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E-commerce, parcel delivery and environmental policy[1]

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Abstract

We study the design of environmental policy in the e-commerce sector and examine two main questions. First, what is the appropriate "level" of intervention along the value chain. Second, which instruments should be used at a specific level in the vertical chain? We consider a model with two retailers/producers who sell a differentiated product and two parcel delivery operators. The production, retailing and delivery of these goods generates CO_2 emissions. We assume that it is more expensive for the retailers and the delivery operators to use "green" technologies. We consider different scenarios reflecting the type of competition and the vertical structure of the industry.

In all cases the equilibria are inefficient for two reasons. First, at both level of the value chain (at the production/retailing stage and the delivery stage), the levels of emissions are too large (given the output levels - the number of items produced and delivered). Second the levels of outputs are not efficient because the cost of emissions is not reflected by the consumer prices. We show that in the perfect competition scenario a uniform Pigouvian tax on emission, reflecting the marginal social damage, is sufficient to correct both types of inefficiencies. Under imperfect competition a Pigouvian emissions tax is also necessary, but it has to be supplemented by positive or negative taxes on the quantity of good produced and delivered. The specific design of these instruments is affected by vertical integration between a retailer and a delivery operator.

Keywords: Pigouvian rule, emission taxes, output taxes, E-commerce, delivery operators, vertical integration.
JEL Codes: H21, L42, L81, L87.

1 Introduction

E-commerce has been growing significantly and the Covid epidemic has further exacerbated this trend. Its expansion has been raising many regulatory issues which ranging from competition policy questions to issues of profit shifting. But in addition to these "traditional" issues the environmental impact of the sector has been subject to ever increasing scrutiny and the appeals for policy intervention have become increasingly pressing.

We study the design of environmental policy in the e-commerce sector. While environmental protection and particularly the limitation of CO_2 emissions is a concern that is relevant for all economic activities, the appropriate regulatory design in the e-commerce sector raises specific questions. First, one has to determine the appropriate "level" of intervention along the value chain. Should the policy target the retailer, the producer or the delivery operator? Alternatively, is an intervention at all levels desirable and necessary? Second, which instrument should be used at a specific level in the vertical chain? Possible options include a carbon/emissions tax that could be levied wherever the emissions are generated or concentrated on the final product. A specific tax per parcel delivered at home has also been discussed. Many regulators are also tempted by more "command and control" oriented policies like restrictions on the vehicles used for delivery.

We consider a model with two retailers/producers who sell a differentiated product and two parcel delivery operators. The production, retailing and delivery of these goods generates CO_2 emissions. We assume that the cost of production and the cost of delivery decrease with the level of emissions, at least up to some level. In other words, it is more expensive for the producers and the delivery operators to use "green" technologies. So they have no incentive to reduce their emissions despite the fact that these emissions create a global (atmosphere) externality which is a potential source of global warming and climate change: this negative externality is not internalized in the individual decision of all economic actors along the value chain.

We consider different scenarios reflecting the type of competition and the vertical structure of the industry. In the reference scenario all firms (upstream and downstream) are independent and behave competitively so that retail prices and delivery rates are set at marginal costs. Then we consider a setting where all firms remain independent but where there is imperfect competition which involves strategic interactions and yields a (subgame perfect) Nash equilibrium. Finally, we assume that there is vertical integration between one of the retailers and one of the delivery operators. The vertically integrated firm may or may not exclusively deliver via its own delivery operator.

The different scenarios yield different equilibria, implying different levels of emissions and outputs. The market structure also affects the environmental policy because this one has to account for the adjustments induced in the market and in particular the pass-through of taxes to consumers.

In all cases the equilibria are inefficient for two reasons. First, at both level of the value chain (at the production/retailing stage and the delivery stage), the levels of emissions are too large (given the output levels - the number of items produced and delivered). Second the levels of outputs are not efficient because the cost of emissions is not reflected by the consumer prices. Under perfect competition output levels are too large but this effect is mitigated under imperfect competition.

We show that in the perfect competition scenario a uniform Pigouvian tax on emission, reflecting the marginal social damage, is sufficient to correct both types of inefficiencies. The same result can be achieved by a Pigouvian subsidy on emission reductions. Under imperfect competition a Pigouvian emissions tax is also necessary, but it has to be supplemented by positive or negative taxes on the quantity of good produced and delivered. The specific design of these instruments is affected by vertical integration.

2 The model

Consider an e-commerce sector with two producers/retailers, $j = A, B$ and two delivery operators, $i = 1, 2$. Consumer prices are denoted p_A, p_B and demand function by $x_A(p_A, p_B)$ and $x_B(p_A, p_B)$. They are obtained by solving

$$\max_{x_A, x_B} U(x_A, x_B) - p_A x_A - p_B x_B \tag{1}$$

Production costs of retailers $j = A, B$ are denoted $y_j k_j(e_j)$, where y_j is the number of items produced, while e_j represents the level of emissions per unit of good produced. We assume that

$$k_j'(e_j) < 0 \text{ for } e_j < \bar{e}_j \quad \text{and} \quad k_j'(e_j) = 0 \text{ for } e_j \geq \bar{e}_j. \tag{2}$$

This assumption represents the property that producing and retailing in a less polluting way is more costly. Formally this means that increasing emissions decreases cost at least up to some level $\bar{e}_j$.

