DISCUSSION PAPER SERIES

Discussion paper No. 243

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

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April 2023

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

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April 4, 2023

Abstract

This study examines the optimal combination of emission and fuel taxes for reducing greenhouse gas emissions in a monopoly market. Greenhouse gases are emitted during both production and consumption stages (life-cycle emissions). We present two cases in which a government should impose an additional strictly positive fuel tax, even when an optimal emission tax is introduced: the case of consumers selecting the fuel consumption and case of a producer selecting fuel efficiency endogenously. The results imply that a government may maintain fuel taxes even after introducing an effective emission tax and be able to construct a socially desirable tax structure by using existing taxes.

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

JEL Classification: Q58, Q48, H23, L51

*We acknowledge financial support from JSPS KAKENHI (Grant Numbers 21K01398 and 18K01638). We thank Editage for English language editing. The authors declare that there's no financial/personal interest or belief that could affect their objectivity. The usual disclaimer applies.

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Highlights

- The optimal combination of fuel and emission taxes is investigated.
- Life-cycle emissions are generated both in production and consumption processes.
- Under perfect competition, fuel tax is unnecessary for attaining the optimum.
- Under imperfect competition, the optimal fuel tax rate is strictly positive.
- The government should impose both emission and fuel taxes.

1 Introduction

Global economy faces the risk of climate change and vulnerability in fossil fuel supply, and shifting from fossil fuels and decarbonization have become increasingly critical for a sustainable economy (Victor, 2022). The European Union (EU) continues to lead the mission for a low emission society.[1] Although the US, China, and Japan had been logging into it, they have recently declared that the US and Japan will pursue the goal of a zero-emission society by 2050, and China by 2060.[2] US President Joe Biden signed a new executive order for the commitment to nationally reach net zero emissions by 2050.[3] In February 2022, the Japanese Ministry of Economy, Trade and Industry (METI) announced the GX (green transformation) League Basic Concept, inviting companies to endorse it.[4] Carbon pricing is one of the most natural policy measures to reduce CO2 emissions and promote decarbonization; thus, the Japanese government plans to introduce effective carbon pricing.

Currently, the Japanese carbon tax rate is significantly low (¥ 289 per ton), thus implying that this tax is insufficient to induce substantial emission reduction. Therefore, the Japanese government is discussing a new carbon pricing system. Conversely, the current gasoline tax rate is high (¥ 53.8 per litter, which is equivalent to ¥ 24000 per ton carbon tax).[5] Therefore, abolishment of gasoline taxes is often insisted while introducing an effective carbon tax, to avoid double taxation.

This study discusses whether the government should abolish fuel taxes like gasoline tax, when an effective carbon tax is introduced. Unsurprisingly, the government should impose

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

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

[3] Energy live news, https://www.energylivenews.com/2021/01/28/biden-wants-carbon-free-electricity-by-2035/

[4] METI, https://www.meti.go.jp/english/press/2022/0201_001.html

[5] Gasoline taxes exist worldwide. In the US, both federal and state governments impose these taxes, in EU, the Netherlands has the highest gasoline tax at €0.82 per litter, Italy applies the second highest rate at €0.73 per litter, and Hungary has the lowest gasoline tax, at €0.34 per litter (https://taxfoundation.org/gas-taxes-in-europe-2022/). In China, a refined oil excise tax is applied to gasoline. (https://www.oecd.org/tax/tax-policy/taxing-energy-use-china.pdf). On 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, and is significantly higher than the carbon tax rate.

additional fuel taxes despite exercising an effective emission tax to cover the cost of road construction (tax revenue purpose), or if consuming gasoline yields other negative externalities (e.g., SOx and NOx emissions). In this study, by considering life-cycle CO2 emissions generated at both the production and consumption stages, we show that despite not having a tax revenue purpose or negative externalities other than CO2 emissions, the government should maintain strictly positive fuel tax rates in imperfectly competitive markets.

Although we believe that the insights have much broader generality, our model is a good representation of the vehicle market, which is usually imperfectly competitive. In a car's lifecycle, CO2 is emitted not only while it is manufactured, but also when a consumer drives it. While the emissions from the production process depend on the quantity of car production, the emissions from the consumption process depend also on the mileage and the fuel efficiency of the cars. We show that a fuel tax should be imposed additionally to the effective carbon tax in either case where each consumer endogenously selects their mileage or a producer endogenously selects fuel efficiency, whereas the fuel tax is redundant if the both are exogenous.

Pigou's (1932) seminal work popularized 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 "Pigovian tax." This implies that, without the government imposing fuel taxes, only a carbon tax is required to reduce CO2 optimally.

