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Abstract

We study how consumers' environmental awareness (CEA) affects the design of environmental policy in the e-commerce sector. We also examine if there is a need for regulation requiring delivery operators to reveal their emissions. We consider a model with two retailers who sell a differentiated product and two parcel delivery operators. Delivery generates CO_2 emissions and their total level creates a global (atmosphere) externality. We assume that it is more expensive for the delivery operator to use less polluting technologies.

We consider different scenarios reflecting the type of competition and the vertical structure of the industry. We shown that CEA mitigates the inefficiency of the equilibrium by bringing the level of emissions closer to its optimal level. This is true under perfect and imperfect competition. This efficiency enhancing effect of CEA also affects the design of emissions taxes, which leads to an amended Pigouvian rule. Under perfect competition the tax is reduced by exactly the level of CEA expressed in monetary terms. Under imperfect competition the adjustment exceeds this level.

Keywords: Consumers' environmental awareness, Pigouvian rule, emission taxes, e-commerce, parcel delivery operators, vertical integration.
JEL Codes: H21, L42, L81, L87.

1 Introduction

Consumers' environmental awareness (CEA) has been increasing considerably over the last decades. It appears to affect their demand behavior in essentially all sectors. However, e-commerce and its environmental impact have drawn a particularly significant attention in the public debate and the appeals for policy intervention have become increasingly pressing as e-commerce has been expanding. This expansion has been particularly drastic during the last two years because of the Covid epidemic and the attention devoted to the environmental footprint of the sector has risen accordingly.

This phenomenon has for instance been documented by recent surveys[1] which showed that individuals declare being more conscious about the impact of their purchasing behavior on environment and most of them, especially the under 35 years old population, would like to modify their behavior accordingly. Being more conscious means that individuals clearly identify and are more sensitive to new characteristics for the goods such as brand responsibility, ethical labor, if repair is feasible, transparency, etc. This will translate into deciding to refuse consuming goods or to reduce the consumption of theses goods that would not be compliant with their tastes in regards environment. This could also translate into refusing to buy imported goods and being willing to pay more for goods satisfying these new characteristics.[2]

One can of course expect CEA to act as a discipline devise which brings retailers and delivery operators to adopt cleaner production technologies. For instance, the use of electric vehicles or cargobikes for urban delivery may be appealing for environmentally conscious customers, enhance their demands, and provide the delivery operator with a competitive edge. While one may doubt that this mechanism might be sufficient to achieve an adequate level of emission reduction, one can certainly expect CEA to affect the appropriate environmental policy design.

[1] OpinionWay questionnaire run on 1000 French persons over 18 years old, online sept. 2021 ; Retail X 2021 report « Sustainability »

[2] However, nowadays there appears to exist a gap between their attitude towards environment and their consumer behavior. One interpretation is the fact that information is difficult to get for consumers on many aspects of the product when it concerns environment. Some policy makers suggest that a label system such as defined for energy could be used.

In this paper, we study how CEA affects the design of environmental policy in the e-commerce sector. We study the appropriate design of taxes at the different levels of the value chain under CEA. We also examine if there is a need for regulation requiring delivery operators to reveal the environmental footprint of their activity. While the retail activity of course also generates emissions, we will concentrate on the environmental impact of delivery.

To deal with those issues, we consider a model which is based on Borsenberger *et al.* (2022). There are two retailers/producers who sell a differentiated product and two parcel delivery operators. The delivery of these goods generates CO2 emissions. The total level of these emissions creates a global (atmosphere) externality which is a potential source of global warming and climate change. We assume that the delivery cost decreases with the level of emissions, at least up to some level. In other words, it is more expensive for the delivery operator to use "green" technologies. Because of CEA consumer's utility decreases with the environmental cost associated with the product they buy. Specifically, the level of emissions generated by its delivery involves a monetary cost in utility. When this level of emissions is not revealed by the delivery operator, consumers assume that it uses a dirty technology. In a first step we assume that the environmental cost that reduces consumers' utility is the same for all consumers, but we also consider the case where consumers differ in their environmental awareness.

We consider different scenarios reflecting the type of competition and the vertical structure of the industry. In a reference scenario, we will consider "pseudo" perfect competition à la Mussa and Rosen (1978) in which retailers and delivery operators are independent and behave competitively so that all prices and delivery rates including the price of environmental quality reflect marginal cost. Then, we will consider a setting where all firms remain independent but where there is imperfect competition which involves strategic interaction in a two-stage game where operators choose environmental quality in a first stage and then compete in delivery rates. We will study the (subgame perfect) Nash equilibrium. In another scenario, we assume that there is vertical integration between one of the retailers and one of the delivery operators.

We study the different equilibria, implying different levels of emissions and outputs, yielded by those different scenarios and the impact of CEA on the optimal environmental policy under the different market structures. Finally, we examine if operators find it profitable to reveal their levels of emissions to consumers.

2 Model

Consider an e-commerce sector with two products $i = 1, 2$ which are substitutes and differentiated by their environmental impact. For simplicity, we assume that this impact is determined by the emissions of the delivery operator.[3] There are two operators, delivering each a single product, so that the index $i = 1, 2$ can also be used for of delivery operators. There are two retailers, indexed A and B, which sell both products.

Preferences are represented by

$$u(x_1, x_2) - p_1 x_1 - p_2 x_2 - \sigma x_1 e_1 - \sigma x_2 e_2, \tag{1}$$

where x_1 and x_2 denote consumption of the two goods, p_1 and p_2 the prices charged by the retailers, while e_1 and e_2 are the (per unit) emissions associated with their delivery. Environmental concern, CEA, is expressed in monetary terms, with σ representing the perceived cost of one unit of emissions. Maximizing (1) yields the demand functions $x_1(q_1, q_2)$ and $x_2(q_1, q_2)$, which are determined by

$$u_1'(x_1, x_2) = p_1 + \sigma e_1 = q_1, \tag{2}$$

$$u_2'(x_1, x_2) = p_2 + \sigma e_2 = q_2, \tag{3}$$

where

$$u_j' = \frac{\partial u}{\partial x_j}, \qquad j = 1, 2,$$

and q_j denotes the "full price" including environmental damage.

Costs of retailers $j = A, B$, for goods $i = 1, 2$ are given by $y_{ji}k$, where k is their marginal cost and y_{ji} the quantity of good i they sell. In words, we assume that marginal costs are constant, equal across retailers and the same for the two products.

[3] In reality, the retail activity will of course also generate emissions. Following Borsenberger *et al.* (2022) one could easily generalize our model to account for these extra emissions. This would complicate the analysis but not affect our main results.

The costs of delivery operator $i = 1, 2$ are given by $c_i(z_i, e_i)$, where z_i is the number of parcels delivered and e_i is emissions per parcel delivered. Each operator delivers a single good. Assume for simplicity that:

$$c_i(z_i, e_i) = C_i(z_i) - \gamma_i(e_i) z_i, \tag{4}$$

where $\gamma_i^{''}(e_i) < 0$ and

$$\gamma_i'(e_i) > 0 \quad \text{for } e_i < \bar{e}_i \quad \text{and} \quad \gamma_i'(e_i) = 0 \quad \text{for } e_i \geq \bar{e}_i. \tag{5}$$

Intuitively, assumption (5) implies that delivering in a less polluting way is more costly. Further we assume that for any level of e we have

$$\gamma_1'(e) < \gamma_2'(e)$$

so that delivery operator 1 is cleaner: we have $\bar{e}_1 < \bar{e}_2$ and when when $\gamma_1'(e_1) = \gamma_2'(e_2)$ we have $e_1 < e_2$. It will become clear below that this assumption implies that in equilibrium delivery operator 1 will use the cleaner technology and thus have a lower level of e.