Delivery costs of operator $i = 1, 2$ are given by $c_i(y_i, e_i)$, where y_i is the number of parcels delivered and e_i is emissions per parcel delivered. Assume for simplicity that:

$$c_i(y_i, e_i) = C_i(y_i) - \gamma_i(e_i)y_i, \tag{3}$$

where

$$\gamma_i'(e_i) > 0 \quad \text{for } e_i < \bar{e}_i \quad \text{and} \quad \gamma_i'(e_i) = 0 \quad \text{for } e_i \geq \bar{e}_i. \tag{4}$$

This is the counterpart to expression (2) and implies that delivering in a less polluting way is more costly.[1]

Total emissions, E, have a social cost $\psi(E)$. Observe that only total emissions matter irrespective of their origin, which is the case for "atmosphere" externalities like CO_2.

2.1 Laissez-Faire

Since there is perfect competition in the delivery segment and the services offered by operators 1 and 2 are considered as perfect substitutes, there is a unique delivery rate r, which is endogenously determined in equilibrium to equalize demand and supply. Delivery operators choose $e_i = \bar{e}_i$ for $i = 1, 2$. Their respective supply function $y_i(r)$ is determined by

$$C_i'(y_i) - \gamma_i(\bar{e}_i) = r \text{ for } i = 1, 2$$

[1] This is a reduced form of a model where the firms invest in emission reducing technologies. Formally we would then have $e \equiv e(g)$ where g is investment per unit of y in reducing e and $e'(g) < 0$. Rewrite $k_j(e) \equiv k_j(e(g_j))$ and $\gamma_i(e) \equiv \gamma_i(e(g_i))$, then yields our formulations.

Turning to the production/selling segment, retailers choose $e_j = \bar{e}_j$ to minimize their production cost. By assumption, retailers are price takers so that $p_j = k_j(\bar{e}_j) + r$ for $j = A, B$.

In equilibrium demand must equal supply both in the production and the delivery part of the value chain, where the demand for delivery services addressed to operators 1 and 2 equals total demand for goods produced and sold by retailers A and B. Formally this is expressed by the following conditions.

$$y_A(r) + y_B(r) = y_1(r) + y_2(r) = x_A(k_A(\bar{e}_A) + r, k_B(\bar{e}_B) + r) + x_B(k_A(\bar{e}_A) + r, k_B(\bar{e}_B) + r)$$

$$y_A(r) = x_A(k_A(\bar{e}_A) + r, k_B(\bar{e}_B) + r); \qquad y_B(r) = x_B(k_A(\bar{e}_A) + r, k_B(\bar{e}_B) + r)$$

Total emissions are $E = \bar{e}_1 y_1(r) + \bar{e}_2 y_2(r) + \bar{e}_A y_A(r) + \bar{e}_B y_B(r)$.

2.2 First best allocation

The first-best allocation (FB) is obtained by maximizing total surplus net of the social cost of emissions. With equation (3), we obtain the following Lagrangian expression

$$\begin{aligned}\mathcal{L} &= U(x_A, x_B) - k_A(e_A)x_A - k_B(e_B)x_b - C_1(y_1) + \gamma_1(e_1)y_1 \\ &- C_2(y_2) + \gamma_2(e_2)y_2 - \psi(y_1e_1 + y_2e_2 + x_Ae_A + x_Be_B) \\ &- \mu[x_A + x_B - y_1 - y_2],\end{aligned}$$

where μ is the multiplier associated with the constraint requiring that all sales are delivered, while $y_1e_1 + y_2e_2 + x_Ae_A + x_Be_B = E$ is the total level of emissions.

The FOCs (first-order conditions) w.r.t x_j, y_i, e_j, e_i are respectively given by

$$\frac{\partial \mathcal{L}}{\partial x_j} = U_j - k_j(e_j) - e_j\psi'(E) - \mu = 0, \tag{5}$$

$$\frac{\partial \mathcal{L}}{\partial y_i} = -C_i'(y_i) + \gamma_i(e_i) - e_i\psi'(E) + \mu = 0, \tag{6}$$

$$\frac{\partial \mathcal{L}}{\partial e_j} = -k_j'(e_j)y_j - y_j\psi'(E) = 0 \tag{7}$$

$$\frac{\partial \mathcal{L}}{\partial e_i} = \gamma_i'(e_i)y_i - y_i\psi'(E) = 0 \tag{8}$$

Using $*$ to denote FB, combining (8) and (7) yields:

$$-k_j'(e_j^*) = \gamma_i'(e_i^*) = \psi'(E^*) \tag{9}$$

These equations state that the private marginal benefit (cost reduction) of emissions from retailer j and delivery operator i should be equal to the marginal social damage per unit of good produced and delivered.

Equation (6) implies that

$$C_1'(y_1^*) - \gamma_1(e_1^*) + e_1^*\psi'(E^*) = C_2'(y_2^*) - \gamma_2(e_2^*) + e_2^*\psi'(E) \tag{10}$$

so that the social marginal cost of delivering one parcel should be the same for the two delivery operators.

Now combining (5) to (6) yields:

$$U_j = k_j\left(e_j^*\right) + C_i'(y_i^*) - \gamma_i(e_i^*) + \left(e_i^* + e_j^*\right)\psi'(E^*) \tag{11}$$

This equation states that the marginal willingness to pay for good j should be equal to the sum of private and social marginal cost of producing and delivering it.

