A tourist tax in a multi-segment destination with congestion effects*

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Abstract

We present a model of a two-segment tourist destination where there are externalities of congestion. We show that if the high category segment is sufficiently more profitable (or more attractive to tourists) than the low category segment then a per-person tourist tax may increase industry aggregate profit. It is optimal to only tax the low segment and in fact until it creates no externality on the high segment.

Key words: Tourist destination; Congestion; Industry profits; Taxes.

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1 Introduction

After the Covid-19 pandemic is mostly over in large parts of the world, overtourism returns as an important phenomenon for many destinations. In this paper we show that a tourist tax can (and should) play a significant role as part of the toolbox of the destination management organizations (DMOs) in their fight against overtourism; in particular, we show that a tourist tax may be beneficial even from the strict point of view of the local providers – when differentiated across segments.

There is ample evidence that congestion[1] caused by overtourism may degrade the tourist experience at a destination (see below for an extended discussion of the literature). By modelling the industry as being composed of two vertically differentiated segments, in this study we also capture the phenomenon that the congestion externality is not homogeneous: there is a difference between within-segment and cross-segment sensibility to congestion and, more relevantly, the cross-segment sensibility is not symmetric: the H-segment tourists (who value and can afford exclusivity) are affected much more by crowds of L-segment tourists than *vice versa*. An intervention, like the tax we consider, can have a positive effect by changing the composition of the destination's tourist demand, switching demand from the L segment (with lower willingness to pay - WTP) to the H segment (with higher WTP for high quality).

While overtourism clearly impacts negatively on the destination's residents and other stakeholders as well, we make our point even stronger by arguing the usefulness of a tourist tax without taking into account the benefit it could generate outwith the tourism industry. Thus, our analysis focuses exclusively on the tax's impact on the (local) industry profits.

Taxes are the typical prescription against congestion externalities. However in our context taxes would definitely hurt the industry profits at a single-segment destination. What we show is that when the industry is segmented, judiciously chosen taxes can increase aggregate (across segments) industry profit at the destination.

We analyze a continuum of scenarios, depending on the weight given to tax revenues in the objective function. At one extreme, we include the tax revenues in the objective function. This captures two possible real life scenarios: either there is a collusive agreement across the industry to charge a surcharge (note that from the tourist's point of view paying a dollar tax or paying a dollar higher price is equivalent), or there is a social planner who

[1] Note that we use the term congestion as equivalent to 'negative crowding', a term more commonly used in the leisure literature; see Shelby et al., 1989.

is maximizing the sum of industry profits and tax revenues. At the other extreme we stack the deck against taxes by assuming that all the tax revenues are forgone, say they are collected by an external authority that spends them somewhere else. Could it then be that the tourism industry would still wish to lobby to have a tourist tax imposed on it? We show that the answer is a qualified yes.

More precisely, when the tax revenues have high enough weight in the objective function, taxes are optimal even if the segments are isolated (the congestion generated by L-tourists on H-tourists, c, is zero).[2] The destination can extract more from the tourists as a combination of profits and tax revenues, despite the cannibalizing effect of the latter on the former. As the externality grows from zero, the optimal per-tourist tax increases in the L segment and decreases in the H segment. The higher tourist tax decreases the demand and arrival of tourists with low WTP who search for low quality products (that is, tourists from the L segment). This reduces congestion, making the destination more attractive for tourists with a higher WTP and looking for high quality products (from the H segment). This, in turn, allows for a lower optimal per-tourist tax in the H segment. As c continues to increase, the optimal tax in the L segment continues to increase as well, but now in the H segment it is recovering towards its initial value. This is because the congestion reducing effect of the tax in the L segment is becoming larger. Finally, if c reaches a critical value, the L segment is optimally taxed out of the destination and the optimal H-segment tax returns to its original value (when $c = 0$).

When the tax revenues are mostly lost, in the absence of cross-segment externalities the optimal tax for both segments is zero. Hence, even with cross-segment congestion, the H-segment is never taxed. Remarkably, however, there is room for taxing the L segment. In fact, the best solution is often an extreme: if the WTP of the L segment tourists is a sufficiently low proportion of the WTP of the H tourist and the differential sensitivity to congestion is sufficently high then it is optimal to close the L segment. Otherwise, however, the optimal tax is zero, and thus taxes cannot increase aggregate profits.

1.1 Related literature: overtourism and tourist taxes

As Peeters et al. (2018) state in their Report for the European Parliament, overtourism can be defined as "the situation in which the impact of tourism, at certain times and in certain

[2]For simplicity, we assume that the extrenality from H tourists to L tourists is zero, so c is also the measure of the difference between the two directions of inter-segment congestion externality.

locations, exceeds physical, ecological, social, economic, psychological, and/or political capacity thresholds." Overtourism is linked to tourist numbers, the type and time frame of their visit, and a destination's carrying capacity, but the perspectives on overtourism may of course vary among its various stakeholders, such as residents, tourists, or businesses.[3] The focus of our analysis is in particular on the negative effect that overtourism may have on the tourist experience, on the loss it may cause in the destination attractiveness, leaving out of the analysis its impact on other stakeholders, residents for instance (McKinsey & Company & World Travel & Tourism Council, 2017).

There is indeed evidence of the effect that tourist density at a destination has on the tourist experience, congestion or crowding as it is usually called in the leisure literature (Shelby et al., 1989). Research has shown that (perceived) crowding is a psychological construct, and while people might consider crowds stressful in specific contexts, they may appreciate in a positive light social density in other environments, for instance in mass events such as festivals (Jacobsen et al., 2019).

As it will become clear in our analysis, the rationale for a tourist tax appears when tourist density (the number of tourists) generates congestion, namely, a situation in which a place is too blocked or crowded, diminishing the tourist experience. As Gago et al. (2009) explain, this includes congestion and environmental costs such as pollution and unpleasant aesthetics that are an input for the tourist sector: "mass tourism may diminish the quality of the tourist experience through congested and overcrowded facilities, psychological stress on local users and visitors, and faster deterioration of natural resources and public services, resulting in ... the loss of aesthetic value" (Gago et al., 2009). There are several papers studying the impact of overtourism on the tourists epxerience. Jurado et al., 2013, do so in the Costa del Sol in Malaga (Spain), showing that 26% of its tourists interviwed view the destination as having too many tourists. This is to our view a large and significant number, specially considering that these are the ones with a higher income and WTP, and also that many of the tourists more negatively affected by crowding likely stopped visiting the destination. Tokarchuk et al. (2022) show that for the city of Berlin positive emotions to crowding show an inverted U shape in the number of tourists, while negative emotions show a U shape.[4] Our prescription for a tourist tax will be valid for those destinations at

[3] A definition of carrying capacity of tourism was developed referring to the maximum quantity of tourists being present in a destination without their activities becoming intolerable to host communities and without preventing fellow tourists from appreciating the destination (McCool & Lime, 2001; Saveriades, 2000).