However, in imperfectly competitive markets, the Pigovian tax is nonoptimal (Buchanan, 1969; Barnett, 1980; Misiolek, 1980; Baumol and Oates, 1988). In a monopoly market, when the monopolist's production levels fall below the optimal level, to mitigate welfare losses the emission tax rate should be lower than the Pigovian rate. However, this low tax rate distorts the incentive for monopolists' emission abatement activities, thereby reducing welfare. Therefore, the first-best optimality is not achieved by an emission tax (second-best optimality).[6]

This study discusses the optimal combination of fuel and emission taxes. In contrast to the aforementioned discussions on emission tax in monopoly 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 show the significance of welfare loss caused by Pigovian tax in an imperfectly competitive market. This implies that, modifying the Pigovian tax policy and mitigating or eliminating this problem using alternative first-best policies, might cause significant welfare gains. We show that the combination of the strictly positive fuel tax and the emission tax that is lower than the Pigovian rate achieve the first-best optimality. In other words, the strictly positive fuel tax is indispensable for the first-best optimality, even in the presence of emission tax.

Ino and Matsumura (2021b) also investigate first-best optimality under imperfect competition, portraying that an emission pricing policy based on emission intensity targets yields the first-best solution; however, our analysis differs from this approach. Our study shows that a combination of existing taxes yields the first-best solution, instead of proposing a new scheme. It also shows that the optimal emission tax rate is lower than the Pigovian tax rate, whereas in Ino and Matsumura (2021b), the optimal tax rate is the Pigovian rate. Thus, our analysis is a natural extension of the literature on emission taxes in monopoly markets.

Regarding the vehicle industry, Fullerton and West (2002) adopt a consumption structure similar to ours, and investigate the policy mix including gasoline tax. They consider heterogeneous consumers who can choose miles and other car characteristics.[7] We consider cases where heterogeneous consumers choose consumption (miles) and the producer chooses fuel efficiency, endogenously. Fullerton and West (2002) focus on emissions at the consumption stage and confirm first-best optimality of the emission tax under perfect competition.

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

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

Moreover, their primary interest is to investigate alternative policies driven by car characteristics, in the absence of the emission tax. Conversely, we show first-best optimality of the combination of the tax on life-cycle emissions and fuel tax, under imperfect competition.

The remainder of this paper is organized as follows. Section 2 formulates the basic model with life-cycle emissions and a monopolistic producer. Section 3 extends this model by endogenizing heterogeneous consumers' fuel consumption. Section 4 extends this model by endogenizing the product's fuel efficiency. Both sections 3 and 4 show the optimal fuel tax rate to be strictly positive. Finally, section 5 concludes the paper.

2 The Model

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

2.1 Basic settings

Consumers are a continuum of mass 1 and price takers. Each consumer decides whether to purchase one product (vehicle), and if purchases it, selects a product's degree of usage (mileage). $x(\theta) \geq 0$ is the degree of usage chosen by type θ, where $\theta \in [0, 1]$ denotes the valuation parameter (type) of consumers. Type θ is distributed as $\theta \sim F(\theta)$, and the density function corresponding to F is denoted as $f(\theta)$. 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 use (mileage) requires $\alpha > 0$ units of fuel (gasoline), and one unit of fuel emits one unit of emission (CO_2).[8] Thus, α represents the fuel (in)efficiency of the product (vehicle).

A twice continuously differentiable function $u(x, \theta)$ represents the valuation (willingness to pay) of type θ for one product. For our subsequent discussion, we consider two alternative assumptions describing the structure of this utility function. The first assumption is used

[8]For an EV, an electricity consumption tax must be considered instead of a gasoline tax. We also observe that electricity consumption taxes are levied globally.

when the consumers endogenously choose their degree of use.

Assumption 1 *$u(x,\theta)$ is strictly concave in (x,θ) and satisfies $u_x > 0$ and $u_\theta > 0$.*[9]

Alternatively, we also consider the case where the degree of use is exogenously given by types θ. In this case, it is useful to specify the utility function as follows.

Assumption 2

$$u(x,\theta) \equiv \begin{cases} vx \ \textit{if}\ x \leq \theta \\ v\theta \ \textit{if}\ x \geq \theta, \end{cases}$$

where $v > 0$ is sufficiently large, such that $x(\theta) = \theta$.

Under this second assumption, we can directly represent the distribution of use of a product by $x \sim F(x)$ on $x \in [0,1]$. Therefore, when Assumption 2 is adopted, we express the consumer type by their given consumption level x instead of by θ.

Consider a monopolistic producer for simplification. Emission (CO2) is also generated when the producer manufactures its products (vehicles). $E(q)$ is the emission function in the production process, with $E' > 0$ and $E'' \geq 0$, where q represents the quantity of production. A second-order continuously differentiable function $C(q,\alpha)$ represents the producer's cost function, where C is convex and satisfies $C_q > 0$ and $C_\alpha < 0$. $C_\alpha < 0$ because a lower α indicates a higher fuel efficiency. We also consider using two alternative assumptions when this fuel efficiency is presumably endogenous and exogenous, respectively.

