Resource and Energy Economics 74 (2023) 101388

Contents lists available at ScienceDirect

Resource and Energy Economics

journal homepage: www.elsevier.com/locate/ree

Regulatory commitment versus non-commitment: Electric vehicle adoption under subsidies and emission standards☆

Bernd Theilen[a], Françeska Tomori[b,*]

[a] Departament d'Economia, ECO-SOS and RESCAT, Universitat Rovira i Virgili, Spain
[b] Departament d'Economia and ECO-SOS, Universitat Rovira i Virgili, Spain

ARTICLE INFO

JEL classification:
O38
Q55
Q58
L51

Keywords:
Environmental regulation
Emission standards
Subsidy scheme
Commitment
Innovation
Electric vehicles
Fuel-powered vehicles

ABSTRACT

We compare two regulatory structures in the application of emission standards and a subsidy scheme in the automobile market. The regulator can either commit to an emission standard or is not able to commit. Firms compete á la Cournot and produce fuel-powered and electric vehicles. The emissions of fuel-powered vehicles can be abated by means of investing in emission-reducing innovation. Our results indicate that under commitment there are less emissions, higher subsidies and a major adoption of electric vehicles. By contrast, non-commitment yields more fuel-powered vehicles, more vehicles in total and higher consumer surplus. Electric vehicle producers obtain higher profits under commitment, whereas fuel-powered vehicle producers might be better off under both regulatory structures. Social welfare is higher under non-commitment as long as environmental damages are regarded severe. Otherwise, commitment is socially preferable. This result provides an explanation for observed differences in the duration of environmental standards between the US, the EU and China.

1. Introduction

The transition from fuel-powered to electric vehicles has become a major policy concern in developed countries. The two most important environmental policies in the automobile market aimed to spur the transition from fuel-powered to electric vehicles are emission standards and financial incentives. Emission standards take the form of performance standards that limit the amount of emissions per vehicle, where the three most relevant emission indicators are carbon monoxides (CO), nitrogen oxides (NOx), and particulate matter (PM). As shown in Table 1, these standards have become more and more stringent over the last decades in order to meet the emission levels assigned to each country in the course of climate summits (e.g., Kyoto 1997; Copenhagen 2003; Paris 2016;

☆ We acknowledge financial support from the Spanish Ministerio de Ciencia, Innovacion y Universidades and the European Union under grants ECO2016-75410-P, BES-2017-080192 and PID2019-105982 GB-I00/AEI/10.13039/501100011033, and from the Universitat Rovira i Virgili and the Generalitat de Catalunya under grants 2019PFR-URV-53 and SGR2021-00729. We thank two anonymous referees, Carmen Arguedas, Juan Antonio Duro, Arantza Estévez Fernández, José Manuel Giménez-Gómez, Harold Houba, Guiomar Martín-Herrán, Stefanie Peer, Stefaan Proost, Santiago Rubio, Hans-Peter Weikard, Katarzyna Werner, and the participants of EAERE-2021, 1st Young AERNA Day 2023 and ITEA-2023 for comments and discussion. Part of this research was performed while Françeska Tomori and Bernd Theilen were visiting Vrije Universiteit Amsterdam and University of Barcelona, respectively. The hospitality and comments from the members of both institutions are gratefully acknowledged.

* Corresponding author.
E-mail address: franceska.tomori@urv.cat (F. Tomori).

https://doi.org/10.1016/j.reseneeco.2023.101388
Received 20 July 2022; Received in revised form 19 June 2023; Accepted 4 July 2023
Available online 13 July 2023

Madrid 2019). While emission standards are commonly set for many years, their duration can vary substantially among jurisdictions. For example, the Californian LEV III standard is set for a period of 10 years (2015–2025). Instead, in the European Union and in China emission standards are changed more frequently and, on average, last only three to four years.[1] Financial incentives take the form either of tax rebates or, most commonly, subsidy schemes for the acquisition of electric vehicles.[2] As an example of financial incentives to the adoption of electric vehicles, Table 1 displays the difference (in percentage) between the final retail price and the manufacturer's suggested retail price (MSRP) of two comparable models of the Volkswagen Golf in 2018.[3] These financial incentives also vary substantially among countries, being Norway the country providing the highest incentives for the purchase of electric vehicles (122.10%), which converts the 11,175$-price disadvantage of the electric vehicle into a 2434$-price advantage.[4] High financial incentives are also provided by the states of California (73.71%) and New York (66.31%), and China (52.99%). Financial incentives vary frequently and, in general, there is no commitment to maintain specific policies for a long time horizon.

From the market shares displayed in the last column of Table 1, it can be observed that both policy instruments have an impact on the market share of electric vehicles sold in 2018. On the one hand, comparing two countries with the same emission standards, the market share of electric vehicles is higher in the country with stronger financial incentives (e.g., Norway as compared to Germany). On the other hand, comparing jurisdictions with similar financial incentives, the market share of electric vehicles is higher in the jurisdiction with stricter performance standards (e.g., China as compared to Mississippi).

From these considerations we may ask: What are the consequences of commitment to an emission standard? What is the role of subsidies as a second policy instrument? Which structure is better for consumers, firms, and social welfare? What are the impacts of the two regulatory structures (with or without commitment) as regards to innovation and emissions? These question are addressed within an oligopoly model with heterogeneous consumers who either buy an electric, a fuel-power or no vehicle at all. Firms compete á la Cournot and produce either fuel-powered vehicles (FPVs) or electric vehicles (EVs). The emissions of FPVs can be abated by means of investing in emission-reduction technologies. Two regulatory instruments are considered to increase social welfare and to abate pollution: emission standards that limit the level of air-pollution caused by FPVs and subsidies to incentivize the purchase of EVs. Two regulatory structures are compared. First, we consider a structure under which the two environmental instruments are chosen after firms have made their investment into emissions abatement, i.e., under non-commitment. Second, we analyze a structure under which the regulator first determines the emission standard, i.e., commits to maintain this standard, and, then, firms make their investment in emission-reduction technologies and the regulator sets the subsidy to the purchase of EVs.

Our main results can be summarized as follows. First, commitment to an emission standard yields less emissions and higher subsidies to the purchase of electric vehicles. Second, as a consequence of this, regulatory commitment achieves a major adoption of electric vehicles. By contrast, under non-commitment firms produce more fuel-powered vehicles. The total number of vehicles and consumer surplus are higher under non-commitment. Third, EV producers obtain higher profits under regulatory commitment, whereas the profits of FPV producers under both regulatory structures depend on market size relative to innovation costs. In large markets and under low innovation costs, firms invest more in emission-reduction technologies and obtain lower profits under non-commitment, because competition is more intense under these circumstances. Finally, social welfare is higher under non-commitment as long as environmental damages are regarded severe. Otherwise, a committed regulatory policy is welfare-enhancing. The welfare differences between the two regulatory policies decrease with the intensity of market competition, i.e., with market entry of new EV producers.

This study borrows from the literature that analyses how regulatory policies affect emission-reducing innovation. The main message from these studies is that, generally, market-based instruments such as tradeable permits and taxes (or subsidies) provide better incentives to innovation than command-and-control instruments such as emission and performance standards (e.g., Lee, 1975; Conrad and Wang, 1993; Gersbach and Requate, 2004; Cato, 2010; David and Sinclair-Desgagné, 2010). By contrast, Montero (2002) finds that, after accounting for direct and strategic effects, in many situations emission and performance standards offer greater R&D incentives than permits. Amir et al. (2018) compare performance and emission standards in terms of total welfare and find that the former are generally preferable to the later. Moner-Colonques and Rubio (2016) analyze how a regulator's non-commitment to an environmental policy (emission standards or taxes) affects innovation incentives in a monopoly market. They show that a tax is preferable to an emission standard in the case that the regulator cannot commit to maintaining the policy once the monopolist has chosen the innovation effort. Instead, under commitment, the two policies are equivalent. Using firm-level panel data of renewable energy investment in China, Zhao et al. (2021) analyze the role of government subsidy and tax rebate policies. Their results show that government subsidies and tax rebates have positive effects on both pure technological and total investment efficiency. However, in comparison with tax rebates, government subsidies have a stronger positive impact on pure technical and total investment efficiency. Karmaker et al. (2021) study the role of environmental taxes in technological innovation. They find that, in the long-run, environmental taxes stimulate technological innovation because of an acceleration of the introduction of environmental-related technologies

[1] The emission standards for passenger vehicles in China are: China 1 (2000), China 2 (2004), China 3 (2007), China 4 (2010), China 5 (2016), China 6a (2020), and China 6b (2023). In the EU the first standard has been set in 1992 (Euro 1) and since then, it has been changed 9 times until the implementation of Euro 6d in 2020.

[2] See Polinsky (1979) for a comparison of taxes and subsidies in pollution control. Azarafshar and Vermeulen (2020) highlight the importance of financial incentives in the purchase of electric vehicles in Canada. Zhao et al. (2022) study the determinants of the acceptance of electric vehicles in Shanghai and find that peer effects, prices and income play a crucial role.

[3] These models are the Volkswagen 110 TSI Comfortline gasoline and the Volkswagen SEL Premium 134-hp Automatic e-Golf.

[4] For details on the calculation of the financial incentives, see Table 2 in the Appendix.

allowing to reduce carbon emissions. As in our study, Shao et al. (2017) focuses on the automobile market and compares a subsidy with a price discount scheme as regards to their incentive provision to the adoption of electric vehicles. Their analysis indicates that while the consumer surplus, the environmental impact and social welfare are the same under both schemes, a subsidy incentive scheme allows to achieve this at a lower cost for the government. The main differences of our study as regards to this literature are: *i*) the comparison of two regulatory structures; *ii*) the simultaneous application of two environmental instruments; and *iii*) the focus on the automobile market with firms that produce heterogeneous products (electric or fuel-powered vehicles).

The remainder of this article is organized as follows. In section 2, we set up the theoretical model. In section 3, we provide the equilibrium results of the market equilibrium and first-best analysis. In section 4, we carry out the analysis under two different environmental regulatory structures (commitment and non-commitment) and establish the results. In section 5, we compare the market outcomes and welfare implications. In section 6, we offer some concluding remarks. All proofs are in the Appendix.