[4] Other studies' findings are less clear cut on whether crowding should always be considered negative.

the decreasing (increasing) end with regards to positive (negative) emotions.

While to our view tourist taxes are given too little consideration in the policy debates on how to address overtourism, there is a relatively abundant academic literature studying them (see PwC, 2017, for an overview of this literature). Gago et al. (2009) explain that (indirect) tourism taxes can be justified on three grounds: (i) revenue-raising objectives, (ii) coverage of conventional costs of public services, and (iii) internalization of external costs. Our analysis shows that the three rationales may indeed be complementary when congestion effects are large enough.

We are not of course the first ones to point out the role that tourism taxes can play in a context of congestion effects. Gago et al. (2009) themselves state that "tourism taxes could have significant direct effects on the quality of tourism demand and the magnitude of the added value generated by the sector through reduced congestion and an increased willingness to pay by tourists". Pintassilgo and Silva (2007) even analyze formally the tragedy of the commons present in a tourism destination because of environmental externalities, and point to the potential role that taxes can play in addressing the tragedy of the commons. But neither of these papers nor any other one to our knowledge do what we do, a formal study of the role that a per-person tourist tax can play with regards to increasing the destination industry's profits. As mentioned in the Introduction, the likely reason for this hyatus is that in a one-segment market the taxes we are considering are never optimal (abstracting away from other stakeholders, as we do).

Academic research on the tourist tax has to a large extent been empirical, analyzing for instance the effect that such a tax may have on a destination's demand (studying the price elasticity of the destination's demand). As an example, Aguiló et al. (2005) evaluate the effect of the tax approved in the Balearic Islands on the destination's demand (see also Adedoyin et al. 2023, and Gooroochurn and Sinclair, 2005, for examples of similar analysis in other destinations). Gago et al. (2009) apply tourist taxes in a general equilibrium model of the Spanish economy so as to study their effect and assess the relative merits of a fixed versus a value added tax. Logar (2010) discusses the appropriateness of an eco-tax in Crikvenica (Croatia), among other policy tools, with common arguments about its usage as a way to "enhance the environmental quality of Crikvenica". Other papers

Neuts and Nijkamp, 2012, for instance, find that in Bruges 'only' 18% of the interviewed gave a negative opinion. However, these are mostly one (or two) days visitors, and the study also likely faces a bias in the sample as in the other cases: those tourists more negatively affected by the overtourism of the destination will likely not be visiting it.

analyze the potential role that taxing tourism might play in the context of the Dutch disease attributed to a growing tourism sector (see Sheng, 2011; Chang, Lu and Hu, 2011, for empirical analysis, and Inchausti-Sintes, 2015, for a general equilibrium model analysis).

A recent report on The Impact of Taxes on the Competitiveness of European Tourism was written for the European Comission (PwC, 2017). It is shown how the occupancy tax, closest to the tourist tax in our analysis, ranges from 0.5€ in various countries to up to 7€ per person/day in Italy, mostly being closer to the lower end of the interval. For instance, in Crikvenica the occupancy fee was between 0.27 and 0.95 € per person/day (Logar, 2010). As it is stated, "the stakeholders interviewed stated that the tourist tax does not have a noticeable effect on the number of tourist arrivals or seasonality issues" (Logar, 2010). Keep in mind also that value-added taxes in the tourism industry are usually well below the general levels; in Spain, for instance, tourism value added – for accommodation and restaurants – is at the 10%, well below the general level of a 21% (PwC, 2017). It seems clear that in order to have significant effects on congestion, a tourist tax should be significantly higher than the levels currently enacted in most European countries (and other tourism destinations).

The rest of the paper is organized as follows. We first present the model in Section 2 and then in Section 3 charcaterise the market equilibrium. Section 4 discusses optimal taxes for the industry considering two alternative scenarios (or objective functions): profits with and without tax revenues. Section 5 provides concluding remarks.

2 The model

We represent a tourist destination by two interconnected market segments for accommodation.[5] In the high category (H) segment there are n_H firms and in the low category (L) segment there are n_L $(> n_H)$ firms. For simplicity, we assume that, within a category, firms are identical, have no (binding) capacity constraints, have no fixed costs and have constant (zero) marginal cost of production. They compete à la Cournot:[6] each firm i (in segment $j = H, L$) simultaneously and independently sets the quantity of tourists it is willing to

[5] This may include hotel accommodation as well as rental flats (via AirBnb), etc.

[6] We assume competition in quantities instead of prices to ensure that the firms have positive profits. As shown by Kreps and Scheinkman (1983) – and later generalized by Burguet and Sákovics (2017) –, Cournot competition is equivalent to a two-stage model where firms first invest in capacity and then compete in price. Consequently, Cournot competition is justified, if we think of firms first building capacity and subsequently competing in price.

serve: q_j^i. The aggregate quantity of lodging available in segment j is then $Q_j = \sum_{i \in j} q_j^i$. As the prices adjust to clear each market segment, all the lodging offered is taken and the total mass of tourists visiting the destination is $Q = Q_H + Q_L$.

There is a continuum of consumers, divided into two groups depending on which category of lodging they wish to consume. That is, to avoid the complication of considering consumers switching between markets, we assume that which segment a consumer belongs to is exogenously fixed.[7] As we will see, this assumption actually strengthens our main result.

The net utility potentially obtained in segment j by both types of consumer is

$$u_j = r_j - p_j - b_j \left| a'_j - Q_j \right| - c_j \max \left\{ Q_{-j} - a_{-j}, 0 \right\}, \tag{1}$$

where r_j stands for the gross utility derived from a hotel of category j, p_j is the market-clearing price and b_j and c_j measure the consumers' sensitivity to congestion in their own segment and in the other segment, respectively. a'_j is the optimal amount of fellow tourists: within segment they wish to have more "company" below this level, and less above it; while across segment, they are not bothered by the first a_{-j} measure of tourists.[8] As our focus is on a mature destination suffering from congestion, we will restrict attention to parameter configurations such that – absent any intervention – the equilibrium measure of tourists exceeds the optimal value: we have "overtourism". That is, $a'_j \leq Q_j$ and $a_{-j} \leq Q_{-j}$, and consequently, (1) can be simplified to

$$u_j = r_j - p_j - b_j \left(Q_j - a'_j \right) - c_j \left(Q_{-j} - a_{-j} \right). \tag{2}$$

Obviously, $r_H >> r_L$. It is also reasonable to assume that $c_H > c_L$: guests of high category hotels appreciate relative exclusivity more than those of low category. In order to significantly simplify the analysis,[9] we take this observation to the limit and assume $c_L = 0$ (and $c_H = c = c_H - c_L$): only tourists visiting the H segment are affected by inter-segment congestion, so c actually measures the difference in inter-segment sensitivity to congestion.