2.3 Decentralization

We now study how the FB allocation can be decentralized under perfect competition. Potential instruments are: a linear tax on each unit of good produced t_j, a linear tax on each parcel delivered δ_i and a linear tax on the pollution emitted by producing and delivering the good τ.

Retailer j solves for given prices p_j and τ

$$\max_{y_j, e_j} \quad \left(p_j - t_j\right)y_j - ry_j - y_jk_j\left(e_j\right) - \tau y_je_j. \tag{12}$$

The FOCs w.r.t y_j and e_j are given by

$$\left(p_j - t_j\right) - r - k_j\left(e_j\right) - \tau e_j = 0 \tag{13}$$

$$-\,y_jk_j'\left(e_j\right) - \tau y_j = 0 \tag{14}$$

Parcel delivery operator i solves

$$\max_{y_i, e_i}\left(r - \delta_i\right)y_i - C_i(y_i) + \gamma_i(e_i)y_i - \tau y_ie_i \tag{15}$$

The FOCs w.r.t y_i and e_i are given by

$$(r-\delta_i) - C_i'(y_i) + \gamma_i(e_i) - \tau e_i = 0 \tag{16}$$

$$\gamma'(e_i)y_i - \tau y_i = 0 \tag{17}$$

The FOCs of the consumers' problem (1) are given by

$$U_j - p_j = 0 \tag{18}$$

From (14) and (17) and using (9), we must have:

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

This is the classical equation of a Pigouvian taxation of emissions. Furthermore, combining (13), (16), (18) and (19) yields (11) with $t_j = \delta_i = 0$.

In words, the optimal solution can be achieved by a uniform tax on emissions at all levels (production and delivery). As explained above, what matters is the total amount of emissions irrespective of their origins. So it is relevant to tax in the same way a ton of CO_2 whatever it is emitted during the production or the delivery phase. This result is quite remarkable because we are able to correct two inefficiencies generated by a laissez-faire approach with a same and unique tool, contrary to the classical rule of "one instrument for one issue". In this LF situation, *(i)* the level of emissions per unit of output is too large (both upstream and downstream); *(ii)* the consumer price does not reflect the social cost of pollution so that output levels will be too large. As usual, the emissions tax achieves the correct level of emissions. Furthermore, under perfect competition with marginal cost pricing, the tax is fully reflected in the price charged by producers. Consequently, the consumer price also increases so that it now reflects the (marginal) social cost of emissions and solve the second inefficiency.

Before turning to imperfect competition, two remarks are in order.

2.3.1 Subsidizing emission reduction

Note that rather than taxing emissions we could subsidize emission reductions $(\overline{e}-e_i)y_i$. Denoting the subsidy s, the producer and delivery operator's profit functions would then respectively be given by

$$\pi_j = (p_j - t_j)\, y_j - r y_j - y_j k_j\,(e_j) + s\,(\overline{e}_j - e_j)\, y_j$$
$$\pi_i = r y_i - C_i(y_i) + \gamma_i(e_i) y_i + s(\overline{e}_i - e_i) y_i,$$

which differs from (12) and (15) only by a constant so that nothing changes and we have of course

$$s = \psi'(E^*).$$

This may at first be surprising, but one has to realize that when emissions reductions are subsidized, emissions have a positive marginal cost: increasing e_j and e_i reduces the subsidy!

2.3.2 Inefficiency of uniform quotas

Another interesting point is that the FB implies in general that delivery operators and producers have different emission levels (unless their cost functions are identical). The solution will imply thus different emissions levels (per unit of output) for the different actors. Consequently uniform emissions quotas or emission standards cannot implement the FB and may actually reduce welfare.

3 Imperfect competition

While the perfect competition case provides an interesting benchmark, in reality market power appears to be pervasive in the e-commerce sector. Consequently it is important to revisit our analysis in a setting of imperfect competition, possibly combined with vertical integration. Market power typically implies that firms reduce their output in order to keep prices high. Now, when the good is polluting this output reduction may, at least in part, be socially desirable. However, imperfect competition does not in itself provide any incentives to retailers or delivery operators to adopt cleaner production technologies.

We study two settings of imperfect competition. In the first one, there is no vertical integration and all retailers and delivery operators are independent. In the second one we assume that one of the retailers is vertically integrated with a delivery operator. We further assume that the integrated delivery operator only delivers the product sold by the integrated firm, but the latter may choose to deliver part of its sales via the independent delivery operator. Alternative types of vertical restraints could be considered but to avoid a multiplication of scenarios, we concentrate on this empirically appealing case.

3.1 Independent retailers and delivery operators

The model is similar to the basic model with emissions both in production and in delivery. However, we no longer assume perfect competitions. We introduce the taxes considered above from the outset (to avoid repetitions). Recall that these are a linear tax on each unit of output produced t_j, a linear tax on each parcel delivered δ_i and a linear tax on emissions generated by the production and the delivery τ. The laissez-faire equilibrium can be obtained by setting all the taxes equal to zero. The timing, inspired by Borsenberger et al. (2021), is as follows.

1. Delivery operators choose r_1, e_1 and r_2, e_2.
2. Retailers choose p_A, e_A and p_B, e_B.
3. Consumers choose x_A and x_B.

We determine the subgame perfect equilibrium and solve the game by backward induction.

3.1.1 Equilibrium

Stage 3 Nothing changes for consumers who continue to solve (1), yielding demand functions $x_j\left(p_A, p_B\right)$ for $j = A, B$.