Assumption 3 *The producer chooses α endogenously.*

Assumption 4 *α is given exogenously.*

When Assumption 4 is adopted, we express the cost by omitting α as $C(q) = C(q,\alpha)$ with $C' = C_q > 0$ and $C'' = C_{qq} \geq 0$.

The environmental damage is

$$D(E(q) + \alpha X),$$

where X is the total usage. Note that $E(q)$ and αX are the emissions generated in different processes. $E(q)$ is generated in the production process, and αX is in the consumption

[9] In this study, the subscripts of functions denote partial derivatives. For example, $u_x \equiv \partial u / \partial x$.

process while using the products. Thus, the total emission is $E(q)+\alpha X$. We assume $D' \geq 0$ and $D'' \geq 0$.

2.2 Benchmark: Exogenous fuel consumption and fuel efficiency

We begin with a simple benchmark case of exogenously provided fuel consumption and efficiency. Therefore, we employ Assumptions 2 and 4 in this subsection.

Type x consumer, where $x = \theta$ by Assumption 2, purchases a product if and only if

$$vx - \gamma\alpha x \geq p \tag{1}$$

where $p > 0$ is the price of one product. γ represents the unit cost of fuel (gasoline) given by

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

where $t_e \geq 0$ is the emission tax, $t_f \geq 0$ is the fuel tax, and $c \geq 0$ is the marginal cost of fuel production. Assuming a perfectly competitive fuel market, γ represents the fuel price.

Being (1) with equality, we obtain the marginal consumer who purchases, $\bar{x}(p;\alpha)$, as

$$\bar{x} = \frac{p}{v - \alpha\gamma}. \tag{2}$$

We focus on the interior case that satisfies $0 < \bar{x} < 1$. The demand and inverse demand for the product are

$$Q(p;\alpha) \equiv 1 - F(\bar{x}(p;\alpha)), \tag{3}$$

$$P(q;\alpha) \equiv Q^{-1}(p;\alpha), \tag{4}$$

respectively. The superscript -1 represents an inverse function that corresponds q to p. Since α is exogenous by Assumption 4, in this subsection we express the demand by omitting α as $P(q) = P(q;\alpha)$ with $P' = P_q$ and $P'' = P_{qq}$.

The producer's profit maximization problem is

$$\max_q \; P(q)q - C(q) - t_e E(q).$$

The first-order condition is

$$P(q) + P'(q)q - C'(q) - t_e E'(q) = 0, \tag{5}$$

where

$$P'(q) = -\frac{v - \alpha\gamma}{f(\bar{x}(q))} < 0, \tag{6}$$

hold.[10] Note that $\bar{x}(q)$ is obtained by substituting $p = P(q)$ into $\bar{x}$ in (2).

The welfare-maximizing problem is

$$\max_{\bar{x}} \ W = \int_{\bar{x}}^{1} vx \ dx - C(q) - c\alpha X - D(E(q) + \alpha X),$$

where $q = 1 - F(\bar{x})$ and total emission from fuel consumption is

$$\alpha X = \alpha \int_{\bar{x}}^{1} x f(x) \ dx.$$

Since q and $\bar{x}$ have a one-to-one relationship through $q = 1 - F(\bar{x})$, we can state the welfare-maximizing problem with respect to $\bar{x}$ instead of q. The first-order condition for this problem is

$$v\bar{x} - c\alpha\bar{x} - C'(q) - [E'(q) + \alpha\bar{x}]D'(E(q) + \alpha X) = 0. \tag{7}$$

Let the superscript o denote the socially optimal outcomes. We denote the optimal total life-cycle emissions as $E_L^o = E(q^o) + \alpha X^o$.

By comparing the market conditions (2) and (5) with the optimal condition (7), we find that the socially optimal outcome is achieved if t_e and t_f satisfies

$$t_e = D'(E_L^o) - \frac{\alpha\bar{x}^o t_f - P'(q^o)q^o}{E'(q^o) + \alpha\bar{x}^o}.$$

This implies that, raising the fuel tax t_f requires reducing the emission tax t_e, which clarifies that the fuel tax is perfectly substitutable to the emission tax. In particular, even when $t_f = 0$, the optimality can be attained by the emission tax alone as

$$t_e = D'(E_L^o) + \frac{P'(q^o)q^o}{E'(q^o) + \alpha\bar{x}^o}.$$

[10] See Appendix for the derivation of (6).

This renders the fuel tax redundant. Under Assumptions 2 and 4, only the production level q is the control variable, and thus, there is no need to use two policy instruments. In the present case, as is often insisted (see Section 1), gasoline taxes should be abolished to avoid double taxation upon introducing effective carbon tax.