[7] The idea is that H consumers have no demand for L lodging, while the (equilibrium) price of H lodgings exceeds the valuation/budget of L consumers.

[8] Note that, if $a_j = a'_{-j} = 0$, then the utility function simplifies to

$$u_j = r_j - p_j - b_j Q_j - c_j Q_{-j}.$$

[9] The unilateral inter-market externality avoids having to look for a fixed point, what in turn would lead to very complicated expressions (solutions to a system of two cubic equations).

Finally, let $D_j(y)$ denote the (inverse) demand function of tourists in segment j, measured in net utility– and therefore upward sloping[10] – instead of price, to be able to account for the externalities. That is, if coming to segment j of the destination reports a net utility of $u_j = D_j(y)$ to a representative tourist, then measure y tourists will come. Putting it another way, the measure of tourists in segment j with an outside option of at most $D_j(y)$ is y. In reality, these functions are likely to be convex, growing to an asymptote (corresponding to the total amount of potential tourists in the segment). The relevant characteristic is that the two curves do not cross: there are more budget-constrained tourists with opportunity cost below any value. To capture this while maintaining tractability, we assume that the demand function of tourists is linear: $D_j(y) := s_j y$.[11] Note that a higher s_j corresponds to a steeper supply curve and thus fewer potential tourists from the j segment. Since in reality the budget-constrained segment is larger, we assume that $s_H > s_L$. It is also reasonable to assume that intra-segment sensitivity to congestion is higher in the H segment: $b_H > b_L$.

3 The market equilibrium

In this section we solve the benchmark model, in the absence of any intervention. We start by deriving the number of tourists that each segment will serve in equilibrium. The outcome of the L segment corresponds to a standard independent Cournot equilibrium (modified by the intra-segment externality). The H segment, however, is affected by the congestion generated by the L segment and thus it clears as a function of the outcome in the L segment.

The marginal tourist in each segment is indifferent between his outside option and visiting our tourist destination: $s_j Q_j = u_j$. Letting $R_j = r_j + a'_j b_j$, from (2), the demand function in segment j is given by

$$p_j = R_j - c_j \left(Q_{-j} - a_{-j}\right) - \left(s_j + b_j\right) Q_j. \tag{3}$$

Note that an increase in the amount of tourists in the segment decreases the equilibrium willingness to pay at two margins: the externality margin, captured by b_j, and the entry margin (for more tourists to come – that is, give up their outside options – their net

[10] In fact they could be interreted as "tourist-supply" functions.

[11] The fact that we ignore the asymptotes does not matter: it will never be the case that all the potential tourists visit the destination. In fact, due to the upper bound on the utilities achievable, de maximu measure of tourists considered will be $\frac{r_j}{s_j}$.

utility must be higher, so *ceteris paribus* the price must decrease), captured by s_j. Due to the linearity of our model, these values simply add up: the sensitivity to intra-segment congestion is a perfect substitute for the slope of the supply curve of tourists.

From (3) the following proposition can be directly obtained (see the detailed proof in the Appendix). Let $M_j = \frac{n_j}{(s_j+b_j)(n_j+1)}$.

Proposition 1. *The equilibrium number (measure) of tourists visiting each segment is*[12]

$$Q_L^*(R_L) = M_L R_L \text{ and } Q_H^*(R_H) = M_H(R_H - c(Q_L^* - a_L)).$$

As expected, both markets sell higher quantities when there are more firms, n_j, or when their customers have higher intrinsic valuations, r_j or higher (but below the actual) optimal level of intra-segment congestion, a_j. We can also observe that the sensitivity to intra-segment congestion and the slope of the (inverse) demand curve of tourists have a negative effect:[13] both b_j and s_j decrease the amount of tourists willing to come, *ceteris paribus.* In the H segment we have the additional effect that the intrinsic valuation of tourists, r_H, is lowered, in proportion to the equilibrium measure of L tourists weighted by the inter-segment congestion sensitivity, c.

Knowing the equilibrium quantities, we can read off from the "tourist-supply curves", $D_j(y)$, the utility obtained by a representative tourist in each segment.

Corollary 1. *The equilibrium utilities obtained by the tourists are*

$$u_L^* = s_L Q_L^* = s_L M_L R_L$$

and

$$u_H^* = s_H Q_H^* = s_H M_H(R_H - c(Q_L^* - a_L)).$$

By construction, the more tourists decide to visit, the higher is their utility as they have to give up higher outside options. The rest of the comparative statics coincide with those of the aggregate quantities in each segment. The negative relation between the H tourists' wellbeing and the quantity of L tourists is salient.

Given the equilibrium quantities, via the demand curve (3), we can also easily obtain the equilibrium prices.

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[12] We assume that r_H is high enough so that $Q_H^* > 0$.

[13] Note that our overtourism assumption ensures that the positive effect of b_j in R_j is more than compensated by the negative effect in M_j.

Corollary 2. *The equilibrium prices in each segment are*

$$p_L^* = \frac{R_L}{n_L + 1} \text{ and } p_H^* = \frac{R_H - c\left(Q_L^* - a_L\right)}{n_H + 1}.$$

Prices in a segment decrease in the number of firms and increase in the consumer valuation, as standard. The H segment's price also decreases in $c\left(Q_L^* - a_L\right)$, reacting to the negative externality. Due to linearity, prices are independent of the supply characteristics of tourists (s_j). Finally, prices are increasing in the valuation of (at least) the optimal group size (b_j).

Multiplying prices and quantities, we can calculate the aggregate profits that each segment makes in equilibrium.

Corollary 3. *In equilibrium, per segment aggregate profits are*

$$\Pi_L^*\left(R_L\right) = Q_L^* p_L^* = \frac{n_L R_L^2}{(s_L + b_L)(n_L + 1)^2}$$

and

$$\Pi_H^*\left(R_L, R_H\right) = Q_H^* p_H^* = \frac{n_H\left(R_H - c\left(Q_L^* - a_L\right)\right)^2}{(s_H + b_H)(n_H + 1)^2}.$$

The within segment comparative statics are as expected: in the L-segment aggregate profits are increasing in the consumers' valuation but they are decreasing in L-tourist scarcity, and in the number of competing firms. If a_j is sufficiently low,[14] profit is also decreasing in intra-segment sensitivity to congestion. In the H segment we have the same effects, complemented by the negative effects of inter-segment consumer sensitivity to congestion, and the quantity of L tourists.

Most importantly for the subsequent analysis, $\frac{dQ_L^*}{dr_L} > 0$ implying that $\frac{d\Pi_H^*(R_L,R_H)}{dr_L} < 0$. The H firms would benefit from a decrease in the L tourists' valuation of the L firms' product, despite the fact that we have assumed away competition between the two segments for tourists. The mediator is once again congestion: if they value those firms less, fewer of them will come, what will decrease congestion.