Market clearing requires that for each good i, the total amount sold by both retailers $y_{Ai} + y_{Bi}$ is equal to demand x_i and to the amount delivered z_i. Formally we have

$$y_{A1} + y_{B1} = x_1 = z_1,$$

$$y_{A2} + y_{B2} = x_2 = z_2.$$

Total emissions, E, have a social cost $\psi(E)$ and they are given by

$$E = x_1 e_1 + x_2 e_2.$$

This definition fits CO_2 emissions, which are global and additive.

3 First best

We start by characterizing the first-best (FB) allocation. To define social welfare, we follow the by now standard approach initially advocated by Hammond (1987) and Harsanyi

(1995) and do not include the CEA term in welfare.[4] This is commonly referred to as "laundering out" the altruistic term.

With this objective function, the FB allocation solves the following problem

$$\begin{aligned}\max_{x_i,e_i} SWF &= u(x_1,x_2) - kx_1 - kx_2 \\ &- C_1(y_1) + y_1\gamma_1(e_1) \\ &- C_2(y_2) + y_2\gamma_2(e_2) \\ &- \psi(E) \end{aligned} \tag{6}$$

The FOCs are:

$$\gamma_i'(e_i^*) = \psi'(E^*) \tag{7}$$

$$u_1'(x_1,x_2) = k + C_1'(x_1^*) - \gamma_1(e_1^*) + e_1^*\psi'(E^*) \tag{8}$$

$$u_2'(x_1,x_2) = k + C_2'(x_2^*) - \gamma_2(e_2^*) + e_2^*\psi'(E^*) \tag{9}$$

We assume throughout the paper that $\sigma < \psi'(E^*)$. In words, the (marginal and average) environmental cost perceived by the consumer is smaller than the full social marginal damage.

We now turn to the laissez-faire and study the equilibrium allocation.

4 Equilibrium when consumers observe emissions

Assume for the time being that emissions associated with the delivery of the two products are observable to consumers. This may be the case for instance because there is a regulatory requirement for retailers and/or delivery operators to report the level of emissions or because the firms decide to reveal their levels of emissions.

As a reference consider outcome which is (pseudo)-competitive following Mussa and Rosen (1978). This implies the usual price marginal cost pricing concerning quantity, but also concerning (environmental) quality e.

[4] See Cremer and Pestieau (2006) for a more detailed discussion. Hammond (1987) pleads in favor of excluding all external preferences, even benevolent ones, from our social utility function. The reason is that including this term would amount to count the externality twice.

Prices and delivery rates $p(e)$ and $r(e)$ are then functions of environmental quality, so that $p_i = p(e_i)$ and $r_i = r(e_i)$. For future reference we consider the possibility that delivery operators are subject to an emission tax τ. Setting this tax to zero then yields the *laissez-faire.* Furthermore we can use the equilibrium expressions to study the FB implementation and in particular the required level of the emissions tax.

Retailers solve

$$\max_{e_j, y_j} \pi_j = p(e_1)y_{j1} - ky_{j1} - r(e_1)y_{j1} + p(e_2)y_{j2} - ky_{j2} - r(e_2)y_{j2},$$

which yields

$$p_i = k + r_i, \tag{10}$$

$$p'(e_i) = r'(e_i). \tag{11}$$

Demand is obtained maximizing utility

$$\begin{aligned} &\max_{x_i, e_i} u(x_1, x_2) - x_1 p(e_1) - x_2 p(e_2) \\ &- \sigma x_1 e_1 - \sigma x_2 e_2 \end{aligned}$$

which yields

$$u_i'(x_1, x_2) = p_i + \sigma e_i \tag{12}$$

$$p'(e_i) = -\sigma \tag{13}$$

for $i = 1, 2$.

Supply functions of delivery operators are obtained by

$$\max_{z_i, e_i} \pi = r(e_i)z_i - C_i(z_i) + \gamma_i(e_i)z_i - \tau e_i z_i$$

which yields

$$r(e_i) = C_i' - \gamma_i + \tau e_i \tag{14}$$

$$r'(e_i) = -\gamma_i'(e_i) + \tau. \tag{15}$$

Substitution (10) and (14) into (12) and using the market clearing conditions yields

$$u_i'(x_1, x_2) = k + C_i' - \gamma_i + \sigma e_i + \tau e_i, \tag{16}$$

while combining (11), (13) and (15) show that in equilibrium we have

$$\gamma_i'(e_i) = \sigma + \tau.$$

When $\tau = 0$ we obtain the *laissez-faire* characterized by

$$\gamma_i'(e_i) = \sigma, \tag{17}$$

$$u_i'(x_1, x_2) = k + C_i' - \gamma_i + \sigma e_i = p_i. \tag{18}$$

Consequently we have $e_1 < e_2$ and $e_i < \overline{e}_i$ as long as $\sigma > 0$. Absent of CEA that is when $\sigma = 0$ both delivery operators set $e_i = \overline{e}_i$ to minimize their delivery cost while neglecting any environmental consideration. Not surprisingly CEA will lead to lower levels of emissions but as long as $\sigma < \psi'(E^*)$, emission will be larger than optimal. Condition (18) shows that prices reflect marginal cost but environmental costs are only included to the extent that they are perceived by consumers. Consequently in spite of the CEA, equilibrium consumption levels will be larger than when the full environmental cost is accounted for.

Let us now turn to the FB implementation. In order to respect equality between (8) and (16), the emissions tax must satisfy

$$\tau = \psi'(E^*) - \sigma. \tag{19}$$

When $\sigma = 0$ we obtain the traditional Pigouvian rule stating that the tax must reflect the marginal social damage. With CEA the rule is amended and now requires that the tax reflects the part of the marginal social damage which is not perceived by consumers.

Substitution of (11) and (13) in (15) show that (7) is also satisfied with such a tax. In other words, the linear tax on emissions via its impact on the delivery operator's marginal cost and the consumer price is sufficient to implement the FB. Consumption levels will also be at their FB levels. This shows that the result obtained by Borsenberger *et al.* (2022) remains valid when CEA is considered.

5 Observability of emissions

In the previous section we have assumed that the levels of emissions e_i are observable. When they are not observable we return to an equilibrium with $e_i = \overline{e}_i$; since e_i is not observed by consumers their willingness to pay is zero. Consequently, there is no incentive for delivery operators to reduce emissions. This leads of course to a lower level of welfare. Consequently, a regulation requiring delivery operators and/or retailers to reveal the level of emissions is welfare improving.

This observation in turn raises the question if firms will spontaneously have an incentive to reveal e_i. In the considered scenario where all firms are price takers the answer is obviously affirmative and this follows from basic microeconomic theory. Delivery operators want to communicate their e, because this shifts the inverse demand curve upwards so that (with increasing marginal costs) equilibrium profits will increase. This suggests that no regulation is necessary. However absent of a regulatory, and possibly certifying authority it is not clear if the operators can credibly announce their e_i, especially since there is a clear incentive to announce a lower level than the actual one.

