# Endogenous Technology Adoption, Government Policy and Tariffication

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**Abstract**

In this paper we integrate government policy into game-theoretic models of endogenous technology adoption to investigate the impact of alternate policy instruments on the adoption of productivity-improving technologies. We show that while ad-valorem taxes have a neutral impact on technology adoption, specific taxes tend to decrease the speed of technology diffusion. As an application of this finding we demonstrate how, in an open-economy setting, tariffication (i.e., the conversion of quotas to ad-valorem tariffs) can lead to faster technology adoption world-wide.

KEYWORDS: Technology Adoption, Specific tax, Ad valorem tax, tariffs, quotas
JEL Classification

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# 1 Introduction

Innovation and technology adoption are widely viewed as the primary sources of productivity growth. In this respect the adoption of new technologies is especially important as a superior technology confers no benefits until that technology is employed by potential users. Thus, evaluation of government policy should consider, not only standard issues of static efficiency, but also it's dynamic impact on the incentives to adopt new technologies. Indeed, Goolsbee (2006) finds that the dynamic costs of taxes, by reducing the incentive for firms to enter new markets, can even outweigh the conventional efficiency costs of taxation. Similarly, we argue that taxes and other government policies can impact the incentives for firms to adopt new cost-saving innovation. In this paper, we integrate government policy into game-theoretic models of endogenous technology adoption to investigate how such policy impacts the diffusion of new technologies.

There exists an extensive literature in the field of public economics on the relative efficiency of different forms of taxation, focusing on the differences between unit (specific) and ad valorem (percentage) taxes. This literature dates back to the seminal paper by Suits and Musgrave (1953) with more recent contributions including Delipalla and Keen (1992), Skeath and Trandel (1994) and Anderson, de Palma, and Kreider (2001). These papers demonstrate that, while per-unit and ad-valorem taxes are equivalent under conditions of perfect competition, they can have differing impacts when the market is characterized by imperfect competition.

There exists a parallel literature in the field of international trade on the relative efficiency of different forms of trade barriers. A key question in this literature is the relative efficiency of tariffs versus quota protection.[1] As in the public economics literature, while tariff and quotas are perfect substitutes under perfect competition they can have differing impacts under imperfect competition (see Bhagwati (1965) and Bhagwati (1968)). More recent contributions to this literature analyze trade policy instruments under different forms of competition (e.g., see Jorgensen and Schröder (2005)) as well as various market frictions (e.g., see Matschke (2003) and Herander (2005)).

The common thread in both the international trade literature and the public economics literature is that the relative efficiency of different governmental policies is almost uniformly analyzed in static models. However, it seems that another way different tax/trade policy instruments could differ is in their respective dynamic effects on firm productivity. Specifically, a key question addressed in this paper is how different governmental policies can impact firm productivity through affecting that rate at which firms adopt new technologies. In this sense, this paper is closely related to that of Miyagiwa and

[1] An analogous question concerns the relative efficiency of specific vs. ad valorem tariffs (for a review see Helpman and Krugman (1989).

Ohno (1995) which investigates the effect of different trade barriers on technology adoption.[2] However, Miyagiwa and Ohno (1995) investigates the adoption decisions of a single import-competing domestic firm engaged in Cournot competition with foreign exporters. In their model, the non-equivalence between tariffs and quotas rested on the lack of a strategic effect to technology adoption in the presence of a quota. Intuitively, under a tariff regime one of the benefits of adopting a cost-saving technology is that it reduces the exports of the foreign firm and thus increases home firm profits. This strategic benefit to adoption is absent under a quota regime and thus Miyagiwa and Ohno (1995) concludes that home firms will adopt new technology earlier under tariff protection than under an equivalent quota.

In contrast this paper models the technology adoption decisions of a large number of small firms engaging in monopolistic competition and thus the strategic effects of Miyagiwa and Ohno (1995) do not arise.[3] Rather, our paper focuses on governmental policies that have a specific (per-unit) impact on marginal costs versus policies that have an ad valorem (percentage) impact. Specifically, we show that in a dynamic model of technology diffusion a specific tax acts as an impediment to the adoption of cost-saving technology improvements since it has a disproportionately negative impact on high-productivity firms as their relative price advantage is reduced.

The intuition for this result parallels that of the classic Alchian-Allen conjecture that specific transportation costs will lead firms to export high-quality goods abroad since per-unit transportation costs lower the relative price of high quality goods. This logic is central to the literature on how quotas can lead to an increase in the average quality of imports by impacting the endogneous quality choices of both consumers and firms (e.g, see Falvey (1979), Krishna (1987) and Krishna (1990)). As we show in this paper, it also has important implications for the decision of whether to adopt a cost-saving technological improvement.[4] In our model, per-unit taxes raise the relative price of high-tech, low marginal cost firms in foreign markets, thus impeding the desire of firms to adopt new cost-saving innovations within a dynamic framework.

As an application of this result we consider the non-equivalence of tariff and quota protection within a dynamic setting of endogenous technology adoption. A primary component of recent GATT/WTO negotiations has been the promotion of tariffication (i.e., the conversion of non-tariff barriers such as quotas to ad-valorem tariffs). Indeed one of the central achievements of the Uruaguay Round was the widespread conversion, in the

[2]Also see Crowley (2006).

[3]Another difference is that Miyagiwa and Ohno (1995) examine a model where both firms produce solely for the home market, while in our model, firms produce for both the home and foreign markets.

[4]The applicability of this result became apparent in the 1980's with the voluntary export restraint applied to Japanese auto exports by the United States. Several studies have noted that in response to this quota, Japanese auto firms shifted toward higher quality models (e.g., see Feenstra (1988)).

agricultural sector, of quantitative import restriction and other forms of protection into equivalent ad-valorem trade barriers. As was mentioned before, in standard static models of perfect competition, tariffs and quotas are perfect substitutes and thus tariffication has no impact on the overall efficiency of the trade regime. Indeed, the main justification for tariffication in WTO agreements is the increased transparency that ad-valorem customs duties provide (thus facilitating future negotiations). In this model, we show that quotas also tend to decrease the speed of technology diffusion (relative to ad-valorem tariff barriers) since they have a disproportionately negative impact on high-productivity firms. This result has the policy-relevant implication that tariffication, in addition to increasing the visibility of trade protection, can also lead to faster technology adoption world-wide..

In the following analysis, Section 2 lays out the model of technology adoption and solves for the equilibrium rate of diffusion of a new technology within a closed economy. It demonstrates that, while ad-valorem taxes have a neutral impact on technology adoption, specific taxes will impede the adoption of new cost-saving technologies. In Section 3, this model is extended to an open-economy to investigate the impact of trade policy on technological progress. Finally, Section 4 concludes.