Stage 2 Retailer j chooses p_j, e_j to solve

$$\max \pi_j = \left(p_j - t_j - \min\left\{r_1, r_2\right\} - k_j\left(e_j\right) - \tau e_j\right) x_j\left(p_A, p_B\right).$$

The FOCs are given by

$$x_j + (p_j - t_j - \min\{r_1, r_2\} - k_j(e_j) - \tau e_j) \frac{\partial x_j}{\partial p_j} = 0 \text{ for } j = A, B, \quad (20)$$

$$-k_j^{'}(e_j) - \tau = 0, \quad (21)$$

which yields $x_j(t_j, \min\{r_1, r_2\}, \tau)$ and $e_j(\tau)$.

Stage 1 Delivery operators solve

$$\max_{r, e_i} \pi_i = (r_i - \delta_i + \gamma_i(e_i) - \tau e_i)\, y_i - C_i(y_i).$$

Since delivery services are prefect substitutes we have Bertrand competition which, with a strictly convex cost function yields marginal cost pricing so that

$$r = \delta_i - \gamma_i(e_i) + \tau e_i + C_i'(y_i) \text{ for } i = 1, 2 \quad (22)$$

$$\gamma_i'(e_i) - \tau = 0 \quad (23)$$

In words each delivery operator chooses the same delivery price because otherwise the operator with the higher price has a zero demand from retailers.

3.1.2 Implementation of the FB

The first-best solution is the same as the one derived in Section 2.2. Recall that in a first best one has to satisfy equation (9) so that one needs again

$$\tau = \psi'(E).$$

In words the emissions tax continues to be given by the Pigouvian rule. With this level of emission taxes equation (10) continues to be satisfied because of pure Bertrand competition on the delivery side.

On the retailer side, we have

$$U_j = k_j(e_j) + C_i'(y_i) - \gamma_i(e_i) + (e_i + e_j)\, \psi'(E),$$

so that the social marginal cost of delivery is equalized across retailers.

However, we now need one more instrument to insure that consumer prices are set at the optimal level. This is because under imperfect competition an increase in marginal cost is not passed on to consumers on a one by one basis. Combining (20) and (22), we have:

$$U_j = t_j + k_j\left(e_j\right) + \delta_i - \gamma_i(e_i) + e_i\psi'(E) + C_i'\left(y_i\right) + e_j\psi'(E) - \frac{x_j}{\frac{\partial x_j}{\partial p_j}}$$

In order to satisfy (11), that is to get the correct level of the consumer prices, one thus needs either:

$$t_j = \frac{x_j}{\frac{\partial x_j}{\partial p_j}} < 0;\ j = A, B \tag{24}$$

$$\text{and } \delta_i = 0, \tag{25}$$

or

$$t_j = 0$$

$$\text{and} \quad \delta_i = -\frac{x_j}{\frac{\partial x_j}{\partial p_j}} < 0,\ i = 1, 2.$$

This is in line with the "classical" result that under imperfect competition implementing the FB requires a subsidy because prices are too high. In our case, either the production or the delivery must be subsidized.

As already mentioned in the *laissez-faire* equilibrium where emissions are not taxed, this effect goes in the right direction because it reduces output, which is otherwise too large because of pollution. Depending on the cost of pollution and the extent of market power, the output may the be smaller or larger than the socially optimal one. However, when emissions are taxed, we return to the case where market power is detrimental to welfare, since price will be too large.

3.2 Integrated firm I and foreclosure

We now assume that retailer A and delivery operator 1 are vertically integrated. We refer to them as the integrated firm I. We assume that the integrated delivery operator (operator 1) delivers exclusively retailer A's product. In that sense there is foreclosure. However, retailer A may decide to have part of its sales delivered by operator 2, as long as this proofs profitable. We'll see below (in particular in the numerical examples) that this may or may not be the case. Indeed, there are two conflicting effects. On the one hand delivery costs are convex which pleads for using both delivery operators. However, in this situation delivery operator 2 has market power and sets its price above marginal cost, a situation that does not encourage the integrated firm to use operator 2's parcel delivery services.

The timing is as follows:

1. The independent delivery operator chooses r_2,e_2
2. The integrated firm chooses p_A, e_A and e_1 and μ which is the proportion of x_A that is delivered by delivery operator 2 at price r_2. Note that a corner solution with $\mu = 0$ is possible if the markup of operator 2 is large. The independent retailer simultaneously chooses p_B, e_B for a given delivery price r_2.
3. Consumers choose x_A and x_B given prices p_A and p_B.

Stage 3 is the same as in the previous sections so that we concentrate on the other two stages.

3.2.1 Stage 2

The integrated firm chooses:

$$\max_{p_A,\mu,e_A,e_1} \quad (p_A - t_A - k_A(e_A) - \tau e_A)\, x_A(p_A,p_B) + (\gamma_1(e_1) - \delta_1 - \tau e_1)(1-\mu)\, x_A(p_A,p_B) \\ - C_1((1-\mu)\, x_A(p_A,p_B)) - r_2 \mu x_A(p_A,p_B).$$

The FOCs are

$$x_A + (p_A - t_A - k_A(e_A) - \tau e_A + (\gamma_1(e_1) - \delta_1 - \tau e_1)(1-\mu) \\ - (1-\mu)\, C_1'((1-\mu)\, x_A(p_A,p_B)) - r_2\mu \frac{\partial x_A}{\partial p_A} \le 0 \tag{26}$$

$$-\gamma_1(e_1) + \delta_1 + \tau e_1 + C_1'((1-\mu)\, x_A) - r_2 = 0 \tag{27}$$

$$-k_A'(e_A) - \tau = 0 \tag{28}$$

$$\gamma_1'(e_1) - \tau = 0 \tag{29}$$

We assume an interior solution for all variables except possibly for μ for which a corner solution at $\mu = 0$ is a possibility that cannot be ruled out. As discussed above and illustrated by the numerical examples below, the integrated firm may prefer to deliver all its parcels via its own delivery operator.

