in general, have polluted more than they were allowed. Moreover, the scandal contributed to the suspicion that the control of emission standards by regulatory authorities has been rather lax.[1] Therefore, a common belief that has formed is that regulatory capture in the control and setting of environmental standards has led to more emissions and less environmental innovation. The objective of this chapter is to analyse whether and under which circumstances this is indeed the case.

Our results indicate that regulatory capture only leads to higher emissions and less innovation effort under a multi-product monopoly or under cartel formation in the automobile industry, while the opposite is true under oligopoly competition with at least two firms. The intuition for these results hinges on two effects of emission standard regulation: a *production cost effect* and a *competition intensifying effect*. The *production cost effect* means that a producer-orientated regulator will abate less pollution to save on environmental innovation costs. The *competition intensifying effect* occurs because a consumer-orientated regulator increases the competition between car manufactures by facilitating the production of diesel cars by allowing more emissions for this type of car. Gasoline car producers respond to this with a price reduction, thereby compensating for their loss of market share by gaining consumers who would otherwise not buy a car. This means that consumers obtain higher surplus as they can buy more cars and at lower prices. The resulting higher total emissions under a consumer-orientated regulator disincentivises environmental innovation effort because emission standards and innovation efforts are strategic substitutes. Since under multi-product monopoly only the *production cost effect* is present, we obtain that regulatory capture yields more emissions and less environmental innovation. In contrast, under oligopoly competition, the *competition intensifying effect* dominates over the *production cost effect,* meaning that regulatory capture leads to less total emissions and more innovation. This result remains valid when the regulator is initially captured only by the gasoline car manufacturer and when the environmental damages of one type of car are (considered) more harmful.

While the impact of regulatory capture has not yet been analysed in the context of environmental regulation and innovation, our analytical framework borrows from three different literatures. First, it relates to the literature that compares the impact of different environmental regulation instruments on innovation effort. Montero (2002) uses a model in which firms compete à la Cournot and compares firms' R&D incentives in a two-stage

[1] See an article in Carrington (2015) for details on this.

game under four environmental policy instruments: two command-and-control instruments (emission and performance standards) and two market-based instruments (tradable permits and auction permits). The results indicate that the command-and-control instruments provide greater incentives for innovation than the market-based instruments. Amir et al. (2018, 2019) compare performance and emission standards in terms of total welfare and find that the former are generally preferable to the latter. Moner-Colonques and Rubio (2016) analyse how a regulator's non-commitment to an environmental policy (emission standards or taxes) affects the innovation incentives of a monopolist. They find that a tax is preferable to an emission standard when the regulator cannot commit to maintaining the policy once the monopolist has chosen their innovation effort. In contrast, when there is commitment, the two policies are equivalent. Our analysis differs in three ways from this literature. First, our focus is on the automobile market, i.e., on durable goods that are not homogeneous. Second, we analyse a multi-stage game in which the regulator sets optimal environmental standards. Finally and most importantly, we focus our attention on the consequences of regulatory capture for environmental standards and innovation.

While ignoring environmental innovation, another stream of the literature that relates to our work compares the welfare properties of specific environmental policies. Requate (2006) surveys the theoretical literature on environmental policy in the presence of imperfect competition. As regulatory instruments he considers emission taxes, tradable permits, and both absolute and relative standards. He concludes that, typically, under imperfect competition the second-best optimal price for pollution is below the marginal social damage caused by the pollution, and that taxes and emission standards are mostly equivalent policy instruments. Besanko (1987) compares performance standards and design standards that regulate pollution through a minimum usage requirement of an emissions control input. He shows that a welfare comparison of these policy instruments depends strongly on the regulator's objective function. Thus, if she wants to minimise the sum of emissions and pollution damage costs, performance standards are preferable. In contrast, if consumer and producer welfare is taken into account, the comparison becomes indeterminate. Helfand (1991) analyses how firm's profits are affected by five different environmental control policies, namely, emission standards, performance standards on outputs and inputs, and output and input restrictions. Her results indicate that an emission standard yields the highest profits. However, she also shows that the comparison of different standards is sensitive to the underlying model assumptions. In contrast to this literature, in this chapter, we do not compare different environmental policies, but focus on second-best emission standards with and without regulatory capture when firms can invest in pollution-reducing technologies.

Finally, some studies have considered different environmental policies in the automobile market. Shao et al. (2017) analyse optimal subsidies and price discount rates for electric cars in the electric and gasoline vehicle market. They find that, while both policy instruments yield equivalent welfare outcomes, a subsidy incentive scheme is preferable for the regulator, as it is less costly to implement. Ahmed and Segerson (2007) compare a quota and an average efficiency standard in terms of their effectiveness in reducing emissions in the automobile market. They find that the optimal policy choice depends on the magnitude of unit damages, where the quota policy is preferable in terms of welfare and profits, as long as unit damages are sufficiently high. While our focus is completely different to that of these studies, our analysis is based on similar modelling assumption regarding consumer demand in the automobile market.

The remainder of this chapter is organised as follows. In Section 2.2, we review some of the main characteristics of the automobile industry. Based on these, Section 2.3 sets up the theoretical model. Section 2.4 contains the main results of the chapter and Section 2.5 some extensions. Section 2.6 provides conclusions. All proofs are in the Appendix.

2.2 Characteristics of the automobile industry

In this section we review some of the characteristics of the automobile market which we enumerate as stylised facts. These facts are used to built up the theoretical framework in Section 2.3.

Consumer demand. Typically consumers purchase one unit of car or none. Consumers are heterogeneous in tastes and when they decide to purchase an automobile, they buy different types of cars. The canonical model for this type of demand in the context of the automobile sector is from Bresnahan (1987). For our purpose, we have to consider that diesel cars are usually more expensive than gasoline cars. In contrast, the energy cost of diesel cars is lower than that of gasoline cars (see Table 2.1). For example, in Germany in 2018 a Volkswagen Golf with a gasoline engine (1.2 TSI BMT) was 2550 euros less expensive than its counterpart with a diesel engine (1.6 TDI BMT). Instead, the costs per kilometre driven were 2 cents higher for the automobile with the gasoline engine.[2] Therefore in Europe, typically, we observe that frequent drivers that travel more than 20,000 kilometres per year purchase diesel cars, while casual drivers buy gasoline cars yielding almost equal market shares for the two type of engine cars. In the US, fuel prices of diesel have been above those of gasoline for a long time. Therefore, despite the higher fuel economy of diesel cars, consumers could hardly recover the higher sales prices of these cars such that the market share of diesel cars has never been above 1% (see Table 2.2). We obtain:

Fact 1: Gasoline and diesel car drivers are segmented at the intensive margin and in general, frequent drivers purchase diesel cars while casual drivers buy gasoline cars.

Competition. The automobile sector is an oligopoly industry that operates worldwide with a considerable number of manufactures (in 2017, there were more than 16 firms with a market share above 1%). Nevertheless, there remain several issues of concern regarding the

[2] For a detailed comparison of these two models see Autozeitung (2018).

Table 2.1: Pump price of fuel.

	European Union		Germany		United States		China	
Year	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel
2010	1.69	1.61	1.90	1.68	0.76	0.84	1.11	1.04
2012	1.92	1.83	1.96	1.88	0.97	1.05	1.37	1.28
2014	1.78	1.64	1.80	1.58	0.76	0.97	1.17	1.09
2016	1.32	1.20	1.39	1.20	0.71	0.65	0.96	0.81

Pump price for gasoline and diesel fuel. Prices are aggregated by the median, and converted to US $ by exchange rates. They refer to the most widely sold grade of fuel. Source: Bank (2020).

Table 2.2: Market share of passenger cars.

	European Union			United States			China		
Year	Gasoline	Diesel	Others	Gasoline	Diesel	Others	Gasoline	Diesel	Others
2008	43.1%	49.3%	7.5%	97.4%	0.1%	2,5%	-	-	-
2009	45.8%	43.8%	10.4%	97.2%	0.5%	2,3%	-	-	-
2010	40.9%	48.6%	10.5%	95.5%	0.7%	3.8%	93.5%	2.5%	4.0%
2011	39.8%	52.4%	7.8%	97.0%	0.8%	2.3%	93.5%	2.5%	4.0%
2012	37.9%	52.4%	9.7%	95.5%	0.9%	3.5%	94.5%	2.5%	3.0%
2013	38.1%	46.7%	15.2%	94.8%	0.9%	4.3%	94.5%	2.5%	3.0%
2014	40.9%	49.0%	10.1%	95.7%	1.0%	3.3%	96.0%	2.0%	2.0%
2015	39.4%	42.6%	18.0%	95.9%	0.9%	3.1%	97.0%	1.0%	2.0%
2016	41.3%	39.5%	19.2%	96.9%	0.5%	2.6%	97.5%	0.0%	2.5%
2017	44.6%	36.8%	18.5%	96.1%	0.3%	3.7%	96.0%	0.0%	4.0%

Market share of passenger cars by engine type. Sources: Eurostat (2020), EPA (2019), JATO (2020).

competitiveness of the industry in specific markets. First, over the last two decades in some regions a tendency towards higher market concentration has been observed. Thus, in the European Union and EFTA in 2019, the 3 largest firms had a market share of 50,6% while in 2007, they had a market share of 43%. During this period the number of firms with a market share of more than 1% declined from 15 in 2007 to 13 in 2019 (Bekker, 2020). Second, different forms of alliances have gained importance since the 2000s. Examples of such alliances are the mergers between Daimler-Benz and Chrysler in 1998 or Fiat-Chrysler and PSA in 2020 and cross-shareholding agreements among firms as between Kia and Hyundai in 1998 or Renault, Nissan and Mitsubishi starting in 1999. Third, common ownership of automobile companies by investment funds has become a salient feature in some markets (López and Vives, 2019). Thus, for the two main US automobile manufactures, Ford and General Motors, we find the same names among its five most important shareholders, namely, *The Vanguard Group* (7.54% and 6.87%), *Capital Research & Management* (1.39% and 7.02%), and *Black Rock Fund Advisers* (2.43% and 4.29%).[3] Finally, it has been apparent that automobile producers have eliminated competition in specific market segments by cartel formation. For instance, Daimler, BMW and Volkswagen received an 100 million euro fine in 2019 for forming a cartel to fix steel prices, and the same companies are currently accused to restrict competition on the development of technology to clean the emissions of petrol and diesel passenger cars. For all these reasons, regulatory agencies should not presume

[3]For further details on the top stockholders of these companies see CNN (2020).

that competition in automobile markets is sufficiently high but rather be concerned about how to guarantee competition in these markets yielding the following conclusion:

Fact 2: Despite the large number of car manufactures, lack of competition is an issue in automobile markets.

Regulatory capture. The current criterion of regulatory agencies used both in the US and the EU to assess alliances among firms emphasises its consequences to consumer welfare. For instance with regard to mergers, as indicated by Banal-Estañol et al. (2008), "in the US, the 'substantial lessening of competition' test (SLC) has been interpreted such that a merger is unlawful if it is likely that it will lead to an increase in price (i.e., to a decrease in consumer surplus). In the EU, the Horizontal Merger Guidelines state that the Commission should take into account, above all, the interests of consumers when considering efficiency claims of merging firms (art. 79–81)".[4] However, in the case of the automobile industry there are compelling reasons to believe that regulatory policy does not always follow that criterion. First, as observed in Table 2.3, emissions standards vary substantially among countries. A possible explanation for this fact are the different environmental concerns in these countries as it is not clear which of the two motors, diesel or gasoline, is more harmful to the environment. Diesel cars emit less hydrocarbons (HC), carbon monoxide (CO) and lead pollution than gasoline cars, and therefore, are advantageous for fighting global warming. However, diesel cars produce more noxious gases, such as nitrogen oxides (NOx), and significantly more particulate matter (PM) than gasoline cars, and hence are more harmful to health. Another explanation is regulatory capture as environmental regulation has a large impact on market performance. Thus, as observed in Table 2.2, in 2017 the market share of diesel cars in the EU was 36.8%, while in the US and China their market share was below 0.5%. This difference can be explained largely by governmental intervention. On the one hand, US emission regulations do not distinguish between diesel and gasoline cars, and apply similar standards to diesel cars as those for gasoline cars in the EU. Therefore, standards are hardly to be met for diesel car producers which are mainly producers from abroad the US. On the other hand, taxation in Europe and particularly in Germany is more favourable for diesel cars. Thus, pump prices for this fuel are substantially lower than those for gasoline. In contrast, in the US the opposite occurs. The differences in emission standards between the US, the EU and China observed in Table 2.3, therefore stem less from differences in environmental objectives and more from the fact that European (particularly German) car producers have a competitive advantage on diesel engine technologies.[5]

Other reasons for regulatory capture are that in many countries automobile manufacturers receive substantial subsidies often justified with the argument that the industry creates

[4] For more information about the recent criteria of the US and EU competition policies see Mateus and Moreira (2010).

[5] Official lobbying expenditure of the automotive industry in 2019 amounted to $69.7 million in the US (CRP, 2020). In 2014, car manufacturers and their trade associations spent more than €18 million on lobbying activities in Brussels (CEO, 2015).

Table 2.3: Emission standards in the EU, US, and China.

		CO		*HC*		NO_x		*PM*	
Year	Standard	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel
European Union									
1992	Euro 1	2.2	1	-	-	-	-	-	0.14
1996	Euro 2	2.3	1	0.2	-	-	-	-	0.08
2000	Euro 3	1	0.5	0.1	-	0.15	0.5	-	0.05
2005	Euro 4	1	0.5	0.1	-	0.08	0.25	-	0.025
2009	Euro 5a	1	0.5	0.1	-	0.06	0.18	0.005	0.005
2014	Euro 6	1	0.5	0.1	-	0.06	0.08	0.005	0.005
United States									
1994	Tier 1	2.11	2.11	0.16	0.16	0.25	0.25	-	-
2004	Tier 2	2.11	2.11	0.05	0.05	0.03	0.03	-	-
2017	Tier 3	2.11	2.11	0.06	0.06	0.04	0.04	-	-
China									
2000	China 1	-	-	-	-	-	-	-	-
2002	China 2	-	-	-	-	-	-	-	-
2005	China 3	2.3	0.64	0.2	-	0.15	0.5	-	0.05
2008	China 4	1	0.5	0.1	-	0.08	0.25	-	0.025
2012	China 5	1	0.5	0.1	-	0.06	0.18	0.0045	0.0045
2015	China 6a	0.7	0.7	0.1	0.1	0.06	0.06	0.0045	0.0045
2018	China 6b	0.5	0.5	0.05	0.05	0.035	0.035	0.003	0.003

Emission standards for passenger cars in the European Union, United States and China (g/km). For the US, emission standards are for passenger cars at 50,000 miles/5 years. US legislation on air quality and vehicle emissions is a combination of federal law, and stricter Californian standards (known as LEV), which may also be voluntarily applied by other states. For details see DGIP (2016) and TransportPolicy.net (2019).

and guarantees employment (CDG, 2014). Moreover, we observe government ownership in some of the most important automobile producers meaning that the public sector is co-owner and regulator of these firms at the same time. For example, on January 31, 2019, the French government had a 15.01% stake in Renault and the German State of Lower Saxony a 11.8% stake in Volkswagen Group. Consequently, we should expect that regulatory policy in relation to this industry follows a criteria that also takes producer profits into account. This sums up to:

Fact 3: Regulatory capture is an important issue in the automobile industry.

Innovation and environmental regulation. Developing and producing automobiles is a highly research intensive activity. In fact, the automobile industry is among the most innovation intensive industries in many developed countries. According to OECD (2020), R&D expenditures in the automobile industry in 2017 amounted to 37.3% of all R&D expenditures in Germany, 25.9% in Japan, 8.5% in China, 7.3% in France, and 6.0% in the United States. Kuik (2006) identifies as the most important drivers of innovation: *i)* consumer demand (for comfort, safety and fuel economy), *ii)* international competition, and *iii)* environmental objectives and regulations. According to survey information from German automobile manufactures in 2004, “the main motives for environmental product innovations were: customer and cost pressure as well as environmental regulation and company environmental policy. The main motives for process innovation were the opening of new markets, gaining of competitive advantage as well as the saving of resources, CO_2 reduction because of the Kyoto Protocol and company environmental policy objectives, and various pieces of environmental regulation" such as Euro 4 and emission limit values (Kuik, 2006).

In this context, the question whether environmental regulation spurs environmental innovation or regulation rather stipulates emission standards that have proven to be already technological feasible by the industry has been extensively discussed. As an example of technology-forcing legislation often the Clean Air Act of 1970 is quoted (Kuik, 2006; Johnson, 2016). The act specified emissions standards for which no technologies existed at the time the act was passed. As a response to its environmental requirements, the three-way catalyst was developed in 1981. This in turn required the implementation of computer technology in cars which prepared the ground for further improvements in car safety and fuel economy. By contrast, Gerard and Lave (2003) argue that the approval of the Clean Air Act required specific technical, political, economic, and administrative conditions that were favourable at that time. In general, a technology-forcing strategy is very risky as its results are highly uncertain and politically often unfeasible due to the influence of stakeholders or an unfavourable business cycle. In fact, many of the changes in environmental regulations are the result of negotiations between regulators and car producers as, for example, the Voluntary Agreement for Clean Cars between EPA and US automobile manufactures in 1998, before the implementation of the Tier 2 standards.[6][7] In this line, a study by DLR (2004) concluded that specific changes in CO_2 emissions over the period 1995-2003 were primarily caused by technological developments and not demand or regulation driven. We summarise these findings as follows:

Fact 4: Environmental innovation and regulation fed back mutually with no clear preponderance regarding their causal relationship.

On the basis of these characteristics of the automobile industry, in the remainder of this chapter, we test the following hypothesis that, particularly in the aftermath of the Volkswagen emissions scandal in 2015 has become a common belief:

H1: "Regulatory capture in the automobile industry has caused more emissions and less environmental innovation with regards to passenger cars".