3 Model 1: Endogenous fuel consumption

In this section, the consumers endogenously select their degree of usage. We extend the benchmark model by employing Assumption 1 instead of Assumption 2. To clarify the effect of endogenous consumption levels, the fuel efficiency is assumed to be exogenous (Assumption 4).[11]

3.1 Market equilibrium

Suppose a consumer purchases a product for now. Then, type θ consumer solves

$$\max_{x} \ u(x,\theta) - \gamma\alpha x.$$

The first-order condition for each consumer is,

$$u_x(x,\theta) - \alpha\gamma = 0, \tag{8}$$

from which we obtain the fuel consumption level for type θ, $x^*(\theta)$.[12]

Given the product price $p > 0$, each consumer purchases a product if and only if $u(x^*(\theta),\theta) - \gamma\alpha x^*(\theta) \geq p$. With equality, we obtain[13] the marginal consumer who purchases, $\bar{\theta}(p)$, by

$$u(x^*(\bar{\theta}),\bar{\theta}) - \gamma\alpha x^*(\bar{\theta}) = p. \tag{9}$$

[11] In the next section, we provide a model enabling the producers to choose α endogenously.

[12] Differentiating (8) with respect to θ yields

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

Thus, while the effect of γ on x^* is always negative, the effect of θ on x^* depends on the sign of $u_{x\theta}$.

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

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

where we use (8).

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

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

where the superscript -1 represents an inverse function. We obtain[14]

$$P'(q) = -\frac{1}{F'(\bar{\theta})\partial\bar{\theta}/\partial p} = -\frac{u_\theta}{f(\bar{\theta})} < 0.$$

The producer solves

$$\max_{q} \; P(q)q - C(q) - t_e E(q).$$

The first-order condition for this problem is

$$P(q) + P'(q)q - C'(q) - t_e E'(q) = 0. \tag{10}$$

This condition uniquely determines the market equilibrium q, and thus, equilibrium $\bar{\theta}$, as q and $\bar{\theta}$ have a one-to-one relationship through $q = 1 - F(\bar{\theta})$.[15]

3.2 Optimal tax combination

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

$$\max_{x(\theta),\bar{\theta}} \; W \equiv \int_{\bar{\theta}}^{1} u(x(\theta), \theta) f(\theta) \; d\theta - C(q) - c\alpha X - D(E(q) + \alpha X),$$

where $q = 1 - F(\bar{\theta})$ and the total emissions from fuel consumption (gasoline) is

$$\alpha X \equiv \alpha \int_{\bar{\theta}}^{1} x(\theta) f(\theta) \; d\theta.$$

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

$$u_x(x(\theta), \theta) - \alpha c - \alpha D'(E(q) + \alpha X) = 0 \tag{11}$$

[14] Differentiating (9) 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 13.

[15] The uniqueness is obtained because the second-order condition is satisfied globally. See Appendix.

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

$$u(x(\bar{\theta}), \bar{\theta}) - c\alpha x(\bar{\theta}) - C'(q) - [E'(q) + \alpha x(\bar{\theta})]D'(E(q) + \alpha X) = 0. \tag{12}$$

Let the superscript o denote socially optimal outcomes. We denote the optimal total life-cycle emissions as $E_L^o \equiv E(q^o) + \alpha X^o$.

As a benchmark, assume the producer to be a price taker. Then, the producer's first-order condition is $p - C'(q) - t_e E'(q) = 0$, where $p = u(x^*(\bar{\theta}), \bar{\theta}) - \gamma\alpha x^*(\bar{\theta})$ from (9). Therefore, together with (8), and comparing with (11) and (12), we find Pigovian tax $t_e = D'(E_L^o)$ and $t_f = 0$ to be attaining optimal outcomes. Under perfect competition, to correct life-cycle emissions' externality, the government need not impose fuel taxes; only an emission tax is required.[16]

In the presence of market power, by comparing market conditions (8), (9), and (10) with optimal conditions (11) and (12), we identify the optimal tax combination (t_e^o, t_f^o) as in the following proposition.