The independent retailer B chooses p_B and e_B such that:

$$\max_{p_B, e_B} \pi_B = (p_B - t_B - r_2 - k_B(e_B) - \tau e_B)\, x_B(p_A, p_B)$$

The FOCs are

$$x_B + (p_B - t_B - r_2 - k_B(e_B) - \tau e_B)\frac{\partial x_B}{\partial p_B} = 0, \tag{30}$$

$$-k_B'(e_B) - \tau = 0 \tag{31}$$

Each players FOCs implicitly define their best-response functions and the Nash equilibrium must satisfy all of them. This yields the equilibrium of the second stage induced by the choices of the independent delivery operator (r_2, e_2) made in the first stage and by the various taxes $p_A(t_A, t_B, r_2, \tau, \delta_1\, \delta_2)$, $p_B(t_A, t_B, r_2, \tau, \delta_1, \delta_2)$, $\mu(t_A, t_B, r_2, \tau, \delta_1, \delta_2)$, $e_A(\tau)$, $e_B(\tau)$, $e_1(\tau)$.

3.2.2 Stage 1

The independent delivery operator chooses r_2, e_2 anticipating the induced equilibrium in stage 2. Formally, it solves

$$\begin{aligned}\max_{r_2, e_2} & (r_2 - \delta_2 + \gamma_2(e_2) - \tau e_2)\,(x_B(p_A(.), p_B(.)) + \mu(.)\, x_A p_A(.), p_B(.)) \\ & - C_2(x_B(p_A(.), p_B(.)) + \mu(.)\, x_A(p_A(.), p_B(.)))\,.\end{aligned} \tag{32}$$

The FOCs are given in Appendix A.1.

3.3 Implementation

We now examine how the first-best solution can be achieved with this game by the use of the considered tax instruments.

First, it follows from (8), (7), (29) and (31) that we again need a linear Pigouvian tax on emissions so that

$$\tau = \psi'(E)\,.$$

To obtain the levels of the other instruments we again have to combine the FOC for the first-best with those characterizing the equilibrium of the game and then solve for the relevant instrument. As shown in Appendix A.2 this yields.:

$$t_A = \frac{x_A}{\frac{\partial x_A}{\partial p_A}} < 0 \tag{33}$$

$$t_B = \frac{x_B}{\frac{\partial x_B}{\partial p_B}} < 0 \tag{34}$$

$$\delta_2 = \frac{\frac{\partial x_B}{\partial r_2} + \frac{\partial \mu(.) x_A(.)}{\partial r_2}}{x_B + \mu x_A} < 0 \tag{35}$$

The first two of these conditions are identical to their counterparts obtained with independent firms because they are evaluated at the FB to be implemented which is the same in both cases. Consequently, they have the same interpretation. The new feature is that we now need δ_2 as an additional instrument. This is necessary because delivery operator 2's rates no longer reflect marginal costs. Consequently, a correction is needed to achieve the efficient allocation of parcels across operators. The property that δ_2 is negative (the independent delivery operator must be subsidized) arises because the rate of operator 2 is too high (because of its market power over retailer B).

4 Numerical illustrations

To illustrate our results we now present some numerical examples. They provide some extra insights even though our analytical results are unambiguous. In particular, they allow us to examine how various asymmetries in costs and the environmental quality of production technologies affect the orders of magnitude of the various effects. Furthermore, they show that we can indeed have interior as well as corner solutions for μ in the scenario with the integrated firm.

4.1 The specification

We used a quadratic utility which yields linear demands. The goods produced by retailers A and B are substitutes. Formally, consumer surplus CS is given by $CS = U(x_A, x_B) + m - p_A x_A - p_B x_B$ where m is the consumer's revenues and U is assumed quadratic and given by

$$U = a_1 x_A + a_2 x_B - b_1 x_A^2 -_2 b_2 x_B^2 - \sigma x_A x_B$$

This yields the following expression for the demand function

$$\begin{aligned} x_A\left(p_A, p_B\right) &= \frac{1}{4b_1 b_2 - \sigma^2}\left[2\left(a_1 - p_A\right) b_2 - a_2\sigma + \sigma p_B\right], \\ x_B\left(p_A, p_B\right) &= \frac{1}{4b_1 b_2 - \sigma^2}\left[2\left(a_2 - p_B\right) b_1 - a_1\sigma + \sigma p_A\right], \end{aligned}$$

where we assume that

(i) $b_i > 0$, $i = 1, 2$ so that demands are decreasing in their own price,

(ii) $\sigma = \partial x_A / \partial p_B = \partial x_B / \partial p_A > 0$ so that the goods x_A and x_B are substitutes because the cross-price elasticity is positive

and *(iii)* $4b_1 b_2 - \sigma^2 > 0$ to ensure concavity of utilities.

