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The optimal fuel and emission tax combination for life-cycle emissions under imperfect competition

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Abstract

This study examines the optimal combination of emission and fuel taxes for reducing greenhouse gas emissions in oligopolies. Greenhouse gases are emitted at both the production and consumption stages (life-cycle emissions). When consumers decide how much to use products, heavier taxes should be imposed on fuel consumption than on production. In other words, a strictly positive fuel tax is necessary in addition to an effective emission tax. The combination of taxes for polluters (emission and fuel taxes) may achieve first-best optimality under market power without any explicit subsidies. We also show that the optimal fuel tax converges to zero when the number of producers becomes sufficiently large. This implies that fuel taxes may be redundant in perfectly competitive markets.

Keywords: fuel taxes, emission taxes, optimal taxation, carbon pricing, heterogeneous consumers, vehicle industry

JEL Classification: Q58, Q48, H23, L51

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1 Introduction

In many countries, fuel taxes have a longer history and are more common than carbon taxes. Moreover, effective fuel tax rates are often higher than emissions tax rates (World Bank, 2023). For example, in Japan, an oil consumption tax was introduced in 1903, and a gasoline tax was introduced in 1953, whereas a carbon tax was introduced in 2012. More importantly, the carbon tax rate is much lower than the gasoline tax rate. The Japanese carbon tax rate is ¥ 289 per ton, which is almost nominal. By contrast, the current gasoline tax rate is significant at ¥ 53.8 per liter, which is equivalent to a ¥ 24,000 per ton carbon tax (Ino and Matsumura, 2024). Gasoline taxes exist worldwide. In the US, both federal and state governments impose these taxes. Among the European Union (EU) countries, the Netherlands has the highest gasoline tax at €0.82 per liter, Italy applies the second-highest rate at €0.73 per liter, and Hungary has the lowest gasoline tax, at €0.34 per liter.[1] In China, a refined oil excise tax is applied to gasoline (OECD, 2019).[2]

Fuel taxes cover only limited economic activities that generate CO2 emissions. To tackle the severe risks of climate change, introducing effective carbon pricing that covers all major industries is essential for achieving a decarbonized society. The EU continues to lead efforts toward a low-emission society.[3] Although China and Japan had been progressing toward this goal, they have recently declared their respective commitments: Japan aims to achieve a zero-emission society by 2050, and China by 2060.[4] Carbon pricing is one of the most natural policy measures for this purpose, and we expect it to prevail globally.[5] For example, the Japanese government plans to introduce effective carbon pricing. In the debate over carbon pricing, however, influential Japanese industry associations argue that fuel taxes

[1]See Tax Foundation, `https://taxfoundation.org/gas-taxes-in-europe-2022`.

[2]When considering an electric vehicle (EV) instead of a gasoline vehicle, electricity taxes should be addressed. In Japan, the total electricity consumption tax and levy is ¥ 3.875 per kWh, which is significantly higher than the carbon tax rate.

[3]Despite facing an energy crisis, it has declared its commitment and presented a new report in May 2022 (European Commission, 2022).

[4]See Reuters, `https://jp.reuters.com/article/japan-politics-suga/japan-aims-for-zero-emissions-carbon-neutral-society-by-2050-pm-idUSKBN27B0FB`.

[5]Carbon taxes are reasonable policy tools even when considering lobbying activities by firms. See Hirose at al. (2024).

should be abolished when effective carbon pricing is introduced, to avoid double taxation or uneven (and thus distorted) taxation at the consumption and production stages.

We address whether fuel taxes, such as gasoline taxes, are redundant in the presence of optimal carbon taxes. Unsurprisingly, the government should impose additional fuel taxes despite implementing an effective emission tax to cover the cost of road construction (for tax revenue purposes), or to account for other negative externalities of gasoline consumption (e.g., SOx and NOx emissions, or congestion).[6] In this study, however, by considering life-cycle CO2 emissions generated at both the production and consumption stages, we show that the government should maintain strictly positive fuel tax rates in imperfectly competitive markets, even in the absence of tax revenue purposes or negative externalities other than CO2 emissions. We also show that the optimal fuel tax converges to zero as the number of producers becomes sufficiently large.

Although we believe that these insights have broader applicability, our model is particularly well-suited to the vehicle market, which is typically imperfectly competitive. Throughout a car's life cycle, CO2 is emitted not only during manufacturing but also during its use by consumers. While emissions from the production process depend on the volume of car production, emissions from consumption depend on mileage. We demonstrate that a fuel tax should be imposed in addition to an effective carbon tax when each consumer endogenously determines their mileage.

Pigou's (1932) seminal work popularized the idea that in perfectly competitive markets, the optimal emission tax rate for harmful emissions is equal to the marginal environmental damage caused by emissions, and that this tax policy leads to first-best optimality. The tax that internalizes emissions' negative externality is known as the "Pigovian tax." This implies that without the government imposing fuel taxes, only a carbon tax is required to optimally reduce CO2 emissions.

However, in imperfectly competitive markets, the Pigovian tax is nonoptimal (Buchanan, 1969; Barnett, 1980; Misiolek, 1980; Baumol and Oates, 1988). In a monopoly market,

[6] These damages are key justifications for fuel taxes, particularly due to regional heterogeneity. See Nehiba (2022).

when monopolists' production levels fall below the optimal level, the emission tax rate should be lower than the Pigovian rate to mitigate welfare losses. However, this lower tax rate distorts the incentive for monopolists' emission abatement activities, thereby reducing welfare. Therefore, first-best optimality is not achieved through an emission tax; instead, only second-best optimality can be reached.[7]

This study examines the optimal combination of fuel and emission taxes. In contrast to the aforementioned discussions on emission taxes in imperfectly competitive markets, we focus on how to achieve first-best optimality in the presence of life-cycle emissions. Fowlie et al. (2016) and Preonas (2017) empirically demonstrate the significance of welfare losses caused by the Pigovian tax in imperfectly competitive markets. This suggests that modifying the Pigovian tax policy and mitigating or eliminating this issue through alternative first-best policies could result in significant welfare gains. We show that a combination of a strictly positive fuel tax and an emission tax that is lower than the Pigovian rate achieves the first-best optimality. In other words, a strictly positive fuel tax is indispensable for first-best optimality, even in the presence of an emission tax. The finding implies that a government may maintain fuel taxes even after introducing an effective emission tax and could construct a socially desirable tax structure by utilizing existing taxes.

Ino and Matsumura (2021a) also investigate first-best optimality under imperfect competition, demonstrating that an emission pricing policy based on emission intensity targets yields a first-best solution.[8] However, our analysis differs from this approach. Our study shows that a combination of existing taxes yields a first-best solution rather than proposing

[7]For discussions on oligopolies, see Levin (1985), Ebert (1991/2), Simpson (1995), Katsoulacos and Xepapadeas (1995), Lee (1999), and Xu et al. (2022). They also prove that an emission tax policy cannot achieve first-best optimality.

[8]This is because the production expansion encouraged by the intensity target can counteract the market power of imperfectly competitive firms. More specifically, Ino and Matsumura (2021b) show that a green portfolio standard between two differentiated (green and gray) products can achieve first-best optimality when combined with monetary penalties. Holland et al. (2009) show that a limit on carbon intensity (low carbon fuel standard, LCFS) may increase total energy consumption and calibrate their model to assess the realistic impacts of the standard. Under perfect competition, Holland et al. (2009) remark that "a fuel tax and an energy-based LCFS may be complementary policies. In fact, a fuel tax combined with an energy-based LCFS can attain an efficient allocation (p.110)." More generally, Holland (2009, 2012) shows that a combined consumption tax and intensity standard leads to first-best optimality, as the consumption tax offsets the consumption expansion caused by the intensity standard.

a new scheme. It also demonstrates that the optimal emission tax rate is lower than the Pigovian tax rate, whereas Ino and Matsumura (2021a) find that the optimal tax rate equals the Pigovian rate. Thus, our analysis is a natural extension of the literature on emission taxes in imperfectly competitive markets.