Proposition 1 *Assume Assumptions 1 and 4. The socially optimal outcomes are achieved if and only if*

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

Proof. For necessity, suppose $x(\theta) = x^*(\theta) = x^o(\theta)$ for all θ and $\bar{\theta} = \bar{\theta}^o$ $(q = q^o)$ at market equilibrium. Then, substituting (11) into (8) yields

$$D' - (t_e + t_f) = 0.$$

Subtracting (12) from (10) yields

$$-(t_e + t_f)\alpha x + P'q - t_e E' + (E' + \alpha x)D' = 0,$$

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

where we use $P = u(x(\bar{\theta}), \bar{\theta}) - \gamma\alpha x(\bar{\theta})$ from (9). 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 $t_f = t_f^o$. Then, substituting $\gamma = c + t_e^o + t_f^o$ into (8) yields

$$u_x(x^*(\theta), \theta) - \alpha c - \alpha D'(E_L^o) = 0, \tag{13}$$

for all θ. Furthermore, substituting $t_e = t_e^o$ into (10) yields

$$P(q) + P'(q)q - C'(q) - \left[D'(E_L^o) + \frac{P'(q^o)q^o}{E'(q^o)} \right] E'(q) = 0. \tag{14}$$

Because $P(q) = u(x^*(\bar{\theta}), \bar{\theta}) - \gamma\alpha x^*(\bar{\theta})$ from (9), (14) is rearranged as

$$u(x^*(\bar{\theta}), \bar{\theta}) - c\alpha x^*(\bar{\theta}) - C'(q) - [E'(q) + \alpha x^*(\bar{\theta})] D'(E_L^o) \\ + \left[P'(q)q - P'(q^o)q^o \frac{E'(q)}{E'(q^o)} \right] = 0.$$

As the last term on the left-hand side vanishes when $q = q^o$, by using (11) and (12), we find that the market conditions (13) and (14) must be satisfied when $x^*(\theta) = x^o(\theta)$ for all θ and $\bar{\theta} = \bar{\theta}^o$ $(q = q^o)$. **Q.E.D.**

In contrast to the exogenous case (Subsection 2.2), the optimal tax combination must contain the strictly positive fuel tax when the consumers choose their fuel consumption endogenously. This imply that a government should maintain a certain fuel tax even after introducing an effective emission tax.

For the producer, the derived formula of t_e^o matches the well-known optimal emission tax for monopolies (Misiolek, 1980; Barnett, 1980). To correct the undersupply resulting from market power, the emission tax should be lower than the marginal damage. However, such a low emission tax level does not make consumers sufficiently reduce their fuel consumption. Therefore, a positive fuel tax t_f^o should be used such that $t_e^o + t_f^o = D'$.

The importance of life-cycle emissions for implementing this optimal tax policy is worth emphasizing. If E' is close to zero, implying that most of the emissions are generated at the consumption stage, t_e^o becomes negative.[17] Introducing such explicit subsidies for polluters will be politically difficult. However, when E' is not too insignificant, implying substantial emissions at the production stage as well, we can attain the first-best optimality by combining taxes for polluters instead of any explicit subsidies. This can be an acceptable policy.

4 Model 2: Endogenous fuel efficiency

This section extends the benchmark model by endogenizing fuel efficiency, $\alpha > 0$, by employing Assumption 3 instead of Assumption 4. To clarify the effect of producer's investment, the consumer side structure is simplified by assuming exogenous consumption levels (Assumption 2).

4.1 Market equilibrium

The consumer side is similar to Subsection 2.2. The marginal consumer $\bar{x}(p;\alpha)$ is obtained by (2), and the demand $Q(p;\alpha)$ and inverse demand $P(q;\alpha)$ are given by (3) and (4), respectively.

The producer's profit maximization problem is

$$\max_{q,\alpha} \; P(q;\alpha)q - C(q,\alpha) - t_e E(q).$$

The first-order conditions are

$$P(q;\alpha) + P_q(q;\alpha)q - C_q(q,\alpha) - t_e E'(q) = 0, \tag{15}$$

$$P_\alpha(q;\alpha)q - C_\alpha(q,\alpha) = 0, \tag{16}$$

where

$$P_q(q;\alpha) = -\frac{v - \alpha\gamma}{f(\bar{x}(q;\alpha))} < 0, \tag{17}$$

$$P_\alpha(q;\alpha) = -\gamma\bar{x}(q;\alpha) < 0 \tag{18}$$

hold.[18] Note that $\bar{x}(q;\alpha)$ is obtained by substituting $p = P(q;\alpha)$ into $\bar{x}$ in (2).

[17] The traditional emission tax for monopolies derived by Misiolek (1980) and Barnett (1980) can also be negative.

[18] See Appendix for the derivation of (17) and (18).

4.2 The optimal tax combination

The welfare-maximizing problem is

$$\max_{\bar{x},\alpha} \; W \equiv \int_{\bar{x}}^{1} vxf(x)\; dx - C(q,\alpha) - c\alpha X - D(E(q) + \alpha X),$$

where $q = 1 - F(\bar{x})$ and the total emission from fuel consumption (gasoline) is

$$\alpha X \equiv \alpha \int_{\bar{x}}^{1} xf(x)\; dx.$$

The first-order conditions are

$$v\bar{x} - c\alpha\bar{x} - C_q(q,\alpha) - [E'(q) + \alpha\bar{x}]D'(E(q) + \alpha X) = 0, \tag{19}$$

$$-[c + D'(E(q) + \alpha X)]X - C_\alpha(q,\alpha) = 0. \tag{20}$$

Let the superscript o denote socially optimal outcomes. We denote optimal total life-cycle emissions as $E_L^o \equiv E(q^o) + \alpha^o X^o$.

