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All-pay auctions with endogenous rewards

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**CORE**

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**All-pay auctions with endogenous rewards**

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**Abstract**

This paper examines a perfectly discriminating contest (all-pay auction) with two asymmetric players. Valuations are endogenous and depend on the effort each player invests in the contest. The shape of the valuation function is common knowledge and differs between the contestants. Some key properties of R&D races, lobbying activity and sport contests are captured by this framework. Once the unique equilibrium in mixed strategies analyzed, we derive a closed form of the expected expenditure of both players. We characterize the expected expenditure by the means of incomplete Beta functions. We focus on unordered valuations.

**Keywords:** all-pay auctions, contests

**JEL Classification:** D44, D72

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# 1 Introduction

Although commonly assumed to be fixed, the size of the prize in a contest may in fact be endogenous and depend on the effort made by the contestants. In particular, a higher level of effort may lead to higher valuations.<sup>1</sup> In other words, the effort expended in a contest may increase both the probability of winning *and* the size of the prize. Moreover, contestants may differ with respect to the magnitude of this effect and the same effort levels may lead to a different valuation of winning the contest (Kaplan, Luski, Sela, and Wettstein, 2002).

Such an environment is descriptive of several economic issues. In R&D races, for example, an increase in the amount of resources spent on developing new technologies may result in a shorter product pipeline and in the firm winning the race. At the same time, the additional resources may improve the quality of the final product and therefore its market value. Asymmetric market structures and differences in marketing, existing product variety or spill-over effects to related research projects are likely to lead to differences in the marginal value of R&D spending. Organizational differences in research departments or a different composition of inputs into the research process may likewise lead to different values of winning the race. In some sense, academic hiring efforts may follow a similar pattern. As long as universities attempt to attract faculty by offering productivity enhancing inducements, such as research funds, expanded seminar series or access to data sets, they are likely to increase the productivity of the potential new hire and at the same time the value of being able to hire the desired candidate.

In the classical example of a lobbying contest, the value of the legislation enacted or the project awarded may depend on the magnitude of the contribution to the political institution involved. Asymmetries may enter the contest through the pre-existing political connection of the lobbyist, so that an organization with conservative credentials would obtain a more favourable outcome with a conservative government than a more liberal lobbyist. Lastly, in professional sports, the effort invested by a team increases its expected score making a win more likely. In addition, conditional on having won the game, a higher score may raise the reputation of the team. For teams quoted on the stockmarket, such as several European soccer teams, this may translate into additional stock price gains. Again, differences between teams may lead to asymmetries in this effect.

This paper therefore examines the equilibrium of a contest with endogenous rewards and calculates the aggregate expenditure of the contestants. In contrast to contest where at given effort levels winning is a probabilistic event (Tullock contests), we examine a contest modelled as an all-pay auction, that is a situation in which the contestant investing the largest effort

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<sup>1</sup>Higher effort levels can also lead to a lower value of winning a contest. In a war of attrition, for example, the effort spent to win is likely to make the winner more vulnerable in future conflicts and contestants prefer to win at lower effort levels.

will win with certainty. Regardless of whether they won or not, all contestants have to pay their effort cost. Information is assumed to be complete and valuations are asymmetric and endogenous. For simplicity, the analysis is limited to two participants. The payoff from winning the contest, that is the valuation less the cost of effort, is assumed to decline strictly in effort despite valuations that increase in the invested effort. Similar to traditional all-pay auctions, the participants in the contest thus prefer to win at lower effort levels. This assumption contrast with [Amegashie \(2001\)](#) who investigates situations where the returns to additional expenditures in all-pay auctions exceed the costs and players therefore could aim to win with higher efforts. Contrary to the case where payoffs strictly decrease he finds that a Nash equilibrium in pure strategies exists.

A second related paper is [Kaplan, Luski, and Wettstein \(2003\)](#), who investigates a model of innovation and R&D races with a structure similar to an all-pay auction. Information is complete, values and innovation cost are time dependent and firms compete in when to bring the innovation to the market. In consequence, the usual equivalence of staying out of the contest and exercising zero effort does not apply. Yet, a closed form solution for expected aggregate expenditure is not given. [Siegel \(2009a,b\)](#) also studies all-pay auctions with complete information and non-ordered contestants. Although in his papers, the contestants differ in the cost of competing our framework is closely related to his. The differences are in the levels of generality. Whereas [Siegel's](#) broad approach covers quite general model specifications – in particular he focus on contests where all-pay auction is a sub-class of contests – our more specific set-up allows us to characterize the shape of valuations and thus to determine a closed form solution for expected equilibrium expenditures.<sup>2</sup> To the best of our knowledge these are the only papers dealing with complete information.

A related paper with incomplete information is [Kaplan, Luski, Sela, and Wettstein \(2002\)](#) who investigate an all-pay auction where the rewards are additively or multiplicatively separable in the type of the players. This setting seems well-suited to R&D races, political contest or lobbying activities. [Kaplan, Luski, Sela, and Wettstein \(2002\)](#) solve for the equilibrium bid function and link the size of the reward as well as the costs of bidding to the expected sum of equilibrium bids. [Cohen, Kaplan, and Sela \(2009\)](#) study an all-pay auction with additively and multiplicatively separable rewards under incomplete information where the designer can set the shape of the reward function. In particular, they determine that the optimal additively separable reward is not necessarily positive. In our model, we investigate additively separable rewards with complete information.

The next section introduces the model and establishes the framework for characterizing the shape of the endogenous valuations. While valuations are not ordered, they are regular in the sense that over some range of effort one player has higher valuations while above a

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<sup>2</sup>[Siegel \(2009b\)](#) provides an algorithm to solve equilibrium expenditures in the general framework of [Siegel \(2009a\)](#).

certain threshold effort level the valuations of the other player are higher. The existence of a Nash equilibrium in mixed strategies and equilibrium effort levels are derived in Section 3. Moreover, a closed form solution for the aggregate expected equilibrium expenditure is derived in Section 4 – this is indeed the main point of this paper.