2. The model

Demand. Consider a market with two types of vehicles, electric and fuel-powered. Consumer's valuation of vehicles, θ, follows a uniform distribution on the interval [0,1]. Each consumer either buys an electric vehicle, a fuel-power vehicle or no vehicle. Denoting p_E and p_F the price of EVs and FPV, respectively, and s the subsidy for the purchase of an electric vehicle, the utility of a consumer of type θ in each of these cases is given by

$$U_E^\theta = (1+\alpha)\theta - p_E + s, \quad \alpha > 0, \tag{1}$$

$$U_F^\theta = \theta - p_F, \quad \text{and} \tag{2}$$

$$U_0^\theta = 0, \tag{3}$$

where α indicates the preference for EVs or consumers environmental awareness. Equations (1)–(3) yield the critical values for buying an electric, a fuel-powered, or no vehicle. Consumers buy an electric vehicle if

$$U_E^\theta \geq U_F^\theta, \quad \text{i.e., } \theta \geq \frac{p_E - p_F - s}{\alpha} \equiv \overline{\theta}, \tag{4}$$

and buy a fuel-powered vehicle if

$$U_F^\theta > U_E^\theta \quad \text{and} \quad U_F^\theta > 0, \quad \text{i.e., } \overline{\theta} > \theta > p_F \equiv \underline{\theta}. \tag{5}$$

Given the prices of fuel-powered and electric vehicles, 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, we obtain the following demand functions

$$q_E = 1 - \overline{\theta} = 1 - \frac{p_E - p_F - s}{\alpha}, \tag{6}$$

$$q_F = \overline{\theta} - \underline{\theta} = \frac{p_E - (1+\alpha)p_F - s}{\alpha}, \tag{7}$$

with their corresponding inverse demand functions

$$p_E = (1+\alpha)(1-q_E) - q_F + s, \tag{8}$$

$$p_F = 1 - q_F - q_E. \tag{9}$$

The aggregate consumer surplus is given by.[5]

$$CS = \int_{\overline{\theta}}^{1} U_E^\theta d\theta + \int_{\underline{\theta}}^{\overline{\theta}} U_F^\theta d\theta = \frac{1+\alpha}{2} q_E^2 + q_F q_E + \frac{1}{2} q_F^2. \tag{10}$$

Production. There are n_E firms that produce electric vehicles (e.g., Tesla, Fisker or Lucid) and n_F firms that produce fuel-powered vehicles.[6] [7] Firms indexed *i*, *j* have linear production costs with $C_{E_i}(q_{E_i}) = kcq_{E_i}$ and $C_{F_j}(q_{F_j}) = cq_{F_j}$, where $0 < c < 1$ and $k > 1$. The innovation process is modeled as in the related literature (e.g., Moner-Colonques and Rubio, 2016; Petrakis and Xepapadeas, 2001).

[5] For a detailed derivation of this expression, see the Appendix.

[6] Hybrid vehicles would be a third category that could be considered as they combine a conventional internal combustion engine system with an electric propulsion system. However, the conclusions of the model remain valid as emission standards will effect only the type of vehicles that are closest in not fulfilling the standards. Currently, these are FPVs such that hybrid vehicles could be aggregated to EVs.

[7] Considering the fact that some firms are multiproduct (i.e., produce both types of vehicles), would reduce the intensity of competition to some extent. However, this has no qualitative impact on our results.

Each FPV generates one unit of pollution such that firms' emissions amount to $e_j = q_{F_j} - x_{F_j}$, where x_{F_j} denotes firm j's innovation effort allowing to reduce emissions of FPVs. This innovation consists in increasing the fuel-efficiency of FPVs, for example, through the installation of start/stop systems, more efficient alternators, coasting functions, solar roofs or LED lights, by a reduction of the rolling resistance of tires, by the downsizing of engines, or by weight reduction of vehicles through the usage of new materials such as carbon fiber and aluminium. These innovations allow to reduce emissions thereby enabling new vehicles to meet more stringent emission standards. The innovation cost is given by $C(x_{F_j}) = \gamma x_{F_j}$, where $\gamma > 0$. The per unit damage caused by pollution is assumed to increase with the emission level and the total damage is given by $D = \frac{d}{2}e^2$, where $d \geq 2$ and $e = \sum_{j=1}^{n} e_j$.[8] As our focus is on local air pollution, environmental damages of EVs are not considered. Firms produce either EVs or FPVs and obtain profits

$$\pi_{E_i} = q_{E_i}(A - (1+\alpha)q_E - q_F + s), \quad i = 1, \ldots, n_E, \tag{11}$$

$$\pi_{F_j} = q_{F_j}(A - q_F - q_E) - \gamma x_{F_j}, \quad j = 1, \ldots, n_F, \tag{12}$$

with $q_E = \sum_{i=1}^{n_E} q_{E_i}, q_F = \sum_{j=1}^{n_F} q_{F_j}$ and $A = 1 + \alpha - kc = 1 - c$, where $A > \underline{A} \equiv \frac{1+\alpha}{\alpha}\gamma + \frac{\gamma}{d} + \frac{1+\alpha+\alpha^2}{\alpha}(n_E+1)(n_F+1)\gamma$. This normalization allows to simplify the notation and to focus on the case in which both types of cars are produced in equilibrium. Moreover, define $z \equiv A - \frac{\gamma}{d} - \frac{1+\alpha}{\alpha}\gamma$, which, henceforth is referred to as the size of the automobile market.

Environmental regulation. The regulator uses two policy instruments to abate pollution stemming from fuel-powered vehicles. First, as a command-and-control instrument, the regulator employs emission standards that limit the level of pollution to $\overline{e} = \sum_{j=1}^{n_F} \overline{e}_j$. Second, as a market-based instrument, the regulator offers a subsidy s for the purchase of each EV. These policies are chosen to maximize social welfare

$$SW = CS + \pi - sq_E - D, \tag{13}$$

where $\pi = \sum_{i=1}^{n_E} \pi_{E_i} + \sum_{j=1}^{n_F} \pi_{F_j}$ denotes total profits.

Timing of the game. Under non-commitment (N), in stage 1, FPV producers choose their innovation effort x_{F_j} to abate FPV emissions. Then, in stage 2, the regulator chooses the emission standard $\overline{e}$ and the subsidy s. Finally, in stage 3 firms determine their production levels q_{E_i} and q_{F_j}, respectively. Under commitment (C), in stage 1, the regulator determines the emission standard. In stage 2, FPV producers determine their environmental innovation effort x_{F_j}, whereas the regulator determines the subsidy s. Finally, in stage 3, firms determine their production levels q_{E_i} and q_{F_j}. The solution concept is subgame perfect Nash equilibrium and the game is solved by backward induction.

3. Market equilibrium and first-best

First consider the case in which firms can freely choose the level of emissions and there is no policy intervention. Firms i and j determine their optimal production levels q_{E_i} and q_{F_j} and the innovation effort x_{F_j}, respectively, by solving

$$\max_{q_{E_i}} \pi_{E_i} = q_{E_i}(A - (1+\alpha)q_E - q_F), \quad i = 1, \ldots, n_E, \tag{14}$$

$$\max_{q_{F_j}, x_{F_j}} \pi_{F_j} = q_{F_j}(A - q_F - q_E) - \gamma x_{F_j}, \quad j = 1, \ldots, n_F. \tag{15}$$

The equilibrium values under market competition are encapsulated in the following result.

Lemma 1. Under laissez-faire competition, the Nash equilibrium values are given by:

$$\begin{aligned} q_E^0 &= \frac{n_E A}{1 + \alpha(n_E+1)(n_F+1) + n_F + n_E}, \quad q_F^0 = \frac{n_F(1 + \alpha(n_E+1))A}{1 + \alpha(n_E+1)(n_F+1) + n_F + n_E}, \\ x_F^0 &= 0, \quad \text{and} \quad e^0 = \frac{n_F(1 + \alpha(n_E+1))A}{1 + \alpha(n_E+1)(n_F+1) + n_F + n_E}. \end{aligned}$$

From Lemma 1 it can be observed that, in the absence of any policy intervention, firms do not invest in abatement technology. The equilibrium quantity of FPVs and emissions increase with n_F and decrease with n_E, whereas the opposite holds for the equilibrium quantity of EVs.

Now, consider the first-best allocation or social optimum which is obtained by solving

$$\max_{q_E, q_F, x_F} SW = CS + \pi - D = -\frac{1+\alpha}{2}q_E^2 + A(q_E + q_F) - q_E q_F - \frac{1}{2}q_F^2 - \gamma x_F - \frac{d}{2}(q_F - x_F)^2. \tag{16}$$

The following result is obtained.

[8] Specifically, the lower bound for d guarantees that emission-reducing innovation, in equilibrium, is always positive.

Lemma 2. The first-best production and innovation levels are

$$q*_E = \frac{\gamma}{\alpha}, \quad q*_F = z + \frac{\gamma}{d}, \quad x*_F = z, \quad \text{and} \quad e* = \frac{\gamma}{d},$$

where $q_E^0 < q*_E$, $q_F^0 < q*_F$, $x_F^0 < x*_F$ and $e^0 > e*$. From Lemmas 1 and 2 we observe that, without any policy intervention, firms produce too few EVs and FPVs, do not innovate enough and pollute too much. Higher environmental damages (d) mean a decrease in the level of socially optimal emissions, FPVs and innovation effort, whereas this does not affect EVs. Surprisingly, an increased preference for EVs (a higher α), reduces the optimal quantity of EVs and increases the one of FPVs. The intuition is that EV producers react to a higher preference for EVs with a price increase that more than compensates the increase in demand (that would be observed otherwise without price changes).

4. Environmental policies

Firm emissions are limited by an emission standard that restricts total emissions to $\overline{e}$. Moreover, the purchase of electric vehicles is subsidized by the amount s. At the final stage of the game, after observing the emission standard and the subsidy, firms choose quantities by solving the following programs:

$$\max_{q_{E_i}} \pi_{E_i} = q_{E_i}(A - (1+\alpha)q_E - q_F + s) \quad \text{for } i = 1, \ldots, n_E, \tag{17}$$

$$\begin{aligned} \max_{q_{F_j}} \pi_{F_j} &= q_{F_j}(A - q_F - q_E) - \gamma x_{F_j} \\ &\text{s.t. } q_{F_j} \le \overline{e}_j + x_{F_j}, \quad \text{for } j = 1, \ldots, n_F. \end{aligned} \tag{18}$$

Noticing that the constraint is binding such that $q_{F_j} = \overline{e}_j + x_{F_j}$, the following equilibrium values are obtained.[9].

$$q_E(\overline{e}, s, x_F) = n_E \frac{A + s - \overline{e} - x_F}{(1+\alpha)(n_E+1)}, \tag{19}$$

$$q_F(\overline{e}, x_F) = \overline{e} + x_F. \tag{20}$$

As it can be observed from equations (19) and (20), stricter emission standards (i.e., lower values of $\overline{e}$) yield more EVs and less FPVs. Instead, as the production of fuel-powered vehicles is fully determined by the emission standard and the firm's innovation effort, subsidies only affect the equilibrium number of electric vehicles. A higher innovation effort (x_F) reduces the equilibrium quantity of EVs and increases the number of FPVs. Consequently, the strategic substitutability of quantities of the two types of vehicles in this oligopoly market in influenced by the regulator through the choice of emission standards and by FPV producers through the choice of their innovation effort. Subsidies have a direct impact on EV producers, whereas, their impact on FPV producers must come indirectly through changes in emission standards and innovation effort.