6 Imperfect competition in the delivery sector: independent firms

6.1 The game

We assume that delivery operators move first and play a two stage game: first they choose e and then r. The retailers continue to set prices at marginal costs. We first determine the subgame perfect equilibrium of the delivery operator's game assuming that they anticipate the retailers' behavior. Then we examine how the first best (which does not change) can be implemented by imposing a tax on delivery of δ_i per unit and a tax on emissions, at rate τ_i. For the time being we assume that consumers know the emission levels associated with their consumption. We revisit this issue in Section 9 below.

Demand functions $x_i(q_1, q_2)$ continue to be determined by equations (2) and (3). Furthermore, marginal cost pricing by retailers implies that

$$p_i = k + r_i \tag{20}$$

remains valid.

6.2 Equilibrium

To avoid repetitions, we introduce the tax instruments from the outset. This gives us the expressions we need for the FB implementation, while we can easily obtain the *laissez-faire* (LF) by setting both taxes at zero. We solve the model by backward induction.

6.2.1 Stage 2: determination of delivery rates r_i

Delivery operator i chooses r_i by solving:

$$\max_{r_i} \pi_i = (r_i + \gamma_i(e_i) - \delta_i - \tau_i e_i)\, x_i\,(q_1, q_2) - C_i\,(x_i(q_1, q_2))$$

where from (2) and (3) and (20) we have $q_i = k + r_i + \sigma$. The FOCs are:

$$x_i\,(q_1, q_2) + \frac{\partial x_i\,(q_1, q_2)}{\partial q_i}[r_i + \gamma_i(e_i) - \delta_i - \tau_i e_i - C_i'\,(x_i\,(q_{1,}q_2))] = 0 \tag{21}$$

for $i = 1, 2$. This defines $r_i^e\,(e_1, e_2)$ and demands

$$x_i^e = x_i\,(k + r_1^e\,(e_1, e_2) + \sigma e_1, k + r_2^e\,(e_1, e_2) + \sigma e_2)\,. \tag{22}$$

6.2.2 Stage 1: determination of emission levels e_i

Delivery operators choose e_i anticipating the induced equilibrium levels of (r_1^e, r_2^e) and the retailers' pricing behavior. They solve

$$\max_{e_i} \pi_i = (r_i^e\,(e_1, e_2) + \gamma_i(e_i) - \delta_i - \tau_i e_i)\, x_i^e - C_i\,(x_i^e)\,,$$

where demand levels are given by (22).

Using the envelop theorem, the first-order conditions are

$$\begin{aligned}&\left(\gamma_i'(e_i) - \tau_i\right) x_i^e \\ &+ \left(\sigma\frac{\partial x_i\,(q_1, q_2)}{\partial q_i} + \frac{\partial x_i\,(q_1, q_2)}{\partial q_j}\frac{\partial r_j^e}{\partial e_i}\right)[r_i^e + \gamma_i(e_i) - \delta_i - \tau_i e_i - C_i'(x_i^e)] = 0,\end{aligned} \tag{23}$$

for $i = 1, 2$.

These expressions evaluated at $\tau_i = 0$ and $\delta_i = 0$ determine the LF. Since now we have imperfect competition on top of the externality generated by emissions, we cannot expect the equilibrium to be efficient. However, comparing the FB and the LF is now much more complex than in the pseudo-competitive scenario considered in Section 4.

Some results concerning emission levels are established in Appendix A. We show that under standard conditions, emissions continue to be set at their maximum levels $e_i = \bar{e}_i$, exactly like in the competitive scenario considered in Section 4. In other words absent of CEA, emissions are too large and at their maximum levels. Intuitively, when $\sigma = 0$, emissions have no impact on demand and firms simply set them to minimize their cost.[5] Furthermore a positive value of σ (the presence of CEA) tends to mitigate this inefficiency and we *may* get smaller emission levels and an interior solution provided that σ is large enough. In that case, e has also an effect on demand which induces delivery operators to limit their emissions.

6.3 Implementation of the first best

Using (2), (3) and (20), the operators' marginal profit $[r_i + \gamma_i(e_i) - \delta_i - \tau_i e_i - C_i']$ which appears in expressions (21) and (23) can be rewritten as

$$\begin{aligned} &r_i + \gamma_i(e_i) - \delta_i - \tau_i e_i - C_i'(x_i) \\ &= u_i' - k - \sigma e_i + \gamma_i(e_i) - \delta_i - \tau_i e_i - C_i'(x_i) \end{aligned} \tag{24}$$

Using (8) and (9) the RHS of (24) can be further rearranged as

$$\begin{aligned} &u_i' - k - \sigma e_i + \gamma_i(e_i) - \delta_i - \tau_i e_i - C_i'(x_i) \\ &= \left(e_i\left(\psi'(E^*) - \sigma\right) - \delta_i - \tau_i e_i\right) \end{aligned} \tag{25}$$

[5] This is true as long as the so called "cost paradox" does not apply; see for instance Amir *et al.* (2014, 2017) or Aderson *et al.* (2001). In a setting with strategic complements and observable costs, the strategic effect of a decrease in own cost on the rival's price could lead, in principle, to a profit loss that is higher than the profit gain from the direct effect of such a decrease. In this case, a firm would not have a unilateral incentive to decrease its own cost. However, this is unlikely to happen in practice as it requires quite extreme assumptions on the demand elasticities; Aderson *et al.* (2001), Proposition 3.

Substituting this expression into (21) and (23) shows that the levels of δ_i and τ_i that implement the FB must satisfy the following system of equations

$$x_i^* + \frac{\partial x_i}{\partial q_i}\left(e_i^*\left(\psi'(E^*) - \sigma\right) - \delta_i - \tau_i e_i^*\right) = 0 \tag{26}$$

$$\left(\psi'\left(E^*\right) - \tau_i\right)x_i^* + \left(\sigma\frac{\partial x_i}{\partial q_i} + \frac{\partial x_i}{\partial q_j}\frac{\partial r_j}{\partial e_i}\right)\left(e_i^*\left(\psi'(E^*) - \sigma\right) - \delta_i - \tau_i e_i^*\right) = 0 \tag{27}$$

We show in Appendix B that these equations can be rearranged to yield the following expressions for the implementing taxes

$$\tau_i = \psi'\left(E^*\right) - \sigma - \frac{\frac{\partial x_i}{\partial q_j}\frac{\partial r_j}{\partial e_i}}{\left(\frac{\partial x_i}{\partial q_i}\right)}, \tag{28}$$

$$\delta_i + \tau_i e_i = \frac{x_i}{\frac{\partial x_i}{\partial q_i}} + e_i\left(\psi'(E^*) - \sigma\right). \tag{29}$$

where $\partial x_i/\partial q_i < 0$ and $\partial x_i/\partial q_j > 0$. Consequently, τ_i will in general differ from $\psi'\left(E^*\right)$ so that the straight Pigouvian rule that applied under perfect competition has to be amended. Furthermore, the sign of the adjustment depends on $\partial r_j/\partial e_i$ that is the impact of an increase in the competitor's emissions on an operator's equilibrium delivery rate. More precisely we have

$$\partial r_j/\partial e_i \lesseqgtr 0 \Longleftrightarrow \tau_i \lesseqgtr \psi'\left(E^*\right) - \sigma.$$