Retailers' unit cost of production is defined by

$$\begin{aligned} k_j\left(e\right) &= \kappa_j + \left(e - \overline{e}_j\right)^2 \text{ for } e \leq \overline{e}_j, \\ &= \kappa_j \text{ otherwise,} \end{aligned}$$

where $\kappa_j > 0$. Note that

$$k_j^{'}\left(e\right) = 2\left(e - \overline{e}\right) \text{ for } e \leq \overline{e}$$

The costs of delivery operator i to deliver y parcels $c_i(y, e)$ are given by

$$c_i(y, e) = C_i\left(y\right) + y\gamma_i\left(e_i\right)$$

where

$$C_i\left(y\right) = \left(\theta_i / 2\right) y^2$$

and

$$\begin{aligned} \gamma_i\left(e\right) &= \eta_i + \left(e_i - \overline{e}_i\right)^2 \text{ for } e_i \leq \overline{e}_i \\ &= \eta_i \text{ otherwise,} \end{aligned}$$

where $\theta_i > 0$ and $\eta_i > 0$. These cost functions satisfy the assumptions made in the analytical part and their interpretations are in line with those discussed there.

The social cost of emissions is given by

$$\psi(E) = \varphi E$$

so that the marginal cost of emissions is constant. Within the context of climate change this would be the social cost of a ton of CO_2.

4.2 Illustrative results

We start with a symmetric benchmark scenario. The illustration uses the following parameters in the benchmark/symmetric scenario: $a = 100$, $b = 2$, $\sigma = 3$, $\bar{e} = 1$, $\kappa = 1$, $\theta = 1$, $\eta = 1$, $\varphi = 5$.[2] Then we introduce various types of asymmetries.

In all tables, LF_1 refers to the competitive equilibrium; LF_2 is the equilibrium with imperfect competition and independent retailers and delivery operators (subsection 3.1); LF_3 is the equilibrium with imperfect competition and foreclosure (subsection 3.2).

We know from theory that emission taxes are given by $\tau = \varphi = 5$ in all scenarios. To avoid repetition we do not report this in each table. We also know that under perfect competition (case LF_1) this is the only instrument we need.

4.2.1 Example 1: benchmark/symmetric scenario

The different allocations are given in Table 1.[3]

When firms are independent (case LF_2), we have $t_A = t_B = -0.046$ while $\delta_1 = \delta_2 = 0$: the production of the goods is subsidized (as noticed in the analytical part of the paper, one could consider the reverse scenario where the delivery is subsidized instead of the production). We can calculate these levels based on the FB without actually calculating LF_2. The fact that $t_A = t_B$ is of course due to the symmetry of the firms. On the other hand, $\delta_1 = \delta_2 = 0$ (or if we consider the reverse scenario where the delivery is subsidized instead of the production, $t_A = t_B = 0$) is a general result we already know from the analytical model.

[2] We have dropped the subscripts because we assume perfect symmetry in the benchmark scenario to that the parameters apply to both retailers or delivery operators.

[3] In LF3, π_1 represents the profits of the integrated firm.

	LF_1	FB	LF_2	LF_3
x_A	12	11.51	9.48	11.62
x_B	12	11.51	9.48	5.84
y_1	12	11.51	9.48	11.62
y_2	12	11.51	9.48	5.84
p_A	16	19.39	31.07	35.96
p_B	16	19.39	31.07	41.75
m	13	14.45	10.84	28.52
e_1	1	0.28	1	1
e_2	1	0.28	1	1
e_A	1	0.28	1	1
e_B	1	0.28	1	1
E	48	13	39	34
CS	1008	928	678	542
π_A	0	0	169	–
π_B	0	0	169	59
π_1	72	66	48	304
π_2	72	66	48	143
SWF	912	995	917	803

Table 1: Benchmark scenario.

With integrated firm and foreclosure (case LF_3), we have again $t_A = t_B = -0.046$ but $\delta_2 = -0.082$, while $\delta_1 = 0$: not only the retailers but also the independent delivery operator are subsidized. We know from the analytical results that t_A and t_B are the same as in the case LF_2. Without these taxes, LF_3 leads to bundling and foreclosure, that is the integrated firm does not use the services offered by the independent delivery operator.

We now examine various asymmetric scenarios, which provide a stylized representation of differences in the current environmental properties of the production technologies across delivery operators. Each scenario is identified by the parameters that differ from the benchmark scenario.

4.2.2 Scenario 2: $\eta_1 = 0.8$, $\bar{e}_1 = 1$, $\bar{e}_2 = 0.8$, $\eta_2 = 1$

This scenario represents a scenario in which the independent delivery operator is currently less polluting than its competitor so that its costs are higher. The results are presented in Table 2.