4.1. *The non-committed regulator*

When there is no commitment, the regulator chooses the two environmental policies after fuel-powered vehicle producers have determined their innovation effort. This is the case, for example in the EU and in China, where emission standards are changed rather frequently such that firms cannot base their innovation decisions on the existence of a stable emission standard, but must base innovation decisions on anticipated policy choices. In this case, the regulator's optimization problem in stage 2 is

$$\begin{aligned} \max_{s,\overline{e}} SW(\overline{e}, s, x_F) &= -\frac{1+\alpha}{2} q_E^2 + A q_E - q_E q_F + A q_F - \frac{1}{2} q_F^2 - \gamma x_F - \frac{d}{2}(q_F - x_F)^2 \\ &\text{s.t. (19) and (20).} \end{aligned} \tag{21}$$

The stage-2 equilibrium values are

$$s(x_F) = \frac{(1+\alpha)d}{n_E(\alpha + (1+\alpha)d)}(A - x_F), \quad \text{and} \tag{22}$$

$$\overline{e}(x_F) = \frac{\alpha}{\alpha + (1+\alpha)d}(A - x_F). \tag{23}$$

We observe that a reduction in innovation effort of FPV producers induces the regulator to allow more emissions by increasing the emission standard. Thereby, FPV producers benefit from their first-mover advantage as they can produce the same quantity with less

[9] A linear relationship between output, the emission standard and innovation is also obtained, for instance, in Amir et al. (2018) and Mon-er-Colonques and Rubio (2016).

innovation costs. In turn, however, the regulator uses the second policy instrument to grant more subsidies to the purchase of EVs, increasing thereby the competitive advantage of EV producers. Substitution of (22) and (23) into (19) and (20) allows to assess the total impact on quantities of these two opposing effects. The stage-2 equilibrium quantities are

$$q_E(x_F) = \frac{(A - x_F)d}{\alpha + (1+\alpha)d}, \quad \text{and} \tag{24}$$

$$q_F(x_F) = \frac{\alpha A + (1+\alpha)dx_F}{\alpha + (1+\alpha)d}. \tag{25}$$

These expressions indicate that FPV producers can increase their market share through more innovation as they can use their innovation effort strategically to increase the production of FPVs and decrease the production of EVs.

In stage 1, firms choose their innovation effort by solving

$$\begin{aligned} \max_{x_{F_j}} \pi_{F_j} &= q_{F_j}(A - q_F - q_E) - \gamma x_{F_j}, \quad \text{for } j = 1, \ldots, n_F, \\ &\text{s.t. (24) and (25).} \end{aligned} \tag{26}$$

The solution of this problem yields the following result.

Lemma 3. The SPNE under non-commitment is given by:

$$\begin{aligned} q_E^N &= \frac{A}{1+\alpha} - \frac{n_F}{n_F+1}\frac{z}{1+\alpha}, \quad q_F^N = \frac{n_F}{n_F+1}z, \quad x_F^N = \frac{\alpha + (1+\alpha)d}{(1+\alpha)d}\frac{n_F}{n_F+1}z - \frac{\alpha}{(1+\alpha)d}A, \\ s^N &= \frac{A}{n_E} - \frac{n_F}{n_F+1}\frac{z}{n_E}, \quad \text{and} \quad e^N = \frac{\alpha}{(1+\alpha)d}\left(A - \frac{n_F}{n_F+1}z\right), \end{aligned}$$

where $q_E^N > q*_E, q_F^N < q*_F, x_F^N < x*_F$, and $e^N > e*$. Lemma 3 indicates that without commitment the production of EVs is above the social optimum, while the production of FPVs is below the social optimum. Innovation effort is suboptimal and the amount of emissions is too high. The intuition for this result is as follows. As FPV producers do not internalize the environmental costs of FPVs, their innovation effort is suboptimal. From equations (22) and (23) we observe that the regulator's reaction to this fact is to allow for more emissions than is socially optimal. The regulator slows down this effect by granting higher subsidies to the purchase of EVs which reduces the quantity of FPVs indirectly through more competition from EV producers. However, this comes at the cost of having more EVs and less FPVs than socially optimal.[10]

4.2. The committed regulator

Now, consider the situation in which the regulator can commit to a certain emission standard but not to a specific level of subsidies. This is the case, for example, in the US where emission standards are set for rather long time spans of eight or ten years. In stage 2, the regulator chooses the subsidy s and, simultaneously, FPV producer j, after observing the emission standard, decides on the innovation effort x_{F_j}. The corresponding optimization programs are

$$\begin{aligned} \max_{x_{F_j}} \pi_{F_j} &= q_{F_j}(A - q_F - q_E) - \gamma x_{F_j}, \quad \text{for } j = 1, \ldots, n_F, \\ &\text{s.t. (19) and (20),} \end{aligned} \tag{27}$$

$$\begin{aligned} \max_{s} SW &= -\frac{1+\alpha}{2}q_E^2 + Aq_E - q_E q_F + Aq_F - \frac{1}{2}q_F^2 - \gamma x_F - \frac{d}{2}(q_F - x_F)^2 \\ &\text{s.t. (19) and (20).} \end{aligned} \tag{28}$$

The stage-2-equilibrium values are

$$x_F = (n_E+1)n_F\frac{\alpha A - (1+\alpha)\gamma}{1 + \alpha(n_E+1)(n_F+1)} - \overline{e}, \tag{29}$$

$$s = \frac{(1 + \alpha(1+n_E))A + (1+\alpha)(n_E+1)n_F\gamma}{n_E(1 + \alpha(n_E+1)(n_F+1))}, \tag{30}$$

[10] The marginal effects of n_E, n_F, d, and α on the equilibrium values are as expected. Equilibrium values are independent of the number of EV producers (considering the total amount of subsidies), whereas, an increase in FPV producers yields more FPVs, more innovation, less emissions, less EVs, and lower subsidies. Higher environmental damages mean higher subsidies, more innovation, more EVs, less FPVs, and less emissions. A higher preference for EVs yields an overproportional price increase of these vehicles such that the quantity of EVs decreases and we observe more FPVs, lower subsidies, and more emissions, whereas the effect on innovation is ambiguous (see the proof of Lemma 3 in the Appendix for details).

which after substitution into (19) and (20) yields the stage-2-equilibrium quantities

$$q_E = \frac{(1+\alpha(n_E+1))A + (1+\alpha)(n_E+1)n_F\gamma}{(1+\alpha)(1+\alpha(n_E+1)(n_F+1))}, \tag{31}$$

$$q_F = (n_E+1)n_F\frac{\alpha A - (1+\alpha)\gamma}{1+\alpha(n_E+1)(n_F+1)}. \tag{32}$$

Evidently, firms respond to an increase in the level of emission standards by decreasing their innovation effort. Increased competition (both either through an increase in the number of EV or FPV producers) leads to higher total innovation effort, while it decreases the total amount of subsidies ($n_E{\cdot}s$) and, consequently, the subsidy per electric vehicle. As regards to quantities, we observe that these are independent from the emission standard because, under commitment, a change in the level of emission standards is fully compensated by an opposite change in innovation effort. The total amount of EVs sold in the market decreases in n_E and in n_F, indicating that the impact of changes in market structure on the quantity of EVs stemming from changes in subsidies dominates the one stemming from changes in innovation effort (see equation (19)). In the case of FPVs, we get the traditional result, i.e., more competition (either by more electric or fuel-powered vehicle producers) yields to an increase in quantity.[11]

In Stage 1, the regulator sets the emission standard $\bar{e}$ by solving

$$\begin{aligned}\max_{\bar{e}} SW \quad &= \quad -\frac{1+\alpha}{2}q_E^2 + Aq_E - q_Eq_F + Aq_F - \frac{1}{2}q_F^2 - \gamma x_F - \frac{d}{2}(q_F - x_F)^2 \\ &\quad\ \text{s.t. } (29)-(32).\end{aligned} \tag{33}$$

The following result is obtained.

Lemma 4. The SPNE under commitment is given by:

$$\begin{aligned} q_E^C &= \frac{1}{1+\alpha}\left(A - \frac{\alpha(n_E+1)n_F}{1+\alpha(n_E+1)(n_F+1)}\left(z+\frac{\gamma}{d}\right)\right), \quad q_F^C = \frac{\alpha(n_E+1)n_F}{1+\alpha(n_E+1)(n_F+1)}\left(z+\frac{\gamma}{d}\right), \\ x_F^C &= \frac{\alpha(n_E+1)n_F}{1+\alpha(n_E+1)(n_F+1)}\left(z+\frac{\gamma}{d}\right) - \frac{\gamma}{d}, \\ s^C &= \frac{1}{n_E}\left(A - \frac{\alpha(n_E+1)n_F}{1+\alpha(n_E+1)(n_F+1)}\left(z+\frac{\gamma}{d}\right)\right), \quad \text{and} \quad e^C = \frac{\gamma}{d}, \end{aligned}$$

where $q_E^C > q{*}_E, 0 < q_F^C < q{*}_F, 0 < x_F^C < x{*}_F$, and $\bar{e}^C = e{*}$. From Lemma 4 we observe that under commitment, as it is also the case under non-commitment, the production of EVs is above the social optimum, while the production of FPVs is below the social optimum. Again, there is not enough innovation effort.[12] However, under commitment, the amount of emissions is first-best. These results indicate that, apart from emissions, the comparison of equilibrium results under commitment and non-commitment is not straightforward. These results are provided in the next section.

5. Policy comparison

A comparison of the equilibrium values obtained in Lemmas 3 and 4 yields the following result.

Proposition 1. As compared to non-commitment, commitment yields:

i) more electric, less fuel-powered, and less vehicles in total ($q_E^C > q_E^N > q{*}_E, q_F^C < q_F^N < q_F^*$, and $q_E^C + q_F^C < q_E^N + q_F^N$);.

[11] Specifically, we obtain:

$$\frac{\partial q_F}{\partial n_E} = -(1+\alpha)\frac{\partial q_E}{\partial n_E} = \frac{\partial x_F}{\partial n_E} = -\frac{\partial(n_E s)}{\partial n_E} = \frac{n_F[A\alpha - (1+\alpha)\gamma]}{(1+\alpha(n_E+1)(n_F+1))^2} > 0, \quad \text{and}$$

$$\frac{\partial q_F}{\partial n_F} = -(1+\alpha)\frac{\partial q_E}{\partial n_F} = \frac{\partial x_F}{\partial n_F} = -\frac{\partial(n_E s)}{\partial n_F} = \frac{(n_E+1)[1+\alpha(n_E+1)][A\alpha - (1+\alpha)\gamma]}{(1+\alpha(n_E+1)(n_F+1))^2} > 0.$$

[12] The marginal effects of d and α on the equilibrium values are as follows. Higher environmental damages have no impact on the quantity of EVs and FPVs, and on subsidies, whereas innovation effort increases and emissions decrease. As observed previously, a higher preference for EVs yields an overproportional price increase of these vehicles such that the quantity of EVs decreases. We have more FPVs, lower subsidies, and more innovation, while emission remain unaltered (see the proof of Lemma 4 in the Appendix for details). For the marginal effects of n_E and n_F on the equilibrium values, see the preceding footnote.

ii) lower innovation effort when environmental damages and market size are large ($x_F^C < x_F^N$ for $d > \widehat{d}$ and $A > \frac{1+\alpha}{\alpha}\gamma + n_F\frac{\alpha+(1+\alpha)d}{\alpha}\frac{\gamma}{d}\frac{\widehat{d}}{d-\widehat{d}}$, $x_F^C > x_F^N$ else, where $\widehat{d} \equiv \frac{\alpha(1+\alpha(n_E+1)(n_F+1))}{(1+\alpha)n_F}$);.
iii) higher subsidies ($s^C > s^N$); and.
iv) less pollution ($e^C = e^* < e^N$).

