Research Article

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Patent Races for COVID-19 Vaccines and Liability Rules

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Abstract: I analyze a model of patent races for COVID-19 vaccines under alternative liability rules. The first inventor of the vaccine gets the monopoly rent, but must assume full liability from its side effects. In this model, firms choose two kinds of investments, one for inventing a vaccine and the other for its safety. I show that firms have an incentive to overinvest in both activities under strict liability. This is contrasted with the established result established that the injurer takes socially optimal accident-preventing precaution under strict liability. This contrast comes from the competition effect. Overinvestment in inventing vaccines due to competition makes a firm overinvest in safety as well. I also argue that it is undesirable for firms to get full or partial exemption from liability, because it would reduce the incentive to invest in safety. Instead, reducing the monopoly rent by regulating the vaccine price resolves both overinvestment problems.

Keywords: COVID-19, liability rules, patent race, product liability, vaccine

JEL Classification Code: K13

1 Introduction

The COVID-19 pandemic has spread with unanticipated speed this year, infecting millions of people and bringing global economy into almost stasis, as most of the countries imposed tight restrictions on movement to halt the spread of the virus. As the health and human toll grows, the economic disaster is evident and the economic shock appears to be the largest that the world has experienced in decades.

The June 2020 Global Economic Prospects forecast a 5.2 percent contraction in global GDP in 2020, which is the deepest global recession in decades, despite every

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effort of governments to counter the downturn with various economic policy supports. The deep recessions triggered by the pandemic are expected to leave significant aftermaths through fragmentation of global trade and reduced investments both in physical capital and human capital especially due to lost work and schooling.

To curb the spread of COVID-19 pandemic, the world is struggling to develop vaccines. Vaccines save millions of lives each year. A vaccine for a particular infectious disease trains the body's natural defences (the immune system) by providing active acquired immunity to the particular virus. A vaccine stimulates the body's immune system to recognize and fight off the virus it targets. If the body is exposed to the disease-causing virus later, it is prepared to destroy the virus, preventing illness. Currently, immunization prevents 2–3 million deaths every year from diseases like influenza, measles and diphtheria, etc.,¹ and research is going on at unprecedented speed to make COVID-19 preventable by a vaccine.

According to the official site of World Health Organization (WHO), over 169 COVID-19 vaccine candidates are currently under development and 26 among them are in the human trial phase. The vaccine developers are racing to find an effective vaccine prior to others. However, there is a crucial limitation to large pharmaceutical companies to invest on COVID-19 vaccines. First of all, it is important to invent a safe vaccine as well as to invent it first in a race. Many of the large companies are hesitant to commit to a large amount of resources in developing vaccines, because it is too risky due to products liability and the possibility of the government's price regulation.² Product liability is considered to be among most contentious issues to secure supply deals for potential COVID-19 vaccines. The United States, however, circumvented this issue by excluding tort claims from products that help to control a public-health crises in the form of the 2005 Public Readiness and Emergency Preparedness (PREP) Act. Based on the Act, AstraZeneca, which is UK's second-largest drugmaker, has been granted protection from future product liability claims related to its COVID-19 vaccine. It agreed to provide a total of more than two billion doses at no profit to many countries including US, UK, EU countries etc.

Then, it is a tricky issue that remains who pays for any claims for damages in case of side effects. When swine flu was prevalent in 1976, the US government promised large pharmaceutical companies that it would compensate them fully for the damages due to side effects and it actually paid \$100 million for damages.³

¹ There are now vaccines to prevent more than 20 life-threatening diseases.

² See Posner (2020, March 2).

³ More than 4000 legal claims followed for damages from Guillain-Barré syndrome (GBS) that is a rare but serious disorder in which the immune system attacks healthy nerve cells.

This experience made it for the US government to be inactive in spreading vaccines for a novel influenza-A virus in 2009, causing 12,649 casualties in US. This problem occurs to any vaccine including COVID-19 vaccines. Pharmaceutical companies tend to be hesitant to invest in developing a vaccine on a large scale, unless people need the vaccine every year as common influenza. For example, a vaccine for Ebola was not invented until the end of 2019, because Ebola is likely to break out mostly in West Africa in which the vaccine price cannot be set high.

One may seek an answer for the question “Who pays for the damages from future side effects?” from liability rules. As is well known, two currently competing rules are the strict liability rule and the negligence rule. Under the strict liability rule, an injurer must pay for all losses he causes, regardless of the extent of his precaution. Under the negligence rule, an injurer is held liable for losses he causes only if he was negligent, that is, only if his care level was less than due care.