Regarding the vehicle industry, Fullerton and West (2002) adopt a consumption structure similar to ours and investigate a policy mix that includes gasoline tax. They consider heterogeneous consumers who can choose their mileage and other car characteristics.[9] Fullerton and West (2002) focus on emissions at the consumption stage and confirm the first-best optimality of the emission tax under perfect competition. Moreover, their primary interest lies in investigating alternative policies based on car characteristics, in the absence of an emission tax. Conversely, we demonstrate the first-best optimality of a combination of a tax on life-cycle emissions and a fuel tax, under imperfect competition.

In a companion paper to this study, Ino and Matsumura (2024) consider life-cycle emissions and show that the optimal fuel tax is strictly positive in a monopoly market when the monopolist can choose energy efficiency, using the principle of Spence (1975). In Ino and Matsumura (2024), the gasoline tax is beneficial because it mitigates the suboptimal incentives for quality-improving investments by the monopolist. This study differs from Ino and Matsumura (2024) in three important ways. First, this study does not endogenize product quality, meaning that our results do not rely on the principle of Spence (1975). Second, this study endogenizes the consumer's choice of vehicle usage (milage), whereas Ino and Matsumura (2024) do not. In reality, consumers can choose their milage. Restricting vehicle usage is as important as restricting vehicle production for reducing emissions; thus, endogenizing consumers' mileage is crucial. Third, we discuss an n-firm oligopoly model, while the analysis of Ino and Matsumura (2024) does not directly apply to an oligopoly market. This study discusses the relationship between the optimal fuel tax and the degree of competition, demonstrating that competition among producers lowers the optimal fuel

[9] Fullerton and West (2010) extend their analytical model and demonstrate that the welfare improvement achieved by a gas tax alone is 62 percent of that achieved by the ideal Pigouvian tax. For empirical studies on the joint choice of vehicles and mileage, see also West (2004) and West et al. (2017) among others.

tax rate.

The remainder of this paper is organized as follows. Section 2 formulates the model with life-cycle emissions. Section 3 investigates equilibrium outcomes. Section 4 presents our main results on the optimal combination of fuel and emission taxes. Section 5 provides a simulation analysis. Finally, section 6 concludes the paper.

2 The Model

We construct a partial equilibrium model in which greenhouse gas emissions are generated during both the production and consumption processes throughout a products' life cycle. The vehicle market is a good example of this scenario. Our model's conceptualization is depicted in Figure 1.

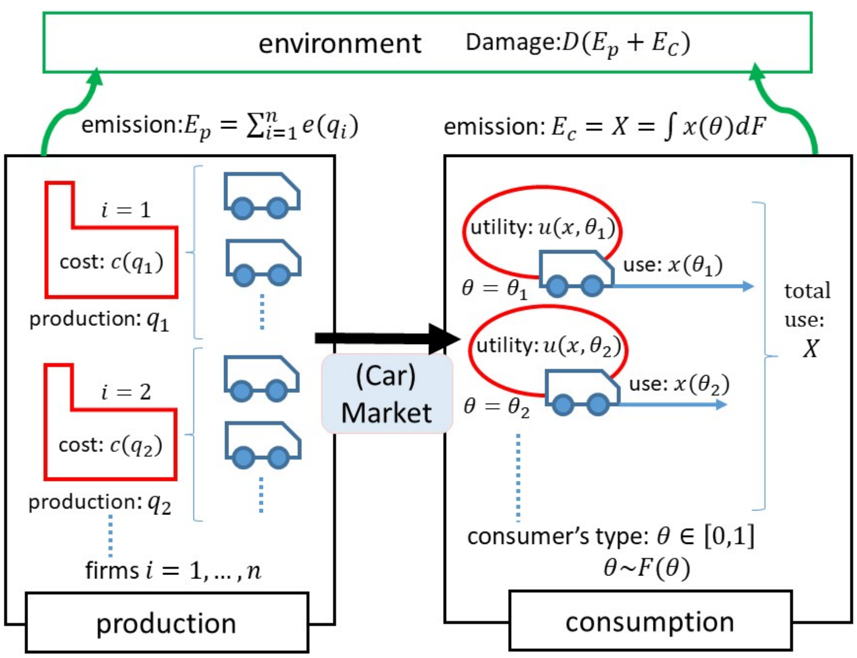

Figure 1: Model with life-cycle emissions

Consumers form a continuum with a total mass of 1 and are price takers. Each consumer decides whether to purchase a product (e.g., a vehicle) and, if they do, selects the product's degree of usage (e.g., mileage). $x(\theta) \geq 0$ is the degree of usage chosen by a consumer of type θ, where $\theta \in [0,1]$ denotes the consumer's valuation parameter (type). Type θ is distributed as $\theta \sim F(\theta)$, with the density function corresponding to F denoted as $f(\theta)$, with $F(0) = 0$, $F(1) = 1$, and $F'(\theta) = f(\theta) > 0$ for $\theta \in [0,1]$. We assume that the hazard rate $f(\theta)/(1-F(\theta))$ is strictly increasing, which is a standard assumption in the literature. One unit of usage (e.g., mileage) requires one unit of fuel (e.g., gasoline) that emits one unit of emission (e.g., CO2).

The valuation (willingness to pay) of type θ for a product is represented by a concave function $u(x,\theta)$, which satisfies $u_x > 0$, $u_{xx} < 0$, and $u_\theta > 0$.[10] Consumers endogenously choose their degree of usage. The total usage of all consumers is denoted by $X \equiv \int x(\theta)dF(\theta)$.

The market is an oligopoly with $n \in \mathbb{N}$ symmetric firms that produce the product (e.g., vehicle) and compete in quantities. Emissions (e.g., CO2) are also generated during the manufacturing process. $e(q_i)$ is the amount of emissions produced by a firm in the production process, where $e' > 0$ and $e'' \geq 0$, and $q_i \geq 0$ represents the production quantity of firm $i = 1, 2, \ldots, n$. $c(q_i)$ represents a firm's cost function, where c satisfies $c' \geq 0$ and $c'' > 0$.

The environmental damage is given by $D(E_L)$, where E_L is the life-cycle emission. We define $E_L \equiv E_P + E_C$, where $E_P \equiv \sum_{i=1}^{n} e(q_i)$ is the emissions generated during production, and $E_C \equiv X$ is the emissions during consumption. We assume $D' \geq 0$ and $D'' \geq 0$.

3 Market equilibrium

3.1 Behavior of consumers

In the following analysis, we first identify the usage level of each consumer type, given that they purchase the product. Then, we examine which consumer type chooses to purchase and derive the corresponding market demand.

[10] In this study, subscripts of functions denote partial derivatives. For example, $u_x \equiv \partial u/\partial x$ and $u_{xx} \equiv \partial^2 u/\partial x^2$.