At market equilibrium, by substituting (16) into the left-hand side of (20), we obtain

$$\frac{\partial W}{\partial \alpha} = -[c + D'(E(q) + \alpha X)]X - P_\alpha(q;\alpha)q.$$

Therefore, denoting the average use per product as $\mu_X \equiv X/q$, we obtain the following relation:

$$SMC \cdot \mu_X \gtreqless -P_\alpha(q;\alpha) \;\Leftrightarrow\; \frac{\partial W}{\partial \alpha} \lesseqgtr 0. \tag{21}$$

Here, $SMC = c + D'(E(q) + \alpha X)$ is the marginal social cost of fuel at market equilibrium. Thus, the left-hand side denoting $SMC \cdot \mu_X$ is the average saving in social costs with a decrease in α (i.e., improvement in fuel efficiency). The right-hand side depicting $-P_\alpha$ is the marginal market valuation of the decrease in α. Relation (21) indicates that when the former social benefit is greater (less) than the latter private benefit, a marginal decrease (increase) in α improves welfare, implying that the market under invests (over invests) in fuel efficiency.

This market failure in fuel efficiency is related to market failure in choosing product quality (Spence, 1975). To demonstrate this, let $\gamma = SMC$ ($t_e + t_f = D'$) (i.e., environmental damage is completely internalized into the fuel cost).[19] In this case, because $P_\alpha = -\gamma\bar{x}$ from (18), (21) is reduced to

$$\mu_X \gtreqless \bar{x} \;\Leftrightarrow\; \frac{\partial W}{\partial \alpha} \lesseqgtr 0. \tag{22}$$

Indeed, $\mu_X > \bar{x}$ always holds true in our model.[20] Thus, the market forces cause underinvestment ($\partial W/\partial\alpha < 0$), despite completely internalizing environmental damages. When a monopoly sets the product quality (here, fuel efficiency), "the social benefits correspond to the increase in the revenues of the firm only if the marginal consumer is average or representative," but "there is nothing at all intrinsic to the market that guarantees that the marginal purchaser is representative," argues Spence (1975, p.418).

The optimal tax combination (t_e^o, t_f^o) is identified by comparing market conditions (2), (15), and (16) with optimal conditions (19) and (20).

Proposition 2 *Assume Assumptions 2 and 3. The socially optimal outcomes are achieved if and only if*

$$t_e^o = D'(E_L^o) + \frac{P_q(q^o;\alpha^o)q^o}{E'(q^o)} - \frac{\alpha^o}{E'(q^o)}(c + D'(E_L^o))(\mu_X^o - \bar{x}^o) < D'(E_L^o),$$
$$t_f^o = -\frac{P_q(q^o;\alpha^o)q^o}{E'(q^o)} + \frac{\alpha^o\bar{x}^o + E'(q^o)}{E'(q^o)\bar{x}^o}(c + D'(E_L^o))(\mu_X^o - \bar{x}^o) > 0.$$

Proof. For necessity, suppose $\bar{x} = \bar{x}^o$ ($q = q^o$) and $\alpha = \alpha^o$ at market equilibrium. Substituting (20) into (16) yields

$$-(c + t_e + t_f)\bar{x}q + [c + D']X = 0.$$

By subtracting (19) from (15), we obtain

$$-(t_e + t_f)\alpha\bar{x} + P_q q - t_e E' + [E' + \alpha\bar{x}]D' = 0,$$

where we use $P = v\bar{x} - \gamma\alpha\bar{x}$ from (2). Solving these two equations yields $t_e = t_e^o$ and $t_f = t_f^o$.

For sufficiency, suppose $t_e = t_e^o$ and $t_f = t_f^o$. Then, owing to the construction of t_e^o and t_f^o (more precisely, similar to the latter half of the proof of Proposition 1), (15) and (16)

[19] Another perspective is to consider the case where $D' = 0$ and $t_e + t_f = 0$, with zero environmental damage and the associated taxes. As $P_\alpha = -c\bar{x}$, (21) is also reduced to (22).

[20] See the third paragraph of the proof of Proposition 2.

must be satisfied when $q = q^o$ and $\alpha = \alpha^o$ under the optimal outcome conditions (19) and (20).