Studying the sign of $\partial r_j/\partial e_i$ is complicated at this level of generality. We show in Appendix A that $\partial r_j/\partial e_i$ has the same sign as $\sigma - \gamma_i'$ (as long as $\partial^2 x_i/\partial q_i \partial q_j \geq 0$).[6] Intuitively, when $\sigma = 0$, so that there is no CEA, e_i has no impact on demand but only on costs and we have $\partial r_j/\partial e_i < 0$. When $\sigma > 0$, e_i reflects quality to that there is also a product differentiation effect which goes in the opposite direction. Expression (A13) indeed shows that the absolute value of $\partial r_j/\partial e_i$ decreases as σ increases but that $\partial r_j/\partial e_i$ remains negative. To see this recall that in the first best we have $\gamma_i'(e_i^*) = \psi'\left(E^*\right)$ and by our assumption $\sigma < \psi'\left(E^*\right)$ we thus have $\sigma - \gamma_i' < 0$. To sum up, under imperfect competition, the emissions tax is always lower than $\psi'\left(E^*\right) - \sigma$ (its counterpart under perfect competition) but the wedge decreases as σ increases.

[6]This property holds for spearable preferences and for many conventionally considered specific utility functions like Cobb-Douglas or CES.

Turning to equation (26), it shows that the total tax per unit of output is given by

$$\delta_i + \tau_i e_i = \frac{x_i}{\frac{\partial x_i}{\partial q_i}} + e_i \left(\psi'(E^*) - \sigma\right).$$

While the first term in the RHS is negative, the second is positive given our assumption that $\psi'(E^*) - \sigma > 0$. Consequently, the sign of the total tax per output is ambiguous.

7 Vertical integration between operator 2 and retailer B

We now assume that retailer B and delivery operator 2 are integrated. We use the index $2B$ for this firm. The game is as follow: in stage 1, delivery operator 1 and firm $2B$ choose their levels of e. In stage 2, delivery operator 1 chooses its delivery price r_1 and the firm $2B$ chooses p_{2B}. As in the previous section we consider a tax on delivery volume of δ_i per unit and tax on emissions at rate τ_i.

First, observe that there will be foreclosure: firm $2B$ has no incentive to deliver product 2 for retailer A. That way it can maintain a monopoly of this product. The price of good 1 continues to be given by its marginal cost

$$p_1 = r_1 + k,$$

With these assumptions, we have $q_1 = r_1 + k + \sigma e_1$ and $q_2 = p_{2B} + \sigma e_2$ so that demands can be rewritten as $x_i\left(r_1 + k + \sigma e_1, p_{2B} + \sigma e_2\right)$ for $i = 1, 2B$.

We solve the game by backward induction, starting with Stage 2. The problem of delivery operator 1 is

$$\max_{r_1} \pi_1 = \left(r_1 + \gamma_1(e_1) - \delta_1 - \tau_1 e_1\right) x_1 - C\left(x_1\right).$$

The FOC is

$$x_1 + \left(r_1 + \gamma_1(e_1) - \delta_1 - \tau_1 e_1 - C'\left(x_1\right)\right) \frac{\partial x_1}{\partial q_1} = 0 \tag{30}$$

The problem of firm $2B$ is

$$\max_{p_{2B}} \pi_{2B} = \left(p_{2B} + \gamma_2(e_2) - k - \delta_2 - \tau_2 e_2\right) x_2 - C(x_2).$$

The FOC is

$$x_2 + \left(p_{2B} + \gamma_2(e_2) - k - \delta_2 - \tau_2 e_2 - C'\left(x_2\right)\right) \frac{\partial x_2}{\partial q_{2B}} = 0 \tag{31}$$

Equations (30) and (31) define $r_1(e_{1,}e_2)$ and $p_{2B}(e_1, e_2)$ so that demands are given by $x_1(r_1(e_1, e_2) + k + \sigma e_1, p_{2B}(e_1, e_2) + \sigma e_2)$ and $x_2(r_1(e_1, e_2) + k + \sigma e_1, p_{2B}(e_1, e_2) + \sigma e_2)$.

Turning to Stage 1, the problem of delivery operator 1 is:

$$\max_{e_1} \pi_1 = (r_1 + \gamma_1(e_1) - \delta_1 - \tau_1 e_1) x_1 - C(x_1)$$

Using the envelop theorem (that is, making use of expression 30) the FOC can be written as

$$\left(\gamma_1'(e_1) - \tau_1\right) x_1 + \left(r_1 + \gamma_1(e_1) - \delta_1 - \tau_1 e_1 - C'(x_1)\right) \left(\sigma \frac{\partial x_1}{\partial q_1} + \frac{\partial x_1}{\partial q_2} \frac{\partial r_2}{\partial e_1}\right) = 0. \quad (32)$$

The problem of firm 2 is

$$\max_{e_2} \pi_{2B} = (p_{2B} + \gamma_2(e_2) - k - \delta_2 - \tau_2 e_2) x_2 - C(x_2)$$

Using the envelop theorem (using expression 31), the FOC is given by:

$$\left(\gamma_2'(e_2) - \tau_2\right) x_2 + (p_{2B} + \gamma_2(e_2) - k - \delta_2 - \tau_2 e_2) \left(\sigma \frac{\partial x_2}{\partial q_2} + \frac{\partial x_2}{\partial q_1} \frac{\partial r_1}{\partial e_2}\right) = 0. \quad (33)$$

These expressions evaluated at $\tau_i = 0$ and $\delta_i = 0$ determine the LF, which with the combination of the externality and imperfect competition will again not be efficient. Interestingly, the properties of this equilibrium regarding emissions are similar to those obtained for independent firms. In particular we establish in Appendix C that when $\sigma = 0$ we continue to have maximum emissions with $e_i = \overline{e}_i$. Furthermore, and not surprisingly, the presence of CEA with $\sigma > 0$ will mitigate this inefficiency.

7.1 Implementation of the first best

We now examine how the FB can be achieved by the two considered tax instruments. In Appendix D we show that this requires

$$\tau_i = \psi'(E^*) - \sigma - \frac{\frac{\partial x_i}{\partial q_j} \frac{\partial r_j}{\partial e_i}}{\left(\frac{\partial x_i}{\partial q_i}\right)} \text{ for } i = 1, 2B. \quad (34)$$

$$\delta_i + \tau_i e_i = \frac{x_i}{\frac{\partial x_i}{\partial q_i}} + e_i \left(\psi'(E^*) - \sigma\right) \quad (35)$$

Interestingly, the expressions are the same as their counterparts in the case of independent firms, that is (28) and (29) and the discussion provided there continues to apply.

However, while the *rules* are the same, the *levels* will differ because equilibrium levels differ.

8 Heterogeneity in the level of environmental concern

A main finding of the model so far is that, the tax required to compensate for the environmental impact of the delivery is reduced (from its Pigouvian level) by the monetary equivalent of the consumers' environmental concern. This simple rule applies when all consumers have the same CEA. We now examine how it has to be amended when consumers differ in their valuation for the environment. To do so, we consider heterogenous consumers who differ only in their σ's. For simplicity assume that a proportion μ of the total population of consumers values the environment at $\sigma > 0$ while the remaining part, $1-\mu$ has no concern for the environment ($\sigma = 0$).