# 2 Model

To study the effects of trade barriers on cost-minimizing technological improvements, we must specify the process by which firms endogenously choose to adopt new technologies. Here we employ a standard game-theoretic model of technology adoption in a closed economy initially proposed by Reinganum (1981) and Fudenberg and Tirole (1985) and extended to a monopolistically competitive environment by Götz (1999) in which decision to adopt is a function of both rank effects (i.e., differences in the return to adoption) and stock effects (i.e., the number of firms that have already adopted the new technology). This framework has the advantage of fitting the empirical evidence on technology adoption in that the cost-saving technological innovation will only gradually diffuse through the industry.[5]

## 2.1 Demand

We assume the presence of two sectors: one sector consists of a numeraire good, $x_0$, while the other sector is characterized by differentiated products. The preferences of a representative consumer are defined by the following intertemporal utility function:

$$U = \int_0^\infty (x_0(t) + logC(t))e^{-rt}dt \tag{1}$$

[5]For a survey of the empirical evidence see Karshenas and Stoneman (1995).

where $x_0(t)$ is consumption of a numeraire good in time $t$ and $C(t)$ represents an index of consumption of the differentiated product good. For $C(t)$ we adopt the Dixit-Stiglitz (1977) specification which reflects tastes for variety in consumption and also imposes a constant (and equal) elasticity of substitution between every pair of goods:

$$C(t) = \left[ \int_0^n y(z,t)^\rho dz \right]^{1/\rho} \tag{2}$$

where $y(z,t)$ represents consumption of brand $z$ at time $t$ and $n$ represents the number of available varieties. It is straightforward to show that, with these preferences, the elasticity of substitution between any two products is $\sigma = 1/(1-\rho) > 1$ and aggregated demand for good $i$ at any point in time is given by:

$$y(i,t) = \frac{p(i,t)^{-\sigma} E}{\int_0^n p(z,t)^{1-\sigma} dz} \tag{3}$$

where $p(i,t)$ is the price of good $i$ in time $t$ and $E$ represents the total number of consumers in the economy.

## 2.2 Production

All goods are produced using constant returns to scale technologies and a single factor of production, labor. Thus, production of any good (or brand) requires a certain amount of labor per unit of output. For simplicity, we assume that production of the numeraire good is defined by $l = x_0$ which ensures that the equilibrium wage is equal to unity.

We assume that varieties of the differentiated good can be produced using either of two types of technology. A low-productivity technology is always available to any firm and is purchased for $F$ upon entering the industry. Production using the low-productivity technology is defined by $l(t) = y(t)$. A high-productivity technology is also available at time $t = 0$, but requires an additional fee of $X(t)$ where $X' < 0$, $X'' > 0$, $X(0) = \infty$, $X(\infty) = 0$. Note that $X(t)$ is defined in present value terms. With this adoption cost function, earlier adoption is more expensive, however, the decreasing costs of technology adoption implies that eventually all firms will adopt the high-tech process. Production using the high-productivity technology is defined by $l(t) = y(t)/\varphi$, where $\varphi > 1$.

## 2.3 Government Policy

The Dixit-Stiglitz preferences result in profit-maximizing firms using a simple mark-up pricing rule for given marginal costs. We assume that the government can impose either specific (per-unit) or ad valorem (percentage) taxes on firm output. On the assumption that government imposes ad-valorem tax of $\tau$, the prices set by the low-tech firms and high-tech firms respectively are:

$$p_L = \frac{\sigma}{(\sigma-1)} \frac{1}{(1-\tau)} \quad , \quad p_H = \frac{\sigma}{\varphi(\sigma-1)} \frac{1}{(1-\tau)} \tag{4}$$

Let $[0, nq]$ be the range of firms that have adopted the high-productivity technology, where $q$ is between 0 and 1 and represents the fraction of firms that have already adopted at a point in time. Then the price index is given by:

$$\int_0^n p(i,t)^{1-\sigma} dz = (\frac{\sigma}{\sigma-1})^{1-\sigma}[q\varphi^{\sigma-1} + (1-q)]n(1-\tau)^{\sigma-1} \tag{5}$$

Substituting (5) and (4) into the profit functions, one derives that profits for high-tech and low-tech firms, when the government imposes an ad-valorem tax of $\tau$, are given respectively by:

$$\pi_H = \frac{\varphi^{\sigma-1}(1-\tau)}{q\varphi^{\sigma-1} + (1-q)} \frac{E}{n\sigma} \quad , \quad \pi_L = \frac{(1-\tau)}{q\varphi^{\sigma-1} + (1-q)} \frac{E}{n\sigma} \tag{6}$$

Alternatively, the government could impose a specific (per-unit) tax of $\lambda$, in which case prices are given by:

$$p_L = \frac{\sigma}{\sigma-1}(1+\lambda) \quad , \quad p_H = \frac{\sigma}{\sigma-1}(\frac{1}{\varphi} + \lambda) \tag{7}$$

It should be noted that, unlike ad valorem taxation, specific taxation affects the relative price of high-technology versus low-technology firms. In particular, as the specific tax increases the relative price of the two firms tends toward unity (i.e., the high-technology firms lose their relative price advantage). With specific taxes, the price index is given by:

$$\int_0^n p(i,t)^{1-\sigma} dz = (\frac{\sigma}{\sigma-1})^{1-\sigma}[(q(\frac{1}{\varphi}+\lambda)^{1-\sigma} + (1-q)(1+\lambda)^{1-\sigma})]n \tag{8}$$

Substituting (8) and (7) into the profit functions, one derives that profits for high-tech and low-tech firms, when the government imposes a specific tax of $\lambda$, are given respectively by:

$$\begin{aligned} \pi_H &= \frac{(\frac{1}{\varphi}+\lambda)^{1-\sigma}}{[(q(\frac{1}{\varphi}+\lambda)^{1-\sigma} + (1-q)(1+\lambda)^{1-\sigma})]} \frac{E}{n\sigma} \\ \pi_L &= \frac{(1+\lambda)^{1-\sigma}}{[(q(\frac{1}{\varphi}+\lambda)^{1-\sigma} + (1-q)(1+\lambda)^{1-\sigma})]} \frac{E}{n\sigma} \end{aligned} \tag{9}$$

### 2.4 Adoption Decision

The equilibrium distribution of technologies, $q(t)$, is determined by the firm's selection of their optimal adoption dates. A firm chooses the adoption date, $T$, to maximize the discounted value of total profits:

$$\Pi = \int_0^T e^{-rt}\pi_L(q(t))dt + \int_T^\infty e^{-rt}\pi_H(q(t))dt - X(T) - F$$