If a type θ consumer purchases a product, they solve

$$\max_{x} \ u(x, \theta) - p_f x,$$

where p_f represents the unit cost of fuel. Assuming a perfectly competitive fuel market, p_f is given by

$$p_f = \gamma + t_e + t_f,$$

where $t_e \in \mathbb{R}$ is the emission tax, $t_f \in \mathbb{R}$ is the fuel tax, and $\gamma > 0$ is the marginal cost of fuel production. Assuming an interior solution over the relevant range of p_f, the first-order condition for each consumer is

$$u_x(x, \theta) - p_f = 0, \tag{1}$$

from which we obtain the fuel consumption level for type θ, $x^*(\theta) > 0$.[11]

At price $p > 0$, each consumer purchases a product if and only if $u(x^*(\theta), \theta) - p_f x^*(\theta) \geq p$. Setting the condition as an equality, we obtain the marginal consumer who purchases, $\bar{\theta}(p)$, by[12]

$$u(x^*(\bar{\theta}), \bar{\theta}) - p_f x^*(\bar{\theta}) = p. \tag{2}$$

We focus on the interior case satisfying $0 < \bar{\theta} < 1$. Since consumers with type $\theta \geq \bar{\theta}$ purchase the product, market demand is given by $Q(p) \equiv 1 - F(\bar{\theta}(p))$. Thus, the inverse demand function is described as

$$P(Q) \equiv Q^{-1}(Q),$$

[11] It is clear that $\partial x^*/\partial p_f < 0$ by (1). Differentiating (1) with respect to θ yields

$$\frac{\partial x^*}{\partial \theta} = -\frac{u_{x\theta}}{u_{xx}}.$$

Thus, the effect of θ on x^* depends on the sign of $u_{x\theta}$.

[12] Note that the surplus for purchasing a product (left-hand side) is strictly increasing in θ because differentiating it with respect to θ yields

$$u_\theta + (u_x - p_f)\frac{\partial x^*}{\partial \theta} = u_\theta > 0,$$

where we use (1).

where the superscript -1 represents an inverse function. We obtain[13]

$$P'(Q) = -\frac{1}{F'(\bar{\theta})\partial\bar{\theta}/\partial p} = -\frac{u_\theta(x^*(\bar{\theta}), \bar{\theta})}{f(\bar{\theta})} < 0. \tag{3}$$

3.2 Behavior of firms

Each firm i solves its profit maximization problem:

$$\max_{q_i} \; P(Q)q_i - c(q_i) - t_e e(q_i),$$

where $Q = \sum_{i=1}^n q_i$.

Assuming the interior solution (i.e., $q_i > 0$), the first-order condition for this problem is

$$P(Q) + P'(Q)q_i - c'(q_i) - t_e e'(q_i) = 0 \tag{4}$$

for $i = 1, 2, \ldots, n$.[14] This condition uniquely determines the symmetric market equilibrium $q_1^* = q_2^* = \cdots = q_n^* = q^*$.[15] Thus, the equilibrium marginal consumer $\bar{\theta}^*$ is also obtained, as $Q^* = nq^*$ and $\bar{\theta}^*$ have a one-to-one relationship through $Q^* = 1 - F(\bar{\theta}^*)$.

4 Optimal tax combination

4.1 Social optimal

Let $x(\theta)$ be an arbitrary level of type θ's consumption contingent on the purchase of type $\theta \in [0, 1]$. The welfare-maximizing problem is

$$\max_{\{x(\theta)\}_{\theta \in [0,1]}, \{q_i\}_{i=1}^n} W \equiv \int_{\bar{\theta}}^1 u(x(\theta), \theta) f(\theta) \; d\theta - \sum_{i=1}^n c(q_i) - \gamma X - D(E_L),$$

where $E_L = E_P + E_C$, and

$$E_C = X = \int_{\bar{\theta}}^1 x(\theta) f(\theta) \; d\theta. \tag{5}$$

[13]Differentiating (2) with respect to p yields:

$$u_\theta \frac{\partial\bar{\theta}}{\partial p} = 1 \;\therefore \frac{\partial\bar{\theta}}{\partial p} = \frac{1}{u_\theta},$$

where we use the equation in footnote 12.

[14]The second-order condition is also satisfied. See Appendix.

[15]See Appendix for the proof that shows the equilibrium is symmetric and unique.

Note that, from $Q = 1 - F(\bar{\theta})$ with $Q = \sum_{i=1}^{n} q_i$, Q and $\bar{\theta}$ have a one-to-one relationship as

$$\bar{\theta} = F^{-1}(1 - Q).$$

For given $x(\theta)$ and Q (or, $\bar{\theta}$), since the first and third terms in W are constant, $q_1, q_2, \ldots, q_n$ solve

$$\min_{q_1, q_2, \ldots, q_n} \sum_{i=1}^{n} c(q_i) + D(E_L).$$

Thus, by the convexity of $c(\cdot)$, $e(\cdot)$, and $D(\cdot)$, all firms produce the same amount of production at the social optimum (i.e., $q_1 = q_2 = \cdots = q_n = q$). Hence, the welfare-maximizing problem is simplified to

$$\max_{x(\theta), q} W = \int_{\bar{\theta}}^{1} u(x(\theta), \theta) f(\theta)\, d\theta - nc(q) - \gamma X - D(E_L),$$

where $\bar{\theta} = F^{-1}(1 - nq)$, $E_L = ne(q) + X$, and X is given by (5).

The first-order condition with respect to $x(\theta)$ is

$$u_x(x(\theta), \theta) - \gamma - D'(E_L) = 0 \tag{6}$$

for all $\theta \in [0, 1]$, and that with respect to q is

$$u(x(\bar{\theta}), \bar{\theta}) - \gamma x(\bar{\theta}) - c'(q) - [e'(q) + x(\bar{\theta})] D'(E_L) = 0. \tag{7}$$

Let the superscript o denote socially optimal outcomes. For example, we denote the optimal total life-cycle emissions as $E_L^o = E_P^o + E_C^o$, where $E_P^o = ne(q^o)$ and $E_C^o = X^o$.

4.2 Optimal combination of the two tax policies

By comparing market conditions (1), (2), and (4) with optimal conditions (6) and (7), we identify the optimal tax combination (t_e^o, t_f^o) as in the following proposition.

Proposition 1 *The socially optimal outcomes are achieved if and only if*

$$t_e^o = D'(E_L^o) + \frac{P'(Q^o) q^o}{e'(q^o)} < D'(E_L^o),$$
$$t_f^o = -\frac{P'(Q^o) q^o}{e'(q^o)} > 0.$$

Thus, $t_e^o + t_f^o = D'(E_L^o)$ *holds.*

Proof. For necessity, suppose $x(\theta) = x^*(\theta) = x^o(\theta)$ for all θ and $q_i = q^o$ for all i (i.e., $\bar{\theta} = F^{-1}(1-Q) = F^{-1}(1-Q^o) = \bar{\theta}^o$) at market equilibrium. Substituting (6) into (1) yields

$$t_e + t_f = D'.$$

Subtracting (7) from (4) yields

$$-(t_e + t_f)x + P'q - t_e e' + (e' + x)D' = 0,$$

where we use $P = u(x(\bar{\theta}), \bar{\theta}) - p_f x(\bar{\theta})$ from (2). Solving these two equations derives $t_e = t_e^o$ and $t_f = t_f^o$.