The preferences of the consumers of type E, who care about the environment are

$$u(x_1, x_2) - p_1 x_1 - p_2 x_2 - \sigma x_1 e_1 - \sigma x_2 e_2,$$

while the preferences of the consumers of type O who are not concerned about environmental issues are

$$u(x_1, x_2) - p_1 x_1 - p_2 x_2.$$

We continue to consider demand levels as function of *full* prices which include environmental concern, if any. We can thus define

$$q_i^E = p_i + \sigma,$$
$$q_i^O = p_i,$$

and denote demand levels by

$$x_i^E(q_1^E, q_2^E),$$
$$x_i^O(q_1^O, q_2^O).$$

They are obtained as shown in expressions (2)–(3), with the q_i's properly redefined. We can then define aggregate demands as

$$X_1(p_1,p_2) = (1-\mu)x_1^O + \mu x_1^E,$$
$$X_2(p_1,p_2) = (1-\mu)x_2^O + \mu x_2^E.$$

For the delivery stage, the market clearing conditions are now:

$$y_{A1} + y_{B1} = X_1 = (1-\mu)x_1^O + \mu x_1^E = z_1,$$
$$y_{A2} + y_{B2} = X_2 = (1-\mu)x_2^O + \mu x_2^E = z_2.$$

Total emissions are determined in the same way as before and so is social welfare, which continues to be given by (6). Recall that the CEA terms are not included in social welfare. Consequently, the first-best solution does not change.

Defining the (pseudo) competitive equilibrium in this setting is complicated and raises some conceptual issues. Consequently it looses its attractiveness as simple benchmark scenario. For the sake of illustration we thus concentrate on the imperfect competition setting with independent firms, which is not more complex when consumers are heterogenous. In particular, one easily checks that the equilibrium conditions derived in Section 6 remain valid, except that x_1 and x_2 have to be replaced by X_1 and X_2. In other words, with homogenous consumers there was no need to distinguish between individual and aggregate demand, but now this distinction becomes relevant and it is the level of aggregate demand that matters for the retailers and the delivery operators. For the rest, the properties of the equilibrium discussed there continue to apply. In particular when $\mu = 0$ were return to maximum emissions in the laissez-faire.[7] Furthermore, CEA will continue to mitigate the level of emissions except that now both μ and σ will be relevant.

Implementing the FB is now more problematic, because it requires personalized taxes, which depend on an individual's σ. These are feasible only when individual σ's are observable. Assume for the time being that they are. Then a simple way to achieve the FB is to impose first of all per unit taxes at rates σe_1 and σe_2 on the consumers who do not have any environmental concern. This brings us back to the model considered

[7] As long as $\partial^2 X_i/\partial q_i \partial q_j \geq 0$.

in Section 6 and the results obtained there continue to apply. To be more precise the taxes on "dirty" consumers come on top of the instruments considered in Section 6 and emissions and output taxes continue to be given by (28) and (29).

9 Revelation of emissions levels

Let us now revisit this issue within the context of imperfect competition. Recall that we have shown in Section 5 that under perfect competition delivery operators find it beneficial to reveal their emissions, assuming of course that they can credibly do this. As regulatory intervention is thus in principle not necessary, except that it may help conveying reliable information on emission levels.

For simplicity we concentrate on the scenario with independent firms. The most natural way to deal with this issue is then to introduce an extra stage into our game. Specifically, assume, that in Stage 0, delivery operators simultaneously decide whether they reveal their level of e_i or not. If both of them decide to reveal their emissions they play the game considered in Section 6. If either one or both operators decide not to reveal their emissions, the Stage 1 of the game is amended. For non revealing operators there is no incentive to reduce their levels of emissions; consequently, they choose maximum emission $e_i = \overline{e}_i$ to minimize their cost. The revealing operator i, if any, will play its best reply to the other operator's strategy, namely $\overline{e}_j$. Once e_i's are chosen the game proceeds with Stage 2, exactly as in Section 6.

Since no action is taken and no information revealed between the added Stage 0 and Stage 1, for an operator not revealing its emissions is equivalent to choosing maximum emissions in Stage 1. But this option already existed in the original game and we have shown that as long as σ is large enough it will not be relevant in equilibrium. Consequently, the equilibrium in Stage 0 involves revelation of emissions by both operators.[8]

To sum up, the result obtained in Section 5 for the competitive scenario continues to apply under imperfect competition when emission levels are chosen in a strategic way.

[8]When σ is close to zero, the equilibrium in Stage 1 involves maximum emissions. In that case, the outcome is the same irrespective of the decision made in Stage 0. Consequently, revelation by both operators continues to be an equilibrium in that case.

10 Concluding comments

We have shown that as can be expected, CEA mitigates the inefficiency of the equilibrium by bringing the level of emissions closer to its optimal level. This is true under perfect competition but it also remains true under imperfect competition both in the independent firms and the vertical integration scenarios.

This efficiency enhancing effect of CEA also affects the design of the appropriate emissions tax, which leads to an amended Pigouvian rule. Under perfect competition the tax is reduced by exactly the monetary level of CEA, σ. Under imperfect competition the taxation rule is more complicated and the reduction exceeds σ but the extra adjustment decreases as the CEA increases.

When consumers differ in their CEA the design of environmental taxes is more complicated. To achieve a first best, personalized taxes are required but they are feasible only when a consumer's degree of CEA is observable. When this is not the case, a uniform tax can only achieve a second-best solution. The characterization of this uniform policy is tedious and left for future research. However, one can expect that the required adjustment from the Pigouvian rule is some weighted average of the individual's levels of CEA.

All these results rely on the assumption that consumers are aware of the levels of emission associated with the product they consume. We show that in our setting delivery operators will find it beneficial to reveal their level of emissions but in practice it may be difficult to do this in a credible way. Consequently, a regulatory intervention associated with some kind of certification is certainly desirable.

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Appendix

A Comparative statics

Consider the FOCs (21) for $i = 1, 2$ and let us define Φ_i as follow:

$$\Phi_1 = x_1(q_1, q_2) + \frac{\partial x_1(q_1, q_2)}{\partial q_1}[r_1 + \gamma_1(e_1) - C_1'(x_1(q_1, q_2))],$$
$$\Phi_2 = x_2(q_1, q_2) + \frac{\partial x_2(q_1, q_2)}{\partial q_2}[r_2 + \gamma_2(e_2) - C_2'(x_2(q_1, q_2))],$$

where $q_i = k + r_i + \sigma e_i$. Define

$$MB_i = r_i + \gamma_i(e_i) - C_i',$$

the marginal benefit of a postal operator i. We have

$$\frac{\delta MB_i}{\delta r_i} = 1 - \frac{\partial x_i}{\partial q_i} C_i'' > 0, \tag{A1}$$

$$\frac{\delta MB_i}{\delta r_j} = -\frac{\partial x_i}{\partial q_j} C_i''. \tag{A2}$$