Scenario	LF_1	FB	LF_2	LF_3
x_A	12,14	11,68	9,96	11,78
x_B	12,14	11,68	9,96	5,89
y_1	12,24	11,55	10,06	11,78
y_2	12,04	11,82	9,86	5,89
p_A	15,04	18,23	30,29	35,20
p_B	15,04	18,23	30,29	41,08
m	13,04	14,29	10,86	28,76
e_1	1,00	0,29	1,00	1,00
e_2	0,80	0,23	0,80	0,80
e_A	1,00	0,29	1,00	1,00
e_B	1,00	0,29	1,00	1,00
CS	1031,23	955,31	694,27	555,36
E	46,14	12,68	37,86	34,17
π_A	0,00	0,00	173,57	312,23
π_B	0,00	0,00	173,57	60,81
π_1	74,88	66,67	50,59	
π_2	71,97	69,82	48,21	146,29
SWF	947,37	1028,42	950,88	903,84
t_A	t_B	δ_2		
-0,049	-0,049	-0,095		

Table 2: Scenario 2: $\eta_1 = 0.8$, $\bar{e}_1 = 1$, $\bar{e}_2 = 0.8$, $\eta_2 = 1$

Qualitatively the outcomes in this case are similar to the benchmark scenario. We have again bundling in case LF_3 and we continue to have $\delta_2 < 0$. Interestingly the asymmetries in delivery costs do not affect the symmetry of the subsidies on the retailers. This may be at first sight surprising since, due to the possibility to have the corner solution for μ, marginal costs differ in LF_3. However, the FB which is implemented requires that marginal delivery costs are equalized which, along with the fact that demands are symmetric, explains that the t's are equal.

4.2.3 Scenario 3: $\theta_1 = 1$, $\bar{e}_1 = 1$, $\bar{e}_2 = 0.8$, $\theta_2 = 0.1$

This scenario returns to the case where the η's are the same for all delivery operators. Like in the previous one operator 2 is cleaner (so its delivery services are most costly all others things being equal) but now has a less convex cost function (so its services are less costly all others things being equal, for instance because it is the incumbent and

Scenario	LF_1	FB	LF_2	LF_3
x_A	13,51	13,03	10,86	10,02
x_B	13,51	13,03	10,86	10,02
y_1	2,46	1,94	1,97	9,30
y_2	24,56	24,11	19,75	10,74
p_A	5,46	8,82	23,98	29,84
p_B	5,46	8,82	23,98	29,84
m	3,46	4,88	2,97	10,30
e_1	1,00	0,29	1,00	1,00
e_2	0,80	0,23	0,80	0,80
e_A	1,00	0,29	1,00	1,00
e_B	1,00	0,29	1,00	1,00
CS	1276,95	1187,71	825,58	703,19
E	49,11	13,51	39,49	37,94
π_A	0,00	0,00	206,40	219,05
π_B	0,00	0,00	206,40	175,80
π_1	3,02	1,88	1,95	
π_2	29,17	29,06	18,70	94,16
SWF	1063,56	1151,11	1061,58	1002,49
t_A	t_B	δ_2		
-0,044	-0,044	-0,154		

Table 3: Scenario 3: $\theta_1 = 1$, $\overline{e}_1 = 1$, $\overline{e}_2 = 0.8$, $\theta_2 = 0.1$

has a larger scale of activity).

The main contribution of this scenario is that it yields an interior solution in LF_3 (a share of the items produced and sold by the integrated firm is delivered by the independent parcel operator) thereby showing that this is indeed a possibility (see Table 3). Intuitively, this case occurs when the independent delivery operator's cost advantage dominates the market power effect and as this example suggests this requires a quite drastic difference in the degree of convexity of delivery costs.

4.2.4 Scenario 4: $\theta_1 = 0.8$, $\overline{e}_1 = 1$, $\overline{e}_2 = 0.8$, $\theta_2 = 1$

This scenario is similar to Scenario 2, except that the cost advantage of the more polluting operator is reflected by a lesser degree of convexity of delivery cost. The results presented in Table 4 are not very different from Table 2 which suggests that what matters is the cost advantage and not so much its exact specification (constant or

Scenario	LF_1	FB	LF_2	LF_3
x_A	12,30	11,83	10,06	12,18
x_B	12,30	11,83	10,06	5,74
y_1	13,66	12,88	11,18	12,18
y_2	10,93	10,78	8,95	5,74
p_A	13,93	17,19	29,56	34,06
p_B	13,93	17,19	29,56	40,50
m	11,93	13,25	9,95	28,45
e_1	1,00	0,29	1,00	1,00
e_2	0,80	0,23	0,80	0,80
e_A	1,00	0,29	1,00	1,00
e_B	1,00	0,29	1,00	1,00
CS	1058,30	979,76	708,90	572,37
E	47,00	12,90	38,46	34,69
π_A	0,00	0,00	177,23	318,95
π_B	0,00	0,00	177,23	57,67
π_1	74,66	66,40	50,01	
π_2	59,29	58,07	39,65	141,11
SWF	957,27	1039,71	960,70	916,64
t_A	t_B	δ_2		
-0,048	-0,048	-0,102		

Table 4: Scenario 4: $\theta_1 = 0.8$, $\bar{e}_1 = 1$, $\bar{e}_1 = 0.8$, $\theta_2 = 1$

quadratic term).

5 Conclusion

This paper has studied the design of environmental policy in the e-commerce sector. We have considered a model with two retailers/producers who sell a differentiated product and two delivery operators. The production, retailing and delivery of these goods generate CO_2 emissions. At all levels of the value chain, it is more expensive to use “green” technologies.

We have considered different scenarios reflecting the type of competition and the vertical structure of the industry. In all cases the equilibria are inefficient for two reasons. First, both upstream and downstream the levels of emissions are too large (given the output levels). Second the levels of outputs are not efficient because the cost of emissions is not reflected by the consumer prices.