## 2 The Model

Consider two players or group of players,  $i = 1, 2$  who choose effort levels  $x_i \in \mathbb{R}_+$  simultaneously and independently in a contest. The shape of their valuations is given by  $e_i(\cdot) : \mathbb{R}_+ \rightarrow \mathbb{R}$  which specifies the size of the prize as a function of their effort. We assume that  $e_i(\cdot)$  is continuous and differentiable and information about the shape of every player's  $e_i(\cdot)$  is common knowledge at the beginning of the contest. If, for example,  $e_i(x_i) = \beta_i x_i^{\alpha_i}$ ,  $\alpha_i$  and  $\beta_i$  will be common knowledge. The valuation of winning the contest  $V_i$  for each  $i = 1, 2$  consists of a common element  $v$  and the function  $e_i(\cdot)$  so that  $V_i(x_i) = v + e_i(x_i)$ . Both players pay their effort cost and final payoffs for each player  $i = 1, 2$  are given by

$$u_i(x_i) = \begin{cases} V_i(x_i) - x_i & \text{if } x_i > x_j \\ \frac{V_i(x_i)}{2} - x_i & \text{if } x_i = x_j \\ -x_i & \text{if } x_i < x_j \end{cases}$$

We make the following two assumptions to characterize our environment.

**Assumption 1 (A1).**  $e_i(x)$  is a non-negative and increasing function for all  $x > 0$  and  $e_i(0) = 0$

**Assumption 2 (A2).**  $\forall x > 0 \frac{\partial u_i}{\partial x}(x) < 0$ , which means that  $e'_i(x) < 1$ .

Assumption A1 ensures that – independently of the original level of effort – an increase in effort has a positive effect on the prize. More research, for example, will lead to a better product in a patent race; more effort in a football match to a higher score and an improved reputation of the winning team. This notwithstanding, assumption A2 makes the contestant prefer winning at lower effort levels. In other words, the net payoff from an additional unit of effort is negative.<sup>3</sup>

The case where  $e_i(x_i) = 0$  for all  $x_i$  corresponds to a pure common value setting. It is well-known that under these circumstances there is no Nash equilibrium in pure strategies. As Amegashie (2001) has shown, if utility is not monotonically decreasing in effort, a pure strategy Nash equilibrium exists. Although his framework is different, the link between increasing utility and equilibrium existence is likely to apply to our set-up as well. Assumption A2 effectively rules out this case even if  $e_i(x) \geq 0$ . In order to compute explicitly the form of the aggregate expected equilibrium expenditure for each player a further assumption is required.

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<sup>3</sup>Weakly decreasing utility functions are common in all-pay auction even when valuations are constant.

**Assumption 3 (A3).**  $\forall i, \forall \lambda > 0, \forall x, \exists k_i \geq 1$  such as  $e_i(\lambda_i x) = \lambda^k e_i(x)$

This assumption means that an increasing of one unit of the contestant's effort increases proportionally the variable part of his valuation. Together, assumptions A1 to A3 imply a specific functional form for the shape of the valuation function  $e_i(\cdot)$ , as the following lemma shows.

**Lemma 1.** *Suppose assumptions A1-A3 hold. Then, there is a unique form for the valuation function  $e_i(\cdot)$  such that  $e_i(x_i) = \beta_i x_i^{\alpha_i}$  with  $\alpha_i \geq 1$  and  $0 < \beta_i < 1$ .*

*Proof.* The first part of the proof to determine that the shape of  $e_i(\cdot)$  is a power function rely mainly on assumption A3. This kind of proof, even if some other assumptions or axioms are required as in this paper, is quite known and can be find in some textbook of mathematics. Moreover, assumption A1 leads to  $\beta_i > 0, \alpha_i > 0$ . Let us assume that  $\alpha_i < 1$ . Then assumption A2 implies that  $x > (\alpha_i \beta_i)^{\frac{1}{1-\alpha_i}}$ . As by definition the agents' efforts should start at zero (even with a mass point) there is a contradiction and  $\alpha_i \geq 1$ . As  $e_i(x)' - 1 < 0$  for all  $x$  it follows that  $\beta_i < \frac{1}{\alpha_i}$ . ■

$\alpha_i$  could be interpreted as the productivity of the effort and  $\beta_i$  as an elasticity. The reward components of the all-pay auction are depicted in Figure 1.

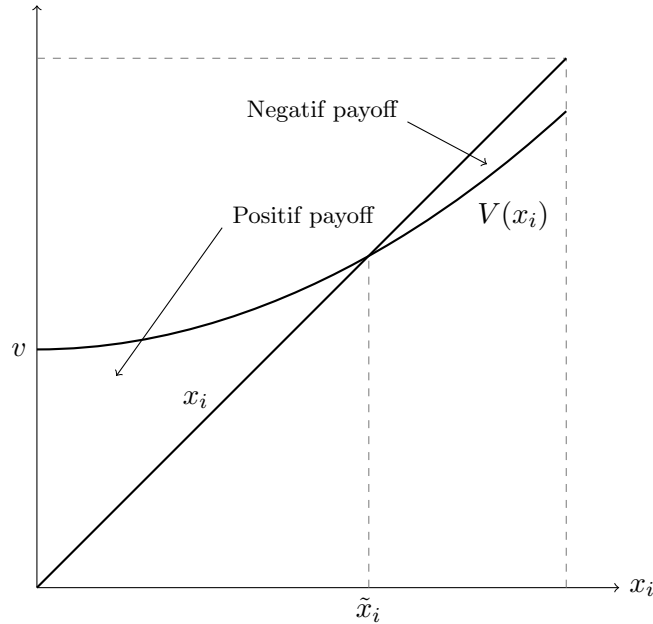


Figure 1: Payoff of Winning

As valuations are dependent on the effort of the two contestants, they need not be ordered. In other words, for two different effort levels, the ranking of the valuations could be reversed. If  $\alpha_i > \alpha_j$ , for example,  $V_j(x) > V_i(x)$  for all  $x < \left(\frac{\beta_j}{\beta_i}\right)^{\frac{1}{\alpha_i - \alpha_j}}$  and  $V_j(x) \leq V_i(x)$  otherwise.

Non-ordered valuations seem well-suited for the real-world applications that motivate our analysis. Indeed, with different marginal returns to effort in R&D races and or lobbying or sports contests, the ranking of the valuations depends on effort levels and valuations are unlikely to be ordered.<sup>4</sup>

### 3 Equilibrium Characterization

It is a well known result that all-pay auctions with constant heterogeneous valuations, that is valuations that are independent of the submitted bids, have a unique equilibrium in mixed strategies (Hillman and Riley (1989), Baye, Kovenock, and de Vries (1996) for linear costs, Che and Gale (1998), Che and Gale (2006), Kaplan and Wettstein (2006) and Vartiainen (2007) for non-linear cost functions). In recent papers, Siegel (2009a,b) extends this result to non-ordered contestants in a general framework.