[6]A similar voluntary agreement to reduce CO_2 emissions from passenger cars and to improve their fuel efficiency has been reached in 1998 between the EU and the European Automobile Manufacturers' Association (ACEA), the Japan Automobile Manufacturers Association (JAMA), and the Korea Automobile Manufacturers Association (KAMA).

[7]See also Gersbach and Glazer (1999), who discuss the commitment problem of regulatory programs in the US to reduce automobile emissions resulting in the non-investment in pollution-reducing technology by firms. The authors show that this hold-up problem may be overcome by the regulator through the issuance of tradeable permits. However, this is only the case when firms do not collude or negotiate environmental standards through industry associations, as it has been often the case in the past.

2.3 The model

Demand

Consider a market with two different types of cars: gasoline (G) and diesel (D). We assume a continuum of consumers who vary in their willingness to pay, denoted by θ, which is uniformly distributed on $[0,1]$ such that demand is linear in price. Each consumer either buys a single car (diesel or gasoline) or decides not to buy a car. The utility of a consumer of type θ in each of these cases is given by

$$U_D^\theta = (1+\alpha)\theta - p_D, \tag{2.1}$$
$$U_G^\theta = \theta - p_G, \quad \text{and} \tag{2.2}$$
$$U_0^\theta = 0, \tag{2.3}$$

where $0 \leq \alpha < 1$, and p_D and p_G denote the price of the diesel and the gasoline car, respectively. If we decompose, as in Ahmed and Segerson (2007), $\alpha = \omega_D - \omega_G - \left(p_D^e r_D - p_G^e r_G\right)$, where ω_m is the quality, p_m^e the unit price of energy and r_m the energy consumption of each car type ($m = D, G$), a positive value of α means that, for cars of the same quality, the energy cost of diesel cars is lower than that of gasoline cars. As observed in Table 2.1, this has been the case over the past decades in the European Union and China. A natural interpretation of the parameter θ is the number of kilometres that consumers drive each year. In this case, under $p_D > p_G$, the lower energy price of diesel cars ($\alpha > 0$) implies, in accordance with Fact 1, that frequent drivers purchase diesel cars and casual drivers gasoline cars.

Equations (2.1) to (2.3) yield the critical values for buying a diesel car, a gasoline car, or no car. When $\alpha > 0$, consumers buy a diesel car if

$$U_D^\theta \geq U_G^\theta, \text{ i.e.,} \quad \theta \geq \frac{p_D - p_G}{\alpha} \equiv \overline{\theta} \tag{2.4}$$

and buy a gasoline car if

$$U_G^\theta > U_D^\theta \text{ and } U_G^\theta > 0, \text{ i.e., } \overline{\theta} > \theta > p_G \equiv \underline{\theta}. \tag{2.5}$$

For $\alpha = 0$ consumers exclusively buy the cheaper car, and when $p_D = p_G = \underline{\theta}$ both types of car share the market evenly, i.e., $q_D = q_G = 1 - \underline{\theta}/2$.

Given the prices of diesel and gasoline cars, we obtain that consumers purchase: *(i)* a diesel car if $\theta \in [\overline{\theta}, 1]$; *(ii)* a gasoline car if $\theta \in [\underline{\theta}, \overline{\theta}]$; *(iii)* no car if $\theta \in [0, \underline{\theta}]$. Consequently, for $\alpha > 0$, we obtain the following demand functions:[8]

[8]In the case that $p_D = p_G = \underline{\theta}$, both types of car share the market equally, i.e., $q_D = q_G = 1 - 2\underline{\theta} = 1 - p_D - p_G$.

$$q_D = 1-\overline{\theta} = 1-\frac{p_D - p_G}{\alpha}, \tag{2.6}$$
$$q_G = \overline{\theta} - \underline{\theta} = \frac{p_D - (1+\alpha)p_G}{\alpha}, \tag{2.7}$$

and their corresponding inverse demand functions:

$$p_D = (1+\alpha)(1-q_D) - q_G, \tag{2.8}$$
$$p_G = 1 - q_D - q_G. \tag{2.9}$$

The resulting consumer surplus is given by

$$CS = \int_{\overline{\theta}}^{1} U_D^{\theta} d\theta + \int_{\underline{\theta}}^{\overline{\theta}} U_G^{\theta} d\theta = \frac{1+\alpha}{2} q_D^2 + q_G q_D + \frac{1}{2} q_G^2. \tag{2.10}$$

Production

Gasoline and diesel cars are produced either by different firms or by multi-product firms. Firms have linear production costs of the form $C_G(q_G) = cq_G$ and $C_D(q_D) = kcq_D$, where $0 < c < 1$, $k > 1$ and $(1-c) = 1+\alpha - kc \equiv A$.[9] We assume that each unit of output generates one unit of pollution such that the firms' emissions can be written as $e_m = q_m - x_m$, $m = D, G$, where x_m stands for the firm's environmental innovation. As it is common in the literature (see e.g., Amir et al., 2018; Moner-Colonques and Rubio, 2016; Montero, 2002; Petrakis and Xepapadeas, 2001), we assume that innovation costs are quadratic, i.e., $C(x_m) = x_m^2/2$. Similarly, the per unit damage caused by pollution is assumed to increase with the emission level and the total damage is given by $D = d\left(e_D^2 + e_G^2\right)/2$, where $d > 3(1+\alpha)$.[10] By assuming a common d for gasoline and diesel car emissions, we consider that both types of cars are considered equally harmful, which is a realistic assumption for environmental regulation in the EU over the past decades.[11] From the above, it follows that firms' profits stemming from the production of diesel and gasoline cars are:

[9]This assumption means that the higher production costs of diesel cars compensate their higher utility for consumers. While the assumption does not affect the result qualitatively, it allows the exposition of the results to be simplified.

[10]Assuming a lower bound for d guarantees non-negative equilibrium values and simplifies the exposition of the results.

[11]Notice that considering gasoline and diesel cars as equally harmful means that environmental standards are set differently for the two types of cars because their engines cause different levels of HC, CO and NOx emissions (see Table 2.3). In Section 2.5 we also consider the case that $d_D > d_G$, which can explain the observation that in the US environmental standards are set in a way that makes them more difficult to fulfil for diesel cars than for gasoline cars.

$$\pi_D = \left(1-\overline{\theta}\right)(p_D - kc) - x_D^2/2 = q_D\left((1+\alpha)(1-q_D) - q_G - kc\right) - x_D^2/2, \quad (2.11)$$
$$\pi_G = \left(\overline{\theta}-\underline{\theta}\right)(p_G - c) - x_G^2/2 = q_G(1-q_D-q_G-c) - x_G^2/2, \quad (2.12)$$

respectively. Following the insights from Fact 2, we consider different market structures according to their degree of competitiveness, namely, multiproduct monopoly, single-product duopoly (one diesel and one gasoline car producer), and oligopoly with both types of firms.

Environmental regulation

The regulator limits the level of pollution generated by each industry by choosing the emission standards $\overline{e}_D$ and $\overline{e}_G$. To determine these standards the regulator maximises a weighted social welfare function of the form

$$W = \lambda CS + \mu(\pi_D + \pi_G) - \nu D. \quad (2.13)$$

With this welfare function, we can capture different regulator concerns regarding the stakeholders' welfare. Without loss of generality, we can normalise one of the parameters and set $\lambda = 1$. Moreover, as higher (lower) concerns about future generations, i.e., pollution captured by ν, is equivalent to assuming higher (lower) environmental damages which is indicated by d. We also set $\nu = 1$ and interpret hereinafter d, as measuring both environmental damages and concerns about future generations.

Regarding μ, we analyse two scenarios. First, we consider the case $\mu = 0$ denoted as a 'consumer-orientated regulator'. This case reflects the current criterion applied by regulatory authorities to assess the effects on welfare of any kind of competition policy such as joint ventures, mergers, and other agreements among firms.[12] Second, we consider the case $\mu = 1$. In this case, producers' profits have the same weight as consumer surplus. We denote this case as a 'producer-orientated regulator' or 'regulatory capture', because under current standards, the regulator gives too much consideration to producers. Later, we consider the case in which μ is continuous and allow for both $0 < \mu < 1$ and $\mu > 1$. Thereby, the formulation of the welfare function in (2.13) captures important aspects of regulatory practices as summarised in Fact 3.

Timing of the game

The timing of the game is as follows. In Stage 1, the firms choose their environmental innovation effort x_D and x_G, respectively. Simultaneously, the regulator decides on the maximum amount of emissions by setting the emission standards $\overline{e}_D$ and $\overline{e}_G$. In Stage 2,

[12] For more information about the recent criteria of the US and EU competition policies see Mateus and Moreira (2010).

after observing the emission standards and the innovation efforts, both firms determine their production levels q_D and q_G, respectively. The assumption that the levels of total emissions and innovation efforts are chosen simultaneously is justified in Fact 4.[13] Note that, here, it is tantamount to assuming that the desired level of total emissions is established directly via emission standards or indirectly via a performance standard $h_m = e_m/q_m$. This is because, once the environmental innovation and emission standards are chosen, performance standards are determined completely as $h_m = e_m/(e_m + x_m)$. The focus on emission standards is motivated by the fact that these are in the focus of all climate summits (e.g. Madrid 2019, Copenhagen 2003, or Kyoto 1997) to determine emission levels at the country level. Then, national governments try to reach the agreed emission levels by using various policy instruments (taxes, subsidies, permission standards, among others). As usual, the game is solved by backward induction.

2.4 Results

2.4.1 Multiproduct monopoly

Consider a regulator that deals with an automobile industry that does not compete in environmental innovation as it seems to have occurred in part of the European car market, where car manufactures have formed cartels to restrict competition on the development of emission-reducing technology. In this sense, let us assume that the regulator faces a multiproduct monopoly, i.e., a firm (or cartel) that produces both types of cars, diesel and gasoline.

In Stage 2, for given levels of x_D, x_G, $\overline{e}_D$, and $\overline{e}_G$, the firm determines its production level q_D and q_G, respectively. As $q_m = e_m + x_m$, this quantity choice is tantamount to choosing the level of emissions. From the profit functions in (2.11) and (2.12), it is straightforward that for the firm it is optimal to set $e_m = \overline{e}_m$, i.e., to pollute as much as allowed.

In Stage 1, the firm's environmental innovation is obtained from:

$$\begin{aligned} \max_{x_D, x_G} \pi &= (x_D + \overline{e}_D)((1+\alpha)(1 - x_D - \overline{e}_D) - x_G - \overline{e}_G - kc) \\ &\quad + (x_G + \overline{e}_G)(1 - x_D - \overline{e}_D - x_G - \overline{e}_G - c) - x_D^2/2 - x_G^2/2 \end{aligned} \tag{2.14}$$

From the first-order conditions, we obtain:

[13] Notice, however, that our main results do not depend on this assumption. For the effect of different assumptions regarding the timing of decisions see, for example, Moner-Colonques and Rubio (2016).

$$x_D = \frac{1}{3+2\alpha}(A-2(1+\alpha)\overline{e}_D-2\overline{e}_G-2x_G), \tag{2.15}$$
$$x_G = \frac{1}{3}(A-2\overline{e}_D-2\overline{e}_G-2x_D). \tag{2.16}$$

From (2.15) and (2.16), we observe that environmental innovation efforts are strategic substitutes. Moreover, higher pollution standards for each type of car lead to a reduction in environmental innovation for both type of cars. Simultaneously, the regulator chooses $\overline{e}_D$ and $\overline{e}_G$ to maximise social welfare in (2.13) yielding the following reaction functions:

$$\overline{e}_D = \frac{\mu d}{\Delta}A+\frac{(1-2\mu)((1+\alpha)d-\alpha(1-2\mu))}{\Delta}x_D+\frac{(1-2\mu)d}{\Delta}x_G, \tag{2.17}$$
$$\overline{e}_G = \frac{\mu(d-\alpha(1-2\mu))}{\Delta}A+\frac{(1-2\mu)d}{\Delta}x_D+\frac{(1-2\mu)(d-\alpha(1-2\mu))}{\Delta}x_G, \tag{2.18}$$

where $\Delta \equiv d^2-(1-2\mu)(\alpha+2)d+(1-2\mu)^2\alpha$. From (2.17) and (2.18), we obtain the following result:

Lemma 2.1. *The regulator's emission standards $\overline{e}_D$ and $\overline{e}_G$, and the firms environmental innovation efforts x_D and x_G are: (i) strategic substitutes if the regulator is producer-orientated (i.e., $\mu > 1/2$), (ii) strategic complements if the regulator is consumer-orientated (i.e., $\mu < 1/2$). For $\mu = 1/2$, the regulator's emission standards are independent of the firms' innovation efforts ($\overline{e}_D = \overline{e}_G = A/d$).*

The regulator uses the emission standards to exert an indirect influence on the producers' environmental innovation efforts. From Lemma 2.1, we observe that a producer-orientated regulator responds to a decrease in innovation efforts with an increase in $\overline{e}_m$, i.e., by abating less pollution. This makes it possible to mitigate the impact of changes in innovation effort on output and profits. By contrast, a consumer-orientated regulator uses emission standards as an incentive device for innovation efforts. Thus, they punish lower innovation efforts with a reduction in $\overline{e}_m$ and reward more innovation with an increase in $\overline{e}_m$. Thereby, the effect of any change in innovation efforts on output and profits is aggravated.

To assess the impact of different weights in the welfare function on equilibrium outcomes obtained from equations (2.15)-(2.18), we consider the two extreme cases: *(i)* a completely consumer-orientated regulator ($\mu = 0$) and *(ii)* a producer-orientated regulator who weights consumer surplus and profits equally ($\mu = 1$). The following result shows the equilibrium values in the two cases.

Lemma 2.2. *Under multiproduct monopoly with a consumer-orientated regulator ($\mu = 0$), the Nash equilibrium values are:*

$$\begin{aligned}
x_D^{M,0} &= \frac{d^2-(3\alpha+2)d+\alpha}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A,\ x_G^{M,0} = \frac{(2\alpha+1)d^2-(3\alpha+2)d+\alpha}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A,\\
e_D^{M,0} &= \frac{(3\alpha+2)d-\alpha}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A,\ e_G^{M,0} = \frac{2(\alpha+1)d-\alpha}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A,\\
q_D^{M,0} &= \frac{d^2}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A,\ q_G^{M,0} = \frac{[(2\alpha+1)d-\alpha]d}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A.
\end{aligned}$$

With a producer-orientated regulator ($\mu = 1$), the Nash equilibrium values are:

$$\begin{aligned}
x_D^{M,1} &= \frac{d^2-(3\alpha+2)d-\alpha}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A,\ x_G^{M,1} = \frac{(2\alpha+1)d^2-(\alpha+2)d-\alpha}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A,\\
e_D^{M,1} &= \frac{3(\alpha+1)d+\alpha}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A,\ e_G^{M,1} = \frac{(3+4\alpha)d+2\alpha}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A,\\
q_D^{M,1} &= \frac{(d+1)d}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A,\ q_G^{M,1} = \frac{[(2\alpha+1)d+\alpha](d+1)}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A.
\end{aligned}$$

The following result gives the comparison of the equilibrium values in both cases.

Proposition 2.1. *Regulatory capture yields to more emissions and less innovation, i.e., $\overline{e}_m^{M,1} > \overline{e}_m^{M,0}$ and $x_m^{M,1} < x_m^{M,0}$, $m = D, G$. The production of gasoline cars is lower and that of diesel cars is lower (higher) when the utility of diesel cars is high (low) and damages are low (high), i.e., $q_G^{M,0} < q_G^{M,1}$ and $q_D^{M,0} \lesseqgtr q_D^{M,1}$ for $\alpha \lesseqgtr \overline{\alpha}_q(d)$ with $\partial\overline{\alpha}_q/\partial d > 0$.*

To interpret this result, note that the firm can increase its production either by increasing emissions or by intensifying environmental innovation. As increasing emissions does not have any cost to the firm, so that it pollutes as much as allowed, naturally, the firm prefers this form of increasing output. Therefore, the regulator exerts a high degree of control over production and production costs by choosing the emission standards. We call this the '*production cost effect*' of emission standard regulation. As an indicator of this control, in Proposition 2.1, we observe that even if the firm compensates higher (lower) standards with less (more) innovation, the effect of changes in emission standards on output dominates the effect of changes in innovation. It follows that a regulator that is concerned about producer profits sets higher levels of $\overline{e}_m$ as this allows the car manufacturer to produce the same output with lower innovation costs and thus with higher profits. We conclude that under multi-product monopoly hypothesis H1 is confirmed, i.e., regulatory capture yields to more emissions and less innovation.

2.4.2 Duopoly competition

To assess in how far the former results depend on the absence of competition in the product market and in environmental innovation, now, consider that the regulator faces duopoly competition under which diesel cars are produced by one firm (D) and gasoline cars by the other firm (G). As before, in Stage 2, quantities are completely determined by the firms' innovation efforts and the emission standards chosen by the regulator.

In Stage 1, firms D and G choose the level of environmental innovation x_D and x_G by solving:

$$\begin{aligned} \max_{x_D} \pi_D &= (x_D + \bar{e}_D)((1+\alpha)(1 - x_D - \bar{e}_D) - x_G - \bar{e}_G - kc) - x_D^2/2, & (2.19) \\ \max_{x_G} \pi_G &= (x_G + \bar{e}_G)(1 - x_D - \bar{e}_D - x_G - \bar{e}_G - c) - x_G^2/2. & (2.20) \end{aligned}$$

This yields the following reaction functions:

$$\begin{aligned} x_D &= \frac{1}{3+2\alpha}(A - 2(1+\alpha)\bar{e}_D - \bar{e}_G - x_G), & (2.21) \\ x_G &= \frac{1}{3}(A - \bar{e}_D - 2\bar{e}_G - x_D). & (2.22) \end{aligned}$$

A comparison of these conditions with equations (2.15) and (2.16) reveals that a multi-product monopoly reacts with a stronger reduction of environmental innovation to cross-product emission standards and innovation than under duopoly competition. Therefore, for the same emission standard levels, we have more environmental innovation with two independent firms producing one car type each than with a multi-product firm.