Differentiating Φ_1 and Φ_2 with respect to r_j, e_j and using $(A1)$ and $(A2)$ for $i, j = 1, 2$ yields

$$\frac{\partial \Phi_1}{\partial r_1} = \frac{\partial x_1}{\partial q_1} + \frac{\partial^2 x_1}{\partial q_1^2} MB_1 + \frac{\partial x_1}{\partial q_1} \frac{\delta MB_1}{\delta r_1}, \tag{A3}$$

$$\frac{\partial \Phi_1}{\partial r_2} = \frac{\partial x_1}{\partial q_2} + \frac{\partial^2 x_1}{\partial q_1 \partial q_2} MB_1 + \frac{\partial x_1}{\partial q_1} \frac{\delta MB_1}{\delta r_2}, \tag{A4}$$

$$\frac{\partial \Phi_2}{\partial r_1} = \frac{\partial x_2}{\partial q_1} + \frac{\partial^2 x_2}{\partial q_1 \partial q_2} MB_2 + \frac{\partial x_2}{\partial q_2} \frac{\delta MB_2}{\delta r_1}, \tag{A5}$$

$$\frac{\partial \Phi_2}{\partial r_2} = \frac{\partial x_2}{\partial q_2} + \frac{\partial^2 x_2}{\partial q_2^2} MB_2 + \frac{\partial x_2}{\partial q_2} \frac{\delta MB_2}{\delta r_2}, \tag{A6}$$

$$\frac{\partial \Phi_1}{\partial e_1} = \sigma \left[\frac{\partial x_1}{\partial q_1} \frac{\delta MB_1}{\delta r_1} + \frac{\partial^2 x_1}{\partial q_1^2} MB_1 \right] + \left(\frac{\partial x_1}{\partial q_1} \right) \gamma_1', \tag{A7}$$

$$\frac{\partial \Phi_1}{\partial e_2} = \sigma \frac{\partial x_1}{\partial q_2} \frac{\delta MB_1}{\delta r_1} + \sigma \frac{\partial^2 x_1}{\partial q_1 \partial q_2} MB_1, \tag{A8}$$

$$\frac{\partial \Phi_2}{\partial e_1} = \sigma \frac{\partial x_2}{\partial q_1} \frac{\delta MB_2}{\delta r_2} + \sigma \frac{\partial^2 x_1}{\partial q_1 \partial q_2} MB_2, \tag{A9}$$

$$\frac{\partial \Phi_2}{\partial e_2} = \sigma \left[\frac{\partial x_2}{\partial q_2} \frac{\delta MB_2}{\delta r_2} + \frac{\partial^2 x_2}{\partial q_2^2} MB_2 \right] + \left(\frac{\partial x_2}{\partial q_2} \right) \gamma_2'. \tag{A10}$$

Using Cramer rule, one has

$$\frac{dr_1}{de_2} = -\left(\frac{\partial \Phi_1}{\partial e_2} \frac{\partial \Phi_2}{\partial r_2} - \frac{\partial \Phi_1}{\partial r_2} \frac{\partial \Phi_2}{\partial e_2} \right) / SOC, \tag{A11}$$

where $SOC > 0$ is the second order condition. so that the sign of dr_1/de_2 is given by the the opposite sign of the numerator in $(A8)$. Using $(A8)$, $(A6)$, $(A4)$ and $(A10)$ yields:

$$\begin{aligned} &\frac{\partial \Phi_1}{\partial e_2} \frac{\partial \Phi_2}{\partial r_2} - \frac{\partial \Phi_1}{\partial r_2} \frac{\partial \Phi_2}{\partial e_2} \\ &= \sigma \left(\frac{\partial x_1}{\partial q_2} \frac{\delta MB_1}{\delta r_1} + \frac{\partial^2 x_1}{\partial q_1 \partial q_2} MB_1 \right) \left(\frac{\partial x_2}{\partial q_2} + \frac{\partial^2 x_2}{\partial q_2^2} MB_2 + \frac{\partial x_2}{\partial q_2} \frac{\delta MB_2}{\delta r_2} \right) \\ &- \sigma \left(\frac{\partial x_1}{\partial q_2} + \frac{\partial^2 x_1}{\partial q_1 \partial q_2} MB_1 + \frac{\partial x_1}{\partial q_1} \frac{\delta MB_1}{\delta r_2} \right) \left(\left[\frac{\partial x_2}{\partial q_2} \frac{\delta MB_2}{\delta r_2} + \frac{\partial^2 x_2}{\partial q_2^2} MB_2 \right] + \left(\frac{\partial x_2}{\partial q_2} \right) \frac{\gamma_2'}{\sigma} \right), \end{aligned} \tag{A12}$$

where the third term in brakets of $(A12)$ can be rewritten as follows:

$$\begin{aligned}
&\frac{\partial x_1}{\partial q_2}+\frac{\partial^2 x_1}{\partial q_1 \partial q_2}MB_1+\frac{\partial x_1}{\partial q_1}\frac{\delta MB_1}{\delta r_2}\\
&=\frac{\partial x_1}{\partial q_2}+\frac{\partial^2 x_1}{\partial q_1 \partial q_2}MB_1-\frac{\partial x_1}{\partial q_1}\frac{\partial x_1}{\partial q_2}C_1''\\
&=\frac{\partial x_1}{\partial q_2}\left(1-\frac{\partial x_1}{\partial q_1}C''\right)+\frac{\partial^2 x_1}{\partial q_1 \partial q_2}MB_1\\
&=\frac{\partial x_1}{\partial q_2}\frac{\partial MB_1}{\partial r_1}+\frac{\partial^2 x_1}{\partial q_1 \partial q_2}MB_1.
\end{aligned}$$

Factorizing out

$$\left(\frac{\partial x_1}{\partial q_2}\frac{\partial MB_1}{\partial r_1}+\frac{\partial^2 x_1}{\partial q_1 \partial q_2}MB_1\right)$$

in A12 yields

$$\begin{aligned}
&\frac{\partial \Phi_1}{\partial e_2}\frac{\partial \Phi_2}{\partial r_2}-\frac{\partial \Phi_1}{\partial r_2}\frac{\partial \Phi_2}{\partial e_2}\\
&=\sigma\left(\frac{\partial x_1}{\partial q_2}\frac{\delta MB_1}{\delta r_1}+\frac{\partial^2 x_1}{\partial q_1 \partial q_2}MB_1\right)\\
&\left(\frac{\partial x_2}{\partial q_2}+\frac{\partial^2 x_2}{\partial q_2^2}MB_2+\frac{\partial x_2}{\partial q_2}\frac{\delta MB_2}{\delta r_2}-\frac{\partial x_2}{\partial q_2}\frac{\delta MB_2}{\delta r_2}-\frac{\partial^2 x_2}{\partial q_2^2}MB_2-\left(\frac{\partial x_2}{\partial q_2}\right)\frac{\gamma_2'}{\sigma}\right)\\
&=\sigma\left(\frac{\partial x_1}{\partial q_2}\frac{\delta MB_1}{\delta r_1}+\frac{\partial^2 x_1}{\partial q_1 \partial q_2}MB_1\right)\left(\frac{\partial x_2}{\partial q_2}-\left(\frac{\partial x_2}{\partial q_2}\right)\frac{\gamma_2'}{\sigma}\right)\\
&=\frac{\partial x_2}{\partial q_2}\left(\frac{\partial x_1}{\partial q_2}\frac{\delta MB_1}{\delta r_1}+\frac{\partial^2 x_1}{\partial q_1 \partial q_2}MB_1\right)\left(\sigma-\gamma_2'\right), \qquad \text{(A13)}
\end{aligned}$$

so that the sign of dr_1/de_2 is given by the sign of $\sigma-\gamma_2'$.