As can be seen, these profits depend on both the firm's own adoption date, $T$, and the adoption decisions of rival firms (which is summarized by the distribution function $q(t)$). Differentiating with respect to $T$ yields the first-order condition:

$$e^{-rT}\left[\pi_H(q(T)) - \pi_L(q(T))\right] = -X'(T) \tag{10}$$

The above first-order condition demonstrates the tradeoff faced by firms in the choice of when to adopt. The left-hand side term is the gain in profits from adopting the high productivity technology while the right-hand side term is the decrease in adoption costs from delaying adoption another period. Note that the profit differential $(\pi_H - \pi_L)$ is decreasing as the number of firms producing with the high-tech production process $(q)$ increases. This is because adoption by rival firms reduces the market share of other firms and, thus, the gain to adopting a cost-saving innovation. It is this property of the model that leads to the gradual diffusion of the new technology through the industry as firms must trade off the increased operating profits from early adoption against the lower adoption costs of later adoption. By substituting the derived profit differential into the above first-order condition, one can solve for $q(t)^*$, the equilibrium distribution function. Note that in equilibrium firms will be indifferent between any adoption date that satisfies this condition.

## 2.5 Present Value of Profits

The model can be closed by solving for the equilibrium number of firms in the industry, $n$. Given perfect foresight, firms will enter the industry until the present value of profits are equal to zero. Since the present value of profits is the same for every firm, it is arbitrary which profit function is used to identify $n$. The following calculation is done for a firm that adopts in time $T_H$. The present value of profits for such a firm is given by:

$$\begin{aligned}\Pi^* = &\int_0^{T_L} e^{-rt}\pi_L(q=0)dt + \int_{T_L}^{T_H} e^{-rt}\pi_L(q(t))dt \\ &+ \int_{T_H}^{\infty} e^{-rt}\pi_H(q=1)dt - X(T_H) - F\end{aligned}$$

Since entry occurs until the present value of profits is equal to zero, this zero-profit condition, along with $q(t)^*$ characterizes the closed economy equilibrium.

## 2.6 Technology Adoption with Ad-Valorem Taxes

The main question of interest in this section is how the equilibrium rate of technology adoption compares in an ad-valorem tax regime relative to a specific tax regime. In the analysis that follows, we will first solve for the equilibrium rate of adoption under an ad-valorem tax of $\tau$.

Substituting the derived profit differential given by (6) into the first-order condition, (10), yields:

$$e^{-rT}(\varphi^{\sigma-1} - 1)\frac{(1-\tau)}{q\varphi^{\sigma-1} + (1-q)}\frac{E}{n\sigma} = X'(T) \tag{11}$$

Solving for $q(t)$ then gives the equilibrium distribution function:

$$q^*(t) = \begin{cases} 0 & \text{for } t \in [0, T_L) \\ \frac{-e^{-rt}E(1-\tau)}{X'(t)n\sigma} - \frac{1}{\varphi^{\sigma-1}-1} & \text{for } t \in [T_L, T_H] \\ 1 & \text{for } t \in [T_H, \infty] \end{cases} \tag{12}$$

The above function describes the diffusion of the new production process through the industry when the government imposes an ad-valorem tax of $\tau$. Since adoption costs are initially very high, no firm will adopt earlier than $T_L$. However, as adoption costs fall, more firms adopt the new technology so that all firms will have adopted the new technology after $T_H$. Finally, for $T_L \leq t \leq T_H$ there exists a mix of low-tech and high-tech firms in equilibrium, and the distribution of firms is defined by $q^*(t)$. Taking the partial of $q^*(t)$with respect to $\tau$ gives:

$$\frac{\partial q^*(t)}{\partial \tau} = \frac{e^{-rt}E}{X'(t)n\sigma} < 0 \text{ for } T_L \leq t \leq T_H \tag{13}$$

As can be seen, holding the number of firms constant, the imposition of an ad-valorem tax on production will reduce $q^*(t)$, the equilibrium rate of adoption. Specifically, since a production tax reduces firm profits/output it reduces the incentive to adopt new cost-saving technologies (since the fixed adoption cost is spread over a reduced output). However, the imposition of a production tax will also impact $n$, the equilibrium number of firms in the market, by reducing the present value of profits. As we show in the following proposition, when the number of firms is endogenously determined, an ad-valorem production tax will not impact the equilibrium rate of adoption.

**PROPOSITION 1** *Ad-valorem taxes will have no effect on the speed of technology diffusion (i.e., both the time of first adoption, $T_L$, and the time of last adoption, $T_H$, will remain unchanged).*
*Proof: See Appendix*

The lack of an impact on technology diffusion is due to the fact that ad-valorem taxation ensures a constant relative price for high-tech versus low-tech firms. This neutrality of ad valorem taxation on relative prices implies that such taxes only effect profit differentials (and thus the incentive to adopt new technologies) through their impact on firm size. However, when entry/exit is endogenous, the zero profit condition results in a constant firm size and thus an overall neutrality of ad valorem taxation on technology adoption. It should be noted that the complete neutrality of ad-valorem taxation also derives from the assumption of a constant elasticity of demand (which ensures that prices are a constant mark-up over marginal cost irrespective of market conditions). Thus, Proposition 1 does not necessarily generalize to other assumptions about the structure of demand, however it serves as a useful benchmark to compare the *relative* effects of ad-valorem taxes and specific taxes.

### 2.7 Technology Adoption with Specific Taxes

We next turn our attention to the equilibrium rate of adoption under a specific tax of $\lambda$. Substituting the derived profit differential with specific taxes into the first-order condition (10) yields:

$$e^{-rT}\frac{(\frac{1}{\varphi}+\lambda)^{1-\sigma}-(1+\lambda)^{1-\sigma}}{[(\frac{1}{\varphi}+\lambda)^{1-\sigma}-(1+\lambda)^{1-\sigma}]q+(1+\lambda)^{1-\sigma}}\frac{E}{n\sigma}=X'(T) \tag{14}$$

Solving for $q(t)$ then gives the equilibrium distribution function:

$$q^*(t)=\begin{cases} 0 & \text{for } t\in[0,T_L) \\ \frac{-e^{-rt}E}{X'(t)n\sigma}-\frac{(1+\lambda)^{1-\sigma}}{[(\frac{1}{\varphi}+\lambda)^{1-\sigma}-(1+\lambda)^{1-\sigma}]} & \text{for } t\in[T_L,T_H] \\ 1 & \text{for } t\in[T_H,\infty] \end{cases} \tag{15}$$

The above function describes the diffusion of the new production process through the industry when the government imposes an ad-valorem tax of $\lambda$. As before, gradual adoption begins at $T_L$ and continues until all firms have adopted the high-productivity technology by $T_H$. Taking the partial of $q^*(t)$with respect to $\lambda$ gives:

$$\frac{\partial q^*(t)}{\partial\lambda}|_{\lambda=0}=\frac{(1-\sigma)[\varphi^{\sigma}-\varphi^{\sigma-1}]}{(1-\varphi^{\sigma-1})^2}<0 \text{ for } T_L\le t\le T_H \tag{16}$$

Thus, as with an ad-valorem production tax, the imposition of a specific tax reduces the equilibrium rate of diffusion. However, a specific tax also indirectly impacts $q^*(t)$ through endogenous entry and exit decisions. As we show in the following proposition, even allowing $n$ to be endogenous, the overall impact of a specific tax is a reduction in the equilibrium rate of adoption (in the sense that both $T_L$ and $T_H$ are delayed).

