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R&D Technology Choice in Durable Goods Monopoly*

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Abstract This paper examines a durable-good monopolist's R&D decision in new product development. We show that the monopolist without commitment faces a time inconsistency problem concerning the choice of research technology, and as a result ends up choosing a safer research project and investing less than the commitment solution. This implies more frequent but smaller quality improvements in durable-good markets. It is shown that the time inconsistency problem in fact serves to increase social welfare by inducing the firm to choose a socially optimal research project.

Keywords durable-goods monopoly, R&D technology, planned obsolescence

JEL Classification D42, L12, L15

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1. INTRODUCTION

Everyday we observe that firms develop and introduce new products. Product innovation is one of the main forces of economic development and growth. For instance, Nobel laureate Robert Solow has estimated in his famous 1957 study that about 80 percent of the increase in gross output per worker-hour from 1909 to 1949 in the United States could be attributed to technological change. In modern economies, most of new product developments are carried out by private firms, and their incentives for R&D investment are governed by a market mechanism. So, it is important to ensure that firms develop new products of the right quality and at the right time in the viewpoint of the firms and policy makers.

In fact, there have been numerous studies on technological innovation and research and development in various disciplines, let alone economics. However, most of these studies have been focused on perishables in static environments, and research on durables has been received relatively little attention.[1] This is maybe because it is rather difficult to analyze pricing mechanism and R&D incentives for a durable good. In spite of these difficulties, however, it is very important to understand firms' R&D incentives in durable goods markets, given that many new products we observe in reality are durable goods such as Apple iPhone and Microsoft Windows 8.

There is a time-inconsistency problem in durable goods markets as noted by Coase in his seminal 1972 article. It occurs because in a dynamic setting a firm's optimal decision at a given time is not optimal anymore at the other time. For instance, the price of a durable good decreases as time passes and this erodes the monopolist's profit because durable goods sold in the future affect the future value of units sold today, and in the absence of the ability to commit, the monopolist does not internalize this externality.[2] In fact, almost all decision-makings of a durable-goods monopolist without commitment to her future behaviors are subject to this kind of time-inconsistency problem, and the R&D decision is not an exception.[3]

There have been some early works on time inconsistency problems related to R&D decisions in durable-goods monopolies. Waldman (1996) shows that a durable-good monopolist invests more in R&D than its commitment optimal level because the firm in choosing its R&D investment does not internalize the negative externality the new product exerts on the future value of the old product.

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[1]See Reinganum (1989) for more detail.

[2]It has been proved formally by Bulow (1982) and others.

[3]See Waldman (2003) for an excellent survey on the economic theory on durable goods markets.

Note that, however, when the buyer type is continuous the time-inconsistency problem related to R&D investment may disappear, as shown by Nahm (2004). In another study, Waldman (1993) showed that in a market with network externalities the monopolist's incentive to adopt the new incompatible technology is too much compared with the optimal commitment level due to a similar time-inconsistency problem. In a related work, Choi (1994) has studied a similar issue focusing on the price discrimination aspect and compatibility choice between new and old technologies. Ellison and Fudenberg (2000) analyzed a monopolist's incentive to introduce an upgrade in the software market with network externalities. Focusing on the case of one way backward compatibility from the new version to the old version, they suggested two reasons why the firm has socially excessive upgrade incentives, based on the firm's lack of commitment and consumer heterogeneity. Also, Fudenberg and Tirole (1998) analyze a firm's marketing strategies such as tradeins and buybacks in a similar durable-good monopoly setup. On the other hand, focusing on the product differentiation rather than new product introduction Hahn (2006) showed that a durable-good monopolist may wish to downgrade the original version in order to evade the time-inconsistency problem, and also may delays the introduction of the damaged low-end version.

This paper aims to offer a new perspective on a durable-good monopolist's R&D decision. In particular, we consider a situation where the R&D technology is modelled as a risky project and the monopolist chooses one from a menu of research projects with different levels of risk.[4] The success probability of a research project decreases with the degree of quality improvement. We assume that there is a fully operative secondary market for used goods, so resale values are explicitly considered in our analysis. In this respect, our model extends the analysis of Waldman (1996) to a setup with endogenous quality improvement and risky R&Ds.