To simplify the notation we define the “weak” and the “strong” player and denote them by the subscripts  $w$  and  $s$ , respectively. The intuition is simple: since payoffs are falling in effort by assumption A2 there will be a level of effort after which the payoff obtained will be negative even if the contest is won. The weak player determines the maximum effort any player is willing to exercise in the contest. At this effort level its utility from winning the contest is zero; the strong player, in contrast, still obtains a positive payoff at the same effort level.

**Definition 1.** *A player is called “weak” if he determines the maximum effort  $\tilde{x}$  in the contest, that is  $v + \beta_w \tilde{x}^{\alpha_w} - \tilde{x} = 0$  and  $v + \beta_s \tilde{x}^{\alpha_s} - \tilde{x} > 0$ . His opponent is called the “strong” player.*

Let us consider  $\alpha_i > \alpha_j$ . Then, if  $\tilde{x}$  such as  $v + \beta_j \tilde{x}^{\alpha_j} - \tilde{x} = 0$  and  $\tilde{x} > \left(\frac{\beta_j}{\beta_i}\right)^{\frac{1}{\alpha_i - \alpha_j}}$  then the player  $i$  is the “strong player”. Otherwise, the player  $j$  is the “strong” player and the maximum effort is given by  $\tilde{x}$  such as  $v + \beta_i \tilde{x}^{\alpha_i} - \tilde{x} = 0$ . Unlike in a standard all-pay auction, it is not enough for a particular player to have the higher valuation over an interval of  $x$  in order to be the “strong” player. Rather, the relative strength of a player is determined not only by the difference between the valuations at a particular  $x$  but also – implicitly – by the distance from the threshold  $\left(\frac{\beta_j}{\beta_i}\right)^{\frac{1}{\alpha_i - \alpha_j}}$  which defines the order of the valuations on each sub-interval.

It follows from the implicit function theorem that the maximum effort is increasing in  $\beta_w$ , decreasing in  $\alpha_w$  if  $\tilde{x} < 1$  and increasing in  $\alpha_w$  if  $\tilde{x} > 1$ ,

$$\frac{d\tilde{x}}{d\beta_w} = \frac{\tilde{x}^{\alpha_w}}{1 - \beta_w \alpha_w \tilde{x}^{\alpha_w - 1}} > 0 \text{ and } \frac{d\tilde{x}}{d\alpha_w} = \frac{\beta_w \tilde{x}^{\alpha_w} \ln \tilde{x}}{1 - \beta_w \alpha_w \tilde{x}^{\alpha_w - 1}} \begin{cases} < 0 \text{ if } \tilde{x} < 1 \\ = 0 \text{ if } \tilde{x} = 1 \\ > 0 \text{ if } \tilde{x} > 1 \end{cases} \quad (1)$$

<sup>4</sup>The case of ordered valuations is considered in Appendix B.

The signs follow from assumption A2.

Define the mixed strategies at the equilibrium by  $F_i(\cdot) = \mathbb{P}(X \leq \cdot)$  for both players  $i = s, w$ . The following proposition determines the unique Nash equilibrium strategies for the two players and the corresponding equilibrium payoffs.

**Proposition 1.** *Suppose assumptions A1-A3 hold. Then, the unique Nash equilibrium is in mixed strategies as follows. Players choose their effort randomly according to the cumulative distributions functions*

$$F_s(x) = \frac{x}{v + \beta_w x^{\alpha_w}} \text{ for all } x \in [0, \tilde{x}]$$

$$F_w(x) = \frac{v + \beta_s \tilde{x}^{\alpha_s} - \tilde{x} + x}{v + \beta_s x^{\alpha_s}} \text{ for all } x \in [0, \tilde{x}]$$

And the expected equilibrium payoffs are

$$u_s^* = \beta_s \tilde{x}^{\alpha_s} - \beta_w \tilde{x}^{\alpha_w}$$

$$u_w^* = 0$$

*Proof.* Let us define  $\tilde{v}_i(x) = v + \beta_i x^{\alpha_i} - x$  and  $\tilde{c}_i(x) = x$ . Then, the bidder's expected utility could be written as  $F_i(x)\tilde{v}_i(x) - (1 - F_i(x))\tilde{c}_i(x)$ . Remark that  $\tilde{v}_i$  and  $-\tilde{c}_i$  are continuous and non-increasing,  $\tilde{v}_i(0) = v$  and  $\lim_{x \rightarrow +\infty} \tilde{v}_i(x) < 0$  and  $\tilde{v}_s^{-1}(0) > \tilde{v}_w^{-1}(0) = \tilde{x}$ . Consequently all assumptions of Siegel (2009b) are satisfied. In addition that he called the threshold  $T$  of the contest is in our case the maximum effort  $\tilde{x}$  of the “weak” bidder. Thus, Theorem 3 of Siegel (2009b) can be applied and our result follows. ■

Remark that the equilibrium expected payoff of the “weak” player is independent of the parameters of the contestants' value functions. The expected equilibrium payoff of the “strong” depends on its own valuation and, via its equilibrium strategy, on the parameters of its opponent.

**Corollary 1.** *Suppose assumptions A1-A3 hold. The expected equilibrium payoff of the “strong” player is (i) decreasing in  $\beta_w$  and (ii) decreasing in  $\alpha_w$  if  $\tilde{x} > 1$  and increasing otherwise.*

*Proof.* See Appendix A. ■

This asymmetry in the parameter effects is interesting for its implications. As the payoff of the strong player is given by  $\beta_s \tilde{x}^{\alpha_s} - \beta_w \tilde{x}^{\alpha_w}$  the impact of the reward parameters  $\beta_w$  and  $\alpha_w$  comes from two sources. On one hand we can identify a *parameter effect* from the endogenous valuation of the “weak” player independently of the effort level, in which a higher  $\beta_w$  (respectively a smaller  $\alpha_w$  if  $\tilde{x} < 1$  and a higher one if  $\tilde{x} > 1$ ) reduces the payoff of the “strong” player independent of the effort levels. The *maximum effect*, on the other hand,

works through the impact of the relative values of  $\beta_w$  and  $\alpha_w$  on  $\tilde{x}$ . If the *maximum effect* and the *parameter effect* could have contradictory signs, the latter dominates.