Moreover, we obtain that:

a) differences in quantities ($|q_m^C - q_m^N|, m = E,F$) are increasing in market size (A), decreasing in the number of EV producers (n_E), and increasing in environmental damages (d);.
b) differences in emissions ($e^N - e^C$) are increasing in market size (A), decreasing in environmental damages (d) and in the number of FPV producers (n_F), and independent from the number of EV producers (n_E).

Proposition 1 indicates that commitment to an emission standard allows to achieve the first-best emission level, i.e., less emissions than under non-commitment. This is an expected result, as a committed regulator can exploit her first-mover advantage to fully internalize the environmental damage of emissions. Instead, under non-commitment, FPV producers benefit from their first-mover advantage to increase their market share to the expense of EV producers. Under commitment EVs also obtain more subsidies than under non-commitment such that both policy instruments (subsidies and emission standards) favor the adoption of EVs yielding to more EVs and less FPVs.

As regards to innovation effort, we observe that the comparison depends crucially on the size of the automobile market relative to the innovation cost. The intuition behind this result is that more innovation under non-commitment has a direct and an indirect effect on quantities. The direct effect is that more innovation allows to increase the production of FPVs which decreases the production of EVs, as both types of vehicles are strategic substitutes. The indirect effect of an increase in innovation is that the regulator reduces the level of allowed emissions and subsidies to the purchase of EVs, which yields a net increase in EVs and a net decrease in FPVs. The direct effect becomes more dominant when market size (relative to innovation costs) increases. Therefore, under these circumstances, we observe more innovation under a non-committed than under a committed regulator.

The results in Proposition 1 give an explanation for what is observed in Table 1. A stronger commitment to emission standards (as in California and New York) comes along with both stricter emission standards and higher subsidies. As a consequence, we observe a larger market share of EVs. Instead, in EU member countries with common emission standards set by the EU regulatory agency, differences in market share of EVs (as observed, e.g., between Norway and Germany) are driven by the gap in subsidies. A possible explanation for these differences could be a greater environmental awareness as regards to the damages caused by FPVs which, as shown before, leads to higher subsidies for the purchase of EVs.

From the previous discussion it is not clear which of the two structures is preferred from the consumers' perspective. While the commitment to an emission standard yields more EVs, under non-commitment we observe a larger number of FPVs and vehicles in total. The next result answers this question.

Proposition 2. Consumers are better off under a non-committed regulator than under a committed regulator ($CS^C < CS^N$), whereas EV producers are better off under a committed regulator ($\pi_E^C > {\pi_E}^N$). FPV producers are better off under commitment as lone as $n_F > 1$ and markets are sufficiently large ($\pi_F^C > {\pi_F}^N$ if $n_F > 1$ and $A/\gamma > \frac{1+\alpha}{\alpha} + \frac{(n_F+1)^2(1+\alpha(n_E+1)(n_F+1))^2}{n_F(\alpha(n_F-1)(n_F+1)(n_E+1)-1)d}$, $\pi_F^C < {\pi_F}^N$ else).

While there are more EVs under commitment, non-commitment yields to more FPVs such that there is a trade-off between the impact of these two quantities on consumer surplus. However, as the total number of vehicles produced is larger under non-commitment, we observe that the quantity effect stemming from FPVs more than compensates the one coming from EVs. Consequently, consumer surplus is higher under non-commitment. EV producers obtain higher profits under commitment because they face less competition from FPV producers and obtain higher subsidies. Instead, FPV producers are only better off under non-commitment (where they have a first-mover advantage in the choice of innovation effort) when they have monopoly power or when market size is large and innovation costs are low. Otherwise, they are better off under a committed regulator. The intuition behind this result is that a side-effect of having a committed regulator is that a stricter emission standard reduces competition in the FPV market which benefits FPV producers as long as there is enough competition, i.e., when there are at least two firms in the market and when market size (relative to the innovation cost) is large.

The result in Proposition 2 hints to a conflict between consumer and producer interests. Considering consumers and producers as two aggregate groups and assuming that consumers do not care about environmental damages, we obtain that consumers prefer a regulatory policy under which there is no strong commitment to emission standards, while producers generally prefer a regulatory policy with such a commitment. However, the results are more complex once these groups are disaggregated. On the one hand, consumers with a strong preference for EVs and consumers that are emission averse prefer a committed regulator. On the other hand, under the aforementioned conditions, FPV producers are better off under a non-committed regulator. Under electoral competition, the relative size of these groups ultimately determines which of the two policies will be implemented by the government.

Next, we consider the total welfare consequences of the two regulatory policy designs, i.e., commitment and non-commitment to emission standards. The following result is obtained.

Proposition 3. Social welfare is higher under non-commitment when environmental damages are high, and higher under commitment when environmental damages are low, i.e.,

$$SW^N - SW^C \begin{cases} \leq 0 & \text{for} \quad d \leq \dfrac{\alpha(1+\alpha(n_E+1)(n_F+1))^2}{(1+\alpha)(2+2\alpha(n_E+1)(n_F+1)+n_F)n_F} \\ > 0 & \text{for} \quad d > \dfrac{\alpha(1+\alpha(n_E+1)(n_F+1))^2}{(1+\alpha)(2+2\alpha(n_E+1)(n_F+1)+n_F)n_F}. \end{cases}$$

The welfare comparison of the two regulatory structures depends on two factors. On the one hand, it depends on the total quantity of vehicles, which (as shown in Proposition 1) is higher under non-commitment. On the other hand, it depends on emissions, which are lower under commitment. Consequently, there is a trade-off between the welfare effects of quantities and emissions. Whether commitment or non-commitment to an emission standard is preferable, therefore, hinges on the importance of these two factors.[13]

As regards to the quantities, Proposition 1(*v*) shows that differences between the number of vehicles increase with market size (i.e., A), whereas it is independent from the severity of environmental damages (i.e., d). The differences in the level of emissions is decreasing in d and increasing in A (see Proposition 1(*vi*)). Consequently, when d and A are large, the quantity effect dominates the emission effect and social welfare is higher under non-commitment. When either of the two values is small, the emission effect dominates the quantity effect and social welfare is larger under commitment.

In a different context, similar results are obtained by Moner-Colonques and Rubio (2016). In a model with a monopoly firm that produces a homogenous product, they find commitment to an emission standard yields less emissions, more innovation and higher social welfare. The monopolist's profit is lower and, depending on the parameters of their model, output is either higher or lower under commitment. The welfare dominance of non-commitment in our model (in the case in which environmental damages are serious) can be explained by the throughout positive output effect that is observed under non-commitment. This difference in the output effect might come through two channels. First, we consider a combination of a subsidy (a market-based instrument) and an emission standard (a command-and-control instrument). The results in Moner-Colonques and Rubio (2016) indicate that while commitment is welfare-enhancing under an emission standard, non-commitment yields higher welfare under an emission tax. Therefore, considering a combination of both instruments can explain that non-commitment in some cases is welfare superior to commitment. Second, differently to Moner-Colonques and Rubio (2016), we consider oligopolistic competition with heterogenous products. Results in Petrakis and Xepapadeas (2001) indicate that competition has a considerable influence on the results. In a game in which the innovation effort is observed before the regulator chooses an environmental tax rate, they obtain that commitment only yields higher innovation effort and welfare under oligopoly competition, whereas under monopoly the opposite is true. Therefore, combining two regulatory instruments and considering a different type of competition can explain the observed difference between our result and the result in Moner-Colonques and Rubio (2016).

It is interesting to assess in how far the market structure influences welfare considerations as regards to regulatory commitment or non-commitment. The effect of changes in the number of car producers is summarized in the following result.

Corollary 1. Welfare differences between commitment and non-commitment to an emission standard decrease with the number of electric vehicle producers.

This result follows immediately from the observation that both the differences in emissions and in quantities are decreasing with market competition, i.e., the number of EV producers. Consequently, an increase in the number of EV producers means a convergence of both regulatory structures in terms of their welfare implications.

From these results we can conclude that the importance of the timing of environmental policies depends on several circumstances. In the case of environmental standards, our results suggest that non-commitment is preferable from a social welfare point of view when environmental damages are high, a situation that is deemed to be realistic for the automobile market. However, this conclusion comes with some caveats. First, as mentioned before, not only consumer and producer interests enter into conflict as regards to the regulatory policy recommendation, but also within these groups we observe opposing interests. EV producers are better off under commitment while FPV producers, are generally, better off under non-commitment. While consumers as a whole prefer non-commitment because they can buy more and cheaper vehicles, this is not the case for those that have a strong preference for EVs or care about environmental damages. This explains why the implementation of a specific regulatory emission standard is a controversial issue and that the political support for a given policy might change after government turnover. Second, our analysis focuses exclusively on the emissions of FPVs

[13] As shown in the Appendix in the proof of Proposition 3, social welfare can be written as a function of q_F and $\bar{e}$ only:

$$SW(q_F, \bar{e}) = \frac{A^2 + 2\alpha A q_F - \alpha q_F^2}{2(1+\alpha)} - \gamma q_F + \gamma \bar{e} - \frac{d}{2}\bar{e}^2.$$

This function has a maximum at $q_{F_{\max}} = A - \frac{1+\alpha}{\alpha}\gamma$ and $\bar{e}_{\max} = \frac{\gamma}{d}$, where $q_F^C < q_F^N < q_{F_{\max}}$ and $\bar{e}_{\max} = \bar{e}^C < \bar{e}^N$. Consequently, the aforementioned trade-off emerges as q_F^N is closer to the optimal value than q_F^C, whereas $\bar{e}^N$ is further away from the optimal value than $\bar{e}^C$.

as sources of environmental damages. However, it is well-documented that the production and disposal of EVs (particularly batteries) also comes with considerable environmental costs. While the inclusion of these damages into the analysis is beyond the scope of this paper, it might accentuate the conclusion that non-commitment is the preferable policy straightforwardly. If both EVs and FPVs are harmful to the environment, the parameter d could be interpreted as the difference between the environmental damages of the two types of vehicles. Consequently, even when environmental damages of EVs and FPVs are high, the difference between these damages might be rather small. Then, the results in Proposition 3 indicate that commitment might be the preferable policy.