Our main finding is that the monopolist without commitment to future R&D decisions tends to choose a safer research project compared with the commitment monopolist. This is because the firm does not take into account the negative externality the introduction of the new improved quality has on total profits when choosing its research project. If the R&D cost increases with the degree of quality improvement, this result also means that the monopolist facing the time

[4] In this respect, our analysis is also related to the literature on the choice of R&D technologies in the race for a patent race. Notably, Dasgupta and Maskin (1987) and Klette and de Meza (1986) have shown that firms choose excessively risky R&D technologies due to a winner-take-all nature of patent races. In these models, however, goods are nondurables and so there are no time inconsistency problems.

inconsistency problem has smaller incentive to invest in R&D than the commitment monopolist. This is in contrast with the result obtained in the previous works, where the firm has too much incentive to invest in R&D or accept a new incompatible technology due to time inconsistency problems.

2. THE MODEL

Consider a market for durable goods where a monopolist produces outputs lasting two periods. In the first period, the monopolist produces goods of quality Q_0. At the beginning of the second period, the monopolist has the opportunity to improve on the existing quality Q_0 by investing in R&D. The R&D technology is modelled as a risky project. Specifically, the monopolist, if she decides to invest, can choose one from a menu of research projects indexed by $Q_\Delta \in [0,\infty)$. Here Q_Δ represents the degree of quality improvement the monopolist can achieve by investing in R&D. The project Q_Δ either succeeds with probability $p(Q_\Delta)$ in which case the monopolist can produces outputs of quality Q_0+Q_Δ in the second period, or fails with probability $1-p(Q_\Delta)$ in which case there is no quality improvement. We assume that $p(\cdot)$ is twice differentiable, and that $p'(\cdot)<0$, $p''(\cdot)\geq 0$, $p(0)=1$ and $\lim_{Q_\Delta\to\infty} p(Q_\Delta)=0$. The cost of R&D, which increases with the degree of quality improvement Q_Δ, is given by $R(Q_\Delta)$, where $R'(\cdot)>0$, $R''(\cdot)>0$ and $R(0)=0$. So, the larger the targeted quality improvement is the smaller the success probability is and the greater its R&D cost is.[5] The constant marginal cost of producing output of quality Q is given by $c(Q)=c\frac{Q}{Q_0}$ for $Q\in[Q_0,Q_0+Q_\Delta]$, where $c>0$. There is no fixed costs of production.

On the demand side, there are two groups of consumers, denoted l and h, where each consumer lives two periods. Group i consists of a continuum of non-atomic consumers of mass n_i, $i=l,h$. Consumers have unit demands in each period. A representative consumer in group i derives a gross benefit v_iQ per period from the consumption of a unit of quality Q, where $v_h>v_l>0$. The consumer type is private information, i.e. in each period the monopolist offers all consumers the same price for a unit of output of the same quality. The values of all the other parameters, including those concerning the R&D technology, are common knowledge. Finally, we assume that the monopolist and all consumers

[5] In this way, we implicitly assume that a risky technology involves smaller success probability as well as larger investment costs. We believe this is a quite plausible in many real-world R&D environments. Even if we allow for the success probability increasing in the amount of R&D investment, qualitative results would not change provided the effect of the amount of R&D investment is weak and so the success probability is dominated by the technology choice.

are risk neutral and have the common discount factor $\delta \in (0,1]$.

The timing of moves in the game is as follows. In period 1, the monopolist announces the price for a unit of the pre-innovation product of quality Q_0, and then all consumers simultaneously decide whether to buy a unit or not. Period 2 consists of four stages. First, at the beginning of the second period the monopolist decides whether to invest in R&D and, if she decides to invest, chooses one from the menu of research projects. Second, the R&D outcome is realized and observed by all the agents. The monopolist announces the price for a unit of quality $Q_0 + Q_\Delta$ if the R&D investment is made and it is successful, while she announces the price for a unit of quality Q_0 if she does not invest in R&D or if the chosen research project has failed. Third, all consumers decide whether to purchase from the monopolist. Fourth, a secondhand market opens up where prices equate supply and demand. We look for a subgame-perfect Nash equilibrium in this game.