The regulator's choice of emission standards is tantamount to the problem under multi-product monopoly and yields the same reaction functions as in (2.17) and (2.18). The following result is the counterpart to Lemma 2.2 and states the equilibrium values obtained from equations (2.17), (2.18), (2.21), and (2.22) for the two cases $\mu = 0$ and $\mu = 1$.

Lemma 2.3. *Under duopoly competition with a consumer-orientated regulator ($\mu = 0$), the Nash equilibrium values are:*

$$\begin{aligned} x_D^0 &= \frac{2d^2 - 4d(1+\alpha) + \alpha}{(2d-1)(4d+3d\alpha-\alpha)}A,\ x_G^0 = \frac{[2d(1+\alpha)-\alpha]d - (4d+2d\alpha-\alpha)}{(2d-1)(4d+3d\alpha-\alpha)}A, \\ \bar{e}_D^0 &= \frac{4d(1+\alpha)-\alpha}{(2d-1)(4d+3d\alpha-\alpha)}A,\ \bar{e}_G^0 = \frac{4d+2d\alpha-\alpha}{(2d-1)(4d+3d\alpha-\alpha)}A, \\ q_D^0 &= \frac{2d^2}{(2d-1)(4d+3d\alpha-\alpha)}A,\ q_G^0 = \frac{[2d(1+\alpha)-\alpha]d}{(2d-1)(4d+3d\alpha-\alpha)}A. \end{aligned}$$

With a producer-orientated regulator ($\mu = 1$), the Nash equilibrium values are:

$$\begin{aligned}
x_D^1 &= \frac{2d(d-1-\alpha)}{(2d+1)(4d+3d\alpha+\alpha)}A,\ x_G^1 = \frac{[2d(1+\alpha)+\alpha](d-1)}{(2d+1)(4d+3d\alpha+\alpha)}A,\\
\bar{e}_D^1 &= \frac{2d(\alpha+2)}{(2d+1)(4d+3d\alpha+\alpha)}A,\ \bar{e}_G^1 = \frac{2[2d(1+\alpha)+\alpha]}{(2d+1)(4d+3d\alpha+\alpha)}A,\\
q_D^1 &= \frac{2d(d+1)}{(2d+1)(4d+3d\alpha+\alpha)}A,\ q_G^1 = \frac{[2d(1+\alpha)+\alpha](d+1)}{(2d+1)(4d+3d\alpha+\alpha)}A.
\end{aligned}$$

Lemma 2.3 shows that emission standards for diesel and gasoline cars compare differently under a consumer-and a producer-orientated regulator. Thus, a consumer-orientated regulator allows higher emissions for diesel cars than for gasoline cars ($\bar{e}_D^0 - \bar{e}_G^0 > 0$). However, under a producer-orientated regulator, the opposite is the case ($\bar{e}_D^1 - \bar{e}_G^1 < 0$). Moreover, we observe that diesel car producers exert less environmental innovation effort than gasoline car producers under both types of regulators ($x_D^0 - x_G^0 < 0$, $x_D^1 - x_G^1 < 0$). Finally, we observe that less diesel cars than gasoline cars are produced in the two cases ($q_D^0 - q_G^0 < 0$, $q_D^1 - q_G^1 < 0$). The next result gives a comparison of the equilibrium outcomes under a producer- and a consumer-orientated regulator.

Proposition 2.2. *Regulatory capture yields to:*

(i) less emissions, less output and more innovation for diesel cars, i.e., $\bar{e}_D^1 < \bar{e}_D^0$, $q_D^1 < q_D^0$ *and* $x_D^1 > x_D^0$;

(ii) less (more) emissions, less (more) output and more (less) innovation for gasoline cars when α *and/or* d *are high (low), i.e.,* $\bar{e}_G^1 \lesseqgtr \bar{e}_G^0$, $q_G^1 \lesseqgtr q_G^0$ *and* $\bar{x}_G^1 \gtreqless \bar{x}_G^0$ *for* $\alpha \gtreqless \bar{\alpha}(d)$, $\partial\bar{\alpha}/\partial d < 0$;

(iii) less emissions and more innovation in total. Total output is larger (smaller) when α *and/or* d *are low (high).*

The intuition behind the results in Proposition 2.2 is as follows. We observe that, as compared to a producer-orientated regulator, a consumer-orientated regulator increases the competition between gasoline and diesel cars. This is achieved by facilitating the production of diesel cars through permitting higher emissions for this type of car. If the standards for gasoline cars are kept constant, the gasoline car producer is forced to reduce prices. Thereby, the gasoline car producer can compensate the loss of market share to the diesel car producer by gaining consumers that otherwise would not buy a car. Consequently, consumers can buy more cars at lower prices and consumer surplus is increased. Naturally, the emission standard for the gasoline car producer also differs between a producer- and a consumer-orientated regulator. We observe that the allowed emission level for the gasoline car producer is also higher under the latter when emission damages are small (i.e., with a low weight in the social welfare function), or when the difference between diesel and gasoline cars in consumer preferences is small. Otherwise, a consumer-orientated regulator requires the gasoline car manufacturer to abate more pollution as compared to a producer-orientated regulator. We call this effect the '*competition intensifying effect*' of environmental regulation.

From Proposition 2.2, we observe that total emissions and quantities are unequivocally higher and total innovation effort is smaller under a consumer-orientated regulator when environmental damages are low and/or the utility of diesel cars is small. By contrast, when d and/or α are high, emissions, quantities, and innovation efforts for gasoline and diesel cars have opposite signs such that the total impact on these variables is not clear a priory. However, the third result in Proposition 2.2 states that, in total, regulatory capture yields to less emissions and more innovation, while with regard to total output the aggregate effect depends on α and d.

While hypothesis H1 is confirmed under multiproduct monopoly (Proposition 2.1), the opposite is the case under duopoly competition (Proposition 2.2). Therefore, we can conclude that under duopoly competition, the '*competition intensifying effect*' dominates the '*production cost effect*'. We obtain that competition intensity is a crucial factor for assessing the impact of regulatory capture on environmental regulation and innovation. Limiting the producer influence on regulatory policies would yield lower emissions under multiproduct monopoly, but higher emissions under duopoly competition.

Proposition 2.2 reveals two important drawbacks of environmental policies focused primarily on maximising consumer surplus. First, this kind of policy inevitably increases total emissions. Second, it disincentivises environmental innovation effort because emission standards and innovation efforts are strategic substitutes, as observed in equations (2.21) and (2.22).

2.4.3 Oligopoly competition

From the preceding analysis, we observe that the degree of market competition is essential to the impact of regulatory capture on environmental emission standards and innovation efforts. Now, we analyse in how far the results are influenced by competition between more than two firms. Let us assume that there are N firms in the market, n of which are multi-product firms producing both car types, while n_D and n_G firms only produce diesel and gasoline cars, respectively. Moreover, we assume that competition between diesel and gasoline car producers is already intense as taste differences regarding the two types of cars become negligible, i.e., $\alpha \to 0$. Consequently, the *competition intensifying effect* is smallest in this situation. In analogy to the baseline model, we assume that the total production of gasoline and diesel cars is determined by the emission standards and the sum of the environmental innovation efforts of all firms, i.e.,

$$q_D = \overline{e}_D + x_D \;\text{ and }\; q_G = \overline{e}_G + x_G, \text{ with } x_D = \sum_i^{n+n_D} x_{D_i},\; x_G = \sum_i^{n+n_G} x_{G_i}.$$

Total emissions are equally distributed over all producers such that the firm's output for each type of car in Stage 1 is given by:

$$q_{D_i} = \frac{1}{n+n_D}\overline{e}_D + x_{D_i} \text{ and } q_{G_i} = \frac{1}{n+n_G}\overline{e}_G + x_{G_i}.$$

In Stage 2, the firms' optimal environmental innovation efforts are the solution of the following maximisation problems:

$$\begin{aligned}
\max_{x_{D_i},x_{G_i}} \pi_i &= \left(\frac{\overline{e}_D}{n+n_D} + x_{D_i}\right)(A-(1+\alpha)(\overline{e}_D+x_D)-\overline{e}_G-x_G) \\
&\quad + \left(\frac{\overline{e}_G}{n+n_G} + x_{G_i}\right)(A-\overline{e}_D-x_D-\overline{e}_G-x_G) - \frac{x_{D_i}^2}{2} - \frac{x_{G_i}^2}{2},\; i=1,\ldots,n, \\
\max_{x_{G_j}} \pi_j &= \left(\frac{\overline{e}_G}{n+n_G} + x_{G_j}\right)(A-\overline{e}_D-x_D-\overline{e}_G-x_G) - \frac{x_{G_j}^2}{2}, \quad j=1,\ldots,n_G, \\
\max_{x_{D_j}} \pi_j &= \left(\frac{\overline{e}_D}{n+n_D} + x_{D_j}\right)(A-(1+\alpha)(\overline{e}_D+x_D)-\overline{e}_G-x_G) - \frac{x_{D_j}^2}{2},\; j=1,\ldots,n_D.
\end{aligned}$$

Summing up the first-order conditions, we obtain the following reaction functions for total environmental innovation efforts:

$$x_D = \frac{(2N-n_G)A}{2N-n_G+4} - \frac{2n+n_G+(N-n_D)(2N-n_G)}{(n+n_G)(2N-n_G+4)}\overline{e}_G - \frac{2N-n_G+2}{2N-n_G+4}(\overline{e}_D+x_G), \quad (2.23)$$

$$x_G = \frac{(2N-n_D)A}{2N-n_D+4} - \frac{2n+n_D+(2N-n_D)(N-n_G)}{(n+n_D)(2N-n_D+4)}\overline{e}_D - \frac{2N-n_D+2}{2N-n_D+4}(\overline{e}_G+x_D), \quad (2.24)$$

that together with the regulator's reaction functions (2.17) and (2.18) determine the Nash equilibrium values for emission standards and total innovation efforts.

Lemma 2.4. *With n multi-product firms, n_D diesel car producers and n_G gasoline car producers, the symmetric Nash equilibrium emission standards are given by:*

$$\overline{e}_D = \overline{e}_G = \frac{[6+(1-\mu)(3N+n-6)](n+n_G)(n+n_D)A}{(2\mu-1)(5n(n_G+n_D)+6n_Gn_D+4n^2)+(n+n_G)(n+n_D)(3N+n+6)d}.$$

The equilibrium innovation efforts are determined by:

$$
\begin{aligned}
x_D &= \frac{2n+3n_D}{3N+n+6}\left(A-\frac{2(N+1)-n_G}{2(n+n_D)}\bar{e}_D-\frac{4n(N+1)+3n_G n_D}{2(n+n_G)(2n+3n_D)}\bar{e}_G\right),\\
x_G &= \frac{2n+3n_G}{3N+n+6}\left(A-\frac{2(N+1)-n_D}{2(n+n_G)}\bar{e}_G-\frac{3n_G n_D+4n(N+1)}{2(n+n_D)(2n+3n_G)}\bar{e}_D\right).
\end{aligned}
$$

The result in Lemma 2.4 makes it possible to assess the impact of market competitiveness on emission standards and innovation efforts in a symmetric equilibrium through changes in the number of firms. We obtain the following result.

Proposition 2.3. *A necessary condition for $e^1 \geq e^0$ is that $N = 1$, i.e., only under monopoly total emissions do not decrease under regulatory capture. Otherwise, for $N > 1$, regulatory capture reduces total emissions and increases environmental innovation, i.e., $\partial \bar{e}_m/\partial \mu < 0$ and $\partial x_m/\partial \mu > 0$ for $N \geq 2$, $m = D, G$.*

The previous analysis shows that, under duopoly competition, a consumer-orientated regulator allows more emissions than a producer-orientated regulator. The reason for this result is that higher emission standards yield more competition in the car market, which benefits consumers, and that the *competition intensifying effect* dominates the *production cost effect* of environmental regulation. We could expect that the competition intensifying effect becomes less important with more competition in the car market such that the duopoly result will not hold in oligopoly. Proposition 2.3 shows that this is not the case. The competition intensifying effect of environmental regulation still dominates the production cost effect such that total emissions will increase and environmental innovation will decrease when the regulator gives less weight to producer surplus, i.e., hypothesis H1 is rejected.

From Lemma 2.4, we also observe that emission standards are monotonically decreasing in μ. Therefore, our results are not limited to the two extreme cases analysed in the preceding subsections and also hold for situations in which regulatory capture means that producer surplus is valued less ($0 < \mu < 1$) or more ($\mu > 1$) than consumer surplus. Hence, the general message of our analysis is that, in a competitive market ($N > 1$), a reduction of the influence that producers exert on environmental regulation, ceteris paribus, yields more emissions and less environmental innovation.

2.5 Extensions

Our previous assumptions capture well the characteristics of European car markets. In this section, we provide two extensions that modify two of our basic assumption in allowing a better fit to some of the aspects of the US (and the recent Chinese) car market. Thus, in the US, the environmental standards for diesel cars and gasoline cars are identical and similar to the ones for gasoline cars in the EU (see Table 2.3). Consequently, it is rather difficult for diesel cars to meet the US standards for NO_x and PM, while they easily fulfil the CO emission standards. This means that diesel cars have a competitive disadvantage in the US, as it is reflected by the observed market shares that diesel cars have reached in the US, as opposed to those obtained in European countries (see Table 2.2).

There are two possible reasons that can explain these differences in setting environmental standards. First, as US car manufactures are mainly producing passenger cars with gasoline engines, regulatory capture in the US might mean that the regulator only values the profits of this industry, i.e., $\mu_G = 1$, while $\mu_D = 0$. Such a policy has been commonly observed in the past and sometimes denominated 'national champions'. Second, as mentioned before, gasoline cars are more harmful than diesel cars with respect to their CO emissions, while the opposite is true with respect to NO_x and PM emissions. Therefore, European standards might reflect the view that health diseases in urban areas and global warming are equally important, while in the US, the former are seen as much more relevant to society. In such a case, environmental damages of diesel cars would be considered to be higher than those of gasoline cars resulting in $d_D > d_G$. This is an alternative justification for the observation that in the US, environmental standards are set in a way that makes them more difficult to fulfil for diesel cars than for gasoline cars.

2.5.1 National Champions

Again, consider a regulator that faces duopoly competition under which diesel cars are produced by one firm (D) and gasoline cars by the other firm (G). However, as opposed to Section 2.4.2, the regulator is only concerned about the profits of one type of car producer. Specifically, she gives weight one to the gasoline car manufacturer ($\mu_G = 1$) and weight zero to the diesel car manufacturer ($\mu_D = 0$). As before, in Stage 1, quantities are completely determined by the firms' innovation efforts and the emission standards chosen by the regulator. In Stage 2, the firms' optimal innovation choices yield the reaction functions in (2.21) and (2.22). Emission standards are obtained by maximising the social welfare function:

$$\begin{aligned}\max_{\bar{e}_D,\,\bar{e}_G} W \quad = \quad & \frac{1+\alpha}{2}(x_D+\bar{e}_D)^2+(x_D+\bar{e}_D)(x_G+\bar{e}_G)+\frac{1}{2}(x_G+\bar{e}_G)^2 \\ & +\mu_G(x_G+\bar{e}_G)(1-x_D-\bar{e}_D-x_G-\bar{e}_G-c)-x_G^2/2-\frac{d}{2}\left(\bar{e}_D^2+\bar{e}_G^2\right). \quad (2.25)\end{aligned}$$

From the solution of this problem, we obtain the following reaction functions for the regulator:

$$\bar{e}_D = \frac{\mu_G(1-\mu_G)}{\widetilde{\Delta}}A + \frac{(\alpha+1)(d-\alpha)+(\alpha+\mu_G)^2}{\widetilde{\Delta}}x_D + \frac{d(1-\mu_G)}{\widetilde{\Delta}}x_G, \tag{2.26}$$

$$\bar{e}_G = \frac{\mu_G(d-\alpha-1)}{\widetilde{\Delta}}A + \frac{d(1-\mu_G)}{\widetilde{\Delta}}x_D + \frac{(d-\alpha-\mu_G)^2-(d-\alpha-1)(d-\alpha)}{\widetilde{\Delta}}x_G, \tag{2.27}$$

where $\widetilde{\Delta} = (d-\alpha-1)(2d-\alpha)-(d-\alpha-\mu_G)^2$.

The following result states the Nash equilibrium values that are determined by the system of equations (2.21), (2.22), (2.26), and (2.27).

Lemma 2.5. *Under duopoly competition with a G-producer-orientated regulator ($\mu_G = 1$), the Nash equilibrium values are:*

$$\begin{aligned}
x_D^G &= \frac{2d^2-2d(1+\alpha)}{(2d-1)(4d+3d\alpha+\alpha)+4d-1}A,\ x_G^G = \frac{2d(d-2)(\alpha+1)+1+\alpha+d\alpha}{(2d-1)(4d+3d\alpha+\alpha)+4d-1}A\\
\bar{e}_D^G &= \frac{2d(1+\alpha)}{(2d-1)(4d+3d\alpha+\alpha)+4d-1}A,\ \bar{e}_G^G = \frac{2(2d-1)(1+\alpha)+2d}{(2d-1)(4d+3d\alpha+\alpha)+4d-1}A,\\
q_D^G &= \frac{2d^2}{(2d-1)(4d+3d\alpha+\alpha)+4d-1}A,\ q_G^G = \frac{2d^2+(2d-1)(1+\alpha+d\alpha)}{(2d-1)(4d+3d\alpha+\alpha)+4d-1}A.
\end{aligned}$$

A comparison of these equilibrium quantities with those obtained for the case where the regulator weights the profits of both firms equally yields the following result.