One of the established results regarding efficiency of liability rules is that both rules are efficient if courts have enough information to set the negligence standard appropriately, unless expected accident losses depend on the victim’s care level or the injurer’s activity level as well as the injurer’s care level. Shavell (1980) mentions both the case that the accident probability depends on the victim’s care level as well and the case that the expected accident losses increase with the injurer’s activity level. His main conclusions are that (i) in the former case, the outcome will be socially optimal under some form of the negligence rule, whereas it will not be under strict liability because the victim will take no care and that (ii) in the latter case, strict liability creates the efficient incentive to take care, while the negligence rule induces too much activity since the injurer is not liable for the accident losses under the negligence rule simply because he engages in the activity too much.

Those analyses have been made on the basis of the most widely accepted efficiency goal of tort law first proposed by Calabresi (1970), that is, minimization of the sum of precaution, accident, and administration costs. In Kim (2006), I asserted that, if the potential injurer’s activity involves positive externalities other than those through accident occurrences, the efficiency goal proposed by Calabresi should be modified and that the social optimum meeting this general objective cannot be induced by the strict liability rule minimizing only the social cost associated with accidents. Moreover, I demonstrated that the negligence rule can perform better than the strict liability rule by choosing due care appropriately.

To address both issues, the expedited development of a vaccine and its reliability in a single model, I adapt a patent race model into introducing the liability possibility. In this model, firms choose two kinds of investments, one for inventing a vaccine and the other for its safety. A firm that is successful in being the first inventor of a vaccine gets the prize (monopoly rent) but is exposed to risks of assuming full responsibility in case the vaccine causes any injuries or deaths. I

show that firms have an incentive to invest too much in both activities in this patent race game under strict liability.

This result is contrasted with the result established by Shavell (1980) that the potential injurer takes socially optimal accident-preventing precaution under strict liability. This contrast comes mainly from the competition effect. If firms compete to invent a vaccine prior to the rival, they make higher level of efforts to innovate than socially optimal level of effort, because the prize from success can only occur when he wins the patent race. This in turn makes him invest more in reducing side effects than social optimum, because his investment in safety is more valuable when the probability of selling vaccines to consumers is higher by investing more in inventing than when he makes the socially optimal level of investment. In other words, although given the stable relation between a monopolist and consumers, the strict liability rule induces the socially optimal activity and precaution of the firm if the firm's action involves no externality, the uncertain relation between a firm and consumers makes each firm overinvest in developing a vaccine in order to secure a monopolistic relation with consumers, and consequently this overinvestment makes the private benefit from increasing the level of investment in safety higher than the social benefit even under the strict liability rule due to the increased probability that the firm will transact with consumers monopolistically. I also argue that it is not desirable for firms to get full exemption from product liability as in the case of AstraZeneca and vaccines for swine flu in 1976. If innovating firms get full liability indemnity, it would completely eliminate their incentives to invest in safety of vaccines.

Calabresi (1961) seems the first who asserted that it might not be socially desirable to place the full costs of accidents of the firm's side in a monopolized industry. The result of Kim (2006) is in support of Calabresi. These results are in a sharp contrast with Polinsky (1980) who argues that strict liability induces efficiency in the case of unilateral accidents. In a monopoly market, there are two sources of inefficiency under strict liability. First, due to the market power, the monopolist charges a higher price than the marginal cost, thereby producing less than the social optimum. Second, the monopolist's exit decision does not correspond with the negativity condition of the social welfare. In a competitive market, it does because a small change in the number of firms affects an individual firm's profit and the social welfare in the same degree, but in a monopoly, it affects the social welfare more than the firm's profit since a monopolist's exit is not an infinitesimal change. Interestingly, in the current paper, I resume a competition model to argue that the strict liability rule does not guarantee efficiency. Note that there is no exit decision to competing firms in this model.

Since the seminal work by Loury (1979), patent races have been modeled by a dynamic game,⁴ but its strategic equivalence with the contest model that originated with Tullock (1980) is also well known.⁵ In a contest model, two or more players expend costly resources in order to win a prize, just as in a patent race.