**PROPOSITION 2** *Specific taxes will delay technology adoption (i.e., both $T_H$ and $T_L$ will occur later).*
*Proof: See Appendix.*

The reason that specific taxes delay technology adoption while ad-valorem taxes have a neutral impact is direct. With ad-valorem taxes the relative prices of the two types of firms are unchanged. In contrast, specific (per-unit) taxes change the relative prices of the differentiated good in favor of the low technology (high cost) firms. Since per-unit taxes reduce the price advantage of high-tech firms, they reduce the profit differential and, thus, the incentive to adopt new cost-saving technology. Thus, even when the number of firms is endogenous (i.e., the zero profit condition is satisfied), per-unit taxation will serve as a drag on technology adoption.

# 3 Tariffication

The basic lesson of the previous section is that governmental regulations that have a specific (per-unit) impact on firm costs can reduce incentives to adopt new cost-saving technologies because they reduce the competitive advantage of low-cost firms. In this section, we apply this lesson to a current issue in international trade. Specifically, the issue of tariffication (i.e., the conversion of quotas and other non-tariff barriers into ad-valorem tariffs).

## 3.1 Open-Economy Model

This model of technology adoption has been previously extended to an open economy by Ederington and McCalman (2004) and here we use a simplified version of that model to investigate the differing effects of tariffs versus quotas on the rate of technology adoption. In this section, we investigate reciprocal trade between two symmetric countries. As is typical in monopolistic competition models of trade, we assume ice-berg transport costs where $b > 1$ units of a good need to be shipped for one unit to arrive. Thus, while each firm's pricing rule in its domestic market is the same as before, firms will set higher prices in the foreign markets to reflect the higher marginal cost of serving those markets. These ice-berg transport costs can reflect a combination of standard shipping costs as well as any ad-valorem tariff barriers. Thus, prices set in the domestic market are defined by:

$$p_L = \frac{\sigma}{\sigma - 1} \;,\; p_H = \frac{\sigma}{\varphi(\sigma - 1)} \tag{17}$$

Likewise prices set in the foreign market are given by:

$$p'_L = \frac{\sigma b}{\sigma - 1} \quad,\quad p'_H = \frac{\sigma b}{\varphi(\sigma - 1)} \tag{18}$$

Define $b_h$ as the total shipping costs (freight costs plus any ad-valorem tariff barriers) of exporting to the home country and $b_f$ as the total shipping costs of exporting to the foreign country. Then the operating profits for home firms from serving both the domestic and foreign market are given by:

$$\begin{aligned}
\pi_L(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz} + \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}b_f^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz} \\
\pi_H(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}\varphi^{\sigma-1}E}{\sigma\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz} + \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}\varphi^{\sigma-1}b_f^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz}
\end{aligned} \tag{19}$$

while the price index in the home country is given by:

$$\begin{aligned}
&\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz = \\
&\quad (\frac{\sigma}{\sigma-1})^{1-\sigma}[(q\varphi^{\sigma-1} + (1-q))n + (q_f\varphi^{\sigma-1}b_h^{1-\sigma} + (1-q_f))n_f b_h^{1-\sigma}]
\end{aligned} \tag{20}$$

and the price index in the foreign country is given by:

$$\int_0^{n+n_f} p_f(i,t)^{1-\sigma} dz = \qquad (21)$$
$$(\frac{\sigma}{\sigma-1})^{1-\sigma}[(q_f\varphi^{\sigma-1}+(1-q_f))n_f+(q\varphi^{\sigma-1}b_f^{1-\sigma}+(1-q))nb_f^{1-\sigma}]$$

As in the closed economy case, governmental policy can impact the rate of technology adoption through influencing the above profit differential.

### 3.2 Ad-Valorem Tariffs and Technology Adoption

First, consider the case where the home country imposes a unilateral tariff on imports from the foreign country (i.e., an increase in $b_h$). The direct impact of such a tariff will be to increase the market-share of home firms while decreasing the market-share of foreign firms. Thus, one would expect a unilateral tariff to increase the rate of adoption in the home country, while delaying adoption in the foreign country. However, countering these direct effects is the fact that a home tariff will endogenously increase the number of home firms while decreasing the number of foreign firms. As we show in the following two propositions, the imposition of a ad-valorem tariff by the home country will not impact the adoption decisions of either home or foreign firms.

**PROPOSITION 3** *The unilateral imposition of an ad-valorem tariff by the home country will have no effect on the speed of technology diffusion by domestic firms (i.e., holding foreign adoption constant, an increase in $b_h$ will not impact either $T_L$ or $T_H$)*
*Proof: See Appendix*

**PROPOSITION 4** *The unilateral imposition of an ad-valorem tariff by the home country will have no effect on the speed of technology diffusion by foreign firms (i.e., holding home adoption constant, an increase in $b_h$ will not impact either $T_L$ or $T_H$ for the foreign country)*
*Proof: See Appendix*

Propositions 3 and 4 are once again a result of the ad-valorem nature of our tariff which ensures that the relative price of high-tech versus low-tech firms is unchanged in both the foreign and domestic markets. Thus, an ad-valorem tariff can only impact technology adoption through influencing the overall size of the firm. However, when entry/exit decisions are endogenous, an ad-valorem tariff will not impact the adoption decisions of either home or foreign firms. Given that a unilateral tariff doesn't impact technology diffusion, one would intuitively expect a similar result for the reciprocal imposition of import tariffs by both the home and foreign country (i.e., $b_h = b_f > 0$). As we derive below, this intuition is correct.