Using the same reasoning, one can show that the sign of dr_2/de_1 is given by the sign of $\sigma-\gamma_1'$.

B Proof of equations (28)–(29)

Equations (26) and (27) can be rewritten as

$$\left(e_i^*\left(\psi'(E^*)-\sigma\right)-\delta_i-\tau_i e_i^*\right)=-\frac{x_i^*}{\frac{\partial x_i}{\partial q_i}}, \qquad \text{(A14)}$$

$$\left(e_i^*\left(\psi'(E^*)-\sigma\right)-\delta_i-\tau_i e_i^*\right)=-\frac{\left(\psi'\left(E^*\right)-\tau_i\right)x_i^*}{\left(\sigma\frac{\partial x_i(.)}{\partial q_i}+\frac{\partial x_i(.)}{\partial r_j}\frac{\partial r_j}{\partial q_i}\right)}. \qquad \text{(A15)}$$

Combining these two equations yields

$$-\left(\frac{x_i^*}{\frac{\partial x_i}{\partial q_i}}\right) = -\frac{\left(\psi'\left(E^*\right)-\tau_i\right)x_i^*}{\left(\sigma\frac{\partial x_i(.)}{\partial q_i}+\frac{\partial x_i(.)}{\partial q_j}\frac{\partial r_j}{\partial e_i}\right)},$$

so that

$$\left(\psi'\left(E^*\right)-\tau_i\right) = \frac{\left(\sigma\frac{\partial x_i}{\partial q_i}+\frac{\partial x_i}{\partial q_j}\frac{\partial r_j}{\partial e_i}\right)}{\left(\frac{\partial x_i}{\partial q_i}\right)}.$$

Simplifying this expression yields (28).

C Comparative statics

Consider the FOCs (30) and (31) and let us define Λ_i, $i=1,2$as follow:

$$\Lambda_1 = x_1\left(q_1,q_2\right)+\left(r_1+\gamma_1(e_1)-C'\left(x_1\left(q_1,q_2\right)\right)\right)\frac{\partial x_1\left(q_1,q_2\right)}{\partial q_1}, \tag{A16}$$

$$\Lambda_2 = x_2\left(q_1,q_2\right)+\left(p_{2B}+\gamma_2(e_2)-k-C'\left(x_2\left(q_1,q_2\right)\right)\right)\frac{\partial x_2\left(q_1,q_2\right)}{\partial q_{2B}}, \tag{A17}$$

where $q_1 = r_1+k+\sigma e_1$ and $q_2 = p_{2B}+\sigma e_2$. Define

$$MB_1 = r_i+\gamma_i(e_i)-C_i', \tag{A18}$$

and

$$MB_2 = p_{2B}+\gamma_2(e_2)-k-C'\left(x_2\left(q_1,q_2\right)\right), \tag{A19}$$

which represent respectively the marginal profit of a postal operator 1 and the integrated firm $2B$. We have

$$\frac{\delta MB_1}{\delta r_1} = 1-\frac{\partial x_1}{\partial q_1}C_1''>0, \tag{A20}$$

$$\frac{\delta MB_1}{\delta p_{2B}} = -\frac{\partial x_1}{\partial q_2}C_1''<0, \tag{A21}$$

and

$$\frac{\delta MB_2}{\delta p_{2B}} = 1-\frac{\partial x_2}{\partial q_2}C_2''>0, \tag{A22}$$

$$\frac{\delta MB_2}{\delta r_1} = -\frac{\partial x_2}{\partial q_1}C_2''<0, \tag{A23}$$

for $i=1,2$. Differentiation of $(A16)$ and $(A17)$ with respect to r_1, p_{2B}, e_1 and e_2 yields

$$\frac{\partial \Lambda_1}{\partial r_1} = \frac{\partial x_1}{\partial q_1} + \frac{\partial x_1}{\partial q_1}\frac{\partial MB_1}{\partial r_1} + \left(\frac{\partial^2 x_1}{\partial q_1^2}\right) MB_1, \tag{A24}$$

$$\frac{\partial \Lambda_1}{\partial p_{2B}} = \frac{\partial x_1}{\partial q_2}\frac{\partial MB_1}{\partial r_1} + MB_1 \frac{\partial x_1}{\partial q_1 \partial q_2}, \tag{A25}$$

$$\frac{\partial \Lambda_2}{\partial r_1} = \frac{\partial x_2}{\partial q_1}\frac{\partial MB_2}{\partial p_{2B}} + \frac{\partial x_2}{\partial q_1 \partial q_2} MB_2, \tag{A26}$$

$$\frac{\partial \Lambda_2}{\partial p_{2B}} = \frac{\partial x_2}{\partial q_2} + \frac{\partial x_2}{\partial q_2}\frac{\partial MB_2}{\partial q_2} + \left(\frac{\partial^2 x_2}{\partial q_2^2}\right) MB_2, \tag{A27}$$

$$\frac{\partial \Lambda_1}{\partial e_1} = \sigma\left(\frac{\partial x_1}{\partial q_1}\frac{\partial MB_1}{\partial r_1} + \frac{\partial^2 x_1}{\partial q_1^2} MB_1\right) + \frac{\partial x_1}{\partial q_1}\gamma_1', \tag{A28}$$

$$\frac{\partial \Lambda_1}{\partial e_2} = \sigma\left(\frac{\partial x_1}{\partial q_2}\frac{\partial MB_1}{\partial r_1} + \frac{\partial x_1}{\partial q_1 \partial q_2} MB_1\right), \tag{A29}$$

$$\frac{\partial \Lambda_2}{\partial e_1} = \sigma\left(\frac{\partial x_2}{\partial q_1}\frac{\partial MB_2}{\partial p_{2B}} + \frac{\partial x_2}{\partial q_1 \partial q_2} MB_2\right), \tag{A30}$$

$$\frac{\partial \Lambda_2}{\partial e_2} = \sigma\left(\frac{\partial x_2}{\partial q_2}\frac{\partial MB_2}{\partial r_2} + \frac{\partial^2 x_2}{\partial q_2^2} MB_2\right) + \frac{\partial x_2}{\partial q_2}\gamma_2', \tag{A31}$$

Using Cramer's rule, one has

$$\frac{dr_1}{de_2} = -\left(\frac{\partial \Lambda_1}{\partial e_2}\frac{\partial \Lambda_2}{\partial p_{2B}} - \frac{\partial \Lambda_1}{\partial p_{2B}}\frac{\partial \Lambda_2}{\partial e_2}\right)/SOC,$$

where $SOC > 0$. Using $(A29)$, $(A31)$, $(A25)$ and $(A31)$ yields:

$$\begin{aligned}
&\left(\frac{\partial \Lambda_1}{\partial p_{2B}}\frac{\partial \Lambda_2}{\partial e_2} - \frac{\partial \Lambda_1}{\partial e_2}\frac{\partial \Lambda_2}{\partial p_{2B}}\right) \\
&= \sigma\left(\frac{\partial x_1}{\partial q_2}\frac{\partial MB_1}{\partial r_1} + MB_1 \frac{\partial x_1}{\partial q_1 \partial q_2}\right)\left(\frac{\partial x_2}{\partial p_B}\frac{\partial MB_2}{\partial p_{2B}} + \frac{\partial^2 x_2}{\partial q_2^2} MB_2 + \frac{\partial x_2}{\partial q_2}\frac{\gamma_2'}{\sigma}\right) \\
&- \sigma\left(\frac{\partial x_1}{\partial q_2}\frac{\partial MB_1}{\partial r_1} + \frac{\partial x_1}{\partial q_1 \partial p_{2B}} MB_1\right)\left(\frac{\partial x_2}{\partial p_{2B}} + \frac{\partial x_2}{\partial p_{2B}}\frac{\partial MB_2}{\partial p_{2B}} + \left(\frac{\partial^2 x_2}{\partial p_{2B}^2}\right) MB_2\right) \\
&= \left(\frac{\partial x_1}{\partial q_2}\frac{\partial MB_1}{\partial r_1} + MB_1 \frac{\partial x_1}{\partial q_1 \partial q_2}\right)\frac{\partial x_2}{\partial q_2}\left(\sigma - \gamma_2'\right),
\end{aligned}$$

so that the sign of dr_1/de_2 is given by the sign of $\sigma - \gamma_2'$.