6. Conclusions

Emission standards and financial incentives by means of either subsidies or tax rebates represent the most important policy instruments applied in the automobile market to facilitate the transition from fuel-powered to electric vehicles. In this context, regulatory authorities have applied different policies. While some jurisdictions, as in the US for example, have opted for long-lasting emission standards, others have changed these standards rather frequently. This article compares regulatory commitment and non-commitment to an emission standard with respect to the adoption of electric vehicles, the innovation in emission-reduction technology of fuel-powered vehicles, total emissions, and social welfare.

The results indicate that commitment yields less emissions, while subsidies to the purchase of electric vehicles are higher. Consequently, commitment yields more EVs, less FPVs, and less vehicles in total, which in turn means that total consumer surplus is higher under non-commitment. EV producers are clearly better off under commitment, whereas this is only the case for FPV producers under competition and when market size is large. Finally, from a social welfare perspective, non-commitment is the preferable regulatory policy when environmental damages are regarded severe. However, the welfare differences between the two regulatory policies diminish when market competition becomes more intense, for instance, through the entrance of new EV producers.

In the light of these results, the difference in the commitment to maintain emission standards for a long time horizon observed between the US and the EU or China might be explained by a different assessment of the severity of FPV emissions and the importance of the automobile market. Generally, non-commitment to the maintenance of standards for a longer time horizon, as observed in the EU and China, is welfare-enhancing under a strong preference for automobiles (particularly FPVs) and when FPV emissions are regarded as sufficiently harmful. Instead, commitment to maintain environmental standards, as observed in the US, is preferable when FPV emissions are regarded as less harmful.

Several limitations of our analysis must be considered. First, EVs are considered not to be harmful to the environment, which is truly not the case. Secondly, regulatory decisions are not taken by a unique government agency but by different government bodies which may pursue different objectives (the federal US government and state governments, or the European Parliament and EU member-state governments). Third, environmental policies in the automobile market are not limited to subsidies and emission standards, but, for example, also to restrictions of some type of vehicles to enter city centers (low emission zones). Fourth, environmental policies change over time. In the framework of a dynamic game, one could also analyze the time consistency of different policies, i.e., the transition from one to another environmental policy (see, e.g., Cadot and Sinclair-Desgagné, 1995 for such an approach). Considering these aspects would allow to delve deeper into the political economy implications as regards to the political support of different policies that is necessary for their implementation.[14] Addressing these issues is left for future research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Appendix

Derivation of consumer surplus

The computational steps in equation (10) are as follows:

[14] For a recent study in this direction, see Fageda et al. (2022).

$$
\begin{aligned}
CS &= \int_{\overline{\theta}}^{1} U_E^{\theta} d\theta + \int_{\underline{\theta}}^{\overline{\theta}} U_F^{\theta} d\theta \\
&= \int_{\overline{\theta}}^{1} ((1+\alpha)\theta - p_E + s) d\theta + \int_{\underline{\theta}}^{\overline{\theta}} (\theta - p_F) d\theta \\
&= \left[\left(1+\alpha\right)\frac{\theta^2}{2} - \theta p_E + \theta s\right]_{\overline{\theta}}^{1} + \left[\frac{\theta^2}{2} - \theta p_F\right]_{\underline{\theta}}^{\overline{\theta}} \\
&= \left(\left(1+\alpha\right)\frac{1}{2} - p_E + s\right) - \left((1+\alpha)\frac{\overline{\theta}^2}{2} - \overline{\theta} p_E + \overline{\theta} s\right) + \left(\frac{\overline{\theta}^2}{2} - \overline{\theta} p_F\right) - \left(\frac{\underline{\theta}^2}{2} - \underline{\theta} p_F\right).
\end{aligned}
\tag{34}
$$

Substituting $\underline{\theta}$ and $\overline{\theta}$ from (4) and (5) yields:

$$CS = \frac{1+\alpha}{2} - p_E + s + \frac{1}{2\alpha}(p_E - p_F - s)^2 + \frac{p_F^2}{2}. \tag{35}$$

Finally, substituting p_E and p_F from (8) and (9) yields:

$$CS = \frac{1}{2}q_F^2 + \frac{1+\alpha}{2}q_E^2 + q_F q_E. \tag{36}$$

Proof of Lemma 1

The first-order conditions of the maximization problems in (15) and (14) are

$$\frac{\partial \pi_{E_i}}{\partial q_{E_i}} = (A - (1+\alpha)q_E - q_F) - (1+\alpha)q_{E_i} = 0, \quad i = 1, \dots, n_E, \tag{37}$$

$$\frac{\partial \pi_{F_j}}{\partial q_{F_j}} = (A - q_F - q_E) - q_{F_j} = 0, \quad j = 1, \dots, n_F, \tag{38}$$

$$\frac{\partial \pi_{F_j}}{\partial x_{F_j}} = -\gamma < 0, \quad j = 1, \dots, n_F. \tag{39}$$

The second-order conditions for a maximum are fulfilled as $\frac{\partial^2 \pi_{E_i}}{\partial q_{E_i}^2} = -2(1+\alpha) < 0$ and $\frac{\partial^2 \pi_{F_j}}{\partial q_{F_j}^2} = -2 < 0$, while $\frac{\partial \pi_{F_j}}{\partial x_{F_j}} = -\gamma$ indicates that $x_{F_j} = 0$. Solving equations (37)–(39) yields the following equilibrium values:

$$q_E^0 = \frac{n_E A}{1 + \alpha(n_E+1)(n_F+1) + n_E + n_F}, \tag{40}$$

$$q_F^0 = \frac{n_F(1 + \alpha(n_E+1))A}{1 + \alpha(n_E+1)(n_F+1) + n_E + n_F}, \tag{41}$$

$$x_F^0 = 0. \tag{42}$$

The equilibrium emissions are given by

$$e^0 = q_F^0 - x_F^0 = \frac{n_F(1 + \alpha(n_E+1))A}{1 + \alpha(n_E+1)(n_F+1) + n_E + n_F}. \tag{43}$$

Proof of Lemma 2

The first-order conditions of the maximization problem in (16) are

$$\frac{\partial SW}{\partial q_E} = -(1+\alpha)q_E + A - q_F = 0, \tag{44}$$

$$\frac{\partial SW}{\partial q_F} = -q_F + A - q_E - d(q_F - x_F) = 0, \tag{45}$$

$$\frac{\partial SW}{\partial x_F} = -\gamma + d(q_F - x_F) = 0. \tag{46}$$

The second-order conditions for a maximum are fulfilled as the Hessian matrix

$$H = \begin{bmatrix} \frac{\partial^2 SW}{\partial q_E^2} & \frac{\partial^2 SW}{\partial q_E \partial q_F} & \frac{\partial^2 SW}{\partial q_E \partial x_F} \\ \frac{\partial^2 SW}{\partial q_E \partial q_F} & \frac{\partial^2 SW}{\partial q_F^2} & \frac{\partial^2 SW}{\partial q_F \partial x_F} \\ \frac{\partial^2 SW}{\partial q_E \partial x_F} & \frac{\partial^2 SW}{\partial q_F \partial x_F} & \frac{\partial^2 SW}{\partial x_F^2} \end{bmatrix} = \begin{bmatrix} -(1+\alpha) & -1 & 0 \\ -1 & -(1+d) & d \\ 0 & d & -d \end{bmatrix} \tag{47}$$

is negative definite with $\det(H_1) = -(1+\alpha) < 0, \det(H_2) = (1+\alpha)(1+d) - 1 > 0$, and $\det(H) = -d(\alpha + (1+\alpha)d)\langle 0$. Solving equations (44)–(46) yields the following equilibrium values

$$q*_E = \frac{\gamma}{\alpha}, \tag{48}$$

$$q*_F = A - \frac{1+\alpha}{\alpha}\gamma = z + \frac{\gamma}{d}, \tag{49}$$

$$x*_F = A - \frac{\gamma}{d} - \frac{1+\alpha}{\alpha}\gamma = z, \tag{50}$$

and the first-best equilibrium emissions

$$e* = q*_F - x*_F = \frac{\gamma}{d}. \tag{51}$$

The comparison of the market and first-best equilibrium values yields

$$q*_E - q_E^0 = \frac{\gamma}{\alpha} > 0, \tag{52}$$

$$\begin{aligned} q*_F - q_F^0 = &\frac{(1+\alpha)(n_E+1)}{1+\alpha(n_E+1)(n_F+1)+n_E+n_F}\left(A - \underline{A} + \frac{\gamma}{d} + \frac{1+\alpha}{\alpha}\gamma\right) \\ &+ \frac{1+\alpha}{\alpha}\frac{(n_E+1)(n_F+1)\left[n_E + \alpha n_E + \alpha^2(n_E+1)\right] + n_F n_E}{1+\alpha(n_E+1)(n_F+1)+n_E+n_F}\gamma > 0, \end{aligned} \tag{53}$$

$$x*_F - x_F^0 = z > 0, \tag{54}$$

$$\begin{aligned} \overline{e}* - \overline{e}^0 = &-\frac{n_F(1+\alpha(n_E+1))}{1+\alpha(n_E+1)(n_F+1)+n_E+n_F}\left(A - \underline{A} + \frac{1+\alpha+\alpha^2}{\alpha}(n_E+1)(n_F+1)\gamma\right) \\ &- \frac{1+\alpha}{\alpha}\frac{\alpha(n_E+1)(dn_F-1)+dn_F}{1+\alpha(n_E+1)(n_F+1)+n_E+n_F}\frac{\gamma}{d} < 0. \end{aligned} \tag{55}$$

Proof of Lemma 3

The first-order conditions of the maximization problem in (21) are

$$\frac{\partial SW}{\partial s} = \left(\frac{A - \overline{e} - x_F - sn_E}{n_E+1}\right)\frac{n_E}{(1+\alpha)(n_E+1)} = 0, \quad \text{and} \tag{56}$$

$$\frac{\partial SW}{\partial \overline{e}} = \frac{(A - \overline{e} - x_F)\left(1+\alpha+2\alpha n_E + \alpha n_E^2\right) - sn_E}{(1+\alpha)(n_E+1)^2} - d\overline{e} = 0. \tag{57}$$