To focus on the time-inconsistency problem related to R&D technology choice, we assume the following restrictions on parameters:

A1) $v_l(1+\delta)Q_0 < c$

A2) $v_h Q_0 > c$

A3) $n_l > n_h$

Under assumption A1, it is guaranteed that the monopolist never has an incentive to sell a new unit of output to group l consumers.[6] This assumption, as in Waldman (1996), allows us to rule out the standard Coasian time inconsistency problem concerning the quantity (or price) of output produced in the future and focus on a time inconsistency problem related to the monopolist's R&D decisions (investment and research project choice) in the second-period. Assumption A2 is sufficient to guarantee that the monopolist wishes to sell units of quality Q_0 to group h consumers in the first period. Further we assume that the discount factor is sufficiently small so that the monopolist prefers selling units of quality Q_0 to group h consumers in period 1 rather than waiting and selling units of quality $Q_0 + Q_\Delta$ to group h consumers in period 2 when the R&D is suc-

[6] A1 means that the gross utility a group l consumer derives from consuming a unit of quality Q_0 in both periods is less than the marginal cost. Note that A1 implies that $v_l Q_0 < c$, i.e. it is not profitable to sell a unit of quality Q_0 to group l consumers in period 2. Also, note that A1 implies that $v_l(Q_0 + Q_\Delta) < c\frac{Q_0+Q_\Delta}{Q_0}$, i.e. the monopolist never sells a unit of quality $Q_0 + Q_\Delta$ to group l consumers in period 2.

cessful.[7] Finally, assumption A3 guarantees that if a secondhand market forms in the second period, the price on the market will be positive. As will be shown later, the presence of secondhand market plays a crucial role in the analysis.

3. ANALYSIS

To begin with, we describe some preliminary results regarding the monopolist's equilibrium behavior, which will be useful for the proceeding analysis.

Lemma 1. *Under the parameter restrictions given by the above assumptions, the following results hold regardless of the monopolist's commitment power.*

i) If the monopolist invests in R&D, she never chooses $Q_\Delta < Q_\Delta^*$, where Q_Δ^* is given by $v_h Q_\Delta^* + v_l Q_0 - c(1 + \frac{Q_\Delta^*}{Q_0}) = 0$.

ii) If $Q_\Delta = 0$ in equilibrium (no investment in R&D), the monopolist sells units of quality Q_0 to group h consumers at the price $(1+\delta)v_h Q_0$ in period 1 and sells nothing in period 2.

iii) If $Q_\Delta \geq Q_\Delta^*$ in equilibrium (positive investment in R&D), the monopolist sells units of quality Q_0 to group h consumers at the price $v_h Q_0 + \delta[p(Q_\Delta)v_l + (1-p(Q_\Delta))v_h]Q_0$ in period 1. In period 2, if the research project is unsuccessful the monopolist sells nothing, and if the research project is successful the monopolist sell units of quality $Q_0 + Q_\Delta$ to group h consumers at the price $v_h Q_\Delta + v_l Q_0$, and group h consumers sell low-quality units to group l consumers at the price $v_l Q_0$ at the secondhand market.

Proof. See Appendix. □

The monopolist's second period behavior depends on the result of R&D investment. It sells nothing in period 2 if either no investment or unsuccessful R&D. However, if the R&D investment is successful, then it sells the improved quality to group *h* consumers in period 2, and the old units change hands in the secondhand market. Here group *h* consumers' willingness-to-pay for the high quality in period 2 is constrained by the incremental value of quality ($v_h Q_\Delta$) plus the secondhand market value of the old unit ($v_l Q_0$).

Note that the price the monopolist charges in period 1 for the low quality units is lower the higher is the success probability of R&D investment, i.e. the safer is the R&D technology. The reason is that by selling new high-quality

[7] A sufficient condition to guarantee this is $(v_h + \delta v_l)Q_0 - c > \delta(v_h - \frac{c}{Q_0})(Q_0 + Q_\Delta)$, which means that a lower bound on the profit from selling units of quality Q_0 to a group *h* consumer in period 1 is greater than the upper bound of the profit from selling units of quality $Q_0 + Q_\Delta$ to a group *h* consumer in period 2.

units in period 2 the monopolist lowers the value of owning an old low-quality unit in period 2, since type h consumers in the process of upgrading to the high quality have to sell a unit of low quality in the secondhand market at the lower price $v_l Q_0$ than their own consumption valuation $v_h Q_0$. Rationally expecting this, consumers are willing to pay less for a unit of low quality in period 1, and thereby the monopolist has to reduce the first-period price of the low quality by $-\delta p(Q_\Delta)(v_h - v_l)Q_0$.