For sufficiency, suppose $t_e = t_e^o$ and $t_f = t_f^o$. Substituting $p_f = \gamma + t_e^o + t_f^o$ into (1) yields

$$u_x(x^*(\theta), \theta) - \gamma - D'(E_L^o) = 0, \tag{8}$$

for all θ. Furthermore, substituting $t_e = t_e^o$ into (4) yields

$$P(Q) + P'(Q)q_i - c'(q_i) - \left[D'(E_L^o) + \frac{P'(Q^o)q^o}{e'(q^o)}\right] e'(q_i) = 0. \tag{9}$$

Since $P(Q) = u(x^*(\bar{\theta}), \bar{\theta}) - p_f x^*(\bar{\theta})$ from (2), (9) is rearranged as

$$u(x^*(\bar{\theta}), \bar{\theta}) - \gamma x^*(\bar{\theta}) - c'(q_i) - [e'(q_i) + x^*(\bar{\theta})]D'(E_L^o) \\ + \left[P'(Q)q_i - P'(Q^o)q^o \frac{e'(q_i)}{e'(q^o)}\right] = 0,$$

where $p_f = \gamma + t_e + t_f = \gamma + t_e^o + t_f^o = \gamma + D'(E_L^o)$ is used. As the last term on the left-hand side vanishes if $q_i = q^o$, by using (6) and (7), we find that the market conditions (8) and (9) must be satisfied when $x^*(\theta) = x^o(\theta)$ for all θ and $q_i = q^o$ for all i (i.e., $\bar{\theta} = \bar{\theta}^o$). **Q.E.D.**

The derived formula for t_e^o matches the well-known optimal emission tax for monopolies (Barnett, 1980) and oligopolies (Katsoulacos and Xepapadeas, 1996), which are typically expressed using the price elasticity of demand.[16] The optimal emission tax t_e^o provided in Proposition 1 can be rearranged as

$$t_e^o = D'(E_L^o) - \frac{P(Q^o)}{n|\epsilon(Q^o)|} \frac{dq(e^o)}{de}, \tag{10}$$

[16] The same formulas can also be found earlier in Misiolek (1980) for the monopoly case (i.e., $n = 1$) and in Ebert (1991/2) for the extension to the oligopoly case (i.e., $n \geq 1$).

where $\epsilon(Q) = -P(Q)/\{QP'(Q)\}$ is the price elasticity of demand, and $q(e) = e^{-1}(e)$ is the inverse function of the emission function. To correct the undersupply resulting from market power, the emission tax should be lower than the marginal damage.[17]

However, at the consumption stage, such a low emission tax level does not sufficiently incentivize consumers to reduce their fuel consumption. Therefore, a positive fuel tax, t_f^o, should be used such that $t_e^o + t_f^o = D'$, i.e.,

$$t_f^o = \frac{P(Q^o)}{n|\epsilon(Q^o)|}\frac{dq(e^o)}{de}. \tag{11}$$

The sum of the taxes on emissions is at the Pigouvian level and thus, taxes imposed on fuel consumption should be higher than those on production.

It should be noted that the life-cycle emissions are important for implementing the proposed policy. If e' is close to zero (i.e., most emissions are generated at the consumption stage) or dq/de is extremely large, then t_e^o becomes negative.[18] Introducing such explicit subsidies for polluters would not be politically implementable, and more importantly, a negative emission tax may be unrealistic. However, when e' is not too small (i.e., when nonnegligible emissions are generated at the production stage), the emission tax rate remains strictly positive. This may be an acceptable policy. In Section 5, we specify the functional forms and present a numerical analysis suggesting that the emission tax rate remains strictly positive under plausible conditions.

4.3 Competition and the optimal taxes

From expressions (10) and (11), the term correcting for market power becomes negligible as n approaches infinity. Then, the optimal tax combination converges to the Pigovian tax with a zero-rate fuel tax.[19] The following proposition states this formally.

Proposition 2 *As $n \to \infty$, $t_e^o \to D'(E_L^o)$ and $t_f^o \to 0$.*

[17] It should be noted that the emission tax rate differs from the rate in the literature (such as Barnett (1980) and Katsoulacos and Xepapadeas (1996)), which analyze second-best taxation under the assumption that the emission tax is the only policy instrument, although the formula is the same as ours. In our analysis, t_e^o is evaluated at the first-best outcomes achieved by the combination of emission and fuel taxes.

[18] The traditional second-best emission tax for monopolies and oligopolies can also be negative.

[19] In the simulation in Section 5, we demonstrate that the optimal emission tax increases, whereas the optimal fuel tax decreases, as the number of producers grows.

Proof. See Appendix. **Q.E.D.**

These outcomes, observed in a large number of firms, are consistent with those under perfect competition. Let us assume that the firms are price takers. Then, each firm's first-order condition is $p - c'(q) - t_e e'(q) = 0$, where $p = u(x^*(\bar{\theta}), \bar{\theta}) - p_f x^*(\bar{\theta})$ from (2). Therefore, together with (1), and by comparing with (6) and (7), we find that the Pigovian tax $t_e = D'(E_L^o)$ and $t_f = 0$ attain the optimal outcomes. Under perfect competition, to correct the externality of life-cycle emissions, the government need not impose fuel taxes; only an emission tax is required.[20]

5 Simulation

5.1 Settings and basic results

Suppose a quadratic utility, $u(x, \theta) = (1+\theta)x - x^2/2$, and a uniform distribution of $\theta \in [0, 1]$ (i.e., $F' = 1$). Under this specification, we obtain $P'(Q) = -u_\theta = -x^*(\bar{\theta})$ from (3), where $Q = 1 - \bar{\theta}$. The production cost is fixed at $c(q_i) = 0.5q_i + q_i^2/2$ in this simulation.[21] We assume that $e(q_i) = \beta q_i$ and $D(E_L) = dE_L$, where both β and d are positive constants. Under this specification, we obtain the socially optimal outcomes as

$$\bar{\theta}^o = 1 - nq^o = \frac{\sqrt{2n^2(0.5 + d\beta) + 2n(2 - (d + \gamma)) + 1} - n(1 - (d + \gamma)) - 1}{n}$$

and $x^o(\theta) = 1 + \theta - (d + \gamma)$. Note that under the optimal tax combination provided in Proposition 1, the market equilibrium outcomes coincide with these optimal ones.

The top-left (bottom-left) panel of Figure 2 depicts the optimal tax levels (the ratio of

[20] This result holds because a single externality from greenhouse gases is considered, and an emission tax is properly imposed on emissions from both consumption and production. Walls and Palmer (2001) show that if several types of pollution are considered throughout a product's life-cycle, an equal number of pollution taxes corresponding to the types of pollution is required to attain the optimum.

[21] According to the estimation of Berry et al. (1995) using data from 1971 to 1990, the marginal costs of automobiles are 4,586 dollars for a Ford Escort and 7,094 dollars for a Ford Taurus. Since the prices of new cars today are nearly twice what they were in 1980 (`https://www.in2013dollars.com/New-cars/price-inflation/`), if $c'(0) = 0.5$ is interpreted as 10,000 dollars, it corresponds to 0.05 dollars per mile, assuming a vehicle's lifetime mileage is 200,000 miles. Given that the average fuel economy for all vehicles is about 25 miles per gallon of gasoline (`https://afdc.energy.gov/data/10310`), the marginal cost of gasoline is assumed to be 2 \$/gallon, it corresponds to $2 \div 25 = 0.08$ \$/mile. For this reason, we primarily adopt $\gamma = 0.8$ in our later simulations. See also Footnote 22.