The inequalities are obtained because $\mu_X > \bar{x}$ always holds true. This is because

$$\mu_X = \frac{X}{q} = \frac{\int_{\bar{x}}^1 xf(x)dx}{1 - F(\bar{x})} > \frac{\int_{\bar{x}}^1 \bar{x}f(x)dx}{1 - F(\bar{x})} = \frac{\bar{x}\int_{\bar{x}}^1 f(x)dx}{\int_{\bar{x}}^1 f(x)dx} = \bar{x},$$

where the inequality is obtained because $x > \bar{x}$ in the integration interval. **Q.E.D.**

The optimal fuel tax t_f^o is composed of two terms: the first term relates to distortion due to market power (Misiolek, 1980; Barnett, 1980), and the second term relates to the market failures associated with product quality (Spence, 1975). Regarding the optimal emission tax t_e^o, the deviation from the Pigovian level D' is similarly composed of two terms. As in the previous section, the terms correcting for market power are positive in t_f^o and negative in t_e^o. Because the proof shows $\mu_X^o > \bar{x}^o$, the terms correcting for product quality are also positive in t_f^o and negative in t_e^o. Thus, the optimal fuel tax level t_f^o is always positive and that of the emission tax t_e^o is always lower than the Pigovian level D'.

We explain why the optimal policy has this structure. Even if environmental damage is completely internalized ($\gamma = SMC$), the producer's choice of fuel efficiency is suboptimal. Thus, to encourage fuel efficiency improvement, the unit cost of fuel, $\gamma^o = c + t_e^o + t_f^o$, should be larger than the marginal social cost of fuel, $SMC^o = c + D'(E_L^o)$, as

$$\gamma^o = SMC^o \frac{\mu_X^o}{\bar{x}^o} > SMC^o, \quad \text{or} \quad t_e^o + t_f^o > D'(E_L^o).$$

Here, the equality stems from Proposition 2. A higher fuel price increases consumers' valuation of a fuel-efficient car. Therefore, an increase in γ increases the producer's incentive to improve the fuel efficiency of the product. However, if such an increase in fuel price is implemented with an increase in the emission tax, it raises the firm's production cost and accelerates welfare loss due to suboptimal production. Therefore, the government should set a positive fuel tax and choose an emission tax rate lower than the Pigovian level.[21]

[21] See Proposition 2 and the last terms of t_e^o and t_f^o, which correct product quality. Their magnitudes are larger in t_f^o than in t_e^o.

5 Concluding remarks

This study investigates the optimal combination of emission and fuel taxes in a monopoly, considering life-cycle emissions and heterogeneity among consumers. We present two stories portraying a strictly positive optimal fuel tax. In other words, heavier taxes should be imposed during fuel consumption than during production. In the first scenario, consumers choose how much they use products (the mileage of vehicles). In the second scenario, the producer chooses fuel efficiency. We believe both to be realistic in the vehicle industry, which is one of major sources of CO2 emissions.

If a production subsidy is available, the first-best outcome is also achieved by combining subsidy and emission taxes (Baumol and Oates, 1988). However, it is politically difficult to introduce direct subsidies to polluters. By contrast, the combination of taxes for polluters (emission and fuel taxes) might be more acceptable. Furthermore, fuel (gasoline) taxes has already been imposed in a lot of countries. Therefore, our analysis presumably has practical policy implications in these respects.

To elucidate each function, we endogenized consumption levels and fuel efficiency separately. If both are simultaneously endogenized, the first-best outcome cannot be implemented by combining fuel and emission taxes. However, by introducing additional policy tools such as regulating energy efficiency, fuel tax can be shown as strictly positive.[22]

This study's sole focus is on emission and fuel taxes, without investigating other policy measures. The fuel taxes thereby investigated may promote the switch from grey products to green products, and thus, may substitute for a green portfolio standard, such as a zero-emission vehicle program.[23] 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.

[22]Energy efficiency is globally regulated by energy conservation laws (Matsumura and Yamagishi, 2017).
[23]See Ino and Matsumura (2021a) and the studies cited therein.

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Appendix

Derivation of (6), (17), and (18)
Derivation of P_q is perfectly similar for (6) and (17). Because $\bar{x} = p/(v - \alpha\gamma)$ from (2), differentiating $Q(p;\alpha) = 1 - F(\bar{x})$ yields

$$\frac{\partial Q}{\partial p} = -\frac{F'}{v - \alpha\gamma}, \quad \frac{\partial Q}{\partial \alpha} = -\frac{\gamma p F'}{(v - \alpha\gamma)^2}.$$

Because $P = Q^{-1}$, we obtain

$$\frac{\partial P}{\partial q} = \frac{1}{\partial Q/\partial p} = -\frac{v - \alpha\gamma}{F'}.$$

P_α in (18) is derived as follows. Because $p = P(Q(p;\alpha);\alpha)$ by definition, differentiating this with respect to α yields

$$0 = \frac{\partial P}{\partial q}\frac{\partial Q}{\partial \alpha} + \frac{\partial P}{\partial \alpha} \quad \therefore \frac{\partial P}{\partial \alpha} = -\frac{\partial Q/\partial \alpha}{\partial Q/\partial p}.$$