Lemma 2.6. *As compared to regulatory capture by both car producers, regulatory capture by a gasoline car producer leads to lower emission permits for diesel cars ($\bar{e}_D^G < \bar{e}_D^1$) and more for gasoline cars ($\bar{e}_G^G > \bar{e}_G^1$), to which D-producers respond with more and G-producers with less environmental innovation ($x_D^G > x_D^1$, $x_G^G < x_G^1$). The output of diesel cars is reduced and that of gasoline cars increased ($q_D^G < q_D^1$, $q_G^G > q_G^1$).*

The intuition behind this result is straightforward. Increasing the permitted emissions of the G-producer and reducing those of the D-producer means higher profits for the G-producer as she can increase production without any cost and without varying prices. Both producers respond to this change by adjusting their environmental innovation effort. As the effect of changes in emission standards on quantities dominates the effect of changes in innovation effort, we have less diesel cars and more gasoline cars in the market. The following result shows the consequences for total emissions, quantities and innovation.

Proposition 2.4. *Regulatory capture by a G-producer yields less emissions and more environmental innovation effort. Total output is larger (smaller) when α and/or d are high (small).*

From this result, we observe that the conclusions from Proposition 2.2 do not change when the regulator initially favours only the gasoline car producer such that hypothesis H1, again, is rejected. Under a regulator that becomes consumer-orientated, total emissions will increase and total environmental innovation effort will decline.[14]

2.5.2 Heterogeneous damages

In Section 2.4, we have assumed that gasoline and diesel cars cause the same marginal damage or are considered as equally harmful. Now, we allow for different assessments of the marginal damages of the two types of cars in the welfare function. Specifically, let the environmental damage caused by diesel and gasoline cars be $D_D = d_D e_D^2/2$ and $D_G = e_G^2$, where $d_D > 2(1+\alpha)$ such that diesel cars are considered as more harmful to society.[15] As can be observed from equations (2.19) and (2.20), this will not change the reaction functions in (2.21) and (2.22), while the regulators' reaction functions in (2.17) and (2.18) become:

$$\bar{e}_D = \frac{2\mu}{\Gamma}A + \frac{(1-2\mu)(2(1+\alpha)-\alpha(1-2\mu))}{\Gamma}x_D + \frac{2(1-2\mu)}{\Gamma}x_G, \tag{2.28}$$

$$\bar{e}_G = \frac{\mu(d_D-\alpha(1-2\mu))}{\Gamma}A + \frac{(1-2\mu)d_D}{\Gamma}x_D + \frac{(1-2\mu)(d_D-\alpha(1-2\mu))}{\Gamma}x_G, \tag{2.29}$$

where $\Gamma \equiv 2d_D-(1-2\mu)[d_D+2(1+\alpha)]+\alpha(1-2\mu)^2$. From equations (2.21), (2.22), (2.28) and (2.29), we obtain the following result.

Lemma 2.7. *Under duopoly competition with a consumer-orientated regulator ($\mu = 0$), the Nash equilibrium values are:*

$$\begin{aligned}
x_D^0 &= \frac{3d_D-7\alpha-6}{\Omega^0}A,\ x_G^0 = \frac{(1+2\alpha)d_D-2-\alpha}{\Omega^0}A,\\
\bar{e}_D^0 &= \frac{8(1+\alpha)-\alpha}{\Omega^0}A,\ \bar{e}_G^0 = \frac{2d_D(2+\alpha)-\alpha}{\Omega^0}A,\\
q_D^0 &= \frac{3d_D+2}{\Omega^0}A,\ q_G^0 = \frac{5d_D+4\alpha d_D-2-2\alpha}{\Omega^0}A,
\end{aligned}$$

where $\Omega^0 \equiv 14d_D+10\alpha d_D-4-5\alpha$. With a producer-orientated regulator ($\mu = 1$), the Nash equilibrium values are:

[14] Moreover, total output increases, as from Propositions 2.3 and 2.5 we obtain $q^G - q^1 = \frac{2d^2(3\alpha+2d\alpha+2)}{(2d+1)(4d+\alpha+3d\alpha)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A > 0$.

[15] This is the case for example in most of the low emission zones (LEZ) in European cities that consider NOx and PM emissions as more harmful than CO emissions, with the result that LEZ regulation is more severe with regards to diesel cars than to gasoline cars.

$$
\begin{aligned}
x_D^1 &= \frac{4(d_D-(1+\alpha))}{\Omega^1}A,\ x_G^1=\frac{2(1+\alpha)d_D+\alpha}{\Omega^1}A,\\
\bar{e}_D^1 &= \frac{4(\alpha+2)}{\Omega^1}A,\ \bar{e}_G^1=\frac{2(\alpha+2(1+\alpha)d_D)}{\Omega^1}A,\\
q_D^1 &= \frac{4(d_D+1)}{\Omega^1}A,\ q_G^1=\frac{3(\alpha+2(1+\alpha)d_D)}{\Omega^1}A,
\end{aligned}
$$

where $\Omega^1 \equiv 18d_D + 14\alpha d_D + 4 + 7\alpha$.

The following result compares the equilibrium outcomes under a producer-orientated and a consumer-orientated regulator.

Proposition 2.5. *Regulatory capture yields to:*

(i) less emissions and more environmental effort ($\bar{e}_m^1 < \bar{e}_m^0$ *and* $x_m^1 > x_m^0$, $m = D, G$)*;*

(ii) a lower production of gasoline cars are produced ($q_G^1 < q_G^0$)*;*

(iii) a lower (higher) production of gasoline cars when α *and/or* d *are low (high), i.e.,* $q_D^1 \lesseqgtr q_D^0$ *for* $d_D \lesseqgtr \overline{d}(\alpha)$.

Proposition 2.5 indicates that the '*competition intensifying effect*' of environmental regulation does not depend on the size of the environmental damages of diesel cars. A consumer-orientated regulator always allows more emissions by diesel cars than a producer-orientated regulator in order to increase the competition between the two car types. As a difference to the previous result in Proposition 2.2 where damages of the two car types were the same, we obtain that a consumer-orientated regulator also always sets higher emission standards for gasoline cars. As expected, this yields lower environmental innovation for the two car types. Usually, the impact of changes in emission standards on output dominates the impact of changes in innovation effort, yielding higher output of the two car types under a consumer-orientated regulator. Interestingly, we obtain that this is not the case when damages of diesel cars are (considered) much larger than those of gasoline cars. Then, we obtain that less diesel cars are produced under a consumer-orientated regulator even when emission standards are set higher. Despite these modifications, the main conclusions from Proposition 2.2 remain valid, namely, two important drawbacks of environmental policies focused primarily on maximising consumer surplus are that they cause more total emissions and disincentivise environmental innovation effort.

2.6 Conclusions

The automobile market is characterised by both substantial regulation of vehicle emissions and high investments in environmental innovation. Moreover, car producers in the US and the European markets have exerted considerable influence on environmental regulation, which was evidenced in the 2015 Volkswagen emissions scandal. In this chapter, we study the consequences of regulatory capture for the choice of emission standards and environmental innovation efforts in the gasoline and diesel car markets. Our results indicate that regulatory capture leads to less total environmental emissions and more innovation effort under oligopoly competition, while the opposite is true under multi-product monopoly. This difference in results stems from a *competition intensifying effect*. To enhance competition among car producers, a consumer-orientated regulator sets higher emission standards for diesel cars from which consumers benefit through lower prices and more automobiles.

An important lesson from our analysis for environmental policy is that the consequences of regulatory capture for emissions and innovation depend essentially on the degree of competition in the car market. On the basis that car producers compete, the common belief that reducing the influence of car manufactures on environmental regulation will lower emissions and spur environmental innovation is wrong, at least, when it is not accompanied by stronger concerns about environmental damages or the welfare of future generations. This indicates that under the assumption that reducing emissions is a general goal, the essential conflict is not between producers and future generations, but between present and future welfare.

Although we have focused throughout this chapter on diesel and gasoline automobiles, the results of our analysis can be applied straightforwardly to environmental regulation policies related to electric vehicles. Similar to diesel cars, the acquisition costs of electric cars are generally higher than those of their equivalents with a gasoline engine, while the operation costs are lower. Assuming that a policy objective is to favour the introduction of electric cars in order to reduce CO emissions, our results indicate that a consumer-orientated regulatory policy will not help to achieve this objective. Instead, meeting this goal requires a welfare shifting from present to future generations.

2.7 Appendix

Proof of Proposition 2.1

From a comparison of the equilibrium values, we obtain:

$$
\begin{aligned}
x_D^{M,0} - x_D^{M,1} &= \frac{d^2-(3\alpha+2)d+\alpha}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A - \frac{d^2-(3\alpha+2)d-\alpha}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A > 0, \\
x_G^{M,0} - x_G^{M,1} &= \frac{(2\alpha+1)d^2-(3\alpha+2)d+\alpha}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A - \frac{(2\alpha+1)d^2-(\alpha+2)d-\alpha}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A \\
&= 2\frac{\alpha^2(d-1)(2d+1)(2d-1)+d^2\alpha(4d-9)+2d^2(d-2)}{((6\alpha+5)d^2-(5\alpha+2)d+\alpha)((6\alpha+5)d^2+(5\alpha+2)d+\alpha)}A > 0, \\
e_D^{M,0} - e_D^{M,1} &= \frac{(3\alpha+2)d-\alpha}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A - \frac{3(\alpha+1)d+\alpha}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A \\
&= \frac{-(6\alpha+5)(d-3\alpha-2)d^2-d\alpha-2\alpha^2}{((6\alpha+5)d^2-(5\alpha+2)d+\alpha)((6\alpha+5)d^2+(5\alpha+2)d+\alpha)}A < 0, \\
e_G^{M,0} - e_G^{M,1} &= \frac{2(\alpha+1)d-\alpha}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A - \frac{(3+4\alpha)d+2\alpha}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A \\
&= \frac{-3\alpha^2(d-1)(2d+1)(2d-1)-d\alpha\left(16d^2-22d-1\right)-5d^2(d-2)}{((6\alpha+5)d^2-(5\alpha+2)d+\alpha)((6\alpha+5)d^2+(5\alpha+2)d+\alpha)}A < 0, \\
q_D^{M,0} - q_D^{M,1} &= \frac{d^2}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A - \frac{(d+1)d}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A \\
&= \frac{\left((4\alpha-1)d^2+(5\alpha+2)d-\alpha\right)d}{((6\alpha+5)d^2-(5\alpha+2)d+\alpha)((6\alpha+5)d^2+(5\alpha+2)d+\alpha)}A \\
&\quad \begin{cases} <0 & \text{for} \quad \alpha < \frac{(d-2)d}{4d^2+5d-1} \\ >0 & \text{for} \quad \alpha > \frac{(d-2)d}{4d^2+5d-1} \end{cases}, \\
q_G^{M,0} - q_G^{M,1} &= \frac{((2\alpha+1)d-\alpha)d}{(6\alpha+5)d^2-(5\alpha+2)d+\alpha}A - \frac{((2\alpha+1)d+\alpha)(d+1)}{(6\alpha+5)d^2+(5\alpha+2)d+\alpha}A \\
&= \frac{-\alpha^2(d-1)(2d+1)(2d-1)-d\alpha(4d(2d-1)-1)-d^2(d-2)}{((6\alpha+5)d^2-(5\alpha+2)d+\alpha)((6\alpha+5)d^2+(5\alpha+2)d+\alpha)}A < 0.
\end{aligned}
$$

Proof of Proposition 2.2

The first statement in *(i)* follows as for the numerators of $\bar{e}_D^0$ and $\bar{e}_D^1$, we have:

$$(4d+4d\alpha-\alpha)-2d(\alpha+2)=\alpha(2d-1)>0,$$

and for the denominators, we have:

$$(2d-1)(4d+3d\alpha-\alpha)-(2d+1)(4d+3d\alpha+\alpha)<0.$$

The second statement in *(i)* follows from

$$q_D^0-q_D^1=2d\frac{4d+\left(5d+4d^2-1\right)\alpha}{(4d^2-1)(4d-\alpha+3d\alpha)(4d+\alpha+3d\alpha)}A>0.$$

Finally, the last statement in *(i)* follows from rewriting

$$x_D^0-x_D^1=-\frac{\alpha\left(4d^2-1\right)(2d+\alpha+3d\alpha)+2d^2(2\alpha+3)(5\alpha+4)}{(4d^2-1)(4d-\alpha+3d\alpha)(4d+\alpha+3d\alpha)}A<0.$$

To prove statement *(ii),* notice that

$$\overline{e}_G^0-\overline{e}_G^1=\frac{32d^2-4d\left(-10d+4d^2-1\right)\alpha-3(d-1)\left(4d^2-1\right)\alpha^2}{(4d^2-1)(4d-\alpha+3d\alpha)(4d+\alpha+3d\alpha)}A.$$

It follows that

$$\overline{e}_G^0\begin{cases}<\overline{e}_G^1 & \text{if} \quad \alpha>\overline{\alpha}_e(d)\\ >\overline{e}_G^1 & \text{if} \quad \alpha<\overline{\alpha}_e(d)\end{cases},$$

where

$$\begin{aligned}\overline{\alpha}_e(d) &\equiv \frac{2d}{3(d-1)(4d^2-1)}\left(10d-4d^2+1+\sqrt{25+4d(4d^2-1)(d+1)}\right) \text{ with}\\ \partial\overline{\alpha}_e/\partial d &= -\frac{\overline{\alpha}_e}{d}\frac{3\left[2(d-1)+4d^2-1\right]\overline{\alpha}_e^2+8d(5d+1)\overline{\alpha}_e+32d^2}{3(d-1)(4d^2-1)\overline{\alpha}_e^2+32d^2}<0.\end{aligned}$$

Similarly, we have:

$$q_G^0-q_G^1=\frac{8d^2-2d\left(4d^2-1-5d\right)\alpha-(d-1)\left(4d^2-1\right)\alpha^2}{(4d^2-1)(4d-\alpha+3d\alpha)(4d+\alpha+3d\alpha)}A,$$

such that

$$q_G^0\begin{cases}<q_G^1 & \text{if} \quad \alpha>\overline{\alpha}_q(d)\\ >q_G^1 & \text{if} \quad \alpha<\overline{\alpha}_q(d)\end{cases},$$

where

$$\begin{aligned}\overline{\alpha}_q(d) &\equiv \frac{d}{(d-1)(4d^2-1)}\left(5d-4d^2+1+\sqrt{9+2d-15d^2-8d^3+16d^4}\right) \text{ with}\\ \partial\overline{\alpha}_q/\partial d &= -\frac{\overline{\alpha}_q^2}{d}\frac{2\left(d-\overline{\alpha}_q\right)+\left(d+4d^3\right)\overline{\alpha}_q+8d^3}{(d-1)(4d^2-1)\overline{\alpha}_q^2+8d^2}<0.\end{aligned}$$

Finally, we have:

$$x_G^0 - x_G^1 = -2\frac{12d^2 - d\left(4d^2 - 15d - 1\right)\alpha - (d-1)\left(4d^2 - 1\right)\alpha^2}{(4d^2-1)(4d-\alpha+3d\alpha)(4d+\alpha+3d\alpha)}A.$$

It follows that

$$\overline{x}_G^0 \begin{cases} > \overline{x}_G^1 & \text{if} \quad \alpha > \overline{\alpha}_x(d) \\ < \overline{x}_G^1 & \text{if} \quad \alpha < \overline{\alpha}_x(d) \end{cases},$$

where

$$\begin{aligned} \overline{\alpha}_x(d) &\equiv \frac{d}{2(d-1)(4d^2-1)}\left(15d - 4d^2 + 1 + \sqrt{49 - 18d + 25d^2 + 72d^3 + 16d^4}\right) \text{ with} \\ \partial\overline{\alpha}_x/\partial d &= -\frac{\overline{\alpha}_x}{d}\frac{\left(2(d-1) + 4d^2 - 1\right)\overline{\alpha}_x^2 + \left(2d + 15d^2\right)\overline{\alpha}_x + 12d^2}{(d-1)(4d^2-1)\overline{\alpha}_x^2 + 12d^2} < 0. \end{aligned}$$

The first statement in *(iii)* follows directly from

$$\left(\overline{e}_D^0 + \overline{e}_G^0\right) - \left(\overline{e}_D^1 + \overline{e}_G^1\right) = \frac{4A}{(4d^2-1)} > 0.$$

To prove the second statement in *(iii)*, notice that

$$\left(x_D^0 + x_G^0\right) - \left(x_D^1 + x_G^1\right) = -\frac{\left[32d^2 + (d-1)\left(4d + 4d^2 + 3\right)\right]\alpha^2 + 76d^2\alpha + 48d^2}{(4d^2-1)(4d-\alpha+3d\alpha)(4d+\alpha+3d\alpha)}A < 0.$$

Finally, regarding total output, we have:

$$\left(q_D^0 + q_G^0\right) - \left(q_D^1 + q_G^1\right) = A\frac{-\alpha^2(d-1)\left(4d^2-1\right) + 20d^2\alpha + 16d^2}{(4d^2-1)(4d-\alpha+3d\alpha)(4d+\alpha+3d\alpha)},$$

such that

$$q_D^0 + q_G^0 \begin{cases} < q_D^1 + q_G^1 & \text{if} \quad \alpha > \widetilde{\alpha}_q(d) \\ > q_D^1 + q_G^1 & \text{if} \quad \alpha < \widetilde{\alpha}_q(d) \end{cases},$$

where

$$\begin{aligned} \widetilde{\alpha}_q(d) &\equiv \frac{2d}{(d-1)(4d^2-1)}\left(5d + \sqrt{4 - 4d + 9d^2 + 16d^3}\right) \text{ with} \\ \partial\widetilde{\alpha}_q/\partial d &= -\frac{\left(2(d-1) + 4d^2 - 1\right)\widetilde{\alpha}_q^2 + 20d^2\widetilde{\alpha}_q + 16d^2}{4\left(5\widetilde{\alpha}_q + 8\right)d^3}\widetilde{\alpha}_q < 0. \end{aligned}$$

Proof of Proposition 2.3

To prove the first statement from Lemma 2.4, by setting $\mu = 0$ and $\mu = 1$, respectively, we obtain:

$$e_D^1 - e_D^0 = \frac{6(N-n_G)(N-n_D)}{d(N-n_D)(N-n_G)(4N-n_G-n_D+6)+5nn_G+5nn_D+6n_Gn_D+4n^2} - \frac{(4n+3n_G+3n_D)(N-n_G)(N-n_D)}{d(N-n_D)(N-n_G)(4N-n_G-n_D+6)-(5nn_G+5nn_D+6n_Gn_D+4n^2)} \tag{2.30}$$

It follows that $e_D^1 - e_D^0 > 0$ if

$$-(N-n_D)(N-n_G)(4N-n_G-n_D-6)d > 5nn_G+5nn_D+6n_Gn_D+4n^2. \tag{2.31}$$

While the right-hand-side is always positive, the left-hand-side of this expression is only positive if $4N-n_G-n_D-6>0$. Therefore, a necessary condition for $e_D^1 > e_D^0$ is that $3N+n<6$, which holds for $N=1$. The condition is sufficient as for $N=n=1$, we obtain that the condition in (2.31) becomes $d>2$, which holds by assumption. For $N=n_D=1$ or $N=n_G=1$, from (2.30), we have $e_D^1 = e_D^0$.