COMMITMENT EQUILIBRIUM:

Let us first consider the case where the monopolist can commit in the first period to its second-period R&D choice. Suppose the monopolist committed to investing in research project $Q_\Delta \in (Q_\Delta^*, \infty)$ before announcing its first-period price. If the R&D project is successful the monopolist wishes to sell new units of quality $Q_0 + Q_\Delta$ to group h consumers in the second period, and if the project is unsuccessful the firm will sell nothing in period 2 (see Lemma 1 above). Then the monopolist's total discounted profit is given by

$$\begin{aligned}\Pi^C(Q_\Delta) &\equiv n_h\{v_h Q_0 + \delta[p(Q_\Delta)v_l + (1-p(Q_\Delta))v_h]Q_0 - c\} \\ &\quad + \delta n_h p(Q_\Delta)[v_h Q_\Delta + v_l Q_0 - c(1+\tfrac{Q_\Delta}{Q_0})] - \delta R(Q_\Delta) \\ &= \Pi^{NI} + \delta n_h p(Q_\Delta)[v_h Q_\Delta - (v_h - v_l)Q_0 + v_l Q_0 - c(1+\tfrac{Q_\Delta}{Q_0})] \\ &\quad - \delta R(Q_\Delta),\end{aligned}$$

where $\Pi^{NI} = n_h\{(1+\delta)v_h Q_0 - c\}$ is the maximum profit the monopolist can obtain without R&D investments.

The monopolist's decision problem can be written as

$$\max_{Q_\Delta} : \delta n_h p(Q_\Delta)[v_h Q_\Delta - (v_h - v_l)Q_0 + v_l Q_0 - c(1+\tfrac{Q_\Delta}{Q_0})] - \delta R(Q_\Delta)$$

Here we assume that the objective function is concave in Q_Δ and the problem has an interior solution.[8] Then the optimal commitment choice of research project Q_Δ^C is given by the first-order condition:

$$\begin{aligned} n_h p'(Q_\Delta^C)[v_h Q_\Delta^C - (v_h - v_l)Q_0 + v_l Q_0 - c(1+\tfrac{Q_\Delta^C}{Q_0})] \\ + n_h p(Q_\Delta^C)(v_h - \tfrac{c}{Q_0}) - R'(Q_\Delta^C) = 0. \end{aligned} \tag{1}$$

[8] A sufficient condition for the concavity is that $n_h p''(Q_\Delta)[v_h Q_\Delta + (v_l - v_h)Q_0 + v_l Q_0 - c(1+\frac{Q_\Delta}{Q_0})] + 2n_h p'(Q_\Delta)(v_h - \frac{c}{Q_0}) - R''(Q_\Delta^C) < 0$ for all $Q_\Delta \in (Q_\Delta^*, \infty)$, which is satisfied when $p''(Q_\Delta)$ is sufficiently small. The problem has an interior solution if $n_h p'(Q_\Delta^*)(v_l - v_h)Q_0 + n_h p(Q_\Delta^*)(v_h - \frac{c}{Q_0}) - R'(Q_\Delta^*) > 0$, i.e. the R&D cost function increases slowly.

An important point to note is that the commitment monopolist, in choosing the type of research project Q_Δ, takes into account the negative effect the sales of high-quality units in period 2 (which occurs with probability $p(Q_\Delta)$) has on the period-1 price of old units and total profits.

NON-COMMITMENT EQUILIBRIUM:

Let us now consider the case where the monopolist cannot commit in period 1 to its R&D choice in period 2. At the beginning of the second period the monopolist decides whether to invest in R&D and which research project to choose to maximize expected second-period profits. Suppose the monopolist invests in R&D and chooses research project $Q_\Delta \in (Q_\Delta^*, \infty)$. As before, if the R&D is successful the monopolist sells new units of quality $Q_0 + Q_\Delta$ to group h consumers in the second period, and if it fails the firm sells nothing in period 2.

Then the problem faced by the monopolist is given by

$$\max_{Q_\Delta} : n_h p(Q_\Delta)[v_h Q_\Delta + v_l Q_0 - c(1 + \tfrac{Q_\Delta}{Q_0})] - R(Q_\Delta). \tag{2}$$

Similar to the commitment case, we assume that the objective function is concave and the problem has an interior solution. Then the optimal non-commitment choice of research project Q_Δ^{NC} is given by the first-order condition:

$$n_h p'(Q_\Delta^{NC})[v_h Q_\Delta^{NC} + v_l Q_0 - c(1 + \tfrac{Q_\Delta^{NC}}{Q_0})] + n_h p(Q_\Delta^{NC})(v_h - \tfrac{c}{Q_0}) - R'(Q_\Delta^{NC}) = 0. \tag{3}$$

Then, the following result is immediate from the comparison of two conditions (1) and (3) and the convexity of R&D cost function $R(\cdot)$.