4 A tourist tax

Having described how the free market works, in this section we investigate the effects on industry profits (at the destination) of imposing fixed amounts of taxes to be paid by each

[14]Given that price p_j is increasing in b_j, $Q_j > a_j$ is no longer sufficient.

tourist in each segment. The question we wish to explore is: under what circumstances – if any – will such a tax benefit the industry as a whole, namely by increasing the aggregate profits across the two segments? In our main treatment we assume that the tax revenue is considered "lost" to the local industry: it is imposed by the government and spent on unrelated issues. In the next subsection, we investigate how our results change if the tax revenues revert to the local industry.

The key observation towards finding the effects of a tourist tax is that a tax of t_j is equivalent to a reduction of the intrinsic valuation by t_j: valuing at $r_j - t_j$ is the same as valuing at r_j and having to pay t_j. Thus, the industry chooses the taxes (t_L, t_H) that maximize

$$\Pi(t_L, t_H) = \Pi_L (R_L - t_L) + \Pi_H (R_L - t_L, R_H - t_H). \tag{4}$$

Let $A = \frac{R_H}{M_L R_L - a_L}$ and $B = \frac{(n_H+1)(M_L R_L + a_L)}{(n_L+1) M_H M_L (M_L R_L - a_L)}$.

Proposition 2. *The optimal taxes are $t_H^* = 0$, and*

$$t_L^* = \begin{cases} R_L - \frac{a_L}{M_L}, \text{ if } c > A - \sqrt{A^2 - B} \\ 0, \text{ otherwise.}^{15} \end{cases}$$

First, it is optimal not to tax the high segment. This is intuitive as, as we can see from (**??**), the profits of the H segment are decreasing in t_H while those of the L segment are independent of it. This result is less obvious than it may sound at first sight. The reason is that in the non-cooperative Cournot equilibrium the firms ignore the negative externality imposed on their competitors when increasing their supply. Consequently, the equilibrium leads to oversupply from the point of view of industry (segment) profits. A typical case of the "tragedy of the commons". Imposing a tax leads to a reduction in quantities what *ceteris paribus* would increase profits via higher prices. However, the taxes also impact on the prices directly, since the consumers' valuation decreases. The second effect outweighs the first, and p_H actually decreases with t_H (together with Q_H).

The optimal tax in the L segment is different, due to the additional effect it has on the profits of the H segment. As we have seen the H segment's profits are decreasing in R_L and, consequently, they are increasing in t_L , as long as $Q_L > a_L$. Of course, just as with the H segment above, the L segment's profits are decreasing in t_L. Consequently, it never pays to increase taxes above the level that would lower Q_L to a_L.[16] Otherwise, the trade-off depends on the strength of the externality, c, and on the relative profitability of

[16] If $Q_L^* < a'_L$ to start with, the optimal tax is $t_L^* = 0$.

the two segments. If the H segment (absent externality) is sufficiently more profitable than the L segment,[17] and c is sufficiently high, then it is optimal to restrict the L segment to $Q_L = a_L$. Otherwise, no tax can increase industry profits ($t_L^* = 0$). As natural, the need for the restriction is the less likely, the higher the lower bound for the cross-segment congestion externality, a_L is.

Note that we have a bang-bang solution: either no tax or "full" tax. This is a consequence of the convexity of the profit function in the consumer's WTP and – consequently – also of the tax, which is just a reduction of the former. This convexity comes from profits being the product of price and quantity, both of which are proportional to $R_j - t_j$. Convexity implies that *if* it is a good idea to raise taxes to a certain level, it is an even better idea to increase them further. The question then boils down to the comparison of the two extreme values. This comparison is a function of c.

A key issue of concern is what happens to the amount of tourists visiting the destination when the L segment is restricted. Does the intervention decrease the externality on other stakeholders, not incorporated into our model? It is obvious that Q_L decreases, from Q_L^* to a_L, while Q_H increases, but how do the magnitudes of change compare? The following corollary clarifies.

Corollary 4. *When the tax intervention is implemented, the change in the measure of tourists visiting each segment is* $\Delta Q_H = cM_H (M_L R_L - a_L)$ *and* $\Delta Q_L = -(M_L R_L - a_L)$. *Consequently,* $\left|\frac{\Delta Q_H}{\Delta Q_L}\right| = cM_H$.

For example, if we wish to account for carbon footprints, this means that if the carbon footprint of a tourist visiting the H segment is x times that of tourist visiting the L segment, the tax reduces total carbon emission if and only if $xcM_H < 1$. While at first it may sound surprising, a low sensitivity to congestion is "good" since the number of extra H tourists is proportional to the size of the externality that the intervention eliminates, what is proportional to c. Other than that, we need a less competitive market with high "elasticity of demand" (s_H).

In a parallel manner do the utilities derived by the tourist vary, as their utility is directly proportional to their equilibrium quantity via their "supply" function $D_j(Q_j)$. That is, despite the price hike, H tourists are better off without the inter-segment externality (and in addition more of them will come who make a gain relative to the outside option they were taking beforehand). At the same time the L tourists are hurt– as the price is lowered by less

[17] It is easy to see that $A^2 > B$ is equivalent to $\Pi_H^* > \Pi_L^* - \frac{(a_L')^2}{(n_L+1)M_L}$.

than the tax –, on two margins: first, some of them will choose their outside option instead but these options will be lower than the utility they would have derived from visiting our destination before the tax was imposed; second, those who continue to come will derive a lower utility than before.

4.1 Keeping the tax revenue

An interesting question is what happens if the tax revenues are included in the objective function. This may happen either because the public authority setting the tax invests it in a way to benefit the industry, or because the tax is self-imposed: say, it is the hotel federation that collects a surcharge. As before the effect of the tax can be fully captured by a decrease in the tourist valuation. Thus, the objective function becomes

$$\Pi_L^* (R_L - t_L) + \Pi_H^* (R_L - t_L, R_H - t_H) + t_L Q_L^* (R_L - t_L) + t_H Q_L^* (R_L - t_L, R_H - t_H). \quad (5)$$

Proposition 3. *If* $a_L \geq \frac{R_L}{2(s_L+b_L)}$ *then* $t_L = \frac{R_L(n_L-1)}{2n_L}$ *and* $t_H = \frac{(n_H-1)R_H}{2n_H}$. *Otherwise, if* $c > 2\sqrt{\frac{s_L+b_L}{s_H+b_H}}$ *then* $t_L = R_L - \frac{a_L}{M_L}$ *and* $t_H = \frac{(n_H-1)R_H}{2n_H}$; *if* $c \leq 2\sqrt{\frac{s_L+b_L}{s_H+b_H}}$ *then* $t_L = \frac{R_L \frac{n_L-1}{n_L+1} + \frac{1}{2}c(s_H+b_H)(R_H+c(a_L-M_L R_L))}{2M_L(s_L+b_L)-\frac{1}{2}c^2 M_L(s_H+b_H)}$ *and* $t_H = \frac{(n_H-1)(R_H-c(M_L(R_L-t_L)-a_L))}{2n_H}$.