There is some literature on multi-dimensional efforts in contest models. Faria et al. (2014) is closest to this paper. They consider a contest model that includes both research effort and legal effort (rent-seeking effort). In their model, contestants make legal efforts to affect the prize value, i.e., increase the winner's prospective rents. Epstein, Nitzan, and Schwarz (2008) considered not only two types of effort but also two types of players. So, contestants expend resources to win the prize, while politicians or bureaucrats expend resources in order to increase their shares in those efforts. Clark and Konrad (2007) considers contests in which the number of prizes is smaller than the number of dimensions along which they compete with each other. Arbatskaya and Mialon (2012) analyzes a dynamic contest model show that rent dissipation is lower in the two-stage multi-activity contest than in the one-stage contest.

In Section 2, I provide a simple model. In Section 3, I analyze the model and compare the private optimum and the social optimum, and discuss the effects of alternative liability and prizing rules. Concluding remarks follow in Section 4.

2 Basic Model

There are two risk-neutral competing firms, firm 1 and firm 2. Consider a patent race between them for covid-19 vaccines. An identical prize is awarded to the successful firm. The value of this prize is V . There is also a possibility of side effects. We denote the damage amount due to side effects by L .

Let x_i be the firm i 's expenditure on vaccine researches, $i = 1, 2$ and y_i be the firm's expenditure to prevent accidents.

The following notation will be used throughout the paper.

- x_i = firm i 's expenditure on vaccine researches ($x_i \geq 0$)
- y_i = firm i 's expenditure on preventing side effects ($y_i \geq 0$)
- $p_i(x_1, x_2)$ = the probability that firm i innovates first
- $q(y_i)$ = the probability that the vaccine of firm i has side effects given that it is deployed
- L = accident losses ($L > 0$)
- π_i = firm i 's profit
- W = social welfare

⁴ See Lee and Wilde (1980), Dasgupta and Stiglitz (1980), and Reinganum (1982).

⁵ See, for example, Baye and Hoppe (2003).

We assume that $p_i = \frac{x_i}{x_1 + x_2 + a}$ and $q(y_i) = \frac{1}{y_i + b}$ where $a > 0$ and $b > 1$. Our contest success function (CSF) is slightly different from the one first introduced by Tullock (1980) which has the form of $p_i = \frac{x_i}{x_1 + x_2}$. Under Tullock's CSF, one of the contestants must succeed in inventing vaccines, that is, there is no possibility that vaccines are invented by neither firm.⁶ To allow the realistic possibility that no vaccines are successful, we introduce the positive constant a to make the sum $p_1 + p_2 = \frac{x_1 + x_2}{x_1 + x_2 + a} < 1$.⁷ The assumption that $a > 0$ is not crucial to the result of my analysis.

3 Analysis

In this section, we assume the strict liability rule following the spirit of product liability law.⁸ We will analyze the patent race between the two firms and compare the private optimum with the social optimum.

3.1 Private Optimum

Since players are assumed to be risk-neutral, the payoff for each player is

$$\pi_i = \frac{x_i}{x_1 + x_2 + a} \left(V - \frac{L}{y_i + b} \right) - (x_i + y_i). \quad (1)$$

Differentiating (1) with respect to x_i and y_i yields the first-order conditions as follows:

$$\frac{\partial \pi_i}{\partial x_i} = \frac{x_i + a}{(x_1 + x_2 + a)^2} \left(V - \frac{L}{y_i + b} \right) - 1 = 0, \quad (2)$$

$$\frac{\partial \pi_i}{\partial y_i} = \frac{x_i}{x_1 + x_2 + a} \frac{L}{(y_i + b)^2} - 1 = 0. \quad (3)$$

⁶ It is well known that the social optimum x_i in the case that $a = 0$ is $\epsilon > 0$ if $L = 0$, which is unrealistic.

⁷ In fact, Tullock considers a more general CSF given by $p(x_1, x_2) = \frac{x_1^r}{x_1^r + x_2^r}$. It is well known that there is a pure strategy equilibrium if $r < 2$ and no pure strategy equilibrium if $r > 2$.

⁸ Under the U. S. products liability law, plaintiffs do not need to prove the negligence of the defendants but the defects of the products in order to be compensated for their injuries caused by the products. In this sense, it roughly corresponds to the strict liability rule, albeit not exactly identical.

I will focus only on the symmetric equilibrium. Let $x^* = x_1^* = x_2^*$ and $y^* = y_1^* = y_2^*$ be the equilibrium investments.