To prove the second statement differentiating the expressions in Lemma 2.4 w.r.t. μ yields:

$$\begin{aligned}
\frac{\partial \bar{e}_D}{\partial \mu} = \frac{\partial \bar{e}_G}{\partial \mu} = & -\frac{5nn_G+5nn_D+6n_Gn_D+4n^2+(n+n_D)(n+n_G)(3N+n-6)d}{[(2\mu-1)(5n(n_G+n_D)+6n_Gn_D+4n^2)+(n+n_G)(n+n_D)(3N+n+6)d]^2} \\
& \times (n+n_D)(n+n_G)(4n+3n_G+3n_D+6)A < 0 \text{ for } N \geq 2. \\
sign\left(\frac{\partial x_m}{\partial \mu}\right) = & -sign\left(\frac{\partial \bar{e}_m}{\partial \mu}\right), \; m = D, G.
\end{aligned}$$

Proof of Lemma 2.6

From Lemmas 2.3 and 2.5, we obtain:

$$\begin{aligned}
\bar{e}_D^G - \bar{e}_D^1 &= \frac{-2d\left[d(3\alpha+4)(2d-2\alpha-1)-2(\alpha+1)^2\right]}{(2d+1)(4d+\alpha+3d\alpha)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A<0,\\
\bar{e}_G^G - \bar{e}_G^1 &= \frac{2d\left[d(2d+1)(3\alpha+4)-2(\alpha+1)\right]}{(2d+1)(4d+\alpha+3d\alpha)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A>0,\\
q_D^G - q_D^1 &= \frac{-2d\left[(4d+1)(d-\alpha-1)+d(\alpha+2)\right]}{(2d+1)(4d+\alpha+3d\alpha)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A<0,\\
q_G^G - q_G^1 &= \frac{2d\left[2d^2(\alpha+2)+d-\alpha-1\right]}{(2d+1)(4d+\alpha+3d\alpha)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A>0,\\
x_D^G - x_D^1 &= \frac{2d(2d(3\alpha+2)+2\alpha+1)(d-\alpha-1)}{(2d+1)(4d+\alpha+3d\alpha)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A>0,\\
x_G^G - x_G^1 &= \frac{-2d(d+1)(4d-1)(\alpha+1)}{(2d+1)(4d+\alpha+3d\alpha)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A<0.
\end{aligned}$$

Proof of Proposition 2.4

Summing the corresponding expressions from Lemmas 2.3 and 2.5, we obtain:

$$\begin{aligned}
\bar{e}^0 - \bar{e}^G &= \frac{4\left[d(2\alpha+3)-\alpha-1\right]}{(2d-1)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A>0,\\
q^0 - q^G &= \frac{4d(3d-1)-\alpha(2d-1)\left(-8d+2d^2+1\right)-\alpha^2(d-1)(2d-1)^2}{(2d-1)(4d+3d\alpha-\alpha)((2d-1)(4d+3d\alpha+\alpha)+4d-1)}A\\
&\quad \begin{cases} <0 & \text{if} \quad \alpha>\widehat{\alpha}_q(d) \\ >0 & \text{if} \quad \alpha<\widehat{\alpha}_q(d) \end{cases},\\
x^0 - x^G &= -A\frac{\alpha(\alpha+1)\left(4d^3+3\right)+d\alpha^2(16d-15)+10d\alpha(5d-3)+12d(3d-1)}{(2d-1)((2d-1)(4d+3d\alpha+\alpha)+4d-1)(4d-\alpha+3d\alpha)}<0,
\end{aligned}$$

where

$$\begin{aligned}
\widehat{\alpha}_q &\equiv \frac{1}{2(2d-1)(d-1)}\left(8d-2d^2-1+\sqrt{4d^2+16d^3+4d^4+1}\right) \text{ with}\\
\partial\widehat{\alpha}_q/\partial d &= -\widehat{\alpha}_q\left(\widehat{\alpha}_q+1\right)\frac{\widehat{\alpha}_q^2(2d-1)(4d-3)+\widehat{\alpha}_q\left(18d^2-20d+3\right)+4d(3d-2)}{d^2\left(4\left(2\widehat{\alpha}_q+1\right)(3d-1)+5\widehat{\alpha}_q^2(2d-1)\right)}<0.
\end{aligned}$$

Proof of Proposition 2.5

From a comparison of the equilibrium values in Proposition 2.7, we obtain:

$$
\begin{aligned}
\bar{e}_D^0-\bar{e}_D^1 &= \frac{7\alpha+8}{\Omega^0}A-\frac{4\alpha+8}{\Omega^1}A>0 \text{ as } \Omega^0-\Omega^1<0\,,\\
\bar{e}_G^0-\bar{e}_G^1 &= \frac{4\alpha+3\alpha^2+2(13\alpha+16)d_D+4(3\alpha+4)(1-\alpha)d_D^2}{\Omega^0\Omega^1}A>0,\\
x_D^0-x_D^1 &= \frac{-(23\alpha+20)(3\alpha+2)-\left(73\alpha+58\alpha^2+24\right)d_D-2(1-\alpha)d_D^2}{\Omega^0\Omega^1}A<0,\\
x_G^0-x_G^1 &= \frac{-2\left(7\alpha+\alpha^2+4\right)-3(9\alpha+8)d_D-2(4\alpha+5)(1-\alpha)d_D^2}{\Omega^0\Omega^1}A<0,\\
q_D^0-q_D^1 &= \frac{34\alpha+24+(8+29\alpha)d_D-2(1-\alpha)d_D^2}{\Omega^0\Omega^1}A\begin{cases}>0 & \text{if } d_D<\bar{d}(\alpha)\\ <0 & \text{if } d_D>\bar{d}(\alpha)\end{cases},\\
q_G^0-q_G^1 &= \frac{16-13\alpha+\alpha^2+(8-\alpha)(d_D-3)+2(2\alpha+3)(1-\alpha)d_D^2}{\Omega^0\Omega^1}A>0,
\end{aligned}
$$

where $\bar{d}(\alpha)\equiv-\frac{29\alpha+8}{4\alpha-4}+\frac{\sqrt{256+544\alpha+569\alpha^2}}{4\alpha-4}$.

Sufficiency of second-order conditions

From equations (2.19) and (2.20), we obtain the first-order conditions of the firms' maximisation problems:

$$
\begin{aligned}
\frac{\partial\pi_D}{\partial x_D} &= (1+\alpha)(1-2x_D-2\bar{e}_D)-x_G-\bar{e}_G-kc-x_D=0,\\
\frac{\partial\pi_G}{\partial x_G} &= 1-x_D-\bar{e}_D-2x_G-2\bar{e}_G-c-x_G=0.
\end{aligned}
$$

The second-order conditions are sufficient for a maximum as

$$\frac{\partial^2\pi_D}{\partial x_D^2}=-3-2\alpha<0 \text{ and } \frac{\partial^2\pi_G}{\partial x_G^2}=-3<0, \text{ respectively.}$$

The regulator's problem in (2.13) is:

$$
\begin{aligned}
\max_{\bar{e}_D,\bar{e}_G} W &= \frac{1+\alpha}{2}(x_D+\bar{e}_D)^2+(x_G+\bar{e}_G)(x_D+\bar{e}_D)+\frac{1}{2}(x_G+\bar{e}_G)^2\\
&\quad+\mu(x_D+\bar{e}_D)((1+\alpha)(1-x_D-\bar{e}_D)-x_G-\bar{e}_G-kc)-x_D^2/2\\
&\quad+\mu(x_G+\bar{e}_G)(1-x_D-\bar{e}_D-x_G-\bar{e}_G-c)-x_G^2/2\\
&\quad-d_D\bar{e}_D^2/2-d_G\bar{e}_G^2/2.
\end{aligned}
$$

The first-order conditions are:

$$\begin{aligned}\frac{\partial W}{\partial \bar{e}_D} &= \mu A + (1-2\mu)(1+\alpha)(x_D+\bar{e}_D) + (1-2\mu)(x_G+\bar{e}_G) - d_D\bar{e}_D = 0,\\ \frac{\partial W}{\partial \bar{e}_G} &= \mu A + (1-2\mu)(x_D+\bar{e}_D) + (1-2\mu)(x_G+\bar{e}_G) - d_G\bar{e}_G = 0.\end{aligned}$$

The second-order conditions are sufficient for a maximum as

$$\begin{aligned}\frac{\partial^2 W}{\partial \bar{e}_D^2} &= (1-2\mu)(1+\alpha) - d_D < 0,\\ \frac{\partial^2 W}{\partial \bar{e}_G^2} &= (1-2\mu)(1+\alpha) - d_G < 0,\\ \frac{\partial^2 W}{\partial \bar{e}_D^2}\frac{\partial^2 W}{\partial \bar{e}_G^2} - \left(\frac{\partial^2 W}{\partial \bar{e}_D \partial \bar{e}_G}\right)^2 &= (d_D-(1-2\mu)(1+\alpha))(d_G-(1-2\mu)(1+\alpha)) - (1-2\mu)^2\\ &> [2(1+\alpha)-(1-2\mu)(1+\alpha)]^2 - (1-2\mu)^2\\ &= (\alpha+2\alpha\mu+2)(\alpha+4\mu+2\alpha\mu)\\ &> 0,\end{aligned}$$

for $d_m > 2(1+\alpha)$.

Chapter 3

Taxes versus emission standards: Welfare consequences and innovation incentives of electric vehicle adoption policies

Overview. We compare which of the two policy instruments —emission standard and acquisition tax— induces a larger adoption of electric vehicles, higher innovation effort, and social welfare. A Cournot oligopoly model with multi-product firms that vertically differentiate their products is used to derive the equilibrium results. Emission standards offer greater innovation incentives, total output, firms' profits, and social welfare as compared to acquisition taxes. Acquisition taxes allow for a major adoption of electric vehicles than emission standards. However, as long as environmental damages are not too large and when the tax revenues are redistributed, consumers prefer an acquisition tax. Otherwise, they are better off under an emission standard.

JEL classification: O38; Q55; Q58; L51.

Keywords: Environmental regulation, Emission standards, Acquisition tax, Innovation, Electric vehicles, Fuel-powered vehicles.

3.1 Introduction

The transition from fuel-powered to electric vehicles has become a major policy concern in most developed countries. As a consequence, there is a growing interest in the analysis of the different environmental policies that can facilitate the adoption of the electric vehicles. Despite the vast theoretical literature that has evolved comparing various environmental policy instruments, its results cannot directly be applied to the automobile market. This is for several reasons. First, many studies have focused on the incentives to innovation of different environmental policies, and not on their welfare implications, which are core in the automobile market. Second, standard models are based on markets with homogeneous goods, and often assume monopoly or duopoly competition, while automobile markets are characterised by demand for vertically differentiated products and oligopoly competition among multi-product firms. Consequently, the focus of this chapter is to compare the market performance and welfare implications of the most commonly applied environmental policies aimed to spur the adoption of electric vehicles.

The two most important environmental policies in the automobile market are emission standards and financial incentives to the purchase of electric vehicles. Emission standards in the automobile industry take the form of performance standards that limit the amount of emissions per vehicle. These standards have become more and more stringent over the last decades in order to meet the emission levels assigned to individual countries in the corresponding climate summits (e.g., Kyoto 1997; Copenhagen 2003; Paris 2016; Madrid 2019). As observed in Table 3.1, performance standards vary not only among countries, but also states inside the US. Interestingly, the most severe standards are nowadays applied in China in all of the three most relevant emission indicators: carbon monoxides (CO), nitrogen oxides (NOx), and particulate matter (PM). With regards to the stringency of CO and NOx emission standards, China is followed by California and New York, and in what concerns PM emissions, by the European Union and countries that impose the Euro 6 emission standard levels (e.g., Norway). The stringency of emission standards can explain part of the observed variation in the market share of electric vehicles as, for example, between California and Mississippi, West Virginia, or Louisiana. However, it does not explain the differences observed in the market share of electric vehicles between Norway and other countries that apply Euro 6 emission standard levels (e.g., Germany, France or the UK).

Financial incentives take the form either of subsidies or, most commonly, tax rebates in the acquisition of electric vehicles. Table 3.2 displays the financial incentives for the purchase of electric vehicles considering the manufacturer's suggested retail price (MSRP) and the final retail price in 2018, for two comparable models of the Volkswagen Golf (110 TSI Comfortline gasoline and SEL Premium 134-hp Automatic e-Golf). Financial incentives are measured as the difference in the final retail price of both vehicle models as compared to the existing price difference in the MSRP of the two models. As observed in Table 3.2, these financial incentives also vary substantially among countries, being Norway the country

Table 3.1: Emission standards and market shares.

		Emission Standards			Market share of EV	
Type of Emissions	Countries	CO	NOx	PM	2017	2018
LEV III (2015-2025)	California	0.6	0.01	0.006	5.02%	7.84%
	New York	0.6	0.01	0.006	1.03%	1.56%
Tier 3 (2017-2025)	Mississippi	2.1	0.04	-	0.15%	0.22%
	West Virginia	2.1	0.04	-	0.15%	0.27%
	Louisiana	2.1	0.04	-	0.15%	0.28%
Euro 6 (2014)	The Netherlands	1	0.06	0.005	1.80%	5.40%
	Norway	1	0.06	0.005	20.08%	49.10%
	Germany	1	0.06	0.005	0.70%	1.10%
	Austria	1	0.06	0.005	1.50%	2.00%
	UK	1	0.06	0.005	0.50%	0.60%
	France	1	0.06	0.005	1.20%	1.40%
	Spain	1	0.06	0.005	0.30%	0.50%
	Italy	1	0.06	0.005	0.10%	0.30%
China 6b (2020)	China	0.5	0.035	0.003	1.80%	3.89%

Emission standards for gasoline passenger vehicles (g/km) and market share of electric vehicles (EV). Recent applied emission standards for gasoline passenger vehicles and market share of electric vehicles in EU, Norway, USA, and China. Specifically in the US, these emissions are for passenger vehicles at 50,000 miles/5 years. The US legislation on air quality and vehicle emissions is a combination of federal law, and stricter Californian standards (known as LEV), which are voluntarily applied by other States. **Sources**: Market share of electric vehicles ICCT (2020) (for EU), and IEA (2018) (for USA, China and Norway). Emission standards DGIP (2016) (for EU and USA), and TransportPolicy.net (2018) (for China).

providing the highest incentives for the purchase of electric vehicles (122.10%), which converts the 11,175$-price disadvantage of the electric vehicle into a 2,434$-price advantage. High financial incentives are also provided by the states of California (73.71%) and New York (66.31%), and China (52.99%) such that the importance of financial incentives correlates positively with the market share of electric vehicles.[1]

In this chapter, we compare the two most prominently applied environmental policies in the automobile market aimed to abate the emissions caused by vehicles with combustion engines. Specifically, we compare an emission standard (a command-and-control instrument) and an acquisition tax (a market-based instrument) with regards to their innovation incentives, market performance, and welfare implications. The analysis is based on an oligopoly model, in which multi-product firms that produce fuel-powered and electric vehicles compete á la Cournot. Firms can abate the emissions of fuel-powered vehicles by means of investment

[1] In fact, based on the data in Tables 3.1 and 3.2, a basic regression model of the form $y = \alpha + \beta_1 FI + \beta_2 FCD + \beta_3 ES + \varepsilon$, reveals that financial incentives (FI) have the highest explanatory content for the market share of electric vehicles (y) as compared to emission standards (ES) and fuel cost differences (FCD).

Table 3.2: Financial incentives for the acquisition of electric vehicles.