The most striking difference with respect to the previous section is that when tax revenues are retained, it becomes worthwhile to tax the H segment as well. The trade-off is the same as before, but the tax revenues tip the balance in favor of restricting capacity. If c is sufficiently high, it is again optimal to restrict the L segment to $Q_L = a_L$, otherwise it is taxed but it still generates negative externalities on the H segment. t_L is strictly increasing in c until it reaches r_L, in the meantime t_H is U-shaped, taking the same value both at $c = 0$ and the value of c at which $t_L = r_L$. The key observation here is that it is always optimal to increase taxes from their base value (for $c = 0$) in the L segment, and the more so the higher the differential sensitivity to congestion is. If the latter is sufficiently high then it is optimal to restrict Q_L to a_L.

On the other hand, as c increases it is optimal to decrease the fiscal pressure on the H segment. In other words, if we were to consider only the change in taxation due to the externality, the H segment should receive a tourist subsidy! The reason, comes from the amount of the externality. As c grows from zero to, the externality, cQ_L, first grows from zero (when $c = 0$) and then reaches zero again (when Q_L becomes zero, due to the tax reaching r_L). This inverted U shape is then reflected in the optimal tax for the H segment:

when the externality is strong it is optimal to compensate for this demand reducing effect by lowering the tax.

5 A numerical illustration

To illustrate the above findings, let us put some values to the parameters. For example, let $r_L = \$200, r_H = \$600, n_L = 9,\ n_H = 2, s_L = b_L = \$1, s_H = \$4, b_H = \$1.$

We then have that in the baseline model

$$Q_L^* = 90 \text{ and } Q_H^* = 80 - 12c,$$

$$u_L^* = s_L Q_L^* = \$90,$$

$$u_H^* = s_H Q_H^* = \$\left(320 - 48c\right),$$

$$p_L^* = \$20 \text{ and } p_H^* = \$(200 - 30c),$$

$$\Pi_L = Q_L^* p_L^* = \$1,800$$

and

$$\Pi_H = Q_H^* p_H^* = \$(200 - 30c)\left(80 - 12c\right) = \$\left(16,000 - 4,800c + 360c^2\right).$$

With $\rho = 0$,

$$a = \frac{20}{3} \text{ and } b = \sqrt{\frac{400}{9} - 5}$$

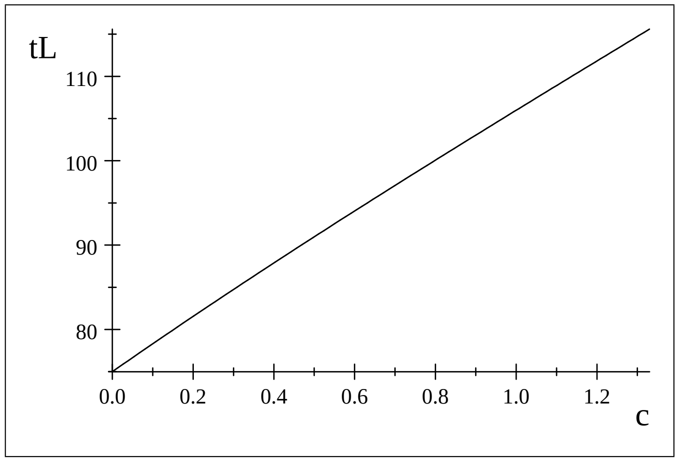
and therefore the lower bound on c for intervention (closing down the L segment) to be optimal is

$$a - b = \frac{20 - \sqrt{355}}{3} \approx 0.386.$$

With $\rho = 0.5,\ \ t_H^* = 0.$ If $c \leq 2.212\,4\sqrt{0.452\ - 0.090\,4} = 1.330\,4$

$$t_L^* = \$\frac{600 + \frac{4}{9}c\left(600 - 90c\right)}{8 - 0.2c^2},$$

otherwise the L segment is closed down.



With $\rho = 1$ the cut-off is

$$\widehat{c} = 3.333$$

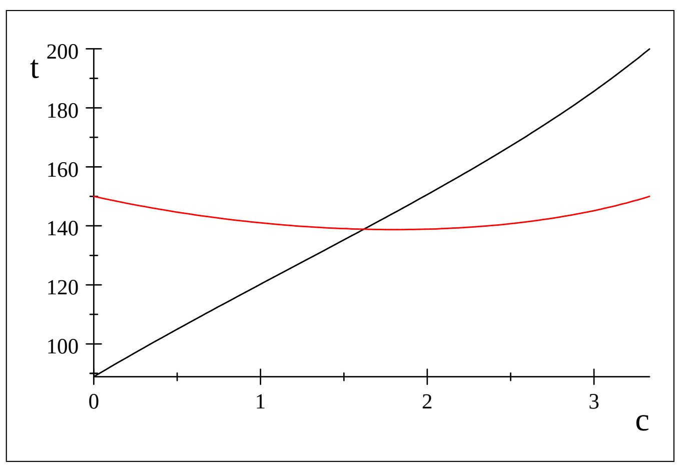
The optimal taxes are

$$t_L^* = \$\frac{1000 + c\,(300 - 45c)}{9 - \frac{9c^2}{40}}$$

and

$$t_H^* = \$\frac{300 - 25c}{2 - \frac{c^2}{20}}.$$

A graph illustrates



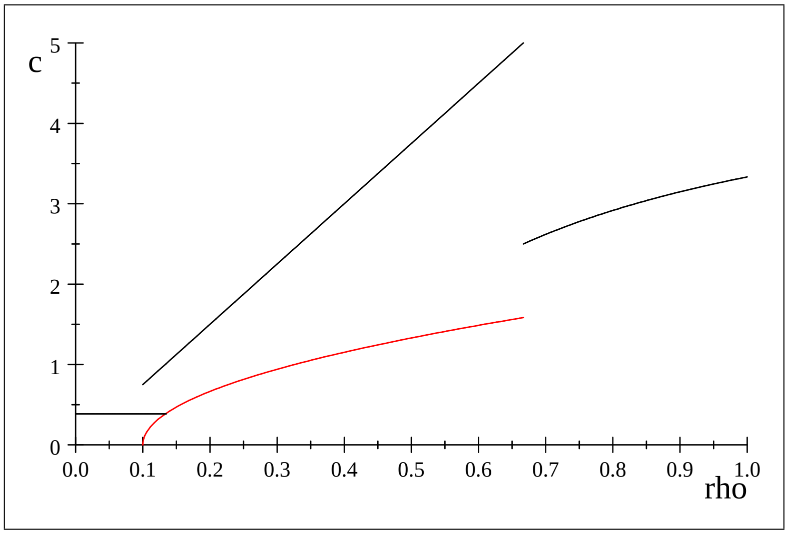
$A = \frac{(3\rho-2)}{2(3\rho-1)}$, $B = \frac{9}{20}$, $C = \frac{2}{45}$, and $D = \frac{2\rho^2}{20(3\rho-1)}$