It is possible to compare the standard all-pay auction with exogenous valuations  $V_i(x) = v_i$  with our setup where  $V_i(x) = v + \beta_i x^{\alpha_i}$ .<sup>5</sup> Even if rewards lead to either a higher or a lower valuation than in the standard case of all-pay auction, it is convenient to assume that the maximum effort is the same in the endogeneous and standard all-pay auctions. Indeed, the maximum effort could be decided *ex ante* for example as a limit of the expenditure in an R&D race. In consequence, in the standard all-pay auction valuations are ordered and the “weak” contestant is the one with the lowest valuation. She determines her maximum effort equal to her valuation  $v_w$  such that  $v_w = \tilde{x} = v + \beta_w \tilde{x}^{\alpha_w}$ . Then,  $v_s$ , the valuation of the “strong” contestant is superior to  $v + \beta_w \tilde{x}^{\alpha_w}$ .

**Corollary 2.** *The expected equilibrium payoff of the “strong” player in the all-pay auction with endogenous rewards is lower than in a standard all-pay auction if and only if her valuation  $v_s$  is superior to  $v + \beta_s \tilde{x}^{\alpha_s}$ .*

This result comes from the comparison of the players’ expected equilibrium payoff given by Proposition 1 and the contestants’ expected equilibrium payoff given by Hillman and Riley (1989) and Baye, Kovenock, and de Vries (1996) in the standard all-pay auction which is  $v_s - v_w$  for the “strong” player.

## 4 Aggregate Expenditures

Given the assumptions made and with the resulting equilibrium strategies, it is now possible to find an explicit expression for the expected equilibrium expenditure of both contestants by the means of the incomplete Beta functions. We present a very short overview of the incomplete Beta functions which are a useful tool for the computations of the expected revenues. The incomplete Beta functions belongs to the general class of hypergeometric functions and are studied in details Spanier and Oldham (1987) Chapter 58 (see also Temme (1996) for a more recent textbook).

**Definition 2.** *The incomplete Beta function,  $B(\nu, \mu, x)$ , with  $0 \leq x < 1, \mu \in \mathbb{R}, \nu > 0$ , is given by the Euler integral representation:*

$$B(\nu, \mu, x) = \int_0^x \frac{t^{\nu-1}}{(1-t)^{1-\mu}} dt$$

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<sup>5</sup>The analysis does not change if the exogenous part of the valuations  $v_i$  is not common to both contestants and  $V_i(x) = v_i + \beta_i x^{\alpha_i}$ .

**Definition 3.** The incomplete Beta function,  $B(\nu, \mu, x)$ , with  $0 \leq x < 1, \mu \in \mathbb{R}, \nu > 0$ , is given by the expansion series:

$$B(\nu, \mu, x) = \frac{(1-x)^\mu}{\nu} \sum_{j=0}^{\infty} \frac{(\mu+\nu)_j}{(1+\nu)_j} x^{j+\nu}$$

where  $(y)_n$  denotes the Pochhammer symbol such that

$$(y)_n = \frac{\Gamma(j+y)}{\Gamma(y)},$$

where  $\Gamma(\cdot)$  is the special function Gamma.

**Proposition 2.** Suppose assumptions A1-A3 hold. Then, the aggregate expected equilibrium expenditures are given by

$$\mathbb{E}R_s = \begin{cases} -\frac{v}{\beta_w} \left[ 1 + \frac{1}{\beta_w} \ln(1 - \beta_w) \right] & \text{if } \alpha_w = 1 \\ \tilde{x} - \frac{1}{\alpha_w v \phi^{\frac{2}{\alpha_w}}} B\left(\frac{2}{\alpha_w}, 1 - \frac{2}{\alpha_w}, \frac{\phi \tilde{x}^{\alpha_w}}{1 + \phi \tilde{x}^{\alpha_w}}\right) & \text{if } \alpha_w > 1 \end{cases}$$

$$\mathbb{E}R_w = \begin{cases} \frac{1 - \beta_s}{\beta_s} \left[ \ln(1 + \varphi \tilde{x}) \left( \tilde{x} + \frac{v}{\beta_s} \right) - \tilde{x} \right] & \text{if } \alpha_s = 1 \\ \tilde{x} - \frac{1}{\alpha_s v \varphi^{\frac{2}{\alpha_s}}} B\left(\frac{2}{\alpha_s}, 1 - \frac{2}{\alpha_s}, \frac{\varphi \tilde{x}^{\alpha_s}}{1 + \varphi \tilde{x}^{\alpha_s}}\right) - \frac{\beta_s \tilde{x}^{\alpha_s} - \beta_w \tilde{x}^{\alpha_w}}{\alpha_s v^2 \varphi^{\frac{1}{\alpha_s}}} B\left(\frac{1}{\alpha_s}, 1 - \frac{1}{\alpha_s}, \frac{\varphi \tilde{x}^{\alpha_s}}{1 + \varphi \tilde{x}^{\alpha_s}}\right) & \text{if } \alpha_s > 1 \end{cases}$$

with  $\tilde{x} = v + \beta_w \tilde{x}^{\alpha_w}$ ,  $\varphi = \frac{\beta_s}{v}$  and  $\phi = \frac{\beta_w}{v}$ .

*Proof.* See Appendix A. ■

The Euler integral form of the incomplete Beta functions is used in the proof to identify it. An explicit form of the expected revenues are given in Appendix A by the means of the expansion series of the incomplete Beta functions.

Assuming a linear relationship between effort and the valuations,  $\alpha_s = \alpha_w = 1$ , one can simplify the expression for  $\mathbb{E}R_w$  to

$$\mathbb{E}R_w = \frac{1 - \beta_s}{1 - \beta_w} \frac{v}{\beta_s} \left[ -1 + \left( \frac{1 - \beta_w + \beta_s}{\beta_s} \right) \ln \left( \frac{\beta_s}{1 - \beta_w} + 1 \right) \right]$$

The relationship between the expected equilibrium expenditure for both players and the values for  $\beta_w$  and  $\beta_s$  can be shown graphically (Figure 2 and Figure 3 with  $v = 2$ ).