Assuming interior solutions,⁹ by using symmetry, I can characterize the equilibrium expenditures x^* and y^* by the following two equations:

$$\frac{x^* + a}{(2x^* + a)^2} \left(V - \frac{L}{y^* + b} \right) = 1, \quad (4)$$

$$\frac{x^*}{2x^* + a} \frac{L}{(y^* + b)^2} = 1, \quad (5)$$

which can be rearranged into

$$\frac{x^*}{2x^* + a} L = (y^* + b)^2. \quad (6)$$

The left hand side of (4) is each firm's marginal benefit from increasing expenditures on developing a vaccine. The benefit comes from increasing the probability of winning the patent race. Similarly, the left hand side of (5) is the firm i 's marginal benefit from increasing expenditures on preventing side effects of the vaccine. Additional expenditure on y_i reduces the probability that accidents occur, i.e., the probability that the firm should be liable for the damages L due to the side effects of the vaccine. The right hand side of (4) and (5) are just direct marginal cost of increasing x_i and y_i respectively. Thus, Eqs. (4) and (5) have the usual interpretation that x^* and y^* must balance each firm's private marginal benefit (of additional expenditures on innovation and accident prevention respectively) and the marginal cost that each innovating firm must bear directly.

Note from (6) that x^* increases if y^* increases, provided that L is given. This implies that if V changes, x^* and y^* move in the same direction. Thus, Proposition 1 follows.

Proposition 1. *As V gets larger, both x^* and y^* get larger.*

It is intuitively clear that firms invest more on innovation as the prize from the patent race is larger. But why firms invest more on safety of the vaccine as well, when the prize gets larger? If x^* gets larger, the probability that he is the winner in the patent race and becomes the sole supplier of vaccines gets higher, implying that he is expected to bear larger losses from the side effects. Therefore, the firm

⁹ If a and b are so large that the benefit from increasing x_i or y_i is small, corner solutions, i.e., $x^* = 0$ or $y^* = 0$, could be possible. This possibility is excluded if a and b are not too large. The assumption of interior solutions also excludes the possibility that $\pi_i^* \equiv \pi_i(x^*, y^*)$ is negative. For example, simulations show that $x^* = 3.8865$, $y^* = 0.3826$ and $\pi^* = 2.7$ if $V = 20$, $L = 8$, $a = 1$ and $b = 1.5$.

will have a stronger incentive to increase the expenditures on the safety of the vaccine to avoid accidents.

3.2 Social Optimum

The social welfare function is usually defined by the sum of the consumer surplus and profits of the firms. For simplicity, we assume that V captures all the consumer surplus.¹⁰ This assumption implies that innovation activities of firms do not generate externalities to consumers in the sense that all the consumer surpluses from purchasing vaccines are absorbed in the profit of the innovating firm.

The social welfare function denoted by W is then written as

$$\begin{aligned} W &= \pi_1 + \pi_2 \\ &= \frac{x_1}{x_1 + x_2 + a} \left(V - \frac{L}{y_1 + b} \right) + \frac{x_2}{x_1 + x_2 + a} \left(V - \frac{L}{y_2 + b} \right) \\ &\quad - (x_1 + x_2 + y_1 + y_2). \end{aligned} \quad (7)$$

Let x_i^s and y_i^s be the socially optimal expenditures of firm i and $W^s = W(x_1^s, x_2^s, y_1^s, y_2^s)$. Then, x_i^s and y_i^s must satisfy the first-order conditions as follows:

$$\frac{\partial W}{\partial x_i} = \frac{\partial \pi_i}{\partial x_i} + \frac{\partial \pi_j}{\partial x_i} = 0, \quad (8)$$

$$\frac{\partial W}{\partial y_i} = \frac{\partial \pi_i}{\partial y_i}. \quad (9)$$

Assuming that $W^s > 0$ implies that $V > \frac{L}{y^s + b}$ where $y^s = y_i^s$ is the symmetric socially optimal expenditure on accident prevention. Then, note that $\frac{\partial \pi_j}{\partial x_i} < 0$ because $\frac{\partial p_j(x_1, x_2)}{\partial x_i} < 0$. This implies that $x^s < x^*$ because $\frac{\partial \pi_i}{\partial x_i} > \frac{\partial W}{\partial x_i}$ and $\frac{\partial^2 \pi_i}{\partial x_i^2}, \frac{\partial^2 W}{\partial x_i^2} < 0$ by the second-order conditions.