We have shown that under perfect competition a uniform Pigouvian tax on emission, reflecting the marginal social damage, is sufficient to correct both types of inefficiencies. The same result can be achieved by a Pigouvian subsidy on emission reductions. Under imperfect competition a Pigouvian emissions tax is also necessary, but it has to be supplemented by positive or negative taxes on delivery and production. The specific design of these instruments is affected by vertical integration.

This paper represents just a first step, and can be extended in various directions. First, we have lumped together production and retail. Separating them would add another layer in the vertical chain and allow for richer representations of vertical restraints. Our main results can be expected to remain valid in such a setting, in particular the optimality of a Pigouvian emissions tax. However, more instruments would be needed at the retail and production levels.

Second, we have neglected two of the issues traditionally dealt with in taxation models, namely, the necessity to raise government revenue, and the redistributive (and probably regressive) impact of environmental taxation; see Sandmo (1974), Cremer et al. (1998, 2010) and Goulder (1995). This would make us leave the realm of a first-best solution and require a second-best analysis. While this might have a drastic impact on the output taxes the results of Cremer and Gahvari (2001) suggest that we can expect that the Pigouvian rule would continue to apply for the taxation of emissions (as these do not directly determine consumer prices).

Last and not least, we have neglected the possibility that consumers might care about the environmental friendliness of the products and particularly the delivery; see for instance Cremer and Thisse (1999). In that case delivery operators would no longer be considered as perfect substitutes and the consumers' environmental concern would "internalize" part of the externality and thus lead to an amended Pigouvian rule (reflecting merely the cost which is not spontaneously accounted for by consumers). Since this might fundamentally affect the strategic interactions and the specification of the game it would require drastic changes in the model. In other words this would not be a mere extension, but essentially represent a different paper. All of these issue are on our research agenda for the future.

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A Appendix

A.1 First-order conditions of problem 32

The FOCs are:

$$x_B + \mu x_A + \left(r_2 - \delta_2 + \gamma_2(e_2) - \tau e_2 - C_2'\left(x_B + \mu\left(.\right)x_A\left(.\right)\right)\right)\left(\frac{\partial x_B}{\partial r_2} + \frac{\partial \mu\left(.\right)x_A\left(.\right)}{\partial r_2}\right) = 0, \tag{A.1}$$

$$\gamma_2'(e_2) - \tau = 0. \tag{A.2}$$

where

$$\frac{\partial x_B}{\partial r_2} = \frac{\partial x_B}{\partial p_A}\frac{\partial p_A}{\partial r_2} + \frac{\partial x_B}{\partial p_B}\frac{\partial p_B}{\partial r_2}.$$
$$\frac{\partial \mu\left(.\right)x_A\left(.\right)}{\partial r_2} = \mu\left(.\right)\left(\frac{\partial x_A}{\partial p_A}\frac{\partial p_A}{\partial r_2} + \frac{\partial x_A}{\partial p_B}\frac{\partial p_B}{\partial r_2}\right) + x_A\left(.\right)\frac{\partial \mu\left(.\right)}{\partial r_2}.$$

A.2 Proof of expressions (33)–(35)

From (26), one has:

$$\begin{aligned} U_A = {} & t_A + k_A\left(e_A\right) + e_A\psi'\left(E\right) - \left(\gamma_1(e_1) - \delta_1 - e_1\psi'\left(E\right)\right)\left(1-\mu\right) \\ & + \left(1-\mu\right)C_1'\left(\left(1-\mu\right)x_A\left(p_A, p_B\right)\right) + r_2\mu - \frac{x_A}{\frac{\partial x_A}{\partial p_A}} \end{aligned}$$

Using (27), one has

$$r_2 = -\gamma_1(e_1) + \delta_1 + e_1\psi'\left(E\right) + C_1'\left(\left(1-\mu\right)x_A\right)$$

so that after substitution:

$$U_A = t_A + k_A\left(e_A\right) + e_A\psi'\left(E\right) - \gamma_1(e_1) + \delta_1 + e_1\psi'\left(E\right) + C_1'\left(\left(1-\mu\right)x_A\left(p_A, p_B\right)\right) - \frac{x_A}{\frac{\partial x_A}{\partial p_A}} \tag{A.3}$$

Combining (30) and $(A.1)$ yields:

$$\begin{aligned} U_B = {} & t_B + \delta_2 - \gamma_2(e_2) + e_2\psi'\left(E\right) + C_2'\left(x_B + \mu\left(.\right)x_A\left(.\right)\right) \\ & + k_B\left(e_B\right) + e_B\psi'\left(E\right) - \frac{x_B}{\frac{\partial x_B}{\partial p_B}} - \frac{\frac{\partial x_B}{\partial r_2} + \frac{\partial \mu(.)x_A(.)}{\partial r_2}}{x_B + \mu x_A} \end{aligned} \tag{A.4}$$

Moreover, combining (27) and $(A.1)$, we have:

$$-\gamma_1(e_1)+\delta_1+e_1\psi'(E)+C_1'((1-\mu)x_A)= \qquad (A.5)$$
$$\delta_2-\gamma_2(e_2)+e_2\psi'(E)+C_2'(x_B+\mu(.)x_A(.))-\frac{\frac{\partial x_B}{\partial r_2}+\frac{\partial\mu(.)x_A(.)}{\partial r_2}}{x_B+\mu x_A}$$

Thus equalizing (11) for $j=A,B,(10)$ to respectively $(A.3),(A.4)$ and $(A.5)$, one can implement the first best with the levels of the instruments defined by equations (33)–(35).