The second-order conditions are given by

$$H = \begin{bmatrix} \frac{\partial^2 SW}{\partial s^2} & \frac{\partial^2 SW}{\partial s \partial \overline{e}} \\ \frac{\partial^2 SW}{\partial s \partial \overline{e}} & \frac{\partial^2 SW}{\partial \overline{e}^2} \end{bmatrix} = \begin{bmatrix} -\frac{n_E^2}{(1+\alpha)(n_E+1)^2} & \frac{-n_E}{(1+\alpha)(n_E+1)^2} \\ \frac{-n_E}{(1+\alpha)(n_E+1)^2} & -\frac{1+\alpha+2\alpha n_E+\alpha n_E^2}{(1+\alpha)(n_E+1)^2} - d \end{bmatrix} \tag{58}$$

with $\det(H_1) = -\frac{n_E^2}{(1+\alpha)(n_E+1)^2} < 0$ and $\det(H) = n_E^2 \frac{\alpha+(1+\alpha)d}{(\alpha+1)^2(n_E+1)^2} > 0$, such that the first-order conditions in both cases are sufficient conditions for a maximum. Solving equations (56)–(57) yields the following stage-2 equilibrium values:

$$s = \frac{(1+\alpha)d(A-x_F)}{n_E(\alpha+(1+\alpha)d)}, \tag{59}$$

$$\bar{e} = \frac{\alpha(A-x_F)}{\alpha+(1+\alpha)d}. \tag{60}$$

The stage-2 quantities in equilibrium are

$$q_E(x_F) = \frac{(A-x_F)d}{\alpha+(1+\alpha)d}, \tag{61}$$

$$q_F(x_F) = \frac{\alpha A+(1+\alpha)dx_F}{\alpha+(1+\alpha)d}. \tag{62}$$

In stage 1, FPV producers solve (26), which yields the first-order condition

$$\frac{\partial \pi_{F_j}}{\partial x_{F_j}} = \frac{-\alpha d}{\alpha+(1+\alpha)d} q_{F_j} + \frac{(1+\alpha)d}{\alpha+(1+\alpha)d}(A-q_F-q_E) - \gamma = 0, \quad j = 1,\ldots,n_F. \tag{63}$$

The second-order condition is $\frac{\partial^2 \pi_{F_j}}{\partial x_{F_j}^2} = -\frac{(1+2\alpha)d}{\alpha+(1+\alpha)d} < 0$, such that the first-order condition is sufficient for a maximum. In equilibrium, after substituting (61) and (62) into (63), the total innovation effort is given by

$$\begin{aligned} x_F^N &= \frac{(1+\alpha)n_F d-\alpha}{(1+\alpha)(n_F+1)d}A - \frac{n_F(\alpha+(1+\alpha)d)^2\gamma}{\alpha(1+\alpha)(n_F+1)d^2} \\ &= \frac{\alpha+(1+\alpha)d}{(1+\alpha)d}\frac{n_F}{n_F+1}z - \frac{\alpha}{(1+\alpha)d}A, \\ &= \frac{(1+\alpha)n_F d-\alpha}{(1+\alpha)(n_F+1)d}(A-\underline{A}) + n_F\frac{1+(1+\alpha)n_E}{\alpha(1+\alpha)}\gamma + \frac{\alpha(d^2 n_E n_F - 1)}{(1+\alpha)d^2}\gamma \\ &\quad + \frac{(1+\alpha)(n_E+2)+\alpha^2(n_E+1)}{1+\alpha}(dn_F-1)\frac{\gamma}{d} > 0. \end{aligned} \tag{64}$$

Substituting (64) into (61) and (62) yields the equilibrium quantities

$$q_E^N = \frac{\alpha dA+\gamma n_F(\alpha+(1+\alpha)d)}{\alpha(1+\alpha)(n_F+1)d} = \frac{A}{1+\alpha} - \frac{n_F}{n_F+1}\frac{z}{1+\alpha}, \tag{65}$$

$$q_F^N = \frac{n_F}{n_F+1}\left(A - \frac{1+\alpha}{\alpha}\gamma - \frac{\gamma}{d}\right) = \frac{n_F}{n_F+1}z, \tag{66}$$

and equilibrium subsidies and emissions

$$s^N = \frac{1+\alpha}{n_E}\frac{\alpha dA+\gamma n_F(\alpha+(1+\alpha)d)}{\alpha(1+\alpha)(n_F+1)d} = \frac{A}{n_E} - \frac{n_F}{n_F+1}\frac{z}{n_E}, \tag{67}$$

$$e^N = \frac{\alpha dA+\gamma n_F(\alpha+(1+\alpha)d)}{(1+\alpha)(n_F+1)d^2} = \frac{\alpha}{(1+\alpha)d}\left(A - \frac{n_F}{n_F+1}z\right), \tag{68}$$

where $\frac{\partial q_E^N}{\partial d} = \frac{n_F}{n_F+1}\frac{\gamma}{(1+\alpha)d^2} > 0, \frac{\partial q_F^N}{\partial d} = -\frac{\gamma}{d^2}\frac{n_F}{n_F+1} < 0, \frac{\partial s^N}{\partial d} = \frac{n_F}{n_F+1}\frac{\gamma}{n_E d^2} > 0, \frac{\partial e^N}{\partial d} = -\frac{e^N}{d} - \frac{\alpha}{(1+\alpha)d}\frac{\gamma}{d^2}\frac{n_F}{n_F+1} < 0, \frac{\partial x_F^N}{\partial d} = \alpha\frac{A+2n_F\left(\frac{(\alpha+1)}{\alpha}\gamma+\frac{\gamma}{d}\right)}{(1+\alpha)(n_F+1)d^2} > 0, \frac{\partial q_E^N}{\partial \alpha} = -\frac{q_E^N}{1+\alpha} - \frac{n_F}{n_F+1}\frac{\gamma}{(1+\alpha)\alpha^2} < 0, \frac{\partial q_F^N}{\partial \alpha} = \frac{n_F}{n_F+1}\frac{\gamma}{\alpha^2} > 0, \frac{\partial s^N}{\partial \alpha} = -\frac{\gamma}{\alpha^2}\frac{n_F}{n_E(n_F+1)} < 0$, and $\frac{\partial e^N}{\partial \alpha} = \frac{Ad+\gamma n_F}{(n_F+1)(1+\alpha)^2 d^2} > 0$. The comparison with the social optimum yields

$$q_E^N - q*_E = \frac{1}{1+\alpha}\left(\frac{z}{n_F+1} + \frac{\gamma}{d}\right) > 0, \tag{69}$$

$$q_F^N - q*_F = -\frac{z}{n_F+1} - \frac{\gamma}{d} < 0, \tag{70}$$

$$x_F^N - x*_F = -\frac{(\alpha+(1+\alpha)d)(\gamma(1+n_F)+dz)}{(1+\alpha)(n_F+1)d^2} < 0, \tag{71}$$

$$e^N - e* = \alpha \frac{\gamma(1+n_F)+dz}{(1+\alpha)(n_F+1)d^2} > 0. \tag{72}$$

Proof of Lemma 4

The first-order conditions of problems (27) and (28) are

$$\frac{\partial \pi_{F_i}}{\partial x_{F_i}} = \frac{(1+\alpha(n_E+1))\left(A - \overline{e} - \frac{\overline{e}}{n_F} - x_F - x_{F_i}\right) - sn_E}{(1+\alpha)(n_E+1)} - \gamma = 0, \tag{73}$$

$$\frac{\partial SW}{\partial s} = n_E \frac{A - \overline{e} - x_F - sn_E}{(1+\alpha)(n_E+1)^2} = 0. \tag{74}$$

The second-order conditions are given by $\frac{\partial^2 \pi_{F_i}}{\partial x_{F_i}^2} = -2\frac{1+\alpha(1+n_E)}{(1+\alpha)(n_E+1)} < 0$ and $\frac{\partial^2 SW}{\partial s^2} = -\frac{n_E^2}{(1+\alpha)(n_E+1)^2} < 0$, such that conditions (73) and (74) are also sufficient for a maximum. From equations (73) and (74), we obtain the stage 2 equilibrium values

$$x_F = \frac{n_F(n_E+1)(A\alpha - (1+\alpha)\gamma)}{1+\alpha(n_E+1)(n_F+1)} - \overline{e}, \tag{75}$$

$$s = \frac{(1+\alpha(n_E+1))A + (1+\alpha)(n_E+1)n_F\gamma}{n_E(1+\alpha(n_E+1)(n_F+1))}. \tag{76}$$

Substituting (75) and (76) into (19) and (20) yields the stage-2 equilibrium quantities

$$q_E = \frac{(1+\alpha(1+n_E))A + (1+\alpha)(n_E+1)n_F\gamma}{(1+\alpha)(1+\alpha(n_E+1)(n_F+1))}, \tag{77}$$

$$q_F = \frac{n_F(n_E+1)(A\alpha - (1+\alpha)\gamma)}{1+\alpha(n_E+1)(n_F+1)}. \tag{78}$$

At stage 1, the government sets $\overline{e}$ by maximizing the social welfare function in (33). The first-order condition is

$$\frac{\partial SW}{\partial \overline{e}} = \gamma - d\overline{e} = 0. \tag{79}$$

The second-order condition for a maximum is fulfilled as $\frac{\partial^2 SW}{\partial^2 \overline{e}} = -d < 0$. Solving equation (79) for $\overline{e}$ yields the optimal emission standard

$$\overline{e}^C = \frac{\gamma}{d}. \tag{80}$$

Substituting (80) into (75) and (76) yields the SPNE innovation effort and subsidy under commitment

$$\begin{aligned} x_F^C &= \frac{n_F(n_E+1)(A\alpha - (1+\alpha)\gamma)}{1+\alpha(n_E+1)(n_F+1)} - \frac{\gamma}{d} \\ &= \frac{\alpha(n_E+1)n_F}{1+\alpha(n_E+1)(n_F+1)}\left(z + \frac{\gamma}{d}\right) - \frac{\gamma}{d} \\ &= \alpha \frac{n_F(n_E+1)(A - \underline{A})}{1+\alpha(n_E+1)(n_F+1)} + \frac{\alpha + \alpha n_E + 1}{1+\alpha(n_E+1)(n_F+1)}\left(\gamma - \frac{\gamma}{d}\right) \\ &\quad + \frac{\alpha(n_E+1)n_F[(1+\alpha)(n_E+1)(n_F+1) - 1] + (n_E+1)^2 n_F(n_F+1) - 1}{1+\alpha(n_E+1)(n_F+1)}\gamma > 0, \end{aligned} \tag{81}$$

$$s^C = \frac{1}{n_E}\left(A - \frac{\alpha(n_E+1)n_F}{1+\alpha(n_E+1)(n_F+1)}\left(z + \frac{\gamma}{d}\right)\right) > 0. \tag{82}$$

The equilibrium quantities are

$$q_E^C = \frac{1}{1+\alpha}\left(A - \frac{\alpha(n_E+1)n_F}{1+\alpha(n_E+1)(n_F+1)}\left(z + \frac{\gamma}{d}\right)\right), \tag{83}$$

$$q_F^C = \frac{\alpha(n_E+1)n_F}{1+\alpha(n_E+1)(n_F+1)}\left(z+\frac{\gamma}{d}\right), \tag{84}$$

where $\frac{\partial q_E^C}{\partial d} = \frac{\partial q_F^C}{\partial d} = \frac{\partial s^C}{\partial d} = 0, \frac{\partial e^C}{\partial d} = -\frac{\gamma}{d^2} < 0, \frac{\partial x_F^C}{\partial d} = \frac{\gamma}{d^2} > 0, \frac{\partial q_F^C}{\partial \alpha} = n_F(n_E+1)\frac{A+(n_E+n_F+n_E n_F)\gamma}{(1+\alpha(n_E+1)(n_F+1))^2} > 0, \frac{\partial q_E^C}{\partial \alpha} = \frac{-1}{1+\alpha}\left(\frac{\partial q_F^C}{\partial \alpha} + q_E^C\right)\langle 0, \frac{\partial s^C}{\partial \alpha} = -\frac{1}{n_E}\frac{\partial q_F^C}{\partial \alpha} < 0, \frac{\partial e^C}{\partial \alpha} = 0$, and $\frac{\partial x_F^C}{\partial \alpha} = \frac{\partial q_F^C}{\partial \alpha} > 0$. The comparison with the social optimum yields

$$q_E^C - q*_E = \frac{1+\alpha(n_E+1)}{(1+\alpha)(1+\alpha(n_E+1)(n_F+1))}\left(z+\frac{\gamma}{d}\right) > 0, \tag{85}$$

$$q_F^C - q*_F = -\frac{1+\alpha(n_E+1)}{1+\alpha(n_E+1)(n_F+1)}\left(z+\frac{\gamma}{d}\right) < 0, \tag{86}$$

$$x_F^C - x*_F = -\frac{1+\alpha(n_E+1)}{1+\alpha(n_E+1)(n_F+1)}\left(z+\frac{\gamma}{d}\right) < 0, \tag{87}$$

$$\bar{e}^C - e* = 0. \tag{88}$$

Proof of Proposition 1

Comparing the equilibrium results of electric and fuel-powered vehicles in Lemmas (3) and (4) yields the following results.