Proposition 1. *Without commitment to future R&D, the monopolist chooses a safer research project and invests less than the commitment monopolist ($Q_\Delta^{NC} < Q_\Delta^C$ and $R(Q_\Delta^{NC}) < R(Q_\Delta^C)$).*

Recall that the introduction of the new product of higher quality inflicts a negative externality on the monopolist's profit since it reduces the second-period value of old units. Note that in the present setup the more likely is the introduction of new product the safer the research project is. The commitment monopolist tends to choose a risky research project in order to internalize this negative externality on its profit, while the non-commitment monopolist not taking into account this negative effect ends up choosing a safe research project.

Here the monopolist faces a time inconsistency problem concerning the choice of R&D technology. The reason is that by choosing a safer research project the monopolist lowers a consumer's expected value for a low-quality unit and this reduces the first-period willingness-to-pay for the low quality. However, this change in the expected value of owning a unit of low quality is not reflected in the second-period profitability of the firm.

So, we can expect that in a durable-goods monopoly without commitment quality improvement tends to be more frequent but smaller than the case of commitment. Given that the R&D cost increases with the degree of quality increment, this result implies that the monopolist without commitment invest less in R&D compared with a commitment monopolist, which is in contrast with Waldman (1996).

SOCIAL OPTIMUM:

Now we consider the problem of a social planner whose objective is to choose a research project in order to maximize social welfare. We look for a second best solution where the planner cannot control any other aspect of the firm's behavior except the R&D decision. The welfare gain from R&D investment is realized when the research project is successful. Lemma 1 says that when the R&D is successful group h consumers upgrade to high-quality units in period 2, and group l consumers consume low-quality units. Then, the problem faced by the social planner is given by

$$\max_{Q_\Delta} : n_h p(Q_\Delta)[v_h Q_\Delta + v_l Q_0 - c(1 + \tfrac{Q_\Delta}{Q_0})] - R(Q_\Delta),$$

which is simply the sum of the expected net surpluses of two groups of consumers from quality improvement less the corresponding R&D cost. With successful R&D, group h consumers gains only the incremental utility from quality improvement and group l consumers purchase a unit of low quality in the secondhand market. Note that the objective function is identical to the one faced by the non-commitment monopolist. Then the solution must be the same as well, and the socially optimal choice of research project Q_Δ^S is given by the first-order condition:

$$n_h p'(Q_\Delta^S)[v_h Q_\Delta^S + v_l Q_0 - c(1 + \tfrac{Q_\Delta^S}{Q_0})] + n_h p(Q_\Delta^S)(v_h - \tfrac{c}{Q_0}) - R'(Q_\Delta^S) = 0, \quad (4)$$

which is exactly the same as (3).

The socially optimal level of quality improvement (i.e. the choice of R&D technology) is determined at the level where the marginal increase in the gross benefit of consuming across the two groups due to the sale of high-quality units is equal to the marginal cost of R&D investment. Then, the following Corollary is immediate from the result in Proposition 1.

Corollary 1. *The monopolist in the absence of commitment chooses the socially optimal research project and R&D investment, while it chooses socially too risky a research project and invests too much in R&D with commitment power.*

The presence of commitment is socially harmful since it allows the monopolist to internalize the negative externality R&D investment has on the future value of old units, so not fully reflecting the whole benefit from the R&D investment. The time inconsistency problem that decreases the monopolist's incentive to take risk serves to increase social welfare by reducing its R&D investment.

The following example illustrates the time inconsistency problem faced by a monopolist without commitment power and how it responds to the problem in terms of the choice of research technology and the R&D investment decision. It verifies that the monopolist without commitment chooses a safer research project and invests less than the commitment solution.

Example 1. *Suppose that* $v_h = 4$, $v_l = 1, n_l = 2, n_h = 1, Q_0 = 1, c = 2, \delta = 1/4$,

$$p(Q_\Delta) = \begin{cases} -\frac{1}{2}Q_\Delta + 1 & \text{for } Q_\Delta \in [0,2] \\ 0 & \text{for } Q_\Delta \in (2,\infty) \end{cases},$$

and

$$R(Q_\Delta) = \frac{1}{2}(Q_\Delta)^2$$

for $Q_\Delta \in [0,2]$.