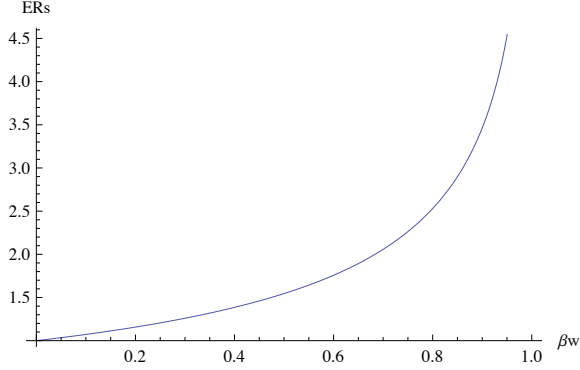


Figure 2:  $\mathbb{E}R_s$  for  $\alpha_s = \alpha_w = 1$

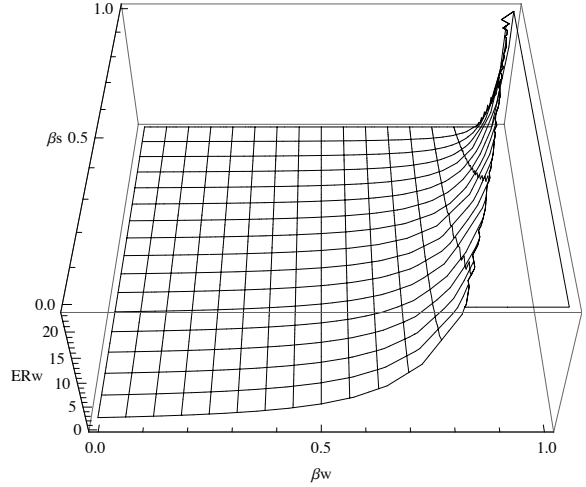


Figure 3:  $\mathbb{E}R_w$  for  $\alpha_s = \alpha_w = 1$

The features of the individual expenditures that we observe in graphs 2 and 3 can be extended to all values of  $\alpha_s$  and  $\alpha_w$ . It is thus possible to compare the standard all-pay auction with exogenous valuations  $V_i(x) = v_i$  with our setup where  $V_i(x) = v + \beta_i x^{\alpha_i}$ . Qualitatively,  $\beta_i$  and  $\alpha_i$  (when  $\tilde{x} > 1$ ) play the same role as  $v_i$  in the standard framework and  $\alpha_i$  (when  $\tilde{x} \leq 1$ ) the inverse one and the results should be comparatively similar with respect to individual expected equilibrium expenditure. The following corollary confirms this intuition.

**Corollary 3.** *Suppose assumptions A1-A3 hold. The individual expected equilibrium expenditures*

- (i) *of the “strong” player are increasing in  $\beta_w$  and decreasing in  $\alpha_w$  if  $\tilde{x} \leq 1$ .*
- (ii) *of the “strong” player are independent in  $\beta_s$  and  $\alpha_s$ .*
- (iii) *of the “weak” player are decreasing in  $\beta_s$ , increasing in  $\alpha_s$  if  $\tilde{x} \leq 1$ .*
- (iv) *of the “weak” player are increasing in  $\beta_w$ , decreasing in  $\alpha_w$  if  $\tilde{x} \leq 1$  and increasing in  $\alpha_w$  if  $\tilde{x} > 1$ .*

*Proof.* See Appendix A. ■

We are not able to compute the sign of the derivatives of the role of the parameters  $\alpha_s$  on the “weak” player and  $\alpha_w$  on the “strong” player’s expected equilibrium expenditure when  $\tilde{x} > 1$ . Yet, we did not find any example which could contradict the intuition given above.

These results (Corollary 3) may have implications for the designer of a contest. If the designer is interested in eliciting the largest amount of effort, due perhaps to spillovers or in cases where the effort accrues directly to him, and if he can manipulate the contest technology of both players, Corollary 3 indicates the method to achieve this goal. In addition, the contestants themselves have an incentive to influence the parameters in the valuation

functions. A “weak” firm in an R&D race, for example, would prefer a larger value for  $\beta_w$  and a smaller value for  $\alpha_w$  if  $\tilde{x} \leq 1$  (respectively a higher value if  $\tilde{x} > 1$ ) in order to decrease the expected equilibrium payoff of its competitor (see Corollary 1). If the contestant can choose the parameters  $\alpha_i$  and  $\beta_i$  at some cost before the beginning of the contest, the game can be extended to include the pre-contest selection of the contest technology.

As in Section 3 for Corollary 2, we compare our setup where  $V_i(x) = v + \beta_i x^{\alpha_i}$  with the standard all-pay auction where the valuation  $v_w$  of the “weak player” is such that  $v_w = \tilde{x}$ .

**Corollary 4.** *The expected equilibrium expenditures of the “strong” player in the all-pay auction with endogenous rewards is lower than in the standard all-pay auction.*

*Proof.* As  $v_w > v + \beta_w x^{\alpha_w}$  for all effort inferior to  $\tilde{x}$ , the “strong” player’s mixed strategy in the contest with rewards is stochastically dominated by the one in the standard contest. Then, the result follows from  $ER_s = \tilde{x} - \int_0^{\tilde{x}} F_s(x) dx$ . ■

Unfortunately, the effect on the expected equilibrium expenditures of the “weak” contestant is not clear. Indeed, as the payoff of the “strong bidder” decreases if  $v_s > v + \beta_s \tilde{x}^{\alpha_s}$ , the effect of the reward on the mixed strategy of the “weak” contestant is ambiguous.

## Conclusion

In this paper we examine a perfectly discriminating contest (all-pay auction) with two asymmetric players and endogenous valuations in a complete information environment. Similar to real-world situations, we postulate that the value of winning depends on the effort levels invested. In particular, we assume that higher effort levels lead to higher prizes but that this increase is smaller than the cost of effort. The contestants thus prefer to win at lower effort levels. We believe that this set-up captures the nature of many contests such as R&D races, lobbying games or sports events.

These properties of the valuation function together with the assumption that prizes increase proportionally with effort lead to a unique functional form mapping efforts into prizes and allow the explicit calculation of equilibrium strategies and expected equilibrium effort levels for both contestant. As the valuation functions are not symmetric, we can define the “strong” contestant as the one having the higher effort limit. The “weak” contestant, analogously, has the lower effort limit. Within these limits, valuations need not be ordered, however, as (due to the asymmetry) both players may have the higher valuation at different levels of effort. This notwithstanding, we show that the equilibrium strategies and expected payoffs depend on the strength of the player.

It is a well-known result that in this kind framework an equilibrium in pure strategies does not exist. We therefore determine the mixed strategy equilibrium effort choices. In equilibrium, the expected equilibrium payoff of the “strong” player is positive and depends on the parameters of both players’ valuation function. In particular, it is decreasing in the steepness of the “weak” player’s valuations.

Moreover, we are able to characterize the expected expenditure thanks to the incomplete Beta functions. This result could be useful for applications of contests with endogenous rewards as in R&D races.

This paper leaves an open question for future research on pre-contests. How do contestants select the contest technology which means their parameter  $\alpha_i$  and  $\beta_i$ ? That is an important subject to study R&D races for example.