Comparison of quantities:

$$\begin{aligned} q_E^C - q_E^N &= \frac{1}{(1+\alpha)}\frac{n_F}{(n_F+1)}\left[\frac{1}{1+\alpha(n_E+1)(n_F+1)}\left(A-\frac{1+\alpha}{\alpha}\gamma\right)-\frac{\gamma}{d}\right] \\ &= \frac{\frac{n_F}{n_F+1}(A-\underline{A}) + n_F(n_E+1)\left(\frac{1+\alpha}{\alpha}d+\alpha(d-1)\right)\frac{\gamma}{d}}{(1+\alpha)(1+\alpha(n_E+1)(n_F+1))} > 0, \end{aligned} \tag{89}$$

$$q_F^C - q_F^N = -\frac{\frac{n_F}{n_F+1}(A-\underline{A}) + n_F(n_E+1)\left(\frac{1+\alpha}{\alpha}d+\alpha(d-1)\right)\frac{\gamma}{d}}{1+\alpha(n_E+1)(n_F+1)} < 0, \tag{90}$$

where $\partial(q_E^C - q_E^N)/\partial A > 0, \partial(q_F^N - q_F^C)/\partial A > 0, \partial(q_E^C - q_E^N)/\partial d < 0, \partial(q_F^N - q_F^C)/\partial d < 0, \partial(q_E^C - q_E^N)/\partial n_E < 0, \partial(q_F^N - q_F^C)/\partial n_E < 0$, and

$$\frac{\partial(q_E^C - q_E^N)}{\partial n_F} = \frac{1}{(1+\alpha)(n_F+1)^2}\left[\frac{1-\alpha(n_F-1)(n_F+1)(n_E+1)}{(1+\alpha(n_E+1)(n_F+1))^2}\left(A-\frac{1+\alpha}{\alpha}\gamma\right)-\frac{\gamma}{d}\right], \tag{91}$$

$$\frac{\partial(q_F^N - q_F^C)}{\partial n_F} = \frac{1}{(n_F+1)^2}\left[\frac{1-\alpha(n_F-1)(n_F+1)(n_E+1)}{(1+\alpha(n_E+1)(n_F+1))^2}\left(A-\frac{1+\alpha}{\alpha}\gamma\right)-\frac{\gamma}{d}\right], \tag{92}$$

where both signs are negative for $\alpha \geq 1$ and positive for $\alpha \to 0$, i.e., $\exists \tilde{\alpha} \in (0,1)$ such that $\partial(q_m^C - q_m^N)/\partial n_F > 0$ for $\alpha < \tilde{\alpha}$ and $\partial(q_m^C - q_m^N)/\partial n_F < 0$ for $\alpha > \tilde{\alpha}, m = E, F$.

Comparison of total output:

$$\left(q_E^C + q_F^C\right) - \left(q_E^N + q_F^N\right) = -\frac{\alpha n_F\left(\frac{A-\underline{A}}{n_F+1} + (n_E+1)\left(\left(\frac{1+\alpha}{\alpha}\right)d+\alpha(d-1)\right)\frac{\gamma}{d}\right)}{(1+\alpha)(1+\alpha(n_E+1)(n_F+1))} < 0. \tag{93}$$

Comparison of innovation effort:

$$x_F^C - x_F^N = \frac{\alpha}{(1+\alpha)(n_F+1)d}\left[\left(\frac{\hat{d}-d}{\hat{d}}\right)\left(A-\frac{1+\alpha}{\alpha}\gamma\right)+n_F\frac{\alpha+(1+\alpha)d}{\alpha d}\right], \tag{94}$$

where $\hat{d} \equiv \frac{\alpha(1+\alpha(n_E+1)(n_F+1))}{(1+\alpha)n_F}$. It follows that

$$x_F^C - x_F^N \begin{cases} > 0 \quad \text{for} \quad d < \hat{d} \text{or} d > \hat{d} \; \& \; A < \frac{1+\alpha}{\alpha}\gamma + n_F\frac{\alpha+(1+\alpha)d}{\alpha}\frac{\gamma}{d}\frac{\hat{d}}{d-\hat{d}} \\ < 0 \quad \text{for} \quad d > \hat{d} \; \& \; A > \frac{1+\alpha}{\alpha}\gamma + n_F\frac{\alpha+(1+\alpha)d}{\alpha}\frac{\gamma}{d}\frac{\hat{d}}{d-\hat{d}}. \end{cases} \tag{95}$$

Table 1
Emission standards and subsidies in the passenger vehicles market. Emission standards are measured in g/km. Financial incentives and market shares refer to 2018. 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 some other States. Emission standards applied in the EU and the US (Directorate general for internal policies, 2016) and in China (TransportPolicy.net, 2018).

Emission standard	Country/State	Max. emission level			Financial incentives to the purchase of EV	Market share of EV
		CO	NOx	PM		
	California	0.37	0.006	0.0037	73.15%	7.84%
LEV III (2015–2025)	New York	0.37	0.006	0.0037	63.31%	1.56%
	Louisiana	1.3	0.024	–	48.11%	0.28%
	Mississippi	1.3	0.024	–	51.18%	0.22%
Tier 3 (2017–2025)	West Virginia	1.3	0.024	–	54.16%	0.27%
	Austria	1	0.06	0.0045	22.04%	2.00%
	France	1	0.06	0.0045	39.06%	1.40%
	Germany	1	0.06	0.0045	43.55%	1.10%
	Italy	1	0.06	0.0045	37.96%	0.30%
Euro 6d (2020–2025)	Netherlands	1	0.06	0.0045	49.46%	5.40%
	Norway	1	0.06	0.0045	122.10%	49.10%
	Spain	1	0.06	0.0045	44.67%	0.50%
	UK	1	0.06	0.0045	33.33%	0.60%
China 6a (2020–2023)	China	0.5	0.035	0.003	52.99%	3.89%

Source: Market share of electric vehicles in the EU (ICCT, 2020), in the US, China and Norway (IEA, 2018).

Comparison of subsidies:

$$s^C - s^N = \frac{n_F\left(A - \underline{A} + (n_E+1)(n_F+1)\frac{(1+\alpha)d+(d-1)\alpha^2}{\alpha}\frac{\gamma}{d}\right)}{n_E(n_F+1)(1+\alpha(n_E+1)(n_F+1))} > 0. \tag{96}$$

Comparison of emission standards:

$$\begin{aligned}\overline{e}^C - \overline{e}^N &= -\frac{\alpha}{(1+\alpha)d}\left(\frac{z}{n_F+1}+\frac{\gamma}{d}\right) < 0 \\ &= -\frac{\alpha}{(1+\alpha)d}\left(\frac{A-\frac{1+\alpha}{\alpha}\gamma}{n_F+1}+\frac{n_F\gamma}{(n_F+1)d}\right),\end{aligned} \tag{97}$$

where $\partial(\overline{e}^N - \overline{e}^C)/\partial A > 0, \partial(\overline{e}^N - \overline{e}^C)/\partial d < 0, \partial(\overline{e}^N - \overline{e}^C)/\partial n_E = 0$, and $\partial(\overline{e}^N - \overline{e}^C)/\partial n_F < 0$.

Proof of Proposition 2

From (19) and (20), we obtain that $q_E = (A - q_F)/(1+\alpha)$, which allows to write consumer surplus in (10) as

$$CS = \frac{A^2 + \alpha q_F^2}{2(1+\alpha)}.$$

As consumer surplus is increasing in $q_F, q_F^C - q_F^N < 0$ in (90) means that $CS^C < CS^N$.

As regards to the comparison of profits, using the fact that $q_E = (A - q_F)/(1+\alpha)$, firms' profits can be rewritten as

$$\pi_E = \frac{A - q_F}{1+\alpha}s, \tag{98}$$

$$\pi_F = \alpha\frac{A - q_F}{1+\alpha}q_F - \gamma x_F. \tag{99}$$

As $q_F^C < q_F^N$ and $s^C > s^N$ (see (90) and (96), respectively), it follows immediately that $\pi_E^C > \pi_E^N$. The profits of producers of fuel-powered vehicles compare as follows:

Table 2

Retail prices, taxes and financial incentives of Volkswagen Golf and e-Golf. The two models are: Volkswagen Golf 110 TSI Comfortline gasoline and Volkswagen e-Golf SEL Premium 134-hp Automatic. MSRP is the manufacturer's suggested retail price. Numbers refer to the average in 2018 and are in US dollars. Financial incentives are the difference in retail prices after incentives as a share of the differences in MSRPs.