Substituting (21) and (22) into the profit functions and analyzing at the symmetric equilibrium, one derives that profits for high-tech and low-tech firms (when both the home and foreign countries impose reciprocal tariffs) are given respectively by:

$$\pi_H = \frac{\varphi^{\sigma-1}}{q\varphi^{\sigma-1} + (1-q)}\frac{E}{n\sigma} \quad , \quad \pi_L = \frac{1}{q\varphi^{\sigma-1} + (1-q)}\frac{E}{n\sigma} \tag{22}$$

Note that reciprocal ad-valorem tariffs do not impact the profit functions (and thus do not impact the equilibrium rate of technology diffusion). This result is due to the act that, in a symmetric model of trade, the increase in domestic market share generated by the domestic tariff is countered by the loss of foreign market share due to the foreign tariff. Thus, we can state the following proposition:

**PROPOSITION 5** *The reciprocal imposition of ad-valorem tariffs by both the home and foreign country will have no effect on the speed of technology diffusion.*

Once again, we do not claim that Proposition 5 is a complete description of the effects of tariffs on the diffusion of new technologies.[6] However, it serves as a useful benchmark to compare the *relative* effects of ad-valorem tariffs to quotas.

### 3.3 Binding Quotas and Relative Prices

This section examines the effects import quotas imposed at time $t = 0$ on the speed of technology adoption. Assume that, in time $t$, firm $i$ is allocated $Q(i,t)$ number of quota licenses. Note that while the profit-maximizing price for the firm in its domestic market is still given by (17), the profit-maximizing price for the firm in the foreign market satisfies the following constrained maximization:

$$max[p(i,t) - c(i,t)]y(i,t) + \lambda_{i,t}[Q(i,t) - y(i,t)] \tag{23}$$

where $c(i,t)$ is the marginal cost of good $i$ in year $t$ and $\lambda_{i,t}$ represents the shadow cost of the quota constraint (i.e., the extra profit that would be generated by relaxing the quota constraint one unit). Assuming that this quota is binding, from the first-order condition of the above maximization one can derive that prices in the foreign market for low-tech and high-tech firms respectively are:

$$p^F_{L,t} = \frac{\sigma}{\sigma-1}(b + \lambda_{L,t}) \quad , \quad p^F_{H,t} = \frac{\sigma}{(\sigma-1)}(\frac{1}{b\varphi} + \lambda_{H,t}) \tag{24}$$

[6] Indeed, in Ederington and McCalman (2004) we provide a model in which the imposition of ad-valorem tariffs can effect the rate of technology adoption.

Thus, the introduction of an import quota (or a voluntary export restraint) acts in the same way as a *specific* price increase, not like a proportional price increase. To discuss the full implications of a quota regime on the diffusion of new technologies we must make some assumptions about the allocation of quota licenses. First, we will assume that a perfectly competitive market for quota licenses exists in which the licenses can be traded.[7] Second, note that as the technological innovation diffuses through the industry, average firm sales increase and, thus, the shadow price of the quota increases. For expositional simplicity we assume that the overall number of quota licenses are adjusted over time so that the marginal impact of the quota on prices remains constant.[8] Under these assumptions, the price of a quota license (and thus the shadow price of the quota constraint) will be equalized over all firms over time (i.e., $\lambda_{L,t} = \lambda_{H,t} = \lambda$). Thus (24) becomes:

$$p_L^F = \frac{\sigma}{\sigma - 1}(1 + \lambda) \quad , \quad p_H^F = \frac{\sigma}{(\sigma - 1)}(\frac{1}{\varphi} + \lambda) \tag{25}$$

Note that the presence of a binding quota affects the relative price of high-technology versus low-technology firms in the foreign market. Specifically, as the quota increases, the relative price of the two firms tends toward unity (i.e., the high-technology firms lose their relative price advantage overseas). It should be apparent that this reduction in the price advantage for high-technology firms will have a disproportionately negative impact on their overseas operating profits. We analyze the implications of this result in the following two sections when first we look at the unilateral imposition of a quota and then we look at the reciprocal imposition of a quota.

## 3.4 Unilateral Quotas and Technology Adoption

In this section we consider the case where only the home country imposes a quota on foreign imports. Thus, prices of domestic firms are unchanged, and defined by (17), while prices of foreign firms in the domestic market are defined by (24). Given iceberg transport costs of $b$, the profits for a home firm are defined by (20). However, now the price index in the home country is given by:

$$\int_0^{n+n_f} p_h(i,t)^{1-\sigma} dz = \tag{26}$$
$$(\frac{\sigma}{\sigma-1})^{1-\sigma}[(q\varphi^{\sigma-1} + (1-q))n + (q_f\frac{b}{\varphi} + \lambda)^{\sigma-1} + (1-q_f)(b+\lambda)^{1-\sigma})n_f]$$

[7] This assumption has no impact on the base results of the paper that quotas tend to reduce the speed of technology adoption. As we show in the appendix, the rate of technology adoption is reduced even further when quota licenses are symmetrically distributed to firms and cannot be transferred.

[8] Once again, this assumption has no impact on the base results of the paper. Indeed, in Proposition 6 we show that, despite the fact that the quota is being relaxed over the diffusion phase so that the shadow price remains constant, the marginal impact of that quota is actually increasing over time.

while the price index in the foreign country is given by:

$$\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz = \quad (27)$$
$$(\frac{\sigma}{\sigma-1})^{1-\sigma}[(q_f\varphi^{\sigma-1}+(1-q_f))n_f+(q(\frac{b}{\varphi})^{1-\sigma}+(1-q)b^{1-\sigma})n]$$

Note that a unilateral quota by the home country will impact home firms by increasing the prices of their foreign competitiors (and thus will increase the domestic market share of home firms). However, as always, given endogenous entry/exit decisions, such a change in market share will result in corresponding changes in the number of home (and foreign) firms. As we show in the following proposition, a unilateral quota, while it delays the date of initial adoption, will increase the rate of diffusion so that the final adoption date occurs earlier:

**PROPOSITION 6** *Holding foreign adoption dates constant, the unilateral imposition of a quota by the home country results in the initial adoption by home firms occurring later (i.e., $T_L$ occurs later), but the last adoption occurring earlier (i.e., $T_H$ occurs earlier).*
*Proof: See Appendix.*

Proposition 6 simply reflects the fact that, even if the marginal cost of the quota is constant over time, the overall impact of the quota is increasing over the diffusion phase. Specifically, since a quota has an increased impact on high productivity firms (as it reduces their cost advantage overseas), it has a greater protectionist impact at the end of the diffusion phase (when foreign firms are high-tech) than at the beginning of the diffusion phase (when foreign firms are low-tech). As a result, it will reduce incentives to adopt at the beginning of the diffusion phase, while increasing incentives to adopt at the end of diffusion.