## Appendix A: Proofs

*Proof of Corollary 1.* (i)

$$\frac{\partial u_s^*}{\partial \beta_w} = \underbrace{\frac{d\tilde{x}}{d\beta_w} (\beta_s \alpha_s \tilde{x}^{\alpha_s - 1} - \beta_w \alpha_w \tilde{x}^{\alpha_w - 1})}_{\text{maximum effect}} - \underbrace{\tilde{x}^{\alpha_w}}_{\text{parameter effect}} \quad (2)$$

$$= \frac{d\tilde{x}}{d\beta_w} (\beta_s \alpha_s \tilde{x}^{\alpha_s - 1} - 1) \quad (3)$$

$$< 0 \quad (4)$$

To arrive at equation (3) from (2) we apply the implicit function theorem to  $\tilde{x} = v + \beta_w \tilde{x}^{\alpha_w}$  in  $\tilde{x}$  and  $\beta_w$  such that  $\frac{d\tilde{x}}{d\beta_w} (1 - \beta_w \alpha_w \tilde{x}^{\alpha_w - 1}) = \tilde{x}^{\alpha_w}$ . The result then follows from assumption A2 and (1).

(ii)

$$\frac{\partial u_s^*}{\partial \alpha_w} = \underbrace{\frac{d\tilde{x}}{d\alpha_w} (\beta_s \alpha_s \tilde{x}^{\alpha_s - 1} - \beta_w \alpha_w \tilde{x}^{\alpha_w - 1})}_{\text{maximum effect}} - \underbrace{\beta_w \tilde{x}^{\alpha_w} \ln \tilde{x}}_{\text{parameter effect}} \quad (5)$$

$$= \frac{d\tilde{x}}{d\alpha_w} (\beta_s \alpha_s \tilde{x}^{\alpha_s - 1} - 1) + \tilde{x}^{\alpha_w} \left( \frac{d\tilde{x}}{d\alpha_w} \frac{d\beta_w}{d\tilde{x}} - \beta_w \ln \tilde{x} \right) \quad (6)$$

$$= \tilde{x}^{\alpha_w} \left( \frac{d\tilde{x}}{d\alpha_w} \frac{d\beta_w}{d\tilde{x}} - \beta_w \ln \tilde{x} \right) \quad (7)$$

$$= \frac{d\tilde{x}}{d\alpha_w} (\beta_s \alpha_s \tilde{x}^{\alpha_s - 1} - 1) \quad (8)$$

Using equations (2) and (3),  $\beta_s \alpha_s \tilde{x}^{\alpha_s - 1} - \beta_w \alpha_w \tilde{x}^{\alpha_w - 1} = (\beta_s \alpha_s \tilde{x}^{\alpha_s - 1} - 1) + \tilde{x}^{\alpha_w} \frac{d\beta_w}{d\tilde{x}}$ . Then

(6) follows. We get (7) as  $\frac{d\tilde{x}}{d\alpha_w} \frac{d\beta_w}{d\tilde{x}} - \beta_w \ln \tilde{x} = 0$  from (1). In (8), the term between brackets is negative from assumption A2 and the sign of  $\frac{d\tilde{x}}{d\alpha_w}$  is given by (1). ■

*Proof of the Proposition 2.* The expected equilibrium expenditure of effort is given by  $\mathbb{E}R_i = \tilde{x} - \int_0^{\tilde{x}} F_i(x)dx$  for  $i = w, s$ .

1. Computation of  $\mathbb{E}R_w$ .

Let us denote  $\varphi = \frac{\beta_s}{v}$ . If  $\alpha_s = 1$ , it follows that

$$\begin{aligned} \int_0^{\tilde{x}} F_w(x)dx &= (v + (\beta_s - 1)\tilde{x}) \int_0^{\tilde{x}} \frac{dx}{v + \beta_s x} + \int_0^{\tilde{x}} \frac{x}{v + \beta_s x} dx \\ &= \frac{v + (\beta_s - 1)\tilde{x}}{v} \int_0^{\tilde{x}} \frac{dx}{1 + \varphi x} + \frac{1}{\beta_s} \int_0^{\tilde{x}} 1 - \frac{1}{1 + \varphi x} dx \\ &= -\frac{1 - \beta_s}{\beta_s} \left( \frac{v}{\beta_s} + \tilde{x} \right) \ln(1 + \varphi \tilde{x}) + \frac{\tilde{x}}{\beta_s} \end{aligned}$$

Therefore,

$$\mathbb{E}R_w = \frac{1 - \beta_s}{\beta_s} \left[ \ln(1 + \varphi \tilde{x}) \left( \tilde{x} + \frac{v}{\beta_s} \right) - \tilde{x} \right]$$

The derivative in  $\tilde{x}$  and the boundedness condition guarantee that  $\mathbb{E}R_w$  is positive.

If  $\alpha_s > 1$

$$\int_0^{\tilde{x}} F_w(x)dx = (\beta_s \tilde{x}^{\alpha_s} - \beta_w \tilde{x}^{\alpha_w}) \int_0^{\tilde{x}} \frac{dx}{v + \beta_s x^{\alpha_s}} + \int_0^{\tilde{x}} \frac{x}{v + \beta_s x^{\alpha_s}} dx$$

Moreover,

$$\begin{aligned} \int_0^{\tilde{x}} \frac{dx}{v + \beta_s x^{\alpha_s}} &= \frac{1}{v} \int_0^{\tilde{x}} \frac{dx}{1 + \varphi x^{\alpha_s}} \\ &= \frac{1}{\alpha_s v \varphi^{\frac{1}{\alpha_s}}} \int_0^{\varphi \tilde{x}^{\alpha_s}} \frac{y^{\frac{1}{\alpha_s} - 1}}{1 + y} dy \end{aligned} \quad (9)$$

$$= \frac{1}{\alpha_s v \varphi^{\frac{1}{\alpha_s}}} \int_0^{\frac{\varphi \tilde{x}^{\alpha_s}}{1 + \varphi \tilde{x}^{\alpha_s}}} \frac{t^{\frac{1}{\alpha_s} - 1}}{(1 - t)^{\frac{1}{\alpha_s}}} dt \quad (10)$$

$$= \frac{1}{\alpha_s v \varphi^{\frac{1}{\alpha_s}}} B\left(\frac{1}{\alpha_s}, 1 - \frac{1}{\alpha_s}, \frac{\varphi \tilde{x}^{\alpha_s}}{1 + \varphi \tilde{x}^{\alpha_s}}\right) \quad (11)$$

$$= \frac{\tilde{x}}{v} \Gamma\left(\frac{1}{\alpha_s}\right) \left(\frac{1}{1 + \varphi \tilde{x}^{\alpha_s}}\right)^{1 - \frac{1}{\alpha_s}} \sum_{j=0}^{\infty} \frac{(\varphi \tilde{x}^{\alpha_s})^j}{(1 + \alpha_s j) \Gamma(\frac{1}{\alpha_s} + j)} \quad (12)$$

To obtain equations (9) and (10), we define  $y = \varphi x^{\alpha_s}$  and  $t = \frac{y}{1+y}$ . As  $\frac{\varphi \tilde{x}^{\alpha_s}}{1 + \varphi \tilde{x}^{\alpha_s}} \in (0, 1)$  and  $\frac{1}{\alpha_s} > 0$ , equation (10) is the Euler integral representation of an incomplete Beta function and equation (12) comes from his expansion series given by Definition 3.