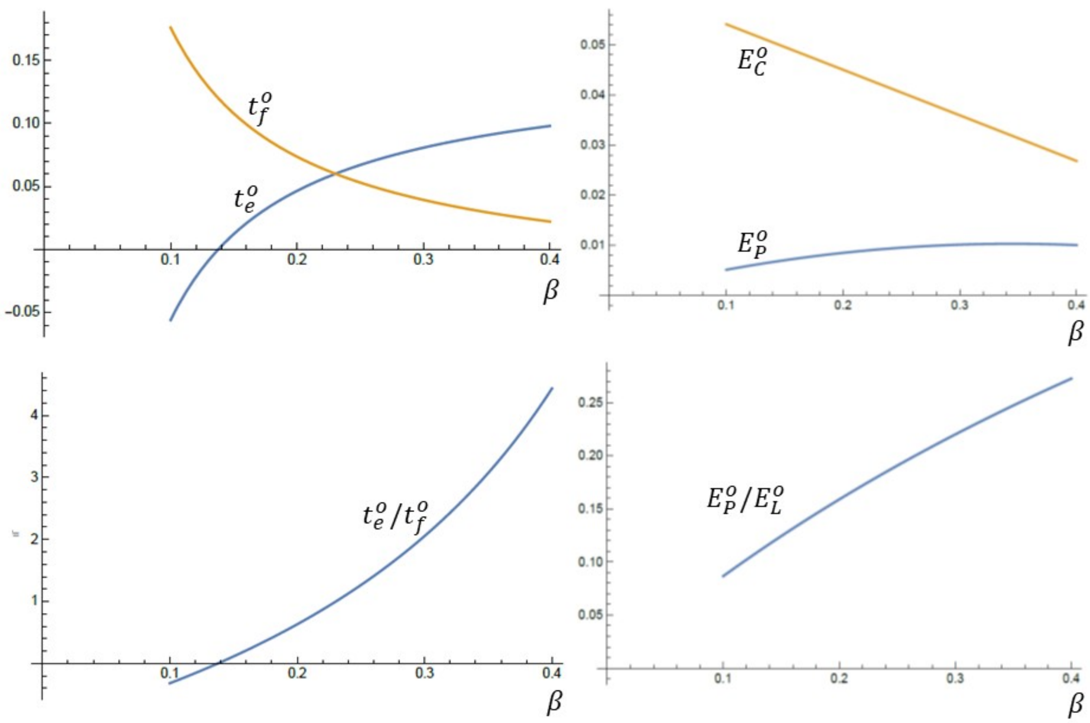

Figure 2: The optimal taxes and emissions (vertical axis) for $0.1 < \beta < 0.4$ (horizontal axis). Depicted in the case with $d = 0.12$, $\gamma = 0.80$, and $n = 3$.

emission and fuel taxes) for various values of β when the market is a triopoly ($n = 3$). The other parameters are set at $d = 0.12$ and $\gamma = 0.80$.[22] The optimal emission tax level t_e^o increases with β and becomes positive when β is approximately greater than 0.14. When β is high (low), the optimal fuel tax level t_f^o is low (high), and thus, the relative size of the emission tax to the fuel tax t_e^o/t_f^o is high (low), as shown in the bottom left panel.

The amounts of emissions generated under these optimal taxes are depicted in the right panels of Figure 2. Emissions from the consumption stage, E_C^o, decrease with β, but emissions from the production stage, E_P^o, do not necessarily follow the same pattern, as seen in the top-right panel. This is because a higher β decreases total car production due to the higher cost, including the emission tax, but increases emissions per car produced. Thus, the proportion of emissions from the production process in total emissions, E_P^o/E_L^o, increases in β, reaching about 12% when $\beta = 0.14$. In the case described here, t_e^o is positive when emissions from production exceed approximately 12%.

5.2 Effects of competition

The emission tax rate is lower than the Pigovian level because a lower tax rate mitigates the distortion caused by suboptimal production. This distortion becomes more important when competition among firms is weak. Thus, the level of competition affects the emission tax rate. Figure 3 depicts the emission tax levels for various numbers of firms n while keeping the other parameters the same as in Figure 2. As shown in the top-left panel, the optimal emission tax level, t_e^o, is higher for larger values of n since the term correcting for market power decreases with competition. As predicted by Proposition 2, as n increases,

[22] The ratio d/γ is 15%, which is not far from the actual ratio. Regarding the marginal social cost of emissions d, Nordhaus (2017) estimates that the social cost of carbon is 31 dollars per ton of CO2 in 2010 US$ for 2015. This cost is converted to 0.275 $/gallon, as CO2 emissions from a gallon of gasoline amount to 8.887 kg (`https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle`). Regarding the marginal cost of fuel γ, U.S. all grades retail gasoline prices are between 2.1 and 2.9 $/gallon in 2015 (`https://www.eia.gov/dnav/pet/hist/leafhandler.ashx?n=pet&s=emm_epm0_pte_nus_dpg&f=m`, accessed Oct. 14, 2024). Since the tax paid on a gallon of gasoline is about 0.5 dollar and the GDP deflator for 2010, with 2015 as the base year, is about 0.92 in the U.S., if we regard $(price - 0.5) \times 0.92$ as the marginal cost of gasoline, it falls between 1.5 and 2.2 $/gallon. Based on these values, the ratio of the marginal social cost of carbon to the marginal cost of gasoline is almost 13% to 18%. The value of d in this simulation may be too small, and the shadow price of carbon may be much larger than 31$ per ton. However, we can demonstrate that qualitatively the same result holds in this simulation when d is much larger, and that t_e^o is more likely to be positive when d is larger (see Figure 4).

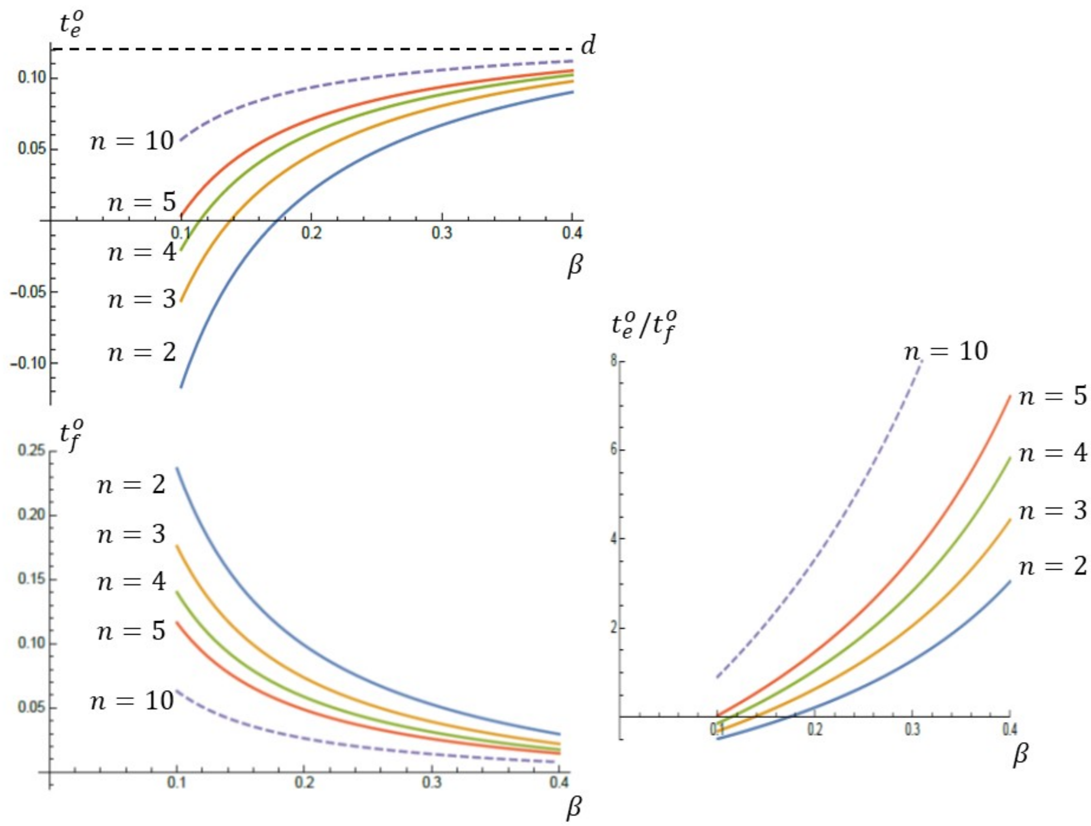

Figure 3: The optimal emission and fuel taxes (vertical axis) for $0.1 < \beta < 0.4$ (horizontal axis). Depicted in the case with $d = 0.12$, $\gamma = 0.80$, and various n.