On the other hand, it is easy to see that the conditions for privately optimal y^* and socially optimal y^s given in (5) and (9) are identical. However, it does not imply that $y^* = y^s$, because $x^* \neq x^s$. Since $x^* > x^s$, it follows that

$$\frac{x^*}{2x^* + a} > \frac{x^s}{2x^s + a}, \quad (10)$$

10 This assumption can be justified in situations in which the first innovator of COVID-19 vaccines will have all the monopoly power and the market demand will be very inelastic to the price.

implying that $y^* > y^s$. The intuitive reason for this is that an increase in y is more beneficial to private firms than to the society, because they overinvest in innovation to become a monopolist and the resulting higher probability of selling vaccines to consumers makes it more beneficial for them to avoid accidents due to side effects.

Proposition 2. *In patent races, firms invest too much in inventing vaccines and preventing accidents, i.e., $x^* > x^s$ and $y^* > y^s$.*

This result is rather contrasted with the established result in literature that a firm's effort level to avoid accidents is socially optimal under the strict liability rule.¹¹ The main driving force for this result is the competition effect. In patent races, the investment in inventing a vaccine by one of the competing firms is completely redundant from the social point of view, because only the first invention will have the commercial value. The investment of the other firm who fails to be the first inventor is completely wasted. However, firms invest to preempt the monopoly position in the market of covid-19 vaccines prior to the rival, even if it turns out to be socially wasteful. Due to overinvestment in innovation, firms take over-investments in the safety of the vaccines as well, which can be seen from (6) and (10). Intuitively, this is because the investment in safety becomes more valuable as the investment in innovation is larger, mainly due to a higher chance that the firm can sell vaccines to consumers.

This result is also contrary to social concerns that private companies may not have an enough incentive to invent a COVID-19 vaccine because they worry about paying a large amount of damages in case the vaccine causes any injuries or deaths. Interestingly, private firms overinvest in developing vaccines in equilibrium rather than underinvest. Then, how can the government discourage firms from making excessive investments in both activities rather than encourage them to make more investments?

What if the government switches from the strict liability rule to the negligence rule? Will the negligence rule induce firms to make socially optimal level of investments? Under the negligence rule, the successful firm may be liable for the damages only if $y_i < \bar{y} = y^s$ and not liable at all if $y_i \geq \bar{y}$. Then, the negligence rule could induce firms to make socially optimal level of investments in y_i because of the discontinuity at $y_i = \bar{y}$,¹² but not socially optimal level of investments in

¹¹ See, for example, Shavell (1980).

¹² If $\bar{y}$ is too high or L is too small, firms may prefer failing to meet the legal investment level $\bar{y}$ by choosing $y^* < \bar{y}$. In this paper, however, I focus on the case that L is high enough for firms to make over-investment $y^* > y^s$.

inventing.¹³ So, firms will still overinvest insofar as they race for a patent. In fact, they will make more severe overinvestment because the net prize is increased from $V - \frac{L}{y^* + b}$ to V by meeting the due care level of $y_i = \bar{y} = y^s$.

Alternatively, the government may share the liability with firms, i.e., reduce the liability that firms bear to αL where $\alpha \in [0, 1]$. I call this a sharing liability rule. Let $x^*(\alpha)$ and $y^*(\alpha)$ be the investments given α . It is clear that $y^*(0) < y^s$ and $y^*(1) > y^s$.¹⁴ Thus, by continuity, there must be $\alpha^* \in (0, 1)$ such that $y^*(\alpha^*) = y^s$. In general, however, there is no α^s that satisfies both $x^*(\alpha^s) = x^s$ and $y^*(\alpha^s) = y^s$.

Finally, consider the possibility that the government can make V flexible, for example, by regulating the price of vaccines.¹⁵ If the government reduces the prize to βV where $\beta \in (0, 1)$ with fixing L , there must be $\beta^s \in (0, 1)$ such that $x^*(\beta^s) = x^s$ by continuity of x^* with respect to β , because $x^*(0) = 0$ and $x^*(1) > x^s$. Note that y^* depends only on L , not on βV . Therefore, $y^*(\beta^s) = y^s$, because $y^*(\beta^s) = y^s$ if and only if $x^*(\beta^s) = x^s$. This suggests that regulation of the vaccine price may resolve both overinvestment problems, although alternative liability rules to the strict liability rule can resolve only the problem of overinvestment in safety, but not both. The insight is quite similar to Kim (2006). The case that $\beta < 1$ corresponds with the case that investments in inventing a vaccine generate positive externalities to consumers because the successful firm's profit βV is not equal to the total social gain V with the difference equal to consumer surplus. In this case, social optimum could be achieved by the government's more flexible choice of a policy variable than the strict liability rule.¹⁶

4 Conclusion

This paper is the first to examine the incentive of firms to invest in inventing a vaccine for COVID-19 virus and in reducing the possibility that the vaccine causes any injuries or deaths. I shows that the strict liability rule does not induce the socially optimal investment in accident prevention in a patent race model. I also argue that socially optimal levels of investment in inventing a vaccine and in safety

¹³ This intuition is quite similar to the result that an injurer takes due care but takes too much activity under the negligence rule.