first ρ: $\frac{2+10\frac{2}{45}c^2\frac{9}{20}}{20} = 0.226\,c^2 + 0.1$

$0.226\,c^2 + 0.1 = x$, Solution is: $2.\,212\,4\sqrt{0.904\,x - 0.090\,4}, -2.\,212\,4\sqrt{0.904\,x - 0.090\,4}$

limit second interval: $\frac{r_L(\rho(n_L+1)-2)+Cc(r_H-Bcr_L)(n_L+1)}{2(\rho(n_L+1)-1)-BCc^2(n_L+1)} = r_L$, Solution is: $\frac{1}{C}\frac{\rho}{r_H}r_L = \frac{\rho 45}{6}$

limit last interval: $\frac{\rho r_L}{2Dr_H} = \frac{\rho}{6\frac{2\rho^2}{20(3\rho-1)}} = \frac{1}{12\rho}\,(60\rho - 20)$



6 Concluding remarks

We have shown that a tourist tax may contribute to industry profit in a congested destination. In particular, it is optimal to tax the tourist segment with lower willingness to pay so as to reduce congestion and, therefore, turn the destination as a more attractive point for high WTP tourists. Such as a tax policy is likely to be optimal in a context of high sensitivity to congestion and when the high H-segment is potentially abundant and shows a significantly higher WTP than that of tourists with lower WTP. The analysis has characterized optimal tax policy for the industry profits showing, among other things that a tax may increase industry profits even net of tax revenues.

For tractability we have restricted our model to two segments with identical firms in each. In principle, we could extend the model to a series of segments and then the choice of which segments are tax free, which are taxed partially and which are taxed till they create no externality could be determined as (a very complicated) function of the parameters.

Finally, in this paper we focussed on short term behavior. It would be interesting to consider exit, entry or even category change as a result of the taxes, endogenizing the number of firms in each segment.

7 Appendix

Proof of Proposition 1: From (3), in a symmetric equilibrium each firm in segment L maximizes (in q)

$$q\left(R_L - (s_L + b_L)\left((n_L - 1)q_L^* + q\right)\right)$$

This leads to the first-order condition[18]

$$R_L - (s_L + b_L)(n_L + 1)q_L^* = 0,$$

leading to

$$q_L^* = \frac{R_L}{(s_L + b_L)(n_L + 1)}.$$

In turn, each firm in segment H maximizes

$$q\left(R_H - (s_H + b_H)\left((n_H - 1)q_H^* + q\right) - c\left(Q_L^* - a_L\right)\right),$$

leading to

$$q_H^* = \frac{R_H - c\left(Q_L^* - a_L\right)}{(s_H + b_H)(n_H + 1)}.$$

Multiplying the per-firm quantities by the number of firms in each segment, we obtain the result. ■

Proof of Proposition 2: Substituting from Corollary 3 into (4) the maximand becomes

$$\Pi = \frac{M_L\left(R_L - t_L\right)^2}{n_L + 1} + \frac{M_H\left(R_H - t_H - c\left[M_L\left(R_L - t_L\right) - a_L\right]^+\right)^2}{n_H + 1} \tag{6}$$

subject to $t_L \in [0, R_L]$ and $t_H \in \left[0, R_H - c\left[M_L\left(R_L - t_L\right) - a_L\right]^+\right]$.

Let us first calculate the optimal t_H given an arbitrary t_L. The derivative of (12) is

$$\frac{d\Pi}{dt_H} = -\frac{2M_H}{n_H + 1}\left(R_H - t_H - c\left[M_L\left(R_L - t_L\right) - a_L\right]^+\right) < 0.$$

Consequently, the optimal tax in the H segment is zero. Substituting $t_H = 0$ into (12) we obtain the objective function

$$\frac{M_L\left(R_L - t_L\right)^2}{n_L + 1} + \frac{M_H\left(R_H - c\left[M_L\left(R_L - t_L\right) - a_L\right]^+\right)^2}{n_H + 1}. \tag{7}$$

[18] The second-order condition is also satisfied.

If $[M_L(R_L - t_L) - a_L]^+ > 0$, the first derivative of (19) with respect to t_L is (we divide through by $2M_L > 0$)

$$\frac{-(R_L - t_L)}{n_L + 1} + \frac{cM_H (R_H - c(M_L(R_L - t_L) - a_L))}{n_H + 1}, \tag{8}$$

while the second-order condition is

$$\frac{1}{n_L + 1} + \frac{M_L M_H}{n_H + 1} c^2 < 0.$$

This is never satisfied, the objective function is convex. Then the optimal solution must be a corner: either $t_L = 0$ or $[M_L(R_L - t_L) - a_L]^+ = 0$.

When $[M_L(R_L - t_L) - a_L]^+ = 0$, the derivative of the objective function is negative, so we must have the lowest tax that leads to $[M_L(R_L - t_L) - a_L]^+ = 0 : t_L = R_L - \frac{a_L}{M_L}$.[19] This implies $Q'_L = M_L(R_L - t_L) = a_L$. Comparing (19) evaluated at the two possible values, we see that it is optimal to keep the L segment to its maximal size such that it does not impact on the H segment, if and only if

$$\frac{(a_L)^2}{M_L(n_L + 1)} + \frac{M_H}{n_H + 1} R_H^2 > \frac{M_L R_L^2}{n_L + 1} + \frac{M_H}{n_H + 1}(R_H - c(M_L R_L - a_L))^2. \tag{9}$$

Note that (22) can be rewritten as,

$$0 > \frac{M_L R_L^2}{n_L + 1} - \frac{(a_L)^2}{M_L(n_L + 1)} - 2\frac{M_H}{n_H + 1} c R_H (M_L R_L - a_L) + \frac{M_H}{n_H + 1} c^2 (M_L R_L - a_L)^2.$$

This is satisfied in between the roots (in c) of

$$\frac{M_L R_L^2 - \frac{(a_L)^2}{M_L}}{(n_L + 1)\frac{M_H}{n_H + 1}(M_L R_L - a_L)^2} - \frac{2cR_H}{M_L R_L - a_L} + c^2 = 0.$$

The roots are

$$A \pm \sqrt{A^2 - B}.$$

Since B is positive, the lower root is positive as well. The higher root is irrelevant, too high sensitivity to congestion cannot lead to less tax on the market creating the negative externality.

$\blacksquare$

[19] Recall that, since we assumed overtourism in the absence of taxes, this value is positive.