	California		New York		Mississippi		West Virginia		Louisiana		The Netherlands		Norway	
Volkswagen	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf
MSRP ($)	24,755	37,345	24,755	37,345	24,755	37,345	24,755	37,345	24,755	37,345	26,128	37,303	26,128	37,303
CO2/Ownership tax ($)	-	-	-	-	-	-	-	-	-	-	41	-	4,909	-
Registration tax ($)	296	296	86	86	39	39	40	40	138	138	-	-	-	-
NOx tax ($)	-	-	-	-	-	-	-	-	-	-	-	-	232	-
Weight/Motor tax	-	-	-	-	-	-	-	-	-	-	-	-	1,936	-
Scrapping fee ($)	-	-	-	-	-	-	-	-	-	-	-	-	281	281
VAT/Sales tax (%)	10.25%	10.25%	8.88%	8.88%	8%	8%	7%	7%	11.45%	11.45%	21%	0%	25%	0%
Clean Fuel Rebate ($)	-	800	-	-	-	-	-	-	-	-	-	-	-	-
Subsidy/Federal tax credit ($)	-	7,500	-	7,500	-	7,500	-	7,500	-	7,500	-	-	-	-
Clean Vehicle Rebate ($)	-	2,200	-	2,200	-	-	-	-	-	-	-	-	-	-
Retail price after incentives ($)	27,588	30,872	27,039	31,247	26,774	32,871	26,527	32,499	27,727	34,259	31,655	37,303	40,018	37,584
Financial Incentives (%)	**-**	**73.71%**	**-**	**66.31%**	**-**	**51.18%**	**-**	**54.16%**	**-**	**48.12%**	**-**	**49.4%**	**-**	**122.10%**
Price of Gasoline 2018 ($/liter)	1.04	-	0.79	-	0.71	-	0.71	-	0.71	-	1.84	-	1.88	-
Price of Energy 2018 ($/kWh)	-	0.188	-	0.185	-	0.111	-	0.112	-	0.096	-	0.20	-	0.23
Liters of Gasoline (l/100km)	8.2	-	8.2	-	8.2	-	8.2	-	8.2	-	8.2	-	8.2	-
Electric energy (kWh/100km)	-	12.7	-	12.7	-	12.7	-	12.7	-	12.7	-	12.7	-	12.7
Cost of Gasoline car ($/100 km)	8.53	-	6.48	-	5.82	-	5.82	-	5.82	-	15.09	-	15.42	-
Cost of Electric car ($/100 km)	-	2.39	-	2.35	-	1.41	-	1.41	-	1.22	-	2.54	-	2.92
Fuel Cost Difference ($)	6.14		4.13		4.41		4.4		4.6		12.55		12.5	

	Germany		Austria		UK		France		Spain		Italy		China	
Volkswagen	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf
MSRP ($)	26,128	37,303	26,128	37,303	26,128	37,303	26,128	37,303	26,128	37,303	26,128	37,303	25,319	36,700
CO2/Ownership tax ($)	345	-	81.30	-	-	-	-	-	-	-	-	-	-	-
Registration tax ($)	-	-	215	-	-	-	-	-	-	-	-	-	-	-
NOx tax ($)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Weight/Motor tax	44.80	-	1,015	-	-	-	-	-	-	-	-	-	-	-
Scrapping fee ($)	-	-	-	-	-	-	-	-	-	-	-	2,200	-	-
VAT/Sales tax (%)	19%	19%	20%	20%	20%	20%	20%	20%	21%	21%	22%	22%	10%	0%
Clean Fuel Rebate ($)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Subsidy/Federal tax credit ($)	-	6,600	-	3,387	-	5,699	-	6,600	-	7,339	-	4,500	-	3,500
Clean Vehicle Rebate ($)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Retail price after incentives ($)	31,482	37,790	32,664	41,376	31,353	39,064	31,353	38,163	31,614	37,797	31,876	38,809	27,850	33,200
Financial Incentives (%)	**-**	**43.55%**	**-**	**22.04%**	**-**	**33.33%**	**-**	**39.06%**	**-**	**44.67%**	**-**	**37.96%**	**-**	**52.99%**
Price of Gasoline 2018 ($/litre)	1.76	-	1.51	-	1.65	-	1.71	-	1.45	-	1.89	-	0.92	-
Price of Energy 2018 ($/kWh)	-	0.35	-	0.24	-	0.24	-	0.21	-	0.29	-	0.25	-	0.075
Litres of Gasoline (l/100km)	8.2	-	8.2	-	8.2	-	8.2	-	8.2	-	8.2	-	8.2	-
Electric energy (kWh/100km)	-	12.7	-	12.7	-	12.7	-	12.7	-	12.7	-	12.7	-	12.7
Cost of Gasoline car ($/100 km)	14.43	-	12.38	-	13.53	-	14.02	-	11.89	-	15.50	-	7.54	-
Cost of Electric car ($/100 km)	-	4.45	-	3.05	-	3.05	-	2.67	-	3.68	-	3.18	-	0.95
Fuel Cost Difference ($)	9.98		9.33		10.48		11.35		8.21		12.32		6.59	

The models compared are Volkswagen Golf 110 TSI Comfortline and Volkswagen e-Golf SEL Premium 134-hp Automatic. MSRP is the manufacturer's suggested retail price. Prices refer to 2018 standardised average prices in US dollars. **Sources**: MSRP from Official (2018); financial incentives from ACEA (2020) (for EU), EVAdoption (2020) (for USA), and ICCT (2019) (for China); prices of gasoline from TE (2020) (for EU), EIA (2020) (for USA), and TE (2020) (for China); prices of energy from Eurostat (2021) (for EU), EIA (2020) (for USA), CEICdata (2020) (for China).

in emission-reducing innovation. In a two-stage game, in the first stage, the regulator chooses the environmental instrument in such a way that the first-best level of emissions is achieved. In the second stage, firms make their quantity and innovation choices.

From the analysis, three major findings are obtained. First, regarding firms' equilibrium decisions, we find that an acquisition tax allows a major adoption of electric vehicles than an emission standard. By contrast, under an emission standard, firms produce more fuel-powered vehicles and exert a higher innovation effort. The intuition behind this result is that an acquisition tax changes the relative prices of electric and fuel-powered vehicles, making the latter more expensive, and eliminates any innovation stimulus. Instead, an emission standard does not alter the relative prices and maintains innovation incentives. Overall, we find that the total vehicle production is larger under an emission standard than under an acquisition tax. Second, consumers are always better off under an emission standard than under an acquisition tax, when tax revenues are not redistributed. This finding is explained by the fact that consumers can purchase more vehicles in total under an emission standard more than compensates the lower quantity of (the higher valued) electric vehicles. Instead, when tax revenues are redistributed, an acquisition tax is preferred by consumers as long as environmental damages are not too large. Third, firms' profits and social welfare are higher under an emission standard than under an acquisition tax. The intuition behind this result is that the lower innovation incentive and the price distortion effect of an acquisition tax turn it to the welfare-inferior instrument as compared to an emission standard.

The remainder of this chapter is organised as follows. Section 3.2 reviews the literature. Section 3.3 sets up the theoretical model. Section 3.4 provides the equilibrium results of the different two-stage games under analysis. Section 3.5 compares the market outcomes and welfare implications of an acquisition tax with an emission standard. Section 3.6 provides conclusions. All proofs are in the Appendix.

3.2 Literature Review

This study builds on and contributes to the previous literature on environmental policy, which focuses on the types of policy instruments, with specific topics including pollution abatement and control, market structure, innovation, and clean products such as electric automobiles (Buchanan, 1969; Lee, 1975; David and Sinclair-Desgagné, 2010; Ouchida and Goto, 2014; Shao et al., 2017; Yu et al., 2018; Bian et al., 2020). In what follows, we review the literature closely related to our study, with research gaps and other details summarised in Table 3.3 below.

First, we begin by briefly reviewing the extensive research done for environmental policies that study different types of instruments: command and control (CAC) and market-based instruments (MBIs). The pioneering work of Buchanan (1969) reveals that applying a pollution tax in a monopoly can reduce social welfare, with pollution being reduced below the desirable level. Lee (1975) discusses Buchanan (1969)'s lack of attention given to the market structure and fills it by analysing the performance of a pollution tax under an oligopoly market. His results show that market structures have an important effect on environmental taxation efficiency. Polinsky (1979) compares environmental subsidies with taxes in a monopoly setting and finds that subsidies are less efficient than taxes in reducing emissions in the long run. Conrad and Wang (1993) provide a comparison of emission taxes and abatement subsidies under three market structures: perfect competition, oligopoly competition, and a dominant firm with a competitive fringe. They study the impact of these two instruments on firm output, total industry output, and the firms' number in the market. Their results reveal that emission taxes and subsidies affect the structure of the polluting firms in opposite ways. Total output and total emissions decrease if emission taxes are levied. They also find that a subsidy on abated emissions serves as an incentive to higher output under each market structure. Cato (2010) investigates a three-part policy mixture of an emission tax, a refunding scheme, and an entry-license tax. His results show that this combination of policy mixture works perfectly as the first-best outcome is always attained. In a Cournot oligopoly, Gersbach and Requate (2004) examine how a tax-refunding scheme mimics a tax-subsidy scheme. They suggest that a first-best outcome can be achieved by simultaneously taxing emissions and subsidising output under both monopoly and Cournot oligopoly. Huang et al. (2013) analyse a fuel-automobile (FA) supply chain and an electric-and-fuel automobile (EA-FA) supply chain, under a subsidy incentive scheme that is implemented to promote the adoption of electric automobiles (EAs) and control the air pollution. Their results indicate that under a duopoly market, the incentive scheme is more effective in increasing the sales of the EAs when consumers' bargaining power is stronger. Luo et al. (2014) study the electric vehicle supply chain with a manufacturer and a retailer serving to heterogeneous consumers, under a price discount rate and a subsidy ceiling. The subsidy ceiling results more effective in influencing the optimal wholesale pricing decision of the manufacturer with a higher unit production cost. Moreover, the discount rate is more effective under lower production cost. Their study suggests to include both a discount rate and a subsidy ceiling as a better incentive scheme. In another study, Yu et al. (2018) examine consumer and manufacturer subsidies. They analyse different settings for determining the optimal subsidy program and study the conditions under which it is optimal for the government to subsidise consumers only, manufacturers only, or both. Their analysis reveals that the structure of the optimal subsidy program depends on whether there is a well-established market selling price for the products. It also depends on the relative emphasis that the government places on consumers welfare versus manufacturer profits. However, they suggest that governments can improve consumer welfare by using subsidy programs that involve competing manufacturers with different market sizes and adequate capacities.

More related to this study, several scholars investigate firms' innovation efforts (R&D) on the production of clean output, in addition to environmental policies imposed by the government. Denicolo (1999) finds that taxes and permits are fully equivalent if the government can commit to a perfectly competitive market. When the government pre-commits, taxes give a higher incentive to invest in R&D than permits. By using a Cournot oligopoly model, Montero (2002) compares firms' R&D incentives under four environmental policy instruments: two CAC instruments (emission and performance standards) and two MBIs (tradable and auction permits). His results indicate that emission and performance standards (CAC instruments) provide greater innovation incentives than tradable and auction permits (MBIs). But, under perfectly competitive markets, tradeable and auctioned permits (MBIs) provide equal innovation incentives that are similar to those offered by emission standards and greater than those offered by performance standards (both CAC instruments). However, these results depend on two effects: the direct or cost-minimising effect (always positive), and the strategic effect resulting from the influence of firm's R&D investment on the other firm's output choice (either positive or negative). David and Sinclair-Desgagné (2010) model pollution taxes and abatement subsidies in an oligopoly market, where firms innovate for the production of a homogeneous good. The regulator deals with two simultaneous price distortions: one coming from pollution and the other caused by the clean firms' market power. Consequently, they show that taxing emissions while subsidising polluters' innovation efforts cannot lead to first-best. The opposite occurs when it is the clean firm's output which is subsidised. Welfare can be higher if the regulator uses only an emission tax in the case when public transfers also create distortions. Under a duopoly and laissez-faire setting with homogeneous products, Ouchida and Goto (2014) analyse emission taxes (subsidies). Their results show that social welfare under an emission tax (emission subsidy) policy is always welfare-enhancing under a duopoly compared to laissez-faire. If the environmental damage is sufficiently small, the equilibrium emission tax rate is negative and so behaving as an emission subsidy. Total emissions in a duopoly under the emission subsidy scenario are less than those under laissez-faire if the damage is sufficiently small, and the R&D cost is low. If R&D cost is high and the damage is sufficiently small, total emissions in a duopoly under an emission subsidy are greater than those under laissez-faire. Moner-Colonques and Rubio (2016) compare an emission standard (CAC instrument) with an emission tax (MBI) in a monopoly market with innovation. They evaluate the strategic behaviour of a polluting monopolist to influence environmental policy by using these two instruments. Their results show that under non-commitment, the strategic behaviour of the firm leads to more environmental innovation and higher welfare than under regulatory commitment with a tax policy. The contrary occurs if an emission standard is applied. Under commitment, both policy instruments are equivalent. However, the emission tax is suggested as an optimal environmental policy because it yields the same welfare level as an emission standard for a committed regulator and larger welfare for a non-committed regulator. Amir et al. (2018) compare firms' incentives to invest in R&D under two CAC instruments such as emission and performance standards. They analyse the impact of these environmental instruments on R&D incentives, equilibrium industry output, and welfare under a two-and-three-stage game. Their study reveals that performance standard is welfare superior to the emission standard when firms invest in innovation. In another study, Bian et al. (2020) examine the effect of two environmental subsidy policies, namely, consumer and manufacturer subsidies on the incentives of investing in emission-reducing technologies. They find that consumer subsidy yields a lower abatement and higher consumption quantity than manufacturer subsidy, under a monopoly market with homogeneous products. Unlike Bian et al. (2020), we focus specifically on the automobile market using two different environmental instruments.

Another strand of the literature related to our study focuses on environmental policies applied for the case of the automobile market considering vertically differentiated products. By using a duopoly model of vertical differentiation Ahmed and Segerson (2007) compare two different policy instruments, a quota (MBI) and an average efficiency standard (CAC), in terms of their effectiveness in reducing emissions, in the automobile market with diesel and gasoline cars. Their results reveal that the optimal policy choice depends on the magnitude of unit damages. However, the quota policy is more preferable in terms of welfare and profits, as long as unit damages are sufficiently high. Under a duopoly market with gasoline and electric vehicles, Shao et al. (2017) examine the effect of two MBI instruments such as government subsidies and price discount schemes on promoting the adoption of electric vehicles. It results that the demand for electric vehicles, the consumer surplus, the environmental impact, and the social welfare are identical under two incentive schemes. However, the government prefers to implement a subsidy incentive scheme due to the lower expenditure involved. Furthermore, the electric vehicles market in the monopoly setting has a smaller environmental impact than that in the duopoly setting, if a subsidy incentive scheme is being used. Theilen and Tomori (2021) analyse an oligopoly model with vertically differentiated products (i.e., diesel and gasoline cars). They investigate the effect of regulatory capture in the automobile industry related to emissions and environmental innovation. Their results reveal that regulatory capture only leads to more emissions and less innovation effort under a multi-product monopoly, while the opposite is true under oligopoly competition. These different results are due to a competition intensifying effect which is only present with at least two firms in the market. In addition to Ahmed and Segerson (2007), Shao et al. (2017), and similar to Theilen and Tomori (2021), we consider an oligopoly automobile market with vertically differentiated products such as fuel-powered and electric vehicles. We concentrate on two-stage game analysis, in which the regulator sets optimal environmental standards ($\overline{e}$) or implements an acquisition tax (t). During the game, the regulator makes policy decisions, and manufacturer responds to these policies by determining its production quantity, innovation effort, and emissions abatement level. To sum up, the comparison of our work and other literature is also summarised in Table 3.3 below.

Table 3.3: Summary of the literature.

Relevant Literature	**Instruments**		**Market**			**Product**		**Innovation**
	MBI	CAC	Monopoly	Duopoly	Oligopoly	Homogeneous	Differentiated	
Buchanan (1969)	x		x			x		x
Lee (1975)	x				x	x		
Polinsky (1979)	x							
Conrad and Wang (1993)	x				x			
Denicolo (1999)	x		x			x		x
Montero (2002)	x	x			x	x		x
Gersbach and Requate (2004)	x				x	x		
Ahmed and Segerson (2007)	x	x		x			x	
Cato (2010)	x		x		x	x		
David and Sinclair-Desgagné (2010)	x				x	x		x
Huang et al. (2013)	x			x		x		
Luo et al. (2014)	x			x		x		
Ouchida and Goto (2014)	x			x		x		x
Moner-Colonques and Rubio (2016)	x	x	x			x		x
Shao et al. (2017)	x		x	x			x	
Amir et al. (2018)		x			x		x	x
Yu et al. (2018)	x				x		x	
Bian et al. (2020)	x		x			x		x
Theilen and Tomori (2021)	x	x	x	x	x		x	x
This chapter	**x**	**x**			**x**		**x**	**x**

The (CAC) represents the command-and-control instruments, while (MBI) the market based instruments.

3.3 The model

In this section, we describe the setup of the model considering the demand, production, and environmental damage. We analyse the impact of two environmental policies in the automobile market with n firms that produce both electric and fuel-powered vehicles. All manufacturers maximise their expected profit, while the government offers either an emission standard ($\overline{e}$) or an acquisition tax (t).