the correction term for market power diminishes, bringing t_e^o closer to the Pigovian level d. Consequently, as seen in the bottom-left panel, the fuel tax, $t_f^o = d - t_e^o$ decreases and approaches zero. Thus, the relative size of the emission tax to the fuel tax, t_e^o/t_f^o, is higher for larger values of n, as shown in the right panel.

In the simulation presented in Figure 3, we calculate the threshold β, $\underline{\beta}$, such that $t_e^o > 0$ when $\beta > \underline{\beta}$. We also calculate E_P^o/E_L^o when $\beta = \underline{\beta}$. These values are shown in Table 1. This table shows that the threshold value of E_P^o/E_L^o for $n = 3$ is approximately 12% and that it is less than 10% when n is greater than 4.

According to Buberger et al. (2022), who investigate vehicles' life-cycle emissions based on a broad selection of commercially available passenger cars, production emissions from

n	1	2	3	4	5	6	7	8	9	10
$\underline{\beta}$	.234	.173	.138	.114	.097	.085	.075	.068	.061	.056
E_P/E_L (%)	18.0	14.1	11.5	9.8	8.5	7.5	6.7	6.1	5.5	5.1

Table 1: Threshold for the emission tax to be positive: The unit emissions per car production $\underline{\beta}$ such that $t_e^o = 0$ and the ratio of production emissions E_P^o/E_L^o at such β.

Internal Combustion Engine Vehicles (ICEVs) account for 15 to 19% of their life-cycle greenhouse gas emissions. Moreover, those from Battery Electric Vehicles (BEVs) account for 58%, primarily because battery production is energy-intensive.[23] Therefore, the above-mentioned simulation results indicate that the optimal policy combination investigated in this study may be implementable and that the constraint of a positive emission tax may not be binding.

It is worth noting that since production emissions constitute a small portion of ICEVs' life-cycle emissions, t_e^o/t_f^o is low, as seen in the right panel of Figure 3. Thus, for gasoline vehicles, it may be reasonable for the carbon tax rate to be significantly lower than the gasoline tax rate. However, for BEVs' life cycle, since production emissions are significant, t_e^o/t_f^o should be higher. This implies that in a future market where EVs are prevailing, the carbon tax should be higher, and the electricity consumption tax should be lower than the gasoline tax.

5.3 Costs of emissions and fuels

The marginal environmental damage d affects the optimal emission tax rate t_e^o. The top panel of Figure 4 shows that the curve of t_e^o (t_f^o) shifts upward (downward) as d increases. Since $t_e^o = d - t_f^o$, the increase in t_e^o is greater than the increase in d by the amount of decrease in t_f^o. An increase of d reduces the optimal production level, which increases the product's price elasticity. This reduces the need to correct inefficiencies caused by firms' market power, and thus, the government can raise the emission tax.

The marginal cost of fuel γ has a qualitatively similar effect on the level of optimal taxes,

[23]These figures vary across studies, with both larger and smaller values being reported, reflecting differing perspectives. For smaller values, Ambrose et al. (2020) report that the proportion of emissions during production is 10% for an ICEV and 40% for a BEV.

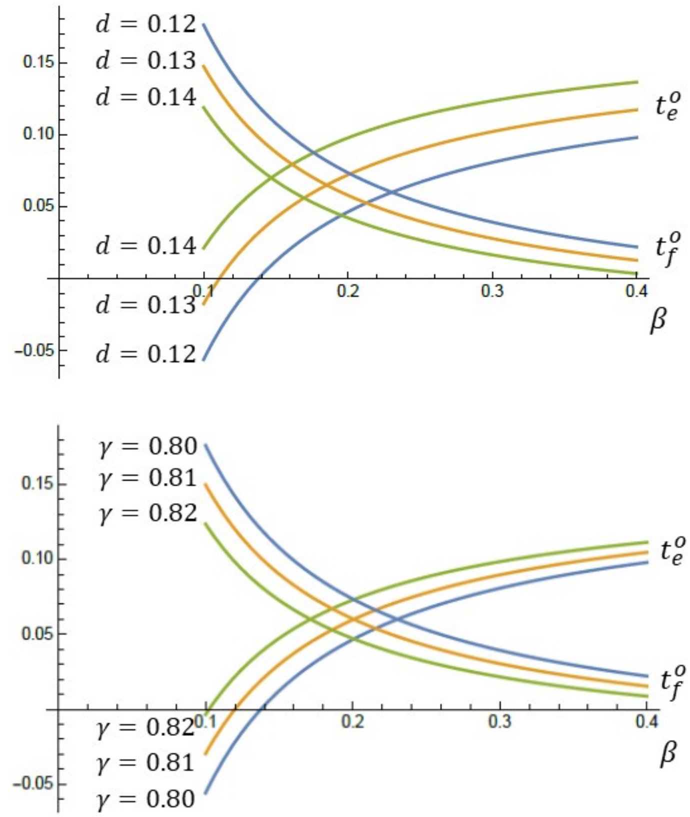

Figure 4: The optimal emission and fuel taxes (vertical axis) for $0.1 < \beta < 0.4$ (horizontal axis). Depicted in the case with $n = 3$, $\gamma = 0.80$, and various d; or the case with $n = 3$, $d = 0.12$, and various γ.

as seen in the bottom panel of Figure 4. This is because an increase in γ directly raises the fuel price, $p_f = \gamma + t_e^o + t_f^o$, similarly to the effect of d. However, it should be noted that an increase in d indirectly affects the fuel price through the changes in tax rates. Changes in γ do not affect $t_e^o + t_f^o$ because it is equal to d, but they do affect t_e^o and t_f^o. Thus, when γ increases, the increase in t_e^o is offset by a decrease in t_f^o.