D Proof of equations (34) and (35)

Demands are implicitly defined by

$$u_1'(x_1, x_2) = q_1 = r_1 + k + \sigma e_1, \tag{A32}$$

$$u_2'(x_1, x_2) = q_2 = p_{2B} + \sigma e_2. \tag{A33}$$

The FOC's wrt. r_1 and p_{2B} are

$$x_1 + \left(r_1 + \gamma_1(e_1) - \delta_1 - \tau_1 e_1 - C'(x_1)\right) \frac{\partial x_1}{\partial q_1} = 0, \tag{A34}$$

$$x_2 + \left(p_{2B} + \gamma_2(e_2) - k - \delta_2 - \tau_2 e_2 - C'(x_2)\right) \frac{\partial x_2}{\partial q_{2B}} = 0. \tag{A35}$$

Recall that

$$q_1 = r_1 + k + \sigma e_1,$$

$$q_2 = p_{2B} + \sigma e_2,$$

so that $(A34)$ and $(A35)$ yield

$$q_1 = -x_1 / \frac{\partial x_1}{\partial q_1} - \gamma_1(e_1) + \delta_1 + \tau_1 e_1 + C'(x_1) + k + \sigma e_1, \tag{A36}$$

$$q_2 = p_{2B} + \sigma e_2 = -x_2 / \frac{\partial x_2}{\partial q_{2B}} - \gamma_2(e_2) + k + \delta_2 + \tau_2 e_2 + C'(x_2) + \sigma e_2. \tag{A37}$$

Substituting $(A36)$ and $(A37)$ into (8) and (9) and using (7) yields

$$-x_1 / \frac{\partial x_1}{\partial q_1} - \gamma_1(e_1) + \delta_1 + \tau_1 e_1 + C'(x_1) + k + \sigma e_1 = k + C_1'(x_1^*) - \gamma_1(e_1^*) + e_1^* \psi'(E^*),$$

$$-x_2 / \frac{\partial x_2}{\partial q_{2B}} - \gamma_2(e_2) + k + \delta_2 + \tau_2 e_2 + C'(x_2) + \sigma e_2 = k + C_2'(x_2^*) - \gamma_2(e_2^*) + e_2^* \psi'(E^*),$$

which after some simplification yields

$$-x_1 / \frac{\partial x_1}{\partial q_1} + \delta_1 + \tau_1 e_1 + \sigma e_1 = e_1^* \psi'(E^*),$$

$$-x_2 / \frac{\partial x_2}{\partial q_{2B}} + \delta_2 + \tau_2 e_2 + \sigma e_2 = e_2^* \psi'(E^*).$$

so that

$$\delta_1 = \frac{x_1}{\delta x_1 / \delta q_1} + e_1 \left(\psi'(E) - \tau_1 - \sigma\right), \tag{A38}$$

$$\delta_2 = \frac{x_2}{\delta x_2 / \delta q_2} + e_2 \left(\psi'(E) - \tau_2 - \sigma\right). \tag{A39}$$

The FOC wrt. e_1 is

$$\left(\gamma_1'(e_1) - \tau_1\right) x_1 + \left(r_1 + \gamma_1(e_1) - \delta_1 - \tau_1 e_1 - C'\left(x_1\right)\right) \left(\sigma \frac{\partial x_1}{\partial q_1} + \frac{\partial x_1}{\partial q_2}\frac{\partial r_2}{\partial e_1}\right) = 0$$

where using $(A38)$:

$$\begin{aligned}
&\left(r_1 + \gamma_1(e_1) - \delta_1 - \tau_1 e_1 - C'\left(x_1\right)\right) \\
&= -x_1/\frac{\partial x_1}{\partial q_1} - \gamma_1(e_1) + \delta_1 + \tau_1 e_1 + C'\left(x_1\right) \\
&+ \gamma_1(e_1) - \delta_1 - \tau_1 e_1 - C'\left(x_1\right) \\
&= -x_1/\frac{\partial x_1}{\partial q_1},
\end{aligned}$$

so that the FOC wrt. to e_1 yields

$$\left(\gamma_1'(e_1) - \tau_1\right) x_1 - x_1/\frac{\partial x_1}{\partial q_1}\left(\sigma \frac{\partial x_1}{\partial q_1} + \frac{\partial x_1}{\partial q_2}\frac{\partial r_2}{\partial e_1}\right) = 0,$$

which using (7) yields

$$\psi'(E) - \tau_1 = \frac{\sigma \frac{\partial x_1}{\partial q_1} + \frac{\partial x_1}{\partial q_2}\frac{\partial q_2}{\partial e_1}}{\frac{\partial x_1}{\partial q_1}}.$$

The FOC wrt. e_2 writes

$$\left(\gamma_2'(e_2) - \tau_2\right) x_2 + \left(p_{2B} + \gamma_2(e_2) - k - \delta_2 - \tau_2 e_2 - C'\left(x_2\right)\right) \left(\sigma \frac{\partial x_2}{\partial q_2} + \frac{\partial x_2}{\partial q_1}\frac{\partial r_1}{\partial e_2}\right) = 0,$$

where using $(A39)$

$$\begin{aligned}
&p_{2B} + \gamma_2(e_2) - k - \delta_2 - \tau_2 e_2 - C'\left(x_2\right) \\
&= -x_2/\frac{\partial x_2}{\partial q_{2B}} - \gamma_2(e_2) + k + \delta_2 + \tau_2 e_2 + C'\left(x_2\right) \\
&+ \gamma_2(e_2) - k - \delta_2 - \tau_2 e_2 - C'\left(x_2\right) \\
&= -x_2/\frac{\partial x_2}{\partial q_{2B}},
\end{aligned}$$

so that the FOC wrt e_2 can be rewritten as:

$$\left(\gamma_2'(e_2) - \tau_2\right) x_2 - \frac{x_2}{\frac{\partial x_2}{\partial q_{2B}}}\left(\sigma \frac{\partial x_2}{\partial q_2} + \frac{\partial x_2}{\partial q_1}\frac{\partial r_1}{\partial e_2}\right) = 0,$$

which using (7) yields

$$\psi'(E) - \tau_2 = \frac{\sigma \frac{\partial x_2}{\partial q_2} + \frac{\partial x_2}{\partial q_1}\frac{\partial r_1}{\partial e_2}}{\frac{\partial x_2}{\partial q_2}}.$$