Demand

Consider a market of vertical product differentiation, with two types of vehicles, electric (E) and fuel-powered (F). For simplicity and keeping the analysis tractable, we assume a continuum of consumers varying in their willingness to pay, denoted by θ, which is uniformly distributed on $[0,1]$ such that demand is linear in price. Consumer heterogeneity with respect to their valuation for the vehicles is allowed. This in turn affects consumer's desire to either buy a single car (fuel-powered or electric) or not to buy any car. The utility of a consumer of type θ in each of these cases is given by

$$U_E^\theta = (1+\alpha)\theta - p_E, \tag{3.1}$$
$$U_F^\theta = \theta - p_F - t, \quad \text{and} \tag{3.2}$$
$$U_0^\theta = 0, \tag{3.3}$$

where p_E and p_F denote the price of the electric vehicle and the fuel-powered vehicle, respectively. Moreover, without loss of generality, we assume $\alpha > 0$. It means that electric vehicles are of higher utility for consumers such that for the same price, all consumers prefer the electric vehicle type.[2] The consumer specific parameter θ may be interpreted as the number of kilometres that consumers drive each year or as consumer's valuation for the services provided by the vehicle. In this case, under $p_E > p_F$, the lower energy price of electric vehicles ($\alpha > 0$) implies that frequent drivers purchase electric vehicles and casual drivers fuel-powered vehicles. Equations (3.1)-(3.3) yield the critical values for buying an electric vehicle, a fuel-powered vehicle, or no vehicle. Consumers buy an electric vehicle if

$$U_E^\theta \geq U_F^\theta, \text{ i.e., } \theta \geq \frac{p_E - p_F - t}{\alpha} \equiv \overline{\theta}, \tag{3.4}$$

and buy a fuel-powered vehicle if

$$U_F^\theta > U_E^\theta \text{ and } U_F^\theta > 0, \text{ i.e., } \overline{\theta} > \theta > p_F + t \equiv \underline{\theta}. \tag{3.5}$$

For $\alpha = 0$ consumers exclusively buy the cheaper car, and when $p_E = p_F = \underline{\theta}$, both types of car share the market evenly, i.e., $q_E = q_F = 1 - \underline{\theta}/2$.[3]

Given the prices of fuel-powered and electric vehicle, consumers purchase: (i) an electric vehicle if $\theta \in [\overline{\theta}, 1]$; (ii) a fuel-powered vehicle if $\theta \in [\underline{\theta}, \overline{\theta}]$; (iii) no vehicle if $\theta \in [0, \underline{\theta}]$. Consequently, for $\alpha > 0$, the following demand functions are obtained:

$$q_E = 1 - \overline{\theta} = 1 - \frac{p_E - p_F - t}{\alpha}, \tag{3.6}$$

$$q_F = \overline{\theta} - \underline{\theta} = \frac{p_E - p_F - t}{\alpha} - (p_F + t), \tag{3.7}$$

and their corresponding inverse demand functions:

$$p_E = (1+\alpha)(1 - q_E) - q_F, \tag{3.8}$$

$$p_F = 1 - q_F - q_E - t. \tag{3.9}$$

The consumer surplus is defined as the aggregate true utility of all consumers participating in the car market. Specifically, the consumer surplus is derived by integrating the utilities of consumers with respect to the valuation parameter θ over purchasing electric vehicle, fuel-powered vehicles, and purchasing none. Thus, the resulting consumer surplus is given by

$$CS = \int_{\overline{\theta}}^{1} U_E^\theta d\theta + \int_{\underline{\theta}}^{\overline{\theta}} U_F^\theta d\theta = \frac{1+\alpha}{2} q_E^2 + q_F q_E + \frac{1}{2} q_F^2. \tag{3.10}$$

[2] If we decompose, following the vertical product differentiation model of Prescott and Visscher (1977), with linear demands as in Bresnahan (1987), and specifically for the automobile market of Ahmed and Segerson (2007), $\alpha = \omega_E - \omega_F - \left(p_E^e r_E - p_F^e r_F\right)$, where ω_m is the quality, p_m^e the unit price of energy and r_m the energy consumption of each car type ($m = E, F$), a positive value of α means that, for cars of the same quality, the energy cost of electric cars is lower than that of fuel-powered cars. As observed in Table 3.2, this has been the case over the past decades in the European Union, U.S., and China.

[3] In the case that $p_E = p_F = \underline{\theta}$, both types of car share the market equally, i.e., $q_E = q_F = 1 - 2\underline{\theta} = 1 - p_E - p_F$.

Production

In this model, there are n multi-product firms indexed i that produce two types of automobiles: electric and fuel-powered vehicles. Production costs are linear with $C_{F_i}(q_F) = cq_F$ and $C_{E_i}(q_E) = kcq_E$, where $0 < c < 1$, and $k \in [\underline{k}, \overline{k}]$ is assumed due to the high cost of battery. The parameter k denotes the cost coefficient of an electric vehicle relative to a fuel-powered vehicle, with $\underline{k} = \alpha + 1 + \frac{\beta d}{c}$ and $\overline{k} = \frac{\alpha + c}{c}$, where $\beta \equiv \alpha + n\alpha + 1$. Assuming that each unit of output generates one unit of pollution in the case of fuel-powered vehicles, the firms' emissions can be written as $e_i = q_{F_i} - x_{F_i}$. Hence, x_F stands for the emission-reducing innovation in the production of fuel-powered vehicles. As it is common in the literature (see e.g., Moner-Colonques and Rubio, 2016; Montero, 2002; Petrakis and Xepapadeas, 2001), we assume that the innovation cost type is quadratic, i.e., $C(x_{F_i}) = x_{F_i}^2/2$. Similarly, the per unit damage caused by pollution is assumed to increase with the emission level such that the total damage is given by $D = D(e) = de$, where $d \in [\underline{d}, \overline{d}]$, with $\underline{d} = \frac{\alpha(1-c)}{\beta(n+1)}$ and $\overline{d} = \frac{\alpha(1-c)}{\beta}$.[4] The damage d is caused only by the pollution emitted by fuel-powered vehicles, while electric cars do not directly pollute the environment.[5] From the above, it follows that firms' profits stemming from the production of fuel-powered-and-electric vehicles are:

$$\pi_{E_i} = q_{E_i}((1+\alpha)(1-q_E) - q_F - kc), \tag{3.11}$$

$$\pi_{F_i} = q_{F_i}(1 - q_F - q_E - t - c) - x_{F_i}^2/2, \tag{3.12}$$

respectively, with $q_E = \sum_{i=1}^{n} q_{E_i}$ and $q_F = \sum_{i=1}^{n} q_{F_i}$. Different market structures according to their degree of competitiveness are considered, i.e., laissez-faire market equilibrium, social optimum and multi-product oligopoly.

Environmental regulation

The regulator constrains the level of pollution generated by the production of fuel-powered vehicles by using an emission standard $\overline{e} = \sum_{i=1}^{n} \overline{e}_i$ as a command-and-control instrument. An acquisition tax t, as a market based instrument can be also used to incentivise the adoption of electric vehicles. The regulator determines the policies that allow to achieve the first-best emission levels. Social optimum case is considered, with a welfare function maximised as following:

$$SW = CS + \pi + tq_F - D, \tag{3.13}$$

where D represents total damages in the environment. Thereby, the formulation of the welfare function in (3.13) captures important aspects of regulatory practices.

[4] These conditions guarantee non-negative equilibrium values and simplify the exposition of the results. Specifically, $\overline{d}$ guarantees that $\overline{k} > \underline{k}$; $\underline{d}$ that $e^0 - e^* > 0$; $\overline{k}$ that $q_E^0 > 0$; and $\underline{k}$ that $q_F^{t^*} > 0$.

[5] Notice that fuel-powered cars are considered as harmful due to the fact that they pollute the environment by emitting emissions. This is the reason why many countries have set emission standards to protect the environment (see Table 3.1 representing the emission standards for CO, NOx, and PM).

Timing of the game

The timing of the game is as follows. In Stage 1, the regulator chooses the emission standard $\overline{e}$ or acquisition tax t that allows to achieve the first-best emission levels. In Stage 2, firms choose their environmental innovation effort for fuel-powered-cars x_F and determine their production levels q_E and q_F, respectively. As usual, the game is solved by backward induction.

3.4 Equilibrium analysis

3.4.1 Laissez-faire market equilibrium

First consider the case in which firms can freely choose the level of emissions and there is no policy intervention. Firm i determines its optimal production levels q_{F_i} and q_{E_i}, and the innovation effort x_{F_i} by maximising the following profit function:

$$\max_{q_{E_i},q_{F_i},x_{F_i}} \pi_i = q_{E_i}((1+\alpha)(1-q_E)-q_F-kc)+q_{F_i}(1-q_F-q_E-c)-x_{F_i}^2/2, \;\; i=1,...,n, \tag{3.14}$$

From the first-order conditions and by summing over all firms, the following reaction functions are obtained:

$$q_E = n\frac{\alpha+1-kc}{(n+1)(\alpha+1)}-\frac{1}{(\alpha+1)}q_F, \tag{3.15}$$

$$q_F = \frac{n}{(n+1)}(1-c)-q_E, \tag{3.16}$$

$$x_F = 0. \tag{3.17}$$

From (3.15) and (3.16), it can be observed that quantities of electric and fuel-powered vehicles are strategic substitutes. The following result gives the equilibrium values.

Lemma 3.1. *Under laissez-faire competition, the Nash equilibrium values are given by:*

$$q_E^0=\frac{n}{n+1}\frac{\left(\overline{k}-k\right)c}{\alpha},\; q_F^0=\frac{n}{n+1}\frac{(k-\alpha-1)c}{\alpha},\; x_F^0=0, \text{ and } e^0=\frac{n}{n+1}\frac{(k-\alpha-1)c}{\alpha},$$

where $\frac{\partial q_F^0}{\partial n}>0$, $\frac{\partial q_E^0}{\partial n}>0$, *and* $\frac{\partial e^0}{\partial n}>0$.

From the results in Lemma 3.1 it can be observed that firms do not invest in abatement technology in the absence of any policy intervention. Moreover, as expected, equilibrium quantities (and the level of emissions) increase with the degree of market competition, i.e., with the number of firms in the market.

3.4.2 Social optimum

Now, consider the first-best allocation or social optimum, which is obtained by choosing the total output of electric and fuel-powered vehicles, and the total innovation level (i.e., q_E, q_F, and x_F) that solves the following maximisation problem:

$$\max_{q_E, q_F, x_F} SW = -\frac{1+\alpha}{2} q_E^2 + q_E (1+\alpha - kc) - \frac{q_F^2}{2} + q_F (1-c) - q_F q_E - \frac{x_F^2}{2n} - d(q_F - x_F). \quad (3.18)$$

The following result is obtained.

Lemma 3.2. *The social optimum is given by:*

$$q_E^* = \frac{c}{\alpha}\left(\bar{k} - k\right) + \frac{d}{\alpha},\ q_F^* = \frac{c}{\alpha}\left(k - \underline{k}\right) + nd,\ x_F^* = nd, \text{ and } e^* = \frac{c}{\alpha}\left(k - \underline{k}\right).$$

A comparison of Lemmas 3.1 and 3.2 indicates that without any policy intervention, firms produce too many fuel-powered and not enough electric vehicles yielding an excess of emissions. Moreover, it can be observed that the innovation effort exerted by firms is sub-optimal.

3.4.3 Acquisition tax

As a first policy intervention aimed to reduce the level of emissions consider an acquisition tax (t) on fuel-power vehicles, which is equivalent to a tax abatement on the acquisition of electric vehicles. At Stage 2, firms determine their optimal quantities and innovation efforts (i.e., q_{E_i}, q_{F_i}, x_{F_i}) by maximising the following profit function:

$$\begin{aligned} \max_{q_{E_i}, q_{F_i}, x_{F_i}} \pi_i &= q_{E_i}\left((1+\alpha)(1-q_E) - q_F - kc\right) + q_{F_i}\left(1 - q_F - q_E - t - c\right) - x_{F_i}^2/2 \quad (3.19) \\ &= q_{E_i}\left((1+\alpha)\left(1 - \sum_i^n q_{E_i}\right) - \sum_i^n q_{F_i} - kc\right) + q_{F_i}\left(1 - \sum_i^n q_{F_i} - \sum_i^n q_{E_i} - t - c\right) \\ &\quad - x_{F_i}^2/2, \text{ for } i = 1, \dots, n. \end{aligned}$$

From the first-order conditions and summing over all firms, the following stage-2 equilibrium values are obtained:

$$q_E^t = \frac{n}{n+1}\frac{c+\alpha-ck+t}{\alpha}, \quad (3.20)$$

$$q_F^t = n\frac{c(k-\alpha-1) - t(\alpha+1)}{\alpha(n+1)}, \quad (3.21)$$

$$x_F^t = 0, \quad (3.22)$$

such that total emissions amount to $e^t = q_F^t - x_F^t = n\frac{c(k-\alpha-1)-t(\alpha+1)}{\alpha(n+1)}$.

At Stage 1, the regulator chooses the tax rate that allows to attain the first-best emission level by solving $e^t = e^*$, which yields:

$$t^* = \frac{c\left(\overline{k}-k\right)+\left(d-\underline{d}\right)(n+1)\beta}{n(\alpha+1)}. \tag{3.23}$$

Substituting 3.23 into (3.20)-(3.22) yields the following result.

Lemma 3.3. *Under an acquisition tax yielding the social optimal level of emissions, equilibrium quantities and innovation effort are:*

$$q_E^{t^*} = \frac{n+n\alpha+1}{\alpha(\alpha+1)(n+1)}c\left(\overline{k}-k\right)+\frac{\beta\left(d-\underline{d}\right)}{\alpha(\alpha+1)},\ q_F^{t^*} = \frac{c}{\alpha}\left(k-\underline{k}\right),\ \textit{and}\ x_F^{t^*} = 0.$$

The results in Lemma 3.3 in comparison with Lemma 3.2 indicate that with policy intervention (i.e., acquisition tax), firms produce too many electric-vehicles and an equal amount of fuel-powered vehicles yielding also the same level of emissions. Moreover, it can be observed that the innovation effort exerted by firms is zero.

3.4.4 Emission standard

Now, as an alternative policy intervention, consider an emission standard that limits total emissions to $\overline{e}$. At Stage 2, firms determine their optimal quantities and innovation effort by maximising the following profit function:

$$\max_{q_{E_i},q_{F_i},x_{F_i}} \pi_i = q_{E_i}\left((1+\alpha)(1-q_E)-q_F-kc\right)+q_{F_i}(1-q_F-q_E-c)-x_{F_i}^2/2 \tag{3.24}$$

$$\text{s.t. } q_{F_i} \leq \overline{e}_i + x_{F_i},\ \text{for } i=1,\dots,n, \tag{3.25}$$

yielding the stage-2 equilibrium values:

$$q_E^e = \frac{n(n+2)(\alpha-ck)+n(c+1+cn)-(n+1)\overline{e}}{(n+1)(2\alpha+n\alpha+1)}, \tag{3.26}$$

$$q_F^e = \frac{(\alpha+1)\overline{e}+cn(k-\alpha-1)}{2\alpha+n\alpha+1}, \tag{3.27}$$

$$x_F^e = \frac{cn(k-\alpha-1)-\alpha(n+1)\overline{e}}{2\alpha+n\alpha+1}. \tag{3.28}$$

and $e^e = \overline{e}$.

At Stage 1, the regulator chooses the optimal emission standard by solving: $\overline{e} = e^{*}$. Thus, the first-best emission standard is:

$$\overline{e}^{*} = \frac{c}{\alpha}\left(k - \underline{k}\right). \tag{3.29}$$

Substituting 3.29 into equations 3.26 to 3.28 yields the following result.

Lemma 3.4. *Under an emission standard yielding the social optimal level of emissions, equilibrium quantities and innovation effort are:*

$$\begin{aligned} q_E^{e^*} &= \frac{\left(d - \underline{d}\right)(n+1)\beta + (n(\alpha+\beta)+1)c\left(\overline{k} - k\right)}{\alpha(n+1)(\alpha+\beta)}, \\ q_F^{e^*} &= \frac{c\left(k - \underline{k}\right)\beta + dn\alpha\beta}{\alpha(\alpha+\beta)}, \text{ and} \\ x_F^{e^*} &= \frac{\left(d - \underline{d}\right)(n+1)\beta + c\left(\overline{k} - k\right)}{\alpha+\beta}. \end{aligned}$$

The results in Lemma 3.4 in comparison with Lemma 3.3 show that the quantity for both types of vehicles and innovation effort increases for the same level of emissions. The number of firms n competing in the market plays an important role in determining these equilibrium results.

3.5 Policy comparison

In this section, acquisition taxes and emission standards are compared with regards to the impact on quantities, innovation effort and consumer welfare. First, a comparison of the equilibrium values obtained in Lemmas 3.3 and 3.4 yields the following result.

Proposition 3.1. *As compared to an acquisition tax causing the same level of total emissions, an emission standard yields:*

(i) less electric vehicles, more fuel-powered vehicles and more innovation effort, i.e., $q_E^{e^*} < q_E^{t^*}$, $q_F^{e^*} > q_F^{t^*}$, *and* $x_F^{e^*} > x_F^{t^*}$;

(ii) more total output, i.e., $q_E^{e^*} + q_F^{e^*} > q_E^{t^*} + q_F^{t^*}$.

Proposition 3.1 reveals that an acquisition tax yields more electric and less fuel-powered vehicles than an emission standard. The intuition behind this result is that an acquisition tax changes the relative prices of electric and fuel-powered vehicles, making the latter more expensive. As a consequence, consumers in equilibrium demand more electric and less fuel-powered vehicles. Instead, an emission standard does not alter the relative prices, but incentivises increased innovation effort to produce cleaner fuel-powered vehicles which is totally abandoned under an acquisition tax. Interestingly, this result is in line with the findings of Montero (2002) who shows that under Cournot competition, command-and-control instruments provide greater innovation incentives than market-based instruments. Regarding total output, the second statement in Proposition 3.1 indicates that the policy impact on fuel-powered vehicles dominates the one on electric vehicles such that total output is larger under an emission standard.

From the previous discussion it is not clear which of the two policies is preferred from the consumers' perspective. While an emission standard yields more fuel-powered and total vehicles, under an acquisition tax, there is a larger number of electric vehicles which are higher valued by consumers. The next result elucidates which of the two policies is preferred by consumers.