Table 2 simulates the level of t_f^o in the case where $d = 0.12$ and $\beta = 0.20$.[24] Since the fuel price under the optimal policy is $p_f^o = \gamma + 0.12$, the fuel price change described in the

[24]When $\beta = 0.20$, in the cases simulated in the table, the ratio of production emissions is between 15.3% and 16.3%, which is consistent with the result of Buberger et al. (2022).

n	1	2	3	4	5	$\cdots$	10
$p_f^o = 0.87$				.112 (12.8%)	.093 (10.7%)	$\cdots$	.050 (5.8%)
$p_f^o = 0.88$				.101 (11.5%)	.084 (9.5%)	$\cdots$	.045 (5.1%)
$p_f^o = 0.88$				.101 (11.5%)	.084 (9.5%)	$\cdots$	.045 (5.1%)
$p_f^o = 0.89$			.114 (12.8%)	.090 (10.2%)	.075 (8.4%)	$\cdots$	.041 (4.6%)
$p_f^o = 0.90$			.100 (11.1%)	.080 (8.9%)	.066 (7.4%)	$\cdots$	.036 (4.0%)
$p_f^o = 0.91$		.117 (12.8%)	.087 (9.5%)	.069 (7.6%)	.057 (6.3%)	$\cdots$	.031 (3.4%)
$p_f^o = 0.92$		.099 (10.7%)	.074 (8.0%)	.059 (6.4%)	.049 (5.3%)	$\cdots$	.026 (2.9%)
$p_f^o = 0.93$		.081 (8.7%)	.060 (6.5%)	.048 (5.2%)	.040 (4.3%)	$\cdots$	.022 (2.3%)
$p_f^o = 0.94$	.096 (10.2%)	.063 (6.7%)	.047 (5.0%)	.038 (4.0%)	.031 (3.3%)	$\cdots$	.017 (1.8%)
$p_f^o = 0.95$	.069 (7.3%)	.046 (4.8%)	.034 (3.6%)	.027 (2.9%)	.023 (2.4%)	$\cdots$	.012 (1.3%)
$p_f^o = 0.96$	.043 (4.4%)	.028 (2.9%)	.021 (2.2%)	.017 (1.8%)	.014 (1.5%)	$\cdots$	.008 (0.8%)
$p_f^o = 0.97$	.016 (1.7%)	.011 (1.1%)	.008 (0.8%)	.006 (0.7%)	.005 (0.6%)	$\cdots$	.003 (0.3%)

Table 2: The levels of optimal fuel tax for various fuel prices p_f^o ($0.75 < \gamma < 0.85$) and various n: Derived under $d = 0.12$ and $\beta = 0.20$; Percentages in the parentheses are the proportions in the fuel prices, t_f^o/p_f^o; Blanks are the cases with $t_e^o < 0$.

first column corresponds to the change in γ. For instance, when $p_f^o = 0.92$ ($\gamma = 0.80$) under triopoly, $t_f^o = 0.074$, which is 8% of the fuel price. The value of t_f^o and the proportion t_f^o/p_f^o are lower for a higher fuel price since t_f^o decreases with γ (as shown in the bottom panel of Figure 4).

As measured by $|dt_f^o/d\gamma| = -dt_f^o/d\gamma$, shown in Figure 5, t_f^o is less sensitive to γ when the market is more competitive (i.e., n increases). For instance, let us focus on the case where the fuel price is initially $p_f^o = 0.92$ ($\gamma = 0.80$). When $n = 3$, if the fuel price increases by 1% (γ increases by 0.0092), t_f^o decreases by about 1.3% of the initial fuel price; when

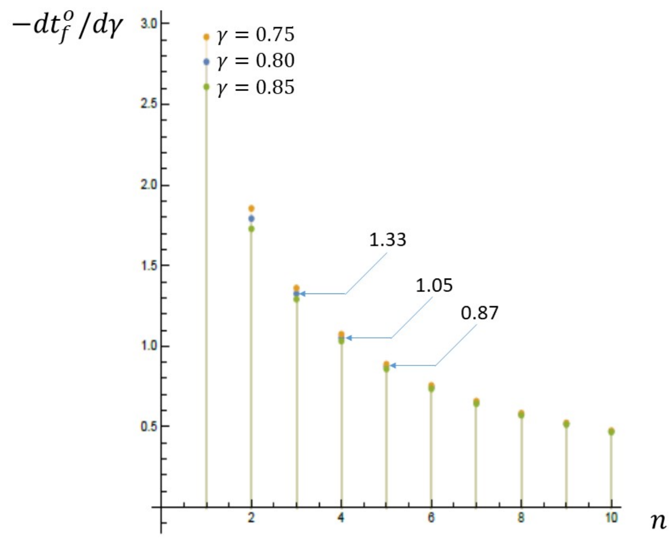

Figure 5: The sensitivity of the optimal fuel tax to the fuel price $|dt_f^o/d\gamma|$ (vertical axis) for various n (horizontal axis). Depicted in the case with $d = 0.12$, $\beta = 0.20$, and $\gamma = 0.75, 0.80, 0.85$.

$n = 4$, it decreases by about 1.1%, and when $n = 5$, by about 0.9% of that.[25]

6 Concluding remarks

This study investigates the optimal combination of emission and fuel taxes in an oligopoly market, considering life-cycle emissions and heterogeneity among consumers. When consumers choose how much they use products (e.g., the mileage of vehicles), a strictly positive optimal fuel tax is required. In other words, heavier taxes should be imposed on fuel consumption than on production. We believe this scenario is realistic in the vehicle industry, which is one of the major sources of CO2 emissions.

If a production subsidy is available, the first-best outcome can also achieved by combining the subsidy with emission taxes (Baumol and Oates, 1988). However, introducing direct

[25] These ratios of the contribution of the fuel tax to the price change ($-1.3, -1.1, -0.9$) are approximated by $dt_f^o/d\gamma$ (evaluated at $\gamma = 0.80$) as shown in Figure 5 since

$$\frac{\Delta t_f/p_f}{\Delta p_f/p_f} = \frac{\Delta t_f}{\Delta p_f} = \frac{\Delta t_f}{\Delta \gamma},$$

where Δ represents the change in each value.

subsidies to polluters is politically difficult. By contrast, a combination of taxes for polluters (i.e., emission and fuel taxes) might be more acceptable. Furthermore, fuel (gasoline) taxes have already been imposed in many countries. Therefore, our analysis presumably has practical policy implications in these respects.

This study focus solely on emission and fuel taxes, without investigating other policy measures. Fuel taxes may promote the switch from grey products to green products, and thus, may serve as a substitute for a green portfolio standard, such as a zero-emission vehicle program.[26] Moreover, tax revenue under the first-best scheme may bring double dividends or be used for subsidies supporting green transformation.[27] The way other environmental policy measures affect the optimal combination of emission and fuel taxes under life-cycle emissions should be investigated in future research.

This study assumes that firms are profit maximizers. However, firms' objectives may deviate from profit-maximization due to specific ownership structures. Firms may also consider environmental corporate social responsibility. The literature on the relationship between non-profit-maximizing objectives and environmental issues has become extensive and diverse.[28] A systematic analysis of this issue should also be considered in future research.

[26] See Ino and Matsumura (2021b) and the studies cited therein.

[27] According to Laffont (2005), the excess burden of taxation is estimated to be around 0.3 (one dollar tax revenue yields a 30-cent deadweight loss) in developed countries and more than 1 in developing countries. For a comprehensive analysis of rebating emission-tax revenues, see Bohringer et al. (2023).

[28] For recent discussions on this topic, see Bárcena-Ruiz et al. (2017, 2023), Fukuda and Ouchida (2020), Hirose and Matsumura (2022, 2023), Tomoda and Ouchida (2023), and Xing and Lee (2024a,b).