	California		Louisiana		Mississippi		New York		West Virginia		Austria		France	
	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf	Golf	e-Golf
MSRP ($)	24,755	37,345	24,755	37,345	24,755	37,345	24,755	37,345	24,755	37,345	26,128	37,303	26,128	37,303
CO2/Ownership tax ($)	–	–	–	–	–	–	–	–	–	–	–	81.30	–	–
Registration tax ($)	296	296	138	138	39	39	86	86	40	40	–	215	–	–
NOx tax ($)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Weight/Motor tax	–	–	–	–	–	–	–	–	–	–	1015	–	–	–
Scrapping fee ($)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
VAT/Sales tax (%)	10.25	10.25	11.45	11.45	8	8	8.88	8.88	7	7	20	20	20	20
Clean Fuel Rebate ($)	–	800	–	–	–	–	–	–	–	–	–	–	–	–
Subsidy/Federal tax credit ($)	–	7500	–	7500	–	7500	–	7500	–	7500	–	3387	–	6600
Clean Vehicle Rebate ($)	–	2200	–	–	–	2200	–	–	–	–	–	–	–	–
Retail price after incentives ($)	27,588	30,968	27,727	34,259	26,774	32,871	27,039	31,247	26,527	32,499	32,664	41,376	31,353	38,163
Financial Incentives (%)	–	73.15	–	48.12	–	51.18	–	63.31	–	54.16	–	22.04	–	39.06

	Germany		Italy		Netherlands		Norway		Spain		UK		China	
	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	–	–	–	41	–	4909	–	–	–	–	–	–	–
Registration tax ($)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
NOx tax ($)	–	–	–	–	–	–	232	–	–	–	–	–	–	–
Weight/Motor tax	44.80	–	–	–	–	–	1936	–	–	–	–	–	–	–
Scrapping fee ($)	–	–	–	2200	–	–	281	281	–	–	–	–	–	–
VAT/Sales tax (%)	19	19	22	22	21	0	25	0	21	21	20	20	10	0
Clean Fuel Rebate ($)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Subsidy/Federal tax credit ($)	–	6600	–	4500	–	–	–	–	–	7339	–	5699	–	3500
Clean Vehicle Rebate ($)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Retail price after incentives ($)	31,482	37,790	31,876	38,809	31,655	37,303	40,018	37,584	31,614	37,797	31,353	39,064	27,850	33,200
Financial Incentives (%)	–	43.55	–	37.96	–	49.46	–	122.10	–	44.67	–	33.33	–	52.99

Source: Price of Volkswagen Golf gasoline and e-Golf: for EU, USA and China (Volkswagen Official, 2018); price of gasoline for EU (Trading Economics, 2020), for USA (US Energy Information Administration, 2020) and for China (Trading Economics, 2020); policies and incentives for EU (ACEA, 2020), for USA (EVAdoption, 2020) and for China (ICCT, 2018).

$$\pi_F^C - \pi_F^N = \frac{\alpha}{1+\alpha}\left[n_F\frac{\alpha(n_E+1)(n_F+1)(n_F-1)-1}{(n_F+1)^2(1+\alpha(n_E+1)(n_F+1))^2}\left(A-\frac{1+\alpha}{\alpha}\gamma\right)-\frac{\gamma}{d}\right]\left(A-\frac{1+\alpha}{\alpha}\gamma\right)$$
$$\begin{cases} <0 & \text{for} \quad n_F = 1 \text{or} n_F > 1 \quad \text{and} \quad \frac{A}{\gamma} < \frac{1+\alpha}{\alpha} + \frac{(n_F+1)^2(1+\alpha(n_E+1)(n_F+1))^2}{n_F(\alpha(n_F-1)(n_F+1)(n_E+1)-1)d} \\ >0 & \text{for} \quad n_F > 1 \quad \text{and} \quad \frac{A}{\gamma} > \frac{1+\alpha}{\alpha} + \frac{(n_F+1)(1+\alpha(n_E+1)(n_F+1))^2}{n_F(\alpha(n_F-1)(n_F+1)(n_E+1)-1)d}. \end{cases} \tag{100}$$

Proof of Proposition 3

Using the fact that $q_E = (A - q_F)/(1+\alpha)$ and $x_F = q_F - \bar{e}$, we obtain

$$SW(q_F, \bar{e}) = \frac{1}{2}\frac{A^2 + 2(A\alpha - (1+\alpha)\gamma)q_F - \alpha q_F^2}{1+\alpha} + \gamma\bar{e} - \frac{d}{2}\bar{e}^2.$$

This function has a maximum at $q_{F_{\max}} = A - \frac{1+\alpha}{\alpha}\gamma$ and $\bar{e}_{\max} = \frac{\gamma}{d}$. As $q_F^C < q_F^N < q_{F_{\max}}$ and $\bar{e}_{\max} = \bar{e}^C < \bar{e}^N$, we observe a trade-off because q_F^N is closer to the optimal value than q_F^C, whereas $\bar{e}^N$ is further away from the optimal value than $\bar{e}^C$. It follows that

$$\begin{aligned} SW^C - SW^N = & \frac{1}{2}\alpha^2\gamma^2\frac{(1+\alpha(n_E+1))^2}{(1+\alpha)^2 d^3} \\ & + \left[\frac{\alpha}{1+\alpha} - \frac{dn_F}{1+\alpha(n_E+1)(n_F+1)}\right]\frac{\alpha(1+\alpha(n_E+1))\gamma\widetilde{A}}{(n_F+1)(1+\alpha)d^2} \\ & + \left[\frac{\alpha}{1+\alpha} - \frac{2+2\alpha(n_E+1)(n_F+1)+n_F}{(1+\alpha(n_E+1)(n_F+1))^2}dn_F\right]\frac{\alpha\widetilde{A}^2}{2(n_F+1)^2(1+\alpha)d}. \end{aligned} \tag{101}$$

This is a convex quadratic function in $\widetilde{A} \equiv A - \frac{1+\alpha}{\alpha}\gamma - (1+\alpha(n_E+1)(n_F+1))\frac{\gamma}{d}$ with three positive terms for

$$d < \widetilde{d} \equiv \frac{\alpha(1+\alpha(n_E+1)(n_F+1))^2}{(1+\alpha)(2+2\alpha(n_E+1)(n_F+1)+n_F)n_F},$$

and a concave function with two negative roots for $d > \widetilde{d}$. Therefore,

$$SW^C - SW^N \begin{cases} \le 0 & \text{for} \quad d \ge \widetilde{d} \\ > 0 & \text{for} \quad d < \widetilde{d}, \end{cases}$$

where $\underline{\widetilde{A}}$ are the roots in equation (101) for $SW^C - SW^N = 0$, i.e.,

$$\underline{\widetilde{A}} = -(n_F+1)(1+\alpha(n_E+1))\left(1 \pm \sqrt{1 - \frac{\alpha}{1+\alpha}\frac{\mu}{\lambda^2}}\right)\frac{\lambda\gamma}{\mu d} < 0,$$

where $\lambda = \frac{\alpha}{1+\alpha} - \frac{dn_F}{1+\alpha(n_E+1)(n_F+1)}$ and $\mu = \frac{\alpha}{1+\alpha}\left(1 - \frac{d}{\widetilde{d}}\right)$.

Tables 1, 2.

References

ACEA. 2020. Incentives for buying electric vehicles. Accessible at: ⟨https://www.acea.be/news/article/incentives-for-buying-electric-vehicles⟩.
Amir, R., Gama, A., Werner, K., 2018. On environmental regulation of oligopoly markets: Emission versus performance standards. Environ. Resour. 70 (1), 147–167.
Azarafshar, R., Vermeulen, W.N., 2020. Electric vehicle incentive policies in Canadian provinces. Energy Econ. 91, 104902.
Cadot, O., Sinclair-Desgagné, B., 1995. Environmental standards and industrial policy. J. Environ. Econ. Manag. 29 (2), 228–237.
Cato, S., 2010. Emission taxes and optimal refunding schemes with endogenous market structure. Environ. Resour. Econ. 46 (3), 275–280.
Conrad, K., Wang, J., 1993. The effect of emission taxes and abatement subsidies on market structure. Int. J. Ind. Organ. 11 (4), 499–518.
David, M., Sinclair-Desgagné, B., 2010. Pollution abatement subsidies and the eco-industry. Environ. Resour. Econ. 45 (2), 271–282.
Directorate general for internal policies. 2016. Comparative study on the differences between the EU and US legislation on emissions in the automotive sector. Accessible at: ⟨https://www.europarl.europa.eu/RegData/etudes/STUD/2016/587331/IPOL_STU(2016)587331_EN.pdf⟩.
EVAdoption. 2020. Factors contributing to EV sales: Market share by US State. Accessible at: ⟨https://evadoption.com/factors-contributing-to-ev-sales-market-share-by-us-state/⟩.
Fageda, X., Flores-Fillol, R., Theilen, B., 2022. Price versus quantity measures to deal with pollutionand congestion in urban areas: A political economy approach. J. Environ. Econ. Manag. 115, 102719.
Gersbach, H., Requate, T., 2004. Emission taxes and optimal refunding schemes. J. Public Econ. 88 (3–4), 713–725.

ICCT. 2018. Assessment of electric car promotion policies in Chinese cities. Accessible at: ⟨https://theicct.org/sites/default/files/publications/China_city_NEV_assessment_20181018.pdf⟩.
ICCT. 2020. European Vehicle Market Statistics, Pocketbook 2019/20. Accessible at: ⟨http://eupocketbook.theicct.org⟩.
IEA. 2018. Global EV Outlook 2018. Accessible at: 10.1787/9789264302365-en.
Karmaker, S.C., Hosan, S., Chapman, A.J., Saha, B.B., 2021. The role of environmental taxes on technological innovation. Energy 232, 121052.
Lee, D.R., 1975. Efficiency of pollution taxation and market structure. J. Environ. Econ. Manag. 2 (1), 69–72.
Moner-Colonques, R., Rubio, S.J., 2016. The strategic use of innovation to influence environmental policy: Taxes versus standards. BE J. Econ. Anal. Policy 16 (2), 973–1000.
Montero, J.P., 2002. Permits, standards, and technology innovation. J. Environ. Manag. 44 (1), 23–44.
Petrakis, E., Xepapadeas, A., 2001. To commit or not to commit: Environmental policy in imperfectly competitive markets. Typescript, Department of Economics, University of Crete.
Polinsky, A.M., 1979. Notes on the symmetry of taxes and subsidies in pollution control. Can. J. Econ. 12 (1), 75–83.
Shao, L., Yang, J., Zhang, M., 2017. Subsidy scheme or price discount scheme? Mass adoption of electric vehicles under different market structures. Eur. J. Oper. Res. 262 (3), 1181–1195.
2020 Trading Economics. 2020. Price of gasoline for EU and China in 2018. Accessible at: ⟨https://tradingeconomics.com/country-list/gasoline-prices⟩, retrieved July10, 2020.
TransportPolicy.net. 2018. China light-duty emissions. Accessible at: ⟨https://www.transportpolicy.net/standard/china-light-duty-emissions/, retrieved⟩ July 12, 2020.
U.S. Energy Information Administration. 2020. Gasoline and Diesel Fuel Update. Accessible at: ⟨https://www.eia.gov/petroleum/gasdiesel/⟩.
Volkswagen Official. 2018. Price of Volkswagen Golf gasoline and e-Golf: for EU, USA and China. Accessible at: ⟨https://www.vw.com/⟩, retrieved June 19, 2020.
Zhao, L., Zhang, Y., Sadiq, M., Hieu, V.M., Ngo, T.Q., 2021. Testing green fiscal policies forgreen investment, innovation and green productivity amid the COVID-19 era. Econ. Change Restruct. 1–22.
Zhao, X., Ma, Y., Shao, S., Ma, T., 2022. What determines consumers' acceptance of electric vehicles: a survey in Shanghai, China. Energy Econ. 108, 105805.