Proposition 3.2. *If acquisition taxes are not redistributed to consumers, consumers are better off under an emission standard than under an acquisition tax, i.e., $CS^{e^*} > CS^{t^*}$. If acquisition taxes are fully redistributed to consumers and environmental damages are high, emission standards are also preferable to acquisition taxes, while with low environmental damages taxes are preferable, i.e., $CS^{e^*} - CS^{t^*} - t^* q_F^{t^*} \gtreqless 0$ for $d \gtreqless \tilde{d}$ with $\tilde{d} \in \left[\underline{d}, \overline{d}\right]$.*

An important difference between acquisition taxes and emission standards is that the former allow to raise revenues such that their assignment becomes crucial for the comparison of both policies. As it turns out, when the tax revenues raised by means of the acquisition tax do not benefit consumers at all, they are better off under an emission standard. This indicates that the fact that under an emission standard consumers can purchase more vehicles in total more than compensates the lower quantity of (the higher valued) electric vehicles.

If acquisition taxes are fully redistributed to consumers, Proposition 3.2 shows that the impact of the two policies on consumer surplus depends on the environmental damage. The intuition for the role of d comes from the tax revenue obtained under the acquisition tax. From equation (3.23), it can be observed that the optimal tax rate increases with d, while $q_F^{t^*}$ does not depend on d (see Lemma 3.3). Consequently, for higher values of d, more tax revenues are redistributed to consumers such that acquisition taxes become the preferred policy alternative.

Next, consider the consequences of the two policies for manufacturers and total welfare. The following result is obtained.

Proposition 3.3. *Firms' profits and social welfare are higher under an emission standard than under an acquisition tax.*

The result in Proposition 3.3 indicates that firms prefer an emission standard that stimulates them to invest in emission-reducing innovation to produce cleaner fuel-powered vehicles rather than an acquisition tax that changes the relative prices of electric and fuel-powered vehicles. Moreover, it turns out that this profit gain under an emission standard more than compensates a possible loss in consumer surplus when environmental damages are low. Consequently, social welfare is always higher under an emission standard than under an acquisition tax. This result is opposed to what is usually found in the literature (see e.g., Moner-Colonques and Rubio, 2016; Ahmed and Segerson, 2007), that states that market-based instruments (emission taxes) yield higher welfare than command-and-control instruments (emission standards). This difference in the results can be explained by two facts. First, while an emission tax affects both the quantity (negatively) and the innovation effort (positively), an acquisition tax only distorts the demand of the good. Consequently, an emission tax provides more innovation incentives than an acquisition tax. Second, while the above literature considers markets with homogeneous products, this study considers a market of vertically differentiated goods. Therefore, changes in the price of the polluting good (fuel-powered vehicles) imply substitution effects with the non-polluting good (electric vehicles). The results in this paper indicate that together both effects (lower innovation incentives and price distortion effects) turn taxes to the welfare-inferior instrument as compared to emission standards.

3.6 Conclusions

The policy choice by the regulators for increasing firms' environmental innovation effort, and electric vehicles' adoption has created a persistent debate in the automobile market of different countries. In this chapter, we compare the impact of two policy instruments (emission standards and acquisition taxes) in their innovation incentives, market performance, and welfare implications. The analysed model depicts an oligopoly automobile market, in which multi-product firms that produce fuel-powered and electric vehicles compete á la Cournot.

The results indicate that there are more electric vehicles produced under an acquisition tax than under an emission standard. A reason for this is that an acquisition tax changes the relative prices of electric and fuel-powered vehicles making the latter more expensive. As a consequence, consumers in equilibrium demand more electric and less fuel-powered vehicles. However, the policy impact on fuel-powered vehicles dominates the one on electric vehicles such that total output is larger under an emission standard.

Considering the automobile market, this chapter reveals the fact that an emission standard provides greater innovation incentives than an acquisition tax. In addition, we find that if acquisition taxes are not redistributed to consumers, they are better off under an emission standard than under an acquisition tax. If acquisition taxes are fully redistributed to consumers, the impact of the two policies on consumer surplus depends on the environmental damage. The intuition for the role of environmental damage comes from the tax revenue obtained under the acquisition tax. Thus, for higher values of damage, more tax revenues are redistributed to consumers such that acquisition taxes become the preferred policy alternative.

This study also presents the impact of the two policy instruments on the firms' profits and total welfare. Firms prefer an emission standard that stimulate them to invest in emission-reducing innovation for producing cleaner fuel-powered vehicles rather than an acquisition tax that changes the relative prices of electric and fuel-powered vehicles. With regards to social welfare, it is always higher under an emission standard than under an acquisition tax. This result can be explained by two effects such as the effect of lower innovation incentives and price distortion.

Several directions can be considered for further research. Firstly, although this study focuses on fuel-powered and electric automobiles, the results of this analysis can be applied easily to environmental regulation policies related to the batteries of electric vehicles, for example. Other practical markets and situations with environmental issues can apply this model and check the consistency of obtained results. Secondly, empirical studies can be performed to compare different environmental policies across different regions and countries. Furthermore, this study suggests an important policy implication that a mixture of these two policies can contribute to obtaining efficient results in terms of clean output and higher innovation incentives. Finally, other environmental policies can also be examined and compared with these two policies to generate more managerial and policy insights.

3.7 Appendix

Proof of Lemma 3.1

The first-order conditions from maximising (3.14) with respect to q_{E_i}, q_{F_i}, x_{F_i}, for $i = 1, ..., n$ are:

$$\begin{aligned}
\frac{\partial \pi_i}{\partial q_{E_i}} &= \left((1+\alpha)\left(1-\sum_i^n q_{E_i}\right)-\sum_i^n q_{F_i}-kc\right)-q_{E_i}(1+\alpha)-q_{F_i}=0,\\
\frac{\partial \pi_i}{\partial q_{F_i}} &= -q_{E_i}+\left(1-\sum_i^n q_{F_i}-\sum_i^n q_{E_i}-c\right)-q_{F_i}=0,\\
\frac{\partial \pi_i}{\partial x_{F_i}} &= -x_{F_i}=0.
\end{aligned}$$

Summing over all firms, the following system of equations is obtained:

$$\begin{aligned}
n(1+\alpha)(1-q_E)-nq_F-nkc-q_E(1+\alpha)-q_F &= 0,\\
-q_E+n-nq_F-nq_E-nc-q_F &= 0,\\
x_F &= 0.
\end{aligned}$$

The solution of this system of equations yields q_F^0, q_E^0, x_F^0 given by:

$$\begin{aligned}
q_E^0 &= \frac{n}{n+1}\frac{\left(\frac{\alpha+c}{c}-k\right)c}{\alpha}=\frac{n}{n+1}\frac{\left(\bar{k}-k\right)c}{\alpha},\\
q_F^0 &= \frac{n}{n+1}\frac{c(k-\alpha-1)}{\alpha},\\
x_F^0 &= 0,
\end{aligned}$$

where $\frac{\partial q_F^0}{\partial n}=\frac{1}{(n+1)^2}\frac{\left(\bar{k}-k\right)c}{\alpha}>0$ and $\frac{\partial q_E^0}{\partial n}=\frac{1}{(n+1)^2}\frac{c(k-\alpha-1)}{\alpha}>0$. The equilibrium emissions are given by $e^0=q_F^0-x_F^0=\frac{n}{n+1}\frac{(k-\alpha-1)c}{\alpha}$.

Proof of Lemma 3.2

The first-order conditions from maximising (3.18) are:

$$\begin{aligned}
\frac{\partial SW}{\partial q_E} &= -(1+\alpha)q_E + (1+\alpha-kc) - q_F = 0, \\
\frac{\partial SW}{\partial q_F} &= -q_F + (1-c) - q_E - d = 0, \\
\frac{\partial SW}{\partial x_F} &= -\frac{x_F}{n} + d = 0.
\end{aligned}$$

From this system of equations the social optimum is obtained as:

$$\begin{aligned}
q_E^* &= \frac{c}{\alpha}\left(\overline{k} - k\right) + \frac{d}{\alpha}, \\
q_F^* &= \frac{c}{\alpha}\left(k - \underline{k}\right) + nd, \\
x_F^* &= nd,
\end{aligned}$$

and the first-best emission level is obtained as $e^* = q_E^* - x_F^* = \frac{c}{\alpha}\left(k - \underline{k}\right)$.

Proof of Lemma 3.4

Notice that the restriction (3.25) in (3.24) is binding such that the maximisation problem can be rewritten as:

$$\begin{aligned}
\max_{q_{E_i}, q_{F_i}} \pi_i &= q_{E_i}\left((1+\alpha)\left(1 - \sum_i^n q_{E_i}\right) - \sum_i^n q_{F_i} - kc\right) + q_{F_i}\left(1 - \sum_i^n q_{F_i} - \sum_i^n q_{E_i} - c\right) \\
&\quad - \left(q_{F_i} - \overline{e}_i\right)^2 / 2.
\end{aligned}$$

From the first order conditions and summing over all firms yield the following reaction functions:

$$\begin{aligned}
q_E &= \frac{n(1-c) + \overline{e} - q_F(n+2)}{n+1}, \\
q_F &= \frac{n(\alpha - ck + 1)}{n+1} - (\alpha+1)q_E,
\end{aligned}$$

from which we obtain the stage-2 equilibrium values:

$$
\begin{aligned}
q_E^e &= \frac{n(n+2)(\alpha - ck) + n(c+1+cn) - (n+1)\bar{e}}{(n+1)(\alpha+\beta)}, \\
q_F^e &= \frac{(\alpha+1)\bar{e} + cn(k-\alpha-1)}{\alpha+\beta}, \\
x_F^e &= \frac{cn(k-\alpha-1) - \alpha(n+1)\bar{e}}{\alpha+\beta}.
\end{aligned}
$$

Proof of Proposition 3.1

Comparison of quantities.

Comparing the equilibrium quantities of electric vehicles and fuel-based cars in Lemmas (3.3) and (3.4) yields:

$$
\begin{aligned}
q_E^{e^*} - q_E^{t^*} &= -\frac{\left(d - \underline{d}\right)(n+1)\beta + c\left(\bar{k} - k\right)}{(\alpha+1)(\alpha+\beta)} < 0, \\
q_F^{e^*} - q_F^{t^*} &= \frac{\left(d - \underline{d}\right)(n+1)\beta + c\left(\bar{k} - k\right)}{\alpha+\beta} > 0,
\end{aligned}
$$

respectively.

Comparison of total output.

Comparing the total output from Lemmas (3.3) and (3.4), it is obtained:

$$
\left(q_E^{e^*} + q_F^{e^*}\right) - \left(q_E^{t^*} + q_F^{t^*}\right) = \alpha \frac{\left(d - \underline{d}\right)(n+1)\beta + c\left(\bar{k} - k\right)}{(\alpha+1)(\alpha+\beta)} > 0.
$$

Comparison of innovation effort.

Comparing the innovation efforts yields:

$$
x_F^{e^*} - x_F^{t^*} = \frac{\left(d - \underline{d}\right)(n+1)\beta + c\left(\bar{k} - k\right)}{\alpha+\beta} > 0.
$$

Proof of Proposition 3.2

First, lets define

$$z \equiv q_E^{t^*} - q_E^{e^*} = \frac{\left(d-\underline{d}\right)(n+1)\beta + c\left(\overline{k}-k\right)}{(\alpha+1)(\alpha+\beta)} > 0.$$

Using this definition yields:

$$\left(q_E^{e^*} + q_F^{e^*}\right) - \left(q_E^{t^*} + q_F^{t^*}\right) = \alpha z.$$

Now, considering that tax revenues are not redistributed to the consumers, a comparison of consumer surplus under the two policies yields:

$$\begin{aligned} CS^{e^*} - CS^{t^*} &= \frac{1+\alpha}{2}\left(q_E^{e^*}\right)^2 + q_F^{e^*} q_E^{e^*} + \frac{1}{2}\left(q_F^{e^*}\right)^2 - \frac{1+\alpha}{2}\left(q_E^{t^*}\right)^2 - q_F^{t^*} q_E^{t^*} - \frac{1}{2}\left(q_F^{t^*}\right)^2 \\ &= \frac{1}{2}\left(q_E^{e^*} + q_F^{e^*}\right)^2 - \frac{1}{2}\left(q_E^{t^*} + q_F^{t^*}\right)^2 + \frac{1}{2}\alpha\left(\left(q_E^{e^*}\right)^2 - \left(q_E^{t^*}\right)^2\right) \\ &= \frac{1}{2}\left(q_E^{t^*} + q_F^{t^*} + \alpha z\right)^2 - \frac{1}{2}\left(q_E^{t^*} + q_F^{t^*}\right)^2 + \frac{1}{2}\alpha\left(\left(q_E^{t^*} - z\right)^2 - \left(q_E^{t^*}\right)^2\right) \\ &= \frac{\alpha z}{2}\left(2q_F^{t^*} + (\alpha+1)z\right) > 0. \end{aligned}$$

Next, considering that tax revenues are totally redistributed to consumers. Then, a comparison of consumer surplus under the two policies yields:

$$\begin{aligned} CS^{e^*} - CS^{t^*} - t^* q_F^{t^*} &= \frac{\alpha z}{2}\left(2q_F^{t^*} + (\alpha+1)z\right) - t^* q_F^{t^*} \\ &= z\left[\alpha\frac{(\alpha+1)z}{2} - \frac{(2\alpha+1)}{n} q_F^{t^*}\right] \\ &= \frac{z}{2n\alpha(\alpha+\beta)}\left[-(\alpha(8\alpha+5n\alpha+6)+2\beta)c\left(k-\underline{k}\right) + dn^2\alpha^2\beta\right]. \quad (3.30) \end{aligned}$$

This expression is monotonically increasing in d, negative for low values of d and positive for high values of d:

$$\begin{aligned} CS^{e^*} - CS^{t^*} - t^* q_F^{t^*}\Big|_{d=\underline{d}} &= -z\frac{n^2\alpha\left(8\alpha + 2n\alpha + 7\alpha^2 + 4n\alpha^2 + 2\right)\frac{1-c}{n+1}}{2n\alpha(\alpha+\beta)(n+1)} \\ &\quad -z\frac{(n+1)\left(8\alpha + 2n\alpha + 8\alpha^2 + 5n\alpha^2 + 2\right)c\left(k-\underline{k}\right)}{2n\alpha(\alpha+\beta)(n+1)} < 0, \\ CS^{e^*} - CS^{t^*} - t^* q_F^{t^*}\Big|_{d=\overline{d}} &= \frac{z}{2}\frac{n^2\alpha^3(1-c) + c\left(\overline{k}-k\right)\left(8\alpha + 2n\alpha + 8\alpha^2 + 5n\alpha^2 + 2\right)}{n\alpha(\alpha+\beta)} > 0, \end{aligned}$$

such that

$$CS^{e^*} - CS^{t^*} - t^* q_F^{t^*} \begin{cases} < 0 & \text{for } d < \widetilde{d} \\ > 0 & \text{for } d > \widetilde{d} \end{cases},$$

where $\widetilde{d}$ is implicitly defined by $CS^{e^*} - CS^{t^*} - t^* q_F^{t^*} = 0$.

Proof of Proposition 3.3

Denoting $z \equiv \frac{\left(d-\underline{d}\right)(n+1)\beta+c\left(\overline{k}-k\right)}{(\alpha+1)(\alpha+\beta)}$ and using:

$$\begin{aligned}
q_E^{t^*} &= \frac{nc\left(\overline{k}-k\right)+z(\alpha+\beta)}{\alpha(n+1)},\ q_F^{t^*} = \frac{n(1-c)}{n+1}-\frac{nc\left(\overline{k}-k\right)}{\alpha(n+1)}-\frac{z(\alpha+1)(\alpha+\beta)}{\alpha(n+1)},\\
q_E^{t^*}+q_F^{t^*} &= \frac{n(1-c)}{n+1}-z\frac{\alpha+\beta}{n+1},\ t^* = \frac{\alpha+\beta}{n}z,\\
q_E^{e^*} &= \frac{z(\alpha+1)+cn\left(\overline{k}-k\right)}{\alpha(n+1)},\ q_F^{e^*} = \frac{n(1-c)}{n+1}-\frac{z(\alpha+1)^2}{\alpha(n+1)}-\frac{nc\left(\overline{k}-k\right)}{\alpha(n+1)},\\
q_E^{e^*}+q_F^{e^*} &= \frac{n(1-c)}{n+1}-z\frac{\alpha+1}{n+1},\ x_F^{e^*} = z(\alpha+1),\\
q_E^{e^*}-q_E^{t^*} &= -z,\ q_F^{e^*}-q_F^{t^*} = z(\alpha+1),
\end{aligned}$$

we obtain that

$$\begin{aligned}
\pi^e-\pi^t &= \left(q_E^{t^*}+q_F^{t^*}\right)^2-\left(q_E^{e^*}+q_F^{e^*}\right)^2+\alpha\left(\left(q_E^{t^*}\right)^2-\left(q_E^{e^*}\right)^2\right)-\frac{1}{2n}\left(x_F^{e^*}\right)^2\\
&\quad+(1+\alpha-kc)\left(q_E^{e^*}-q_E^{t^*}\right)+(1-c)\left(q_F^{e^*}-q_F^{t^*}\right)+t^*q_F^{t^*}\\
&= \frac{1}{2}z(3\alpha+1)\frac{(\alpha+2\beta)c\left(k-\underline{k}\right)+dn\alpha\beta}{n\alpha(\alpha+\beta)}>0. \qquad (3.31)
\end{aligned}$$

Moreover, using (3.30) and (3.31), regarding the comparison of social welfare we obtain:

$$\begin{aligned}
SW^e-SW^t &= CS^{e^*}-CS^{t^*}-t^*q_F^{t^*}+\pi^e-\pi^t\\
&= \frac{1}{2}z\beta\frac{c\left(k-\underline{k}\right)+dn(2\alpha+\beta)}{n(\alpha+\beta)}>0.
\end{aligned}$$

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