Proof of Proposition 3

$$\begin{aligned}
\Pi &= \frac{M_L\left(R_L-t_L\right)^2}{n_L+1}+\frac{M_H\left(R_H-t_H-c\left[M_L\left(R_L-t_L\right)-a_L\right]^+\right)^2}{n_H+1}+ \\
&\quad t_L M_L\left(R_L-t_L\right)+t_H M_H\left(R_H-t_H-c\left[M_L\left(R_L-t_L\right)-a_L\right]^+\right) \\
&= M_L\left(R_L-t_L\right)\frac{R_L+n_L t_L}{n_L+1}+M_H\left(R_H-t_H-c\left[M_L\left(R_L-t_L\right)-a_L\right]^+\right)\frac{R_H+n_H t_H-c\left[M_L\left(R_L-t_L\right)\right.}{n_H+1}
\end{aligned}$$

Differentiating with respect to t_H we obtain

$$\frac{M_H}{n_H+1}\left(\left(n_H-1\right)\left(R_H-c\left[M_L\left(R_L-t_L\right)-a_L\right]^+\right)-2n_H t_H\right).$$

As the second derivative is clearly negative, we have the first-order condition

$$\left(n_H-1\right)\left(R_H-c\left[M_L\left(R_L-t_L\right)-a_L\right]^+\right)=2n_H t_H.$$

Substituting into the objective function we have the new maximand as

$$M_L\left(R_L-t_L\right)\frac{R_L+n_L t_L}{n_L+1}+M_H\left(R_H-c\left[M_L\left(R_L-t_L\right)-a_L\right]^+\right)^2\frac{n_H+1}{4n_H}.$$

Assume $M_L\left(R_L-t_L\right)>a_L$. Differentiating with respect to t_L we obtain

$$\frac{M_L}{n_L+1}\left(R_L(n_L-1)-2n_L t_L\right)+cM_L M_H\frac{n_H+1}{2n_H}\left(R_H-c\left(M_L\left(R_L-t_L\right)-a_L\right)\right).$$

The second-order condition is

$$-4+c^2\frac{s_H+b_H}{s_L+b_L}<0.$$

Thus, if $c<2\sqrt{\frac{s_L+b_L}{s_H+b_H}}$,the objective function is concave and the first-order condition determines the solution, implying

$$t_L=\frac{R_L\frac{n_L-1}{n_L+1}+\frac{1}{2}c\left(s_H+b_H\right)\left(R_H+c\left(a_L-M_L R_L\right)\right)}{2M_L\left(s_L+b_L\right)-\frac{1}{2}c^2 M_L\left(s_H+b_H\right)}.$$

Otherwise, we have a corner solution: either $t_L=0$ or $t_L=R_L-\frac{a_L}{M_L}$, but the second case does not satisfy $M_L\left(R_L-t_L\right)>a_L$. If $M_L\left(R_L-t_L\right)\leq a_L$ then the derivative of the objective becomes

$$\frac{M_L}{n_L+1}\left(R_L(n_L-1)-2n_L t_L\right)$$

leading to

$$t_L=\frac{R_L(n_L-1)}{2n_L},$$

what leads to the requirement that $a_L \geq M_L(R_L - t_L) = M_L\left(R_L - \frac{R_L(n_L-1)}{2n_L}\right) = \frac{R_L}{2(s_L+b_L)}$.

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Let $A = \frac{(\rho(n_H+1)-2)}{2(\rho(n_H+1)-1)}$, $B = \frac{n_L}{(s_L+b_L)(n_L+1)} = \frac{Q_L^*}{r_L}$, $C = \frac{n_H}{(s_H+b_H)(n_H+1)^2}$, and $D = \frac{n_H\rho^2}{4(s_H+b_H)(\rho(n_H+1)-1)}$. Note that they are independent of c, r_H, and r_L. We will prove the following result:

Proposition 2 *The optimal taxes are*

i *If* $\rho \geq \frac{2}{n_H+1}$, *then*

a *if* $c < \frac{\rho r_L}{2Dr_H}$, *then*

$$t_L^* = \frac{\left(\frac{r_L}{2}\rho + cD\left(r_H - Bcr_L\right)\right)(n_L+1) - r_L}{(\rho - Bc^2D)(n_L+1) - 1}$$

and

$$t_H^* = \frac{A}{2}\frac{2r_H - \rho(n_L+1)(2r_H - Bcr_L)}{(Bc^2D - \rho)(n_L+1) + 1};$$

b *if* $c \geq \frac{\rho r_L}{2Dr_H}$, *then* $t_L^* = r_L$ *and* $t_H^* = Ar_H$.

ii *If* $\rho < \frac{2}{n_H+1}$, *then* $t_H^* = 0$. Moreover,

a *if* $\rho \in \left(\frac{2+(n_L+1)Cc^2B}{2(n_L+1)}, \frac{2}{n_H+1}\right)$, *then*

$$t_L^* = \min\left\{\max\left\{\frac{r_L(\rho(n_L+1)-2) + Cc(r_H - Bcr_L)(n_L+1)}{2(\rho(n_L+1)-1) - BCc^2(n_L+1)}, 0\right\}, r_L\right\};$$

b *otherwise, it is optimal to close down the L segment if*

$$\left(\frac{r_H}{n_H+1}\right)^2 \frac{n_H}{s_H+b_H} > \left(\frac{r_L}{n_L+1}\right)^2 \frac{n_L}{s_L+b_L} \tag{10}$$

and

$$c > a - b(> 0),$$

where

$$a = \frac{r_H(n_L+1)(s_L+b_L)}{n_L r_L}$$

and[20]

$$b = \sqrt{a^2 - (s_H+b_H)(s_L+b_L)\frac{(n_H+1)^2}{n_L n_H}}. \tag{11}$$

Otherwise, $t_L^* = 0$.

[20] (10) ensures that b is real.

Proof: Substituting from Corollary 3 into (4) the maximand becomes

$$\begin{aligned}\Pi &= \frac{n_L (r_L - t_L)^2}{(s_L + b_L)(n_L + 1)^2} + \frac{n_H}{(s_H + b_H)(n_H + 1)^2}\left(r_H - t_H - c\frac{n_L (r_L - t_L)}{(s_L + b_L)(n_L + 1)}\right)^2 + \\ &\quad \frac{\rho t_L n_L (r_L - t_L)}{(s_L + b_L)(n_L + 1)} + \frac{\rho t_H n_H}{(s_H + b_H)(n_H + 1)}\left(r_H - t_H - c\frac{n_L (r_L - t_L)}{(s_L + b_L)(n_L + 1)}\right),\end{aligned}$$

subject to $t_L \in [0, r_L]$ and $t_H \in [0, r_H - cB(r_L - t_L)]$.[21] This can be rewritten as

$$\begin{aligned}& B(r_L - t_L)\left(\frac{r_L + t_L(\rho(n_L + 1) - 1)}{n_L + 1}\right) + \\ & C(r_H - t_H - cB(r_L - t_L))(r_H - cB(r_L - t_L) + t_H(\rho(n_H + 1) - 1)).\end{aligned} \tag{12}$$