R&D decision of the commitment monopolist:

$$\begin{aligned} \max_{Q_\Delta} \quad &: \quad n_h p(Q_\Delta)[v_h Q_\Delta - (v_h - v_l)Q_0 + v_l Q_0 - c(1 + \frac{Q_\Delta}{Q_0})] - R(Q_\Delta) \\ &= \quad -\frac{3}{2}Q_\Delta^2 + 4Q_\Delta - 4 \end{aligned}$$

The solutions are $Q_\Delta^C = \frac{4}{3}, p(Q_\Delta^C) = \frac{1}{3}$, *and* $R(Q_\Delta^C) = \frac{8}{9}$.

R&D decision of the non-commitment monopolist:

$$\begin{aligned} \max_{Q_\Delta} \quad &: \quad n_h p(Q_\Delta)[v_h Q_\Delta + v_l Q_0 - c(1 + \frac{Q_\Delta}{Q_0})] - R(Q_\Delta) \\ &= \quad -\frac{3}{2}Q_\Delta^2 + \frac{5}{2}Q_\Delta - 1 \end{aligned}$$

The solutions are $Q_\Delta^{NC} = \frac{5}{6}, p(Q_\Delta^{NC}) = \frac{7}{12}$, *and* $R(Q_\Delta^{NC}) = \frac{25}{72}$.

4. CONCLUSION

In this paper, we looked at how time inconsistency problems affect a durable-good monopolist's R&D incentives when the nature of R&D investment is the choice from a menu of research projects with different levels of risk. It has been shown that the monopolist without commitment chooses a safer research project and invests less than the commitment monopoly case. This result implies more frequent but gradual product innovations in durable good markets. In fact, it is the frequency of new product introduction rather than the amount of R&D investment which affects the time inconsistency problem regarding a durable-good monopolist's R&D decisions. We also found that the lack of commitment power is in fact socially beneficial.

The above conclusion has been reached under several simplifying assumptions, an so it would be important to check the robustness of the main result in other situations. In particular, the present model is based on two discrete types of consumers, which greatly simplifies the analysis since the second-period price of old units is simply the low type's willingness-to-pay in the secondhand market, independently of the extent of quality improvement. If the model is extended to the case of a continuum of consumer types, the analysis would become much more complicated since the monopolist's second-period optimal strategy would show different patterns (e.g. net sales or buybacks) depending on the magnitude of quality innovation, as shown by Fudenberg and Tirole (1988) and Nahm (2004). It would be interesting to see whether our result obtained under two types of consumers still holds under this set up. We leave this important task as a future work.

5. APPENDIX

i) The profit from selling output of quality $Q_0 + Q_\Delta$ to group h consumers in period 2 is given by $\pi(Q_0 + Q_\Delta) = v_h Q_\Delta + v_l Q_0 - c(1 + \frac{Q_\Delta}{Q_0})$. Note that $\pi(\cdot)$ is increasing in Q_Δ and $\lim_{Q_\Delta \to 0} \pi(Q_0 + Q_\Delta) = v_l Q_0 - c < 0$ by A1, so there exists a cut-off value Q_Δ^* such that $\pi(Q_0 + Q_\Delta^*) = 0$.

ii) Recall that our analysis is restricted to cases where the monopolist sells units of quality Q_0 to group h consumers in the first period, and does not sell new units to group l consumers in either period. Given this, if $Q_\Delta = 0$ (no R&D investment) the firm will not sell new units to group h consumers in the second period. Then, given that group h consumers rationally expect that no sales will take place in the second period, in period 1 the firm will be able to charge each group h consumer the gross benefit from consuming a unit of quality Q_0 for two periods, which equals $(1+\delta)v_h Q_0$.

iii) Now suppose $Q_\Delta \geq Q_\Delta^*$ (positive R&D investment). If the R&D investment is unsuccessful, then the monopolist will not sell new units to either group of consumers in the second period. If the R&D investment is successful, the firm must sell new units to group h consumers in the second period, given that the analysis is restricted to parameterizations such that the monopolist will not sell a new unit to a group l consumer in the second period. Further, given Assumption A3, this means that in period 2 group h consumers will sell old units to group l consumers at a price $v_l Q_0$. Then, the price the firm can charge for new units in period 2 is $v_h Q_\Delta + v_l Q_0$. Group h consumers in the first period will anticipate that in the second period with probability $1 - p(Q_\Delta)$ they will consume the quality Q_0 and with probability $p(Q_\Delta)$ they will sell the units of quality Q_0 for the price $v_l Q_0$. So, they will be willing to pay $v_h Q_0 + \delta[p(Q_\Delta)v_l + (1-p(Q_\Delta))v_h]Q_0$ for a unit of quality Q_0 in the first period.

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