Then, by substituting the derived expressions, we obtain

$$\frac{\partial P}{\partial \alpha} = -\frac{\gamma p}{v - \alpha\gamma} = -\gamma\bar{x}.$$

Second-order condition of the problem (10)
Because of the one-to-one relationship through $q = 1 - F(\bar{\theta})$, the problem can be stated as maximization with respect to $\bar{\theta}$, instead of that with respect to q as

$$\max_{\bar{\theta}} \; P(1 - F(\bar{\theta}))(1 - F(\bar{\theta})) - C(1 - F(\bar{\theta})) - t_e E(1 - F(\bar{\theta})).$$

The first-order condition is

$$-f(\bar{\theta})\left[P - \frac{1 - F(\bar{\theta})}{f(\bar{\theta})}u_\theta - C' - t_e E'\right] = 0.$$

As the left-hand side is strictly decreasing in $\bar{\theta}$ under our assumptions, the second-order condition is satisfied globally. Here, we used

$$\frac{\partial}{\partial\bar{\theta}}\frac{[1 - F(\bar{\theta})]u_\theta(x^*(\bar{\theta}), \bar{\theta})}{f(\bar{\theta})} = u_\theta \frac{\partial}{\partial\bar{\theta}}\frac{1 - F}{f} + \frac{1 - F}{f}\left[\frac{u_{xx}u_{\theta\theta} - (u_{x\theta})^2}{u_{xx}}\right] < 0$$

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

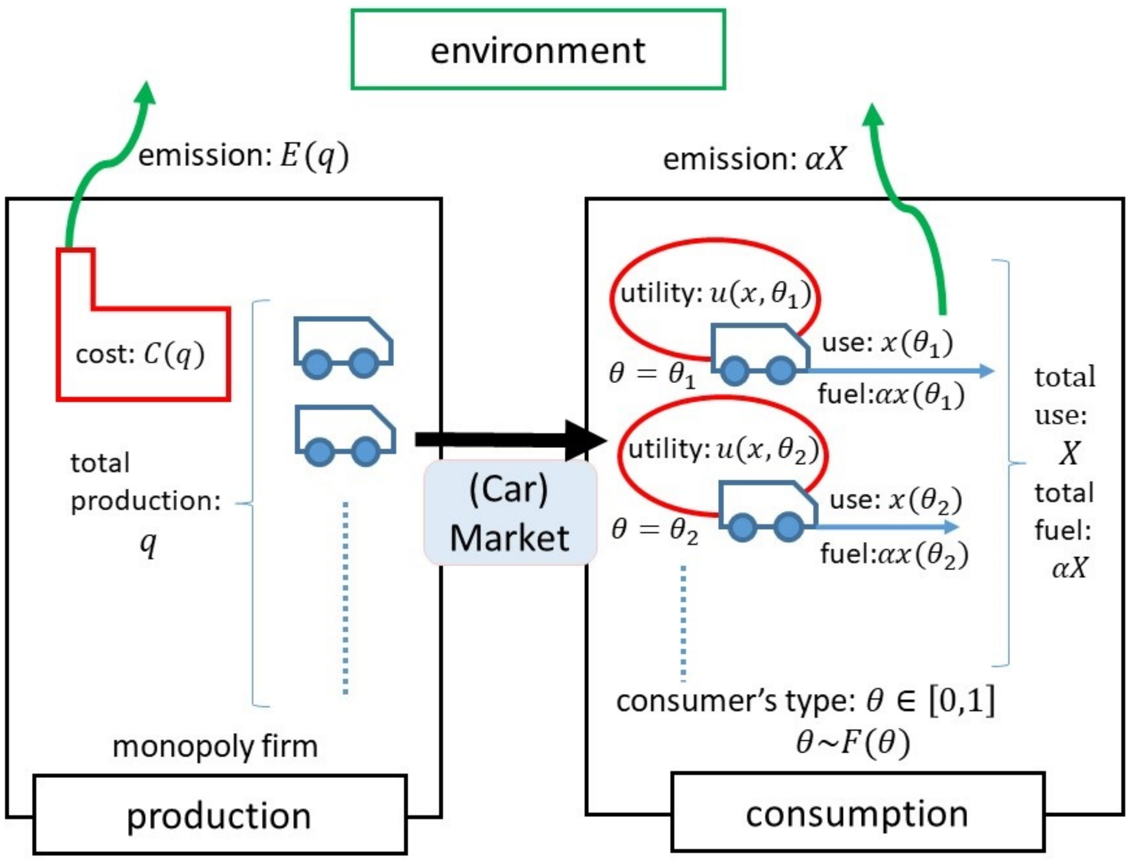

Figure 1: Model with life-cycle emissions