The second question of interest is how the unilateral imposition of a quota by the home country impacts the technology adoption decisions of foreign firms. Not surprisingly, given the intuition of the model, a quota, which reduces the competitive cost advantage of high-tech firms overseas, will delay the adoption of new technologies by foreign exporting firms:

**PROPOSITION 7** *Holding domestic adoption dates constant, the unilateral imposition of a quota results in delayed adoption by foreign firms (i.e., both $T_L$ and $T_H$ occur later).*
*Proof: See Appendix*

Proposition 7 reflects the fact that, since quotas have an impact equivalent to a per-unit tax on foreign firms, they delay adoption of cost-saving technologies since they benefits of such technology adoption is diminished. In this sense, it is instructive to compare

Propositions 6 and 7 (that concern the impact of a unilateral quota) with Propositions 3 and 4 (that concerns the impact of a unilateral tariff). As can be seen, assuming endogenous entry and exit decisions, governments have no ability to influence the rate of technology adoption by unilaterally imposing ad valorem tariff protection. However, one can influence the rate of technology adoption (by both domestic and foreign firms) by unilaterally imposing a comparable quota. In the next section we consider the case where both countries impose a symmetric quota on imports.

### 3.5 Reciprocal Quotas and Technology Adoption

In this section we consider the case where reciprocal quotas are placed on trade. In such a situation, profit-functions of firms in either country are defined symmetrically. For expositional purposes we will assume the absence of transport costs (i.e., $b = 0$). The symmetric price index in the open economy equilibrium is then given by:

$$\int_0^{n+n_f} p(i,t)^{1-\sigma} dz = \tag{28}$$
$$(\frac{\sigma}{\sigma-1})^{1-\sigma}[(q\varphi^{\sigma-1} + (1-q))n + (q_f\varphi^{\sigma-1}(1+\lambda\varphi)^{1-\sigma} + (1-q_f))n_f(1+\lambda)^{1-\sigma}]$$

Imposing symmetry between the two countries and substituting (29) into the profit functions gives operating profits (from both domestic and foreign markets) as:

$$\begin{aligned}\pi_H &= \frac{\varphi^{\sigma-1}[1+(1+\lambda\varphi)^{1-\sigma}]}{(1+(1+\lambda\varphi)^{1-\sigma}q\varphi^{\sigma-1} + (1-q)(1+(1+\lambda)^{1-\sigma}}\frac{E}{n\sigma} \\ \pi_L &= \frac{[1+(1+\lambda)^{1-\sigma}]}{(1+(1+\lambda\varphi)^{1-\sigma}q\varphi^{\sigma-1} + (1-q)(1+(1+\lambda)^{1-\sigma}}\frac{E}{n\sigma}\end{aligned} \tag{29}$$

Substituting the above profit functions into the first-order condition for the adoption decision and solving for $q(t)$, one derives that:

$$q^*(t) = \begin{cases} 0 & \text{for } t \in [0, T_L) \\ \frac{-e^{-rt}E}{X'(t)n\sigma} - \frac{[1+(1+\lambda)^{1-\sigma}]}{([1+(1+\lambda)^{1-\sigma}]-[1+(1+\lambda\varphi)^{1-\sigma}]\varphi^{\sigma-1}} & \text{for } t \in [T_L, T_H] \\ 1 & \text{for } t \in [T_H, \infty] \end{cases} \tag{30}$$

The question that we are interested in is how this rate of adoption compares to the open economy rate of diffusion with an ad-valorem tariff. First, note that when $\lambda = 0$ the equilibrium rate of diffusion is the same as that in the open economy cases. Taking the partial of $q(t)$with respect to $\lambda$ gives:

$$\frac{\partial q(t)}{\partial \lambda}|_{\lambda=0} = \frac{2(1-\sigma)[\varphi^{\sigma} - \varphi^{\sigma-1}]}{4(1-\varphi^{\sigma-1})^2} < 0 \text{ for } T_L \leq t \leq T_H \tag{31}$$

So holding $n$ constant, a small specific transport cost will decrease the speed of technology adoption below that of the open economy case (i.e., at anytime $T_L \leq t \leq T_H$ a smaller fraction of firms will have adopted the new technology). This implies that the presence of a quota regime will slow down the rate of technology diffusion relative to an ad-valorem tariff regime. The reason for this is simple. Specific transport costs change the relative prices of the differentiated good in favor of the low technology (high cost) firms in the foreign markets, thus reducing the relative profitability of the high technology firms and the incentive to adopt the new technology.

While the preceding analysis assumed that the number of firms in the industry is constant, the imposition of specific transport costs is also likely to have an impact on the number of firms in an industry. Thus, in deriving the complete impact of specific transport costs on the rate of technology adoption, we must also take into account its indirect impact (i.e., how it may affect $q(t)$ indirectly through $n$). However, as we verify in the following proposition, even allowing $n$ to be endogenous, it is still the case that the presence of specific trade barriers reduces the rate of technology adoption.

**PROPOSITION 8** *The reciprocal introduction of a quota will delay the adoption on new cost-saving technologies (i.e., both $T_H$ and $T_L$ will occur later).*

*Proof: See Appendix*

Propositions 5 and 8 have a direct implication for the question of tariffication in international trade agreements. Assume two open economies impose symmetric quotas on each other. The above Propositions imply that a reciprocal trade agreement to convert these quota constraints into equivalent ad-valorem tariff constraints will increase the rate of technology adoption in both countries. Thus, this paper implies that the preference in GATT/WTO negotiations for the conversion on non-tariff barriers into tariff barriers actually has a potential dynamic rationale in that it tends to have a positive effect on the diffusion of new technology.

# 4 Conclusion

This paper has examined the linkage between policy instruments and the speed with which firms adopt a cost-saving innovation. We argue that the form of taxation has important implications for this question. Specifically, while ad-valorem taxation has a neutral effect on technology adoption, specific taxation tends to delay adoption of new technologies. This is due to the fact that specific taxes, by raising the relative price of high-technology firms, reduce the gains to adopting a cost-saving innovation and delays the transition to a new technology.

As we argue in this paper, this result has implications, not only for domestic policy, but also for trade policy. Specifically, since a quota constraint has effects similar to a specific price increase, the imposition of quota protection will also tend to delay the adoption of new, superior technologies. This result has important policy implications since it implies that the conversion of current non-tariff barriers into equivalent ad-valorem tariffs (i.e., tariffication) will have a positive impact on the worldwide diffusion of new technology.