¹⁴ It is obvious that firms make no efforts to prevent an accident if the government bears all the burden of paying for the losses due to side effects as in the case of 1976 swine flu vaccines. It is not surprising because a potential injurer does not make any effort to prevent accidents under no liability rule.

¹⁵ This policy corresponds with the principle of Médecins Sans Frontières (MSF, Doctors Without Borders) that is manifested in its policy paper MSF (2020), “to set prices to insure equitable access during a pandemic.”

¹⁶ In this paper, the policy variable is β , while it is the due care level in Kim (2006).

cannot be induced by any liability rule considered in this paper (including the negligence rule), but can be induced by the prizing rule whereby the government reduces the prize by regulating the vaccine price.

The present model can be extended in several ways. In particular, one can consider a more general model with a general contest success function (CSF). However, I believe that this generalization does not qualitatively affect the main insight of this paper. Second, I assumed that accidents are unilateral. However, accidents from COVID-19 vaccines may be bilateral, because accidents could occur due to the fault of consumers after inoculations. I believe that extending the model into the case of bilateral accidents will strengthen the result significantly.

Appendix

Proof of Proposition 1

To exploit symmetry, we will suppress subscript i . Differentiating first-order conditions given by (4) and (5) with respect to V , we obtain

$$\begin{bmatrix} \pi_{xx} & \pi_{xy} \\ \pi_{yx} & \pi_{yy} \end{bmatrix} \begin{bmatrix} dx_i \\ dy_i \end{bmatrix} = - \begin{bmatrix} \pi_{xV} \\ 0 \end{bmatrix} dV, \quad (11)$$

where $\pi_{xx} = \frac{\partial^2 \pi}{\partial x_i^2}$, $\pi_{xy} = \frac{\partial^2 \pi}{\partial x_i \partial y_i}$, $\pi_{yx} = \frac{\partial^2 \pi}{\partial y_i \partial x_i}$, $\pi_{yy} = \frac{\partial^2 \pi}{\partial y_i^2}$ and $\pi_{xV} = \frac{\partial^2 \pi}{\partial x_i \partial V}$.

By Cramer Rule, we have

$$\frac{dx_i}{dV} = \frac{\begin{vmatrix} -\pi_{xV} & \pi_{xy} \\ 0 & \pi_{yy} \end{vmatrix}}{|H|} = - \frac{\pi_{yy}\pi_{xV}}{|H|}, \quad (12)$$

where H is the Hessian matrix.

Also, we have

$$\pi_{yy} = - \frac{2x_i}{x_1 + x_2 + a} \frac{L}{(y_i + b)^3} < 0, \quad (13)$$

$$\pi_{xV} = \frac{x_i}{x_1 + x_2 + a} > 0. \quad (14)$$

Since $|H| > 0$ by the second order condition, it follows that

$$\frac{dx_i}{dV} = - \frac{\pi_{yy}\pi_{xV}}{|H|} > 0. \quad (15)$$

Similarly, by Cramer Rule, we have

$$\frac{dy_i}{dV} = \frac{\begin{vmatrix} \pi_{xx} & -\pi_{xV} \\ \pi_{yx} & 0 \end{vmatrix}}{|H|} = \frac{\pi_{yx}\pi_{xV}}{|H|}. \quad (16)$$

Since $\pi_{yx} = \frac{x_j+a}{x_1+x_2+a} \frac{L}{(y_i+b)^2} > 0$ for $j \neq i$, it follows that

$$\frac{dy_i}{dV} > 0. \quad (17)$$

Since $\frac{\partial x_i}{\partial V}, \frac{\partial y_i}{\partial V} > 0$ for all $i = 1, 2$, the proof is completed. ■

Proof of Proposition 2

- (i) Proof for $x^* > x^s$: This is immediate from comparing (4) and (8) because $\frac{\partial \pi_i}{\partial x_i} < 0$ and $\frac{\partial^2 \pi_i}{\partial x_i^2}, \frac{\partial^2 W}{\partial x_i^2} < 0$ by the second-order conditions.
- (ii) Proof for $y^* > y^s$: This is also immediate from comparing (5) and (9) because $x^* > x^s$. ■

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