Moreover,

$$\int_0^{\tilde{x}} \frac{x}{v + \beta_s x^{\alpha_s}} dx = \frac{1}{\alpha_s v \varphi^{\frac{2}{\alpha_s}}} \int_0^{\frac{\varphi \tilde{x}^{\alpha_s}}{1 + \varphi \tilde{x}^{\alpha_s}}} \frac{t^{\frac{2}{\alpha_s} - 1}}{(1 - t)^{\frac{2}{\alpha_s}}} dt \quad (13)$$

$$= \frac{1}{\alpha_s v \varphi^{\frac{2}{\alpha_s}}} B\left(\frac{2}{\alpha_s}, 1 - \frac{2}{\alpha_s}, \frac{\varphi \tilde{x}^{\alpha_s}}{1 + \varphi \tilde{x}^{\alpha_s}}\right) \quad (14)$$

As before, we find (13) after change in variables as for equation (9) and (10).

Therefore,

$$\begin{aligned} \mathbb{E}R_w &= \tilde{x} - \frac{\tilde{x}}{v} \Gamma\left(\frac{2}{\alpha_s}\right) \left(\frac{1}{1 + \varphi \tilde{x}^{\alpha_s}}\right)^{1 - \frac{2}{\alpha_s}} \sum_{j=0}^{\infty} \frac{(\varphi \tilde{x}^{\alpha_s})^j}{(2 + \alpha_s j) \Gamma(\frac{2}{\alpha_s} + j)} \\ &\quad - \tilde{x} \frac{\beta_s \tilde{x}^{\alpha_s} - \beta_w \tilde{x}^{\alpha_w}}{v} \Gamma\left(\frac{1}{\alpha_s}\right) \left(\frac{1}{1 + \varphi \tilde{x}^{\alpha_s}}\right)^{1 - \frac{1}{\alpha_s}} \sum_{j=0}^{\infty} \frac{(\varphi \tilde{x}^{\alpha_s})^j}{(1 + \alpha_s j) \Gamma(\frac{1}{\alpha_s} + j)} \end{aligned}$$

## 2. Computation of $\mathbb{E}R_s$ .

Let us denote  $\phi = \frac{\beta_w}{v}$ . If  $\alpha_w = 1$

$$\begin{aligned} \mathbb{E}R_s &= -\frac{1}{\beta_w} \left[ (1 - \beta_w) \tilde{x} + \frac{1}{\phi \beta_w} \ln(1 + \phi \tilde{x}) \right] \\ &= -\frac{v}{\beta_w} \left( 1 + \frac{1}{\beta_w} \ln(1 - \beta_w) \right) \end{aligned}$$

which is positive as  $\beta_w < 1$ .

If  $\alpha_w > 1$  the calculation is the same as for  $\mathbb{E}R_w$ , thus

$$\mathbb{E}R_s = \tilde{x} \left( 1 - \frac{1}{v} \Gamma\left(\frac{2}{\alpha_w}\right) \left(\frac{1}{1 + \phi\tilde{x}^{\alpha_w}}\right)^{1 - \frac{2}{\alpha_w}} \sum_{j=0}^{\infty} \frac{(\phi\tilde{x}^{\alpha_w})^j}{(2 + \alpha_w j) \Gamma(\frac{2}{\alpha_w} + j)} \right)$$

■

*Proof of the Corollary 3.* Let us remind that the expected equilibrium expenditure is given by  $\mathbb{E}R_i = \tilde{x} - \int_0^{\tilde{x}} F_i(x) dx$  for  $i = w, s$ .

(i)

$$\begin{aligned} \frac{\partial \mathbb{E}R_s}{\partial \beta_w} &= \frac{d\tilde{x}}{d\beta_w} \underbrace{(1 - F_s(\tilde{x}))}_{=0} + \int_0^{\tilde{x}} \frac{x^{\alpha_w+1}}{(v + \beta_w x^{\alpha_w})^2} dx \\ &> 0 \end{aligned}$$

$$\frac{\partial \mathbb{E}R_s}{\partial \alpha_w} = \frac{d\tilde{x}}{d\alpha_w} \underbrace{(1 - F_s(\tilde{x}))}_{=0} + \int_0^{\tilde{x}} \frac{x^{\alpha_w+1} \beta_w \ln x}{(v + \beta_w x^{\alpha_w})^2} dx$$

which is negative if  $\tilde{x} \leq 1$ .

(ii) The mixed strategies and the maximum effort are independent in  $\beta_s$  and  $\alpha_s$ . Hence the result.

(iii)  $\frac{\partial \mathbb{E}R_w}{\partial \beta_s} = - \int_0^{\tilde{x}} \frac{v(\tilde{x}^{\alpha_s} - x^{\alpha_s}) + x^{\alpha_s}(\tilde{x} - x)}{(v + \beta_s x^{\alpha_s})^2} dx < 0$ . Moreover, if  $\tilde{x} \leq 1$ ,

$$\begin{aligned} \frac{\partial \mathbb{E}R_w}{\partial \alpha_s} &= -\beta_s \int_0^{\tilde{x}} \frac{v\tilde{x}^{\alpha_s} \ln \tilde{x} - x^{\alpha_s} \ln x (v - \tilde{x} + x)}{(v + \beta_s x^{\alpha_s})^2} dx \\ &\geq \beta_s \int_0^{\tilde{x}} \frac{x^{\alpha_s} (\tilde{x} - x) \ln x}{(v + \beta_s x^{\alpha_s})^2} dx \\ &\geq 0 \end{aligned}$$

(iv) Using assumption A2 and equation (1), it follows that

$$\frac{\partial \mathbb{E}R_w}{\partial \beta_w} = \frac{d\tilde{x}}{d\beta_w} \underbrace{(1 - F_s(\tilde{x}))}_{=0} - \int_0^{\tilde{x}} \frac{d\tilde{x}}{d\beta_w} \frac{\alpha_s \beta_s \tilde{x}^{\alpha_s-1} - 1}{v + \beta_s x^{\alpha_s}} dx > 0 \text{ and}$$

$\frac{\partial \mathbb{E}R_w}{\partial \alpha_w} = \frac{d\tilde{x}}{d\alpha_w} \underbrace{(1 - F_s(\tilde{x}))}_{=0} - \int_0^{\tilde{x}} \frac{d\tilde{x}}{d\alpha_w} \frac{\alpha_s \beta_s \tilde{x}^{\alpha_s-1} - 1}{v + \beta_s x^{\alpha_s}} dx$  which is negative if  $\tilde{x} \leq 1$  and non-negative if  $\tilde{x} > 1$ .