# 5 Appendix

## 5.1 Non-transferable Quota Licenses

In this section we analyze the effects of a quota regime under the assumption that $\overline{Q}$ quota licenses are distributed to each firm and these quota licenses are non-transferable. In that case, assuming the quota binds, each firm sells $\overline{Q} = \frac{p(i,t)^{-\sigma}E}{\int_0^n p(i,t)^{1-\sigma}dz}$ units in the foreign country. From (24) this implies that in each period:

$$1 + \lambda_L = \frac{1}{\varphi} + \lambda_H \tag{32}$$

Note that (32) implies that symmetric allocated quota licenses impose greater costs on high-tech firms than they do on low-tech firms (i.e., $\lambda_H > \lambda_L$). Basically, in this framework, quotas act as a conditional tariff, where the trade tax is increased on those firms which choose to adopt the new technology. Thus, a non-transferable quota results in an even greater delay in adoption than a transferable quota (since firms which adopt the cost-saving technology cannot purchase additional licenses from the low-tech firms). Intuitively this result is is not surprising as the main benefit of adopting a productivity-improving technology is that one can sell a greater volume of goods at a lower price (i.e., a scale effect). Thus, quantity constraints (such as a quota) which prevent the expropriation of these scale effects by firms tend to deter the adoption of such technologies in a dynamic setting.

## 5.2 Proof of Proposition 1

The zero-profit condition is defined by:

$$\Pi = \Pi_1 + \Pi_2 + \Pi_3 - F = 0 \tag{33}$$

where $\Pi_1 = \int_0^{T_L} e^{-rt}\pi_L(q=0)dt$; $\Pi_2 = \int_{T_L}^{T_H} e^{-rt}\pi_L(q(t))dt - X(T_L)$, and $\Pi_3 = \int_{T_H}^{\infty} e^{-rt}\pi_H(q=1)dt$.

Totally differentiating (33) and applying the envelope theorem, one derives that:

$$\frac{d\Pi}{d\tau} = 0 = \frac{d\Pi_1}{d\tau} + \frac{d\Pi_2}{d\tau} + \frac{d\Pi_3}{d\tau} \tag{34}$$

First, from the profit conditions, (6), one derives that the profit differential is given by:

$$\pi_H(q) - \pi_L(q) = (\varphi^{\sigma-1} - 1)\pi_L(q) \tag{35}$$

Thus, during the diffusion phase, the first-order condition, (10) fixes low-tech profits at:

$$\pi_L(q^*) = \frac{1}{\varphi^{\sigma-1} - 1}\frac{-X'(T)}{e^{-rT}} \tag{36}$$

Which implies that:

$$\Pi_2 = \frac{1}{\varphi^{\sigma-1}-1}[X(T_L) - X(T_H)] - X(T_H) \tag{37}$$

Note that profits during the diffusion phase are completely independent of $\tau$ or $n$ (i.e., $\frac{d\Pi_2}{d\tau} = 0$). Since $\pi_H(q=1) = \pi_L(q=0)$, $\Pi_1$ and $\Pi_3$ are proportional and, from (34):

$$\frac{d\Pi_1}{d\tau} = \frac{d\Pi_3}{d\tau} = 0 \tag{38}$$

Finally, note that $\frac{d\Pi_1}{d\tau} = 0$ implies that $\frac{d\pi_L(q=0)}{d\tau} = 0$ as $\Pi_1 = A[\pi_L(q=0)]$ where $A = [1 - e^{-rT_L}]/r$. Thus, from (35) $\frac{d\pi_H(q=0)-\pi_L(q=0)}{d\tau} = 0$. Since ad-valorem taxes have no impact on the profit differential at $q = 0$, it will have no impact on the timing of $T_L$. The fact that ad valorem tariffs do not effect $T_H$ is similarly established. Q.E.D.

## 5.3 Proof of Proposition 2

From the profit conditions, (9), one derives that the profit differential is given by:

$$\pi_H(q) - \pi_L(q) = \frac{[(\frac{1}{\varphi}+\lambda)^{1-\sigma} - (1+\lambda)^{1-\sigma}]}{(1+\lambda)^{1-\sigma}}\pi_L(q) \tag{39}$$

As before, the first-order condition, (10) fixes low-tech profits during the diffusion phase at:

$$\pi_L(q^*) = \frac{(1+\lambda)^{1-\sigma}}{[(\frac{1}{\varphi}+\lambda)^{1-\sigma} - (1+\lambda)^{1-\sigma}]}\frac{-X'(t)}{e^{-rt}} \tag{40}$$

and thus,

$$\Pi_2 = \frac{(1+\lambda)^{1-\sigma}}{[(\frac{1}{\varphi}+\lambda)^{1-\sigma} - (1+\lambda)^{1-\sigma}]}[X(T_L) - X(T_H)] - X(T_H) \tag{41}$$

By direct calculation, one derives that $\frac{d\Pi_2}{d\lambda}|_{\lambda=0} > 0$, and thus, from (34):

$$\frac{d\Pi_1}{d\lambda} + \frac{d\Pi_3}{d\lambda} < 0 \tag{42}$$

Finally, $\frac{d(\Pi_1+\Pi_3)}{d\lambda} < 0$ implies that $\frac{d\pi_L(q=0)}{d\lambda}|_{\lambda=0} < 0$ as $\Pi_1 + \Pi_3 = A[\pi_L(q=0)]$ where $A = [1 - e^{-rT_L} + e^{-rT_H}]/r$. Thus, from (39), $\frac{d\pi_H(q=0)-\pi_L(q=0)}{d\lambda}|_{\lambda=0} < 0$. Since a specific tax (an increase in $\lambda$) will decrease the profit differential at $q = 0$, the diffusion phase will be delayed (i.e., $T_L$ will occur later). Similar calculations show that $T_H$ will occur later as well. Q.E.D.

## 5.4 Proof of Proposition 3

From the profit conditions, (20), one derives that the profit differential, for a home firm, is given by:

$$\pi_H(q) - \pi_L(q) = (\varphi^{\sigma-1} - 1)\pi_L(q) \tag{43}$$

Holding foreign adoption dates constant and applying the envelope condition, one can derive (34). Thus, the remainder of the proof is equivalent to that of Proposition 1. Q.E.D.

## 5.5 Proof of Proposition 4

Profits for a foreign firm, given a home tariff of $b_h$, are given by:

$$\begin{aligned}
\pi_L(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} b_h^{1-\sigma} E}{\sigma \int_0^{n+n_f} p_h(i,t)^{1-\sigma} dz} + \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} E}{\sigma \int_0^{n+n_f} p_f(i,t)^{1-\sigma} dz} \\
\pi_H(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} \varphi^{\sigma-1} b_h^{1-\sigma} E}{\sigma \int_0^{n+n_f} p_h(i,t)^{1-\sigma} dz} + \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} \varphi^{\sigma-1} E}{\sigma \int_0^{n+n_f} p_f(i,t)^{1-\sigma} dz}
\end{aligned} \tag{44}$$

From the above, the profit differential for a foreign firm, is given by:

$$\pi_H(q) - \pi_L(q) = (\varphi^{\sigma-1} - 1)\pi_L(q) \tag{45}$$

Holding home adoption dates constant and applying the envelope condition, one can derive (34). Thus, the remainder of the proof is equivalent to that of Proposition 1. Q.E.D.