Let us first calculate the optimal t_H given an arbitrary t_L. The first-order condition becomes (we divide through by $C > 0$)

$$\frac{d\Pi}{dt_H} = (\rho(n_H + 1) - 2)(r_H - cB(r_L - t_L)) - 2t_H(\rho(n_H + 1) - 1) = 0.$$

I. Suppose $\rho \geq \frac{2}{n_H+1}$. Then the second-order condition is satisfied and the optimal tax is given by

$$t_H(t_L) = \frac{(\rho(n_H + 1) - 2)(r_H - cB(r_L - t_L))}{2(\rho(n_H + 1) - 1)}, \tag{13}$$

what is clearly in $(0, r_H - cB(r_L - t_L))$. Let us turn to the optimal t_L. Substituting (13) into (12) we obtain the objective function

$$B(r_L - t_L)\left(\frac{r_L + t_L(\rho(n_L + 1) - 1)}{n_L + 1}\right) + D(r_H - cB(r_L - t_L))^2. \tag{14}$$

The first-order condition becomes (we divide through by $B > 0$)

$$\frac{r_L(\rho(n_L + 1) - 2) - 2t_L(\rho(n_L + 1) - 1)}{n_L + 1} + 2D(r_H - cB(r_L - t_L))c = 0, \tag{15}$$

while the second-order condition is

$$BDc^2 < \frac{\rho(n_L + 1) - 1}{n_L + 1}. \tag{16}$$

Note that the derivative of (14) evaluated at $t_L = 0$ is positive. Thus, the optimal tax is always positive. Moreover, when either the second-order condition is violated, or – since (14) is quadratic – when the derivative of (14) evaluated at $t_L = r_L$ is positive, the optimal

[21] By Assumption 1 the intervals are nonempty.

tax is $t_L = r_L$, effectively closing down the L segment. Since convexity implies a positive derivative at $t_L = r_L$, the condition for closing down is the one implying the latter

$$c \geq \frac{\rho r_L}{2Dr_H}. \tag{17}$$

Substituting $t_L = r_L$ into (13) we obtain the optimal t_H.

Suppose (17) is not satisfied. Then the derivative of (14) evaluated at $t_L = r_L$ is negative (and the objective function is concave). Solving (15) for t_L, we obtain

$$t_L = \frac{\left(\frac{r_L}{2}\rho + cD\left(r_H - Bcr_L\right)\right)\left(n_L+1\right) - r_L}{\left(\rho - Bc^2D\right)\left(n_L+1\right) - 1}, \tag{18}$$

what – by construction – is in $(0, r_L)$.

Substituting (18) into (13) we obtain the optimal t_H.

II. Suppose $\rho < \frac{2}{n_H+1}$. Then, since we only consider $t_H \leq r_H - cB\left(r_L - t_L\right)$,

$$\begin{aligned} \frac{d\Pi}{dt_H} &= \left(\rho(n_H+1) - 2\right)\left(r_H - cB\left(r_L - t_L\right)\right) - 2t_H\left(\rho(n_H+1) - 1\right) \\ &\leq \left(\rho(n_H+1) - 2\right)t_H - 2t_H\left(\rho(n_H+1) - 1\right) = -t_H\rho(n_H+1) < 0. \end{aligned}$$

Consequently, the aggregate profit is decreasing in t_H and the optimal tax is $t_H = 0$. Substituting $t_H = 0$ into (12) we obtain the objective function

$$B\left(r_L - t_L\right)\left(\frac{r_L + t_L\left(\rho(n_L+1) - 1\right)}{n_L+1}\right) + C\left(r_H - cB\left(r_L - t_L\right)\right)^2 \tag{19}$$

The first derivative of (19) with respect to t_L is (we divide through by $B > 0$)MISTAKE!

$$\frac{2t_L\left(1 - \rho(n_L+1)\right) - \left(2 - \rho(n_L+1)\right)r_L}{n_L+1} + Cc\left(r_H - cB\left(r_L - t_L\right)\right). \tag{20}$$

while the second-order condition is

$$\frac{2\left(1 - \rho(n_L+1)\right)}{n_L+1} + Cc^2B < 0.$$

This is satisfied when

$$\rho > \frac{2 + (n_L+1)Cc^2B}{2(n_L+1)}.$$

Then, solving the first-order condition, we obtain

$$t_L = \frac{r_L\left(\rho\left(n_L+1\right) - 2\right) + Cc\left(r_H - Bcr_L\right)\left(n_L+1\right)}{2\left(\rho\left(n_L+1\right) - 1\right) - BCc^2(n_L+1)}. \tag{21}$$

As the tax cannot exceed r_L – and the objective function is quadratic in t_L – the optimal tax is the minimum of r_L and the solution to the first-order condition.

If $\rho \leq \frac{2+(n_L+1)Cc^2B}{2(n_L+1)}$ then the optimal solution must be a corner: either $t_L = 0$ or $t_L = r_L$. Comparing (19) evaluated at the two possible values, we see that it is optimal to close down the L segment if and only if

$$Cr_H^2 > B\frac{r_L^2}{n_L+1} + C\left(r_H - cBr_L\right)^2. \tag{22}$$

Note that (22) can be rewritten as,

$$0 > \frac{r_L}{n_L+1} - 2Ccr_H + Cc^2Br_L.$$

This is satisfied in between the roots of

$$\frac{1}{(n_L+1)BC} - \frac{2cr_H}{Br_L} + c^2 = 0.$$

The roots are

$$\frac{r_H}{Br_L} \pm \sqrt{\left(\frac{r_H}{Br_L}\right)^2 - \frac{1}{(n_L+1)BC}},$$

what is the same as $a \pm b$ in the statement of the proposition. The roots are real – and $a > b$ – if and only if

$$\left(\frac{r_H}{Br_L}\right)^2 > \frac{1}{(n_L+1)BC}$$

or

$$Cr_H^2 > \frac{Br_L^2}{n_L+1},$$

what is the same as (10).■

Proof of Corollary ??: By definition

$$g = \frac{\left(\frac{r_H}{n_H+1}\right)^2 \frac{n_H}{s_H+b_H}}{\left(\frac{r_L}{n_L+1}\right)^2 \frac{n_L}{s_L+b_L}}.$$

Note that

$$a^2 = \left(\frac{r_H(n_L+1)\left(s_L+b_L\right)}{n_Lr_L}\right)^2 = g\frac{\left(n_H+1\right)^2\left(s_H+b_H\right)\left(s_L+b_L\right)}{n_Ln_H}.$$

As the term multiplying g is the same as the negative term in (**??**), the latter can be written as

$$b = a\sqrt{1 - \frac{1}{g}},$$

leading to the lower bound on c being

$$a\left(1 - \sqrt{1 - \frac{1}{g}}\right).$$

Finally, note that $a = \frac{r_H}{Q_L^*}$. ■

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