Appendix

Second-order condition of the problem (4)

Let $Q_{-i} = Q - q_i$ and define θ_{-i} such that satisfies $Q_{-i} = 1 - F(\theta_{-i})$. Then, since $Q = 1 - F(\bar{\theta})$, we obtain

$$q_i = Q - Q_{-i} = F(\theta_{-i}) - F(\bar{\theta}).$$

Thus, choosing q_i for given Q_{-i} is equivalent to choosing $\bar{\theta}$ for given θ_{-i}. Because of this relationship, the firm's problem can be stated as maximization with respect to $\bar{\theta}$, instead of that with respect to q_i as

$$\max_{\bar{\theta}}\ P(1 - F(\bar{\theta}))(F(\theta_{-i}) - F(\bar{\theta})) - c(F(\theta_{-i}) - F(\bar{\theta})) - t_e e(F(\theta_{-i}) - F(\bar{\theta})).$$

The first-order condition is

$$-f(\bar{\theta})\left[P - c' - t_e e' - \frac{u_\theta}{f(\bar{\theta})}(F(\theta_{-i}) - F(\bar{\theta}))\right] = 0, \tag{12}$$

where we used $P' = -u_\theta/f$ by (3). Denoting the terms in the bracket as $H(\bar{\theta})$, the second-order condition can be written as

$$-f(\bar{\theta})H'(\bar{\theta}) - f'(\bar{\theta})H(\bar{\theta}) = -f(\bar{\theta})H'(\bar{\theta}) < 0,$$

where the equality is obtained by the first-order condition, $H(\bar{\theta}) = 0$. The second order condition is satisfied if $H'(\bar{\theta}) > 0$ holds.

$H'(\bar{\theta}) > 0$ is shown as follows. We have

$$H'(\bar{\theta}) = -f(\bar{\theta})(P' - c'' - t_e e'') - \frac{\partial}{\partial\bar{\theta}}\left[u_\theta \frac{F(\theta_{-i}) - F(\bar{\theta})}{f(\bar{\theta})}\right], \tag{13}$$

where the first term is strictly positive by our assumptions. Regarding the second term, we obtain

$$\begin{aligned}&\frac{\partial}{\partial\bar{\theta}}\left[u_\theta(x^*(\bar{\theta}), \bar{\theta})\frac{F(\theta_{-i}) - F(\bar{\theta})}{f(\bar{\theta})}\right] \\ &\qquad = u_\theta \frac{\partial}{\partial\bar{\theta}}\frac{F(\theta_{-i}) - F(\bar{\theta})}{f(\bar{\theta})} + \frac{F(\theta_{-i}) - F(\bar{\theta})}{f(\bar{\theta})}\left[\frac{u_{xx}u_{\theta\theta} - (u_{x\theta})^2}{u_{xx}}\right] < 0\end{aligned}$$

because $u_{xx} < 0$, $u_{xx}u_{\theta\theta} - (u_{x\theta})^2 \geq 0$ ($\because$ u is concave) and the hazard rate $f/(1-F)$ is strictly increasing. Note that

$$\frac{\partial}{\partial\bar{\theta}}\frac{1-F(\bar{\theta})}{f(\bar{\theta})} < 0 \Rightarrow \frac{\partial}{\partial\bar{\theta}}\frac{F(\theta_{-i})-F(\bar{\theta})}{f(\bar{\theta})} < 0$$

because if $f' < 0$,

$$\frac{\partial}{\partial\bar{\theta}}\frac{F(\theta_{-i})-F(\bar{\theta})}{f(\bar{\theta})} = -1 - \frac{f'}{f^2}q_i < -1 - \frac{f'}{f^2}Q = \frac{\partial}{\partial\bar{\theta}}\frac{1-F(\bar{\theta})}{f(\bar{\theta})} < 0$$

and if $f' \geq 0$,

$$\frac{\partial}{\partial\bar{\theta}}\frac{F(\theta_{-i})-F(\bar{\theta})}{f(\bar{\theta})} = -1 - \frac{f'}{f^2}q_i < 0.$$

Symmetry and uniqueness of market equilibrium

First, we prove that a market equilibrium is symmetric. By (4), for all i,

$$q_i^* = \frac{1}{P'(Q^*)}[P(Q^*) - c'(q_i^*) - t_e e'(q_i^*)],$$

where $Q^* = \sum_{i=1}^n q_i^*$. Suppose that $\exists i, j$ $(i \neq j)$ such that $q_i^* \neq q_j^*$. Then, if $q_j^* \gtrless q_i^*$,

$$q_i^* \lesseqgtr \frac{1}{P'(Q^*)}[P(Q^*) - c'(q_j^*) - t_e e'(q_j^*)] = q_j^*$$

by $c'' > 0$ and $e'' \geq 0$, which leads contradiction.

Second, we prove that the market equilibrium is unique. The symmetric equilibrium output q^* can be expressed as

$$q^* = \frac{Q^*}{n} = \frac{1-F(\bar{\theta}^*)}{n}.$$

By substituting this into the alternative expression (12) of the first-order condition, $\bar{\theta}^*$ must solve

$$P(1-F(\bar{\theta}^*)) - c'(q^*) - t_e e'(q^*) - \frac{u_\theta(x^*(\bar{\theta}^*), \bar{\theta}^*)}{f(\bar{\theta}^*)}q^* = 0. \tag{14}$$

Differentiating the left-hand side with respect to $\bar{\theta}^*$ yields

$$-f(\bar{\theta}^*)\left(P' - \frac{c''}{n} - t_e\frac{e''}{n}\right) - \frac{1}{n}\frac{\partial}{\partial\bar{\theta}}\left[u_\theta\frac{1-F(\bar{\theta}^*)}{f(\bar{\theta}^*)}\right] > 0,$$

where the inequality is obtained by a similar manipulation to H' in (13). Thus, because the left-hand side of (14) monotonically increase in $\bar{\theta}^*$, the equilibrium $\bar{\theta}^*$, which satisfies (14), must be unique, and so $q^* = (1 - F(\bar{\theta}^*))/n$ must hold.

Proof of Proposition 2

It suffices if

$$\lim_{n\to\infty} \frac{P'(Q^o)q^o}{e'(q^o)} = 0.$$

This is satisfied by the following two facts.

First, $\lim_{n\to\infty} q^o = 0$. If this equality does not hold, there exists sufficiently large n such that $Q^o = nq^o \geq 1$, which contradicts the assumption of interior solution, $Q^o = Q^* < 1$ ($\bar{\theta}^o = \bar{\theta}^* > 0$), under the optimal taxes (t_e^o, t_f^o).

Second, $P'(Q^o)/e'(q^o)$ is bounded regardless of n. Consider $x^*(\theta)$ demanded when the fuel price is γ and let $\hat{x}(\gamma)$ be the maximized value of it with respect to $\theta \in [0, 1]$. Note that $\hat{x}(\gamma)$ does not depend on n. Then, $x^o(\bar{\theta}^o) \leq \hat{x}(\gamma)$ because $p_f^o = \gamma + t_e^o + t_f^o = \gamma + D'(E_L^o) \geq \gamma$ and $\partial x^*/\partial p_f < 0$ (Footnote 11). Thus, by (3), $P'(Q^o) < 0$ and

$$P'(Q^o) = -\frac{u_\theta(x^o(\bar{\theta}^o), \bar{\theta}^o)}{f(\bar{\theta}^o)} \geq -\max_{\substack{x\in[0,\hat{x}(\gamma)]\\ \theta\in[0,1]}} \frac{u_\theta(x, \theta)}{f(\theta)}$$

for all n, where the last maximum exists because u_θ/f is continuous in (x, θ) on the compact cube $[0, \hat{x}(\gamma)] \times [0, 1]$. Moreover, $e'(q^o) \geq e'(0)$ holds for all n by $e'' \geq 0$. Thus, $P'(Q^o)/e'(q^o)$ is bounded.

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