## 5.6 Proof of Proposition 6

From the profit conditions, (20), one derives that the profit differential is given by:

$$\pi_H(q) - \pi_L(q) = (\varphi^{\sigma-1} - 1)\pi_L(q) \tag{46}$$

Holding foreign adoption dates constant and applying the envelope condition, one can derive (34). Thus, by similar calculations to the proof of Proposition 1, profits during the diffusion phase are completely independent of $\lambda$ (i.e., $\frac{d\Pi_2}{d\lambda}|_{\lambda=0} = 0$). However, given the presence of a quota, $\pi_H(q = 1) > \pi_L(q = 0)$ for home firms, and thus $\Pi_1$ is not porportional to $\Pi_3$. Since $\frac{d\pi_H(q=1)}{d\lambda}|_{\lambda=0} > \frac{d\pi_L(q=0)}{d\lambda}|_{\lambda=0}$, from (34) it must be the case that:

$$\frac{d\Pi_1}{d\lambda} < 0 \quad and \quad \frac{d\Pi_3}{d\lambda} > 0 \tag{47}$$

Finally, $\frac{d\Pi_1}{d\lambda} < 0$ implies that $\frac{d\pi_L(q=0)}{d\lambda}|_{\lambda=0} < 0$ as $\Pi_1 = A[\pi_L(q = 0)]$ where $A = [1 - e^{-rT_L}/r$. Thus, from (39), $\frac{d\pi_H(q=0)-\pi_L(q=0)}{d\lambda}|_{\lambda=0} < 0$. Since a specific tax (an increase in $\lambda$) will decrease the profit differential at $q = 0$, the diffusion phase will be delayed (i.e., $T_L$ will occur later). Similar calculations show that, since $\frac{d\Pi_3}{d\lambda} > 0$, $T_H$ will occur earlier. Q.E.D.

## 5.7 Proof of Proposition 7

Profits for a foreign firm in both the foreign country market, $\pi^f$, and the home country market, $\pi^h$ are given by:

$$\pi^h_L(t) = \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}(b_h+\lambda)^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz} \;,\; \pi^h_L(t) = \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz}$$
$$\pi^h_H(t) = \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}\varphi^{\sigma-1}(b_h+\lambda\varphi)^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz} \;,\; \pi^f_H(t) = \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}\varphi^{\sigma-1}E}{\sigma\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz} \tag{48}$$

From the above, the profit differential for a foreign firm, is given by:

$$\pi_H(q)-\pi_L(q) = (\varphi^{\sigma-1}-1)\pi^f_L(q) + \frac{\varphi^{\sigma-1}(b_h+\lambda\varphi)^{1-\sigma}-(b_h+\lambda)^{1-\sigma}}{(b_h+\lambda)^{1-\sigma}}\pi^h_L(q) \tag{49}$$

Note that, from the first-order condition, $\frac{d\pi_H(q)-\pi_L(q)}{d\lambda}=0$, during the diffusion phase. Thus, from (49), one can derive that $\frac{d\pi_L(q)}{d\lambda}|_{\lambda=0}>0$ during diffusion which implies that $\frac{d\Pi_2)}{d\lambda}|_{\lambda=0}>0$. Holding home adoption dates constant and applying the envelope condition, one can derive (34) and thus:

$$\frac{d\Pi_1}{d\lambda}+\frac{d\Pi_3}{d\lambda}<0 \tag{50}$$

Given the presence of a quota, $\pi_H(q=1)<\pi_L(q=0)$ for foreign firms, and thus $\Pi_1$ is not porportional to $\Pi_3$. Since $\frac{d\pi_H(q=1)}{d\lambda}|_{\lambda=0} < \frac{d\pi_L(q=0)}{d\lambda}|_{\lambda=0}$, from (50) it must be the case that $\frac{d\Pi_3}{d\lambda}<0$ which implies that $\frac{d\pi_H(q=1)}{d\lambda}|_{\lambda=0}<0$. Thus, from (49), one can derive that $\frac{d\pi_H(q=1)-\pi_L(q=1)}{d\lambda}|_{\lambda=0}<0$ which implies that $T_H$ occurs later. Finally, using (49) and the fact that $\frac{d\pi_H(q=1)}{d\lambda}|_{\lambda=0}<0$, one can derive that $\frac{d\pi_H(q=0)-\pi_L(q=0)}{d\lambda}|_{\lambda=0}<0$ which implies that $T_L$ occurs later as well. Q.E.D.

## 5.8 Proof of Proposition 8

First, from the profit conditions, (29), one derives that the profit differential is given by:

$$\pi_H(q)-\pi_L(q) = \frac{\varphi^{\sigma-1}[1+(b+\lambda\varphi)^{1-\sigma}]}{(1+(b+\lambda)^{1-\sigma}}\pi_L(q) \tag{51}$$

Thus, during the diffusion phase, the first-order condition fixes low-tech profits at:

$$\pi_L(q) = \frac{(1+(b+\lambda)^{1-\sigma}}{\varphi^{\sigma-1}[1+(b+\lambda\varphi)^{1-\sigma}]-[(1+(b+\lambda)^{1-\sigma}]}\frac{-X'(T)}{e^{-rT}} \tag{52}$$

Which implies that:

$$\Pi_2 = \frac{(1+(b+\lambda)^{1-\sigma}}{\varphi^{\sigma-1}[1+(b+\lambda\varphi)^{1-\sigma}]-[(1+(b+\lambda)^{1-\sigma}]}[X(T_L)-X(T_H)]-X(T_H) \tag{53}$$

From the above it is direct to derive that $\frac{d\Pi_2}{d\lambda}|_{\lambda=0} > 0$. Since $\Pi_1$ and $\Pi_3$ are proportional, from (34), one derives that $\frac{d\Pi_1}{d\lambda} < 0$ and $\frac{d\Pi_3}{d\lambda} < 0$.

Finally, note that $\frac{d\Pi_1}{d\lambda} = 0$ implies that $\frac{d\pi_L(q=0)}{d\lambda}|_{\lambda=0} = 0$ as $\Pi_1 = A[\pi_L(q=0)]$ where $A = [1 - e^{-rT_L}]/r$. Thus, from (51), one can derive that $\frac{d\pi_H(q=0)-\pi_L(q=0)}{d\lambda}|_{\lambda=0} < 0$ which implies that $T_L$ occurs later. Similar calculations show that, since $\frac{d\Pi_3}{d\lambda} < 0$, $T_H$ will occur later as well. Q.E.D.

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