■

## Appendix B: Ordered Valuations

An alternative way to analyze the problem would be to consider ordered valuations such that  $V_i(x) > V_j(x)$  over the relevant range of  $x$ . Due to the form of the valuation functions, two separate cases have to be examined:  $\alpha_i > \alpha_j$  for  $x > \left(\frac{\beta_j}{\beta_i}\right)^{\frac{1}{\alpha_i - \alpha_j}}$  and  $\alpha_i < \alpha_j$  for  $x \leq \left(\frac{\beta_j}{\beta_i}\right)^{\frac{1}{\alpha_i - \alpha_j}}$ . In the following, let us denote the threshold  $\left(\frac{\beta_j}{\beta_i}\right)^{\frac{1}{\alpha_i - \alpha_j}}$  by  $x^*$ .

### Case (i): $\alpha_i > \alpha_j$ , Positive Minima

If the maximum effort  $\tilde{x}$  is superior to the effort level  $x^*$  the mixed equilibrium strategies for both players can be computed. Otherwise, there is not positive density in equilibrium. The main difference to the standard all-pay auction, in a sense, is that the non-participation level of effort and the minimum effort level have to be distinguished. In particular, the players do not participate below the threshold level  $x^*$ . In the following, only the results that do not follow straightforwardly from Hillman and Riley (1989) and Baye, Kovenock, and de Vries (1996) will be given.

**Lemma 2.** *Under assumptions A1-A3, if the minimum effort  $x^*$  is strictly positive and inferior to  $\tilde{x}$  then the two players' strategies have an atom such that*

$$F_i(x^*) = \frac{x^*}{V_j(x^*)} \text{ and } F_j(x^*) = \frac{V_j(x^*)}{V_i(x^*)} F_i(x^*) + \frac{V_i(\tilde{x}) - V_j(\tilde{x})}{V_i(x^*)}$$

*Proof.* Since the strategy spaces are the same, and expected utilities are constant at the equilibrium we obtain  $V_i(\tilde{x}) - \tilde{x} = F_j(x)V_i(x) - x$  and  $V_j(\tilde{x}) - \tilde{x} = F_i(x)V_j(x) - x$  for all  $x \in [x^*, \tilde{x}]$ . As  $V_j(\tilde{x}) - \tilde{x} = 0$ , the two last equations lead to the result. ■

In this case, player  $i$  is “strong” and player  $j$  “weak” in the sense defined above with probability one for all  $x$ . Thus, with the exception of the common mass point at the lower end of the distribution and the length of the strategy space, the mixed equilibrium strategies should be the same as in the case with non-ordered valuations and  $i$  as the strong player. In other words, for all  $x \in [x^*, \tilde{x}]$

$$F_i(x) = \frac{x}{v + \beta_j x^{\alpha_j}} \text{ and } F_j(x) = \frac{v + \beta_i \tilde{x}^{\alpha_i} - \tilde{x} + x}{v + \beta_i x^{\alpha_i}}.$$

Even if the distributions are the same, the expected revenue will differ as the strategy spaces are different. We do not provide the closed form solution here, but the computation is straightforward and similar to the one for non-ordered valuations.

### Case (ii): $\alpha_i < \alpha_j$ , Caps

Here, two cases have to be distinguished. In both, player  $i$  is “strong” and player  $j$  is “weak” for all  $x$ . If the maximum effort  $\tilde{x}$  is inferior to  $x^*$  the situation is as same as that of ordered-valuations with endogenous rewards and the results of Proposition 1 apply. Alternatively, the agents face a cap in their bids that they could not exceed such as  $\tilde{x} > x^*$ . This last case was studied by Che and Gale (1998) with exogenous valuations. As in their paper, we consider two cases. When  $x^* \leq \frac{\tilde{x}}{2}$ , there is a pure strategy Nash equilibrium where the effort of the players is  $x^*$ . Otherwise, mixed strategies have to be computed. It can be shown that the players have a nonzero density on  $(0, x']$  and a zero density on  $(x', x^*)$  with a mass point at  $x^*$ .<sup>6</sup> Then, with similar technical arguments than Che and Gale (1998) we find that for all  $x \in [0, x']$   $F_i(x) = \frac{x}{V_j(x)}$  and  $F_j(x) = \frac{x}{V_i(x)} + \frac{V_i(x') - V_j(x')}{V_i(x)}$  and for all  $x \in [x', x^*[$   $F_i(x) = \frac{x'}{V_j(x')}$  and  $F_j(x) = \frac{x'}{V_i(x')} + \frac{V_i(x') - V_j(x')}{V_i(x')}$ . To sum up, if  $x^* \in (\frac{\tilde{x}}{2}, \tilde{x})$

$$F_i(x) = \begin{cases} \frac{x}{v + \beta_j x^{\alpha_j}} & \text{for all } x \in [0, x'] \\ \frac{x'}{v + \beta_j x'^{\alpha_j}} & \text{for all } x \in [x', x^*[ \quad \text{and} \\ 1 & \text{for } x = x^* \end{cases}$$

$$F_j(x) = \begin{cases} \frac{x}{v + \beta_i x^{\alpha_i}} + \frac{\beta_i x'^{\alpha_i} - \beta_j x'^{\alpha_j}}{v + \beta_i x^{\alpha_i}} & \text{for all } x \in [0, x'] \\ \frac{x'}{v + \beta_i x'^{\alpha_i}} + \frac{\beta_i x'^{\alpha_i} - \beta_j x'^{\alpha_j}}{v + \beta_i x'^{\alpha_i}} & \text{for all } x \in [x', x^*[ \\ 1 & \text{for } x = x^* \end{cases}$$

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<sup>6</sup>See the Lemma 3 of Che and Gale (1998).

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