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Abstract

In network industries, we often observe frequent upgrades of existing products as well as delayed introductions of new products. In order to explain these contrasting phenomena, this paper examines a durable-good monopolist's incentive for R&D investment in new product development in a market with network effects. We show that if the network effect is strong the monopolist underinvests in R&D compared to the commitment level, whereas overinvestment occurs when the network effect is weak. The monopolist also chooses full intergenerational compatibility between products. We then extend the analysis to the cases of potential entry and successive innovations, and examine how the results change in these extensions.

JEL Classifications L12, L15, M21.

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1 Introduction

The past decades have seen the introduction of successive generations of innovative products in the computer, telecommunications, and consumer electronics industries, such as smart phones, game consoles and audio/visual equipment, in a relatively short period of time. New products have been often developed by firms with significant market power, and the business strategy to produce new products replacing old ones too often came to be known as 'planned obsolescence.' On the other hand, in some other markets especially computer software or video games new products are often released after a long delay or released with little improvement over existing products. Such products are labelled as 'vaporware,' and the term has been used in a wide range of industries by the press. Economists have typically analyzed one of these two issues at a time. That is, in the former case manufacturers bring out new products too often whereas in the latter case product developments are too slow or insufficient. The traditional view is that vaporware are strategic preannouncements vis-à-vis competitors although there is little conclusive evidence to support this claim.[1]

The purpose of this paper is to show that these two phenomena (i.e., over- and under-investments in R&D) can be explained in a coherent framework. To be more specific, we focus on the interplay between the time-inconsistency problem and network effects in determining the firm's R&D investment and intergenerational compatibility decisions. In contrast to some of the papers in the literature on network compatibility (e.g., Katz and Shapiro 1986,

[1] For instance, the Untied States Government first accused Microsoft in 1994 of anti-competitive licensing practicess, where the district judge focused on the allegation that Microsoft engaged in vaporware. Judge Sporkin refused to approve a consent decree that did not address vaporware allegations whereas Microsoft explained that it preannounces products because software vendors need such early notification to begin developing compatible applications software. The review was dismissed for lack of proof.

1992), we endogenize the monopolist's decision on new product introduction through R&D investments and the compatibility choices between the new and the old products. Also, in our model there is a fully operative secondary market for used goods, so resale values are explicitly considered in our analysis. A similar approach has been taken by Waldman (1996) in a model without network effects. In this respect, our model extends the analysis of Waldman to a market with network effects and endogenous compatibility choices. Later we enrich our base model by considering extensions to the introduction of a potential entrant and sequential innovations.

Our main finding is that the monopolist generally prefers full compatibility between the new and the old products, and it may underinvest in new product R&D relative to the commitment level if the network effect is sufficiently strong. With network externalities, the introduction of a new product induces low-valuation buyers to purchase old units via the secondary market at a higher price, and this increases the high-valuation buyers' surplus from the secondary market trade under full compatibility. However, the firm does not take into account this positive externalities once old units are sold. If this effect outweighs the standard overinvestment tendency (see, e.g., Waldman 1996), then the monopolist's overall R&D incentive becomes smaller than the commitment solution. We also show that the monopolist's decisions are socially optimal in this setting. On the other hand, if the secondary market is eliminated (due to, say, excess supply or other technological measures), then the monopolist invests less than the social optimum, even though the non-commitment level of R&D investment would be always larger than the profit-maximizing (commitment) solution.

We then extend our analysis in two ways. In our first extension, we consider the effect of potential entry on the behavior of the incumbent monopolist. The entrant and the monopolist can both invest in new product development, where the R&D success probabilities are symmetric and the entrant's product is incompatible with the monopolist's. We show that there exists a range of moderate network intensity where the underinvestment result continues to hold. Further, the monopolist underinvests and the potential entrant overinvests relative to the socially optimum level. In our second extension, we introduce two successive R&D opportunities for the monopolist, where the first innovation is required to undertake the second. Here we show that a similar conclusion holds for both the first and the second R&D investments. That is, as long as the high-valuation consumers exploit network benefits via the secondary market trade, the monopoly may underinvest in R&D relative to the commitment solution for sufficiently strong network intensity; however, the underinvestment incentive is weaker for the first R&D.

The outline for the paper is as follows. Section 2 discusses the relevant literatures. Section 3 sets forth our basic model. Section 4 analyzes the monopolist's compatibility and R&D decisions. Section 5 extends the analysis to the cases of potential entry and sequential innovation. Sections 6 contains concluding remarks. All formal proofs can be found in the Appendix.

2 Related Literature

There are broadly two types of literature on research and development. One is regarding perishable goods (see, e.g., Reinganum 1989 for a survey), while the other is concerned with durable goods. Understanding R&D incentives in a durable goods market is complicated by the time-inconsistency problem à la Coase (1972). Coase in his seminal article suggested that the monopoly seller has an incentive to introduce new products that make old units obsolete, known as planned obsolescence. Earlier literature focused on the monopolist's durability choice.[2] However, there has been a growing literature concerning the monopolist's incentive to introduce new versions of its products, which may be (in)compatible with the old unit. This paper contributes to this strand of literature by investigating how the monopoly's R&D incentive interacts with network effects.

As mentioned earlier, our analysis is related to Waldman (1996). In a two-period model, Waldman shows that a durable-goods monopolist invests too much in developing a new product relative to the profit-maximizing solution. That is, the monopolist faces a time-inconsistency problem, where the R&D investment that maximizes profits from now onwards does not maximize overall profits. This happens because the firm does not internalize the negative externality the new product exerts on the future value of the old product. In a related study, Nahm (2004) shows that when the buyer type is continuous there is a time-inconsistency problem in the monopolist's R&D decisions when the firm buys back old units in period two. The difference is that in our baseline model we focus on the interaction between the time-inconsistency problem and the intensity of network effects.

Other papers on planned obsolescence in network industries include Waldman (1993), Choi (1994), Ellison and Fudenberg (2000), and Miao (2010). Waldman and Choi focus on the monopolist's incentive to introduce a new product that is incompatible with old units. In particular, Choi finds that the monopolist may want to make the new product compatible

[2] Swan (1970, 1972) famously argued that a monopolist would not distort the optimal level of durability; however, a number of authors demonstrated that Swan's independence result breaks down in various circumstances (see, e.g., Bulow 1982; Liebowitz 1982; Rust 1986). In particular, Grout and Park (2005) and Strausz (2009) showed that planned obsolescence may occur even in competitive markets if some quality attributes are unobservable.

with the old one when it wants to sell only to new consumers. Ellison and Fudenberg show that the monopolist may supply upgrades excessively assuming that the new technology is only backward compatible. Miao (2010) considers the monopolist's incentive to tie a competitively-supplied add-on product that is only backward compatible.[3] In contrast to our paper, all these works assume exogenous technological improvements and find only excessive incentives to adopt new incompatible technologies.

Also related is the literature on the interaction between new product introduction and compatibility choices (see, e.g., Katz and Shapiro 1992; Regibeau and Rockett 1996; Kristiansen 1998). In this literature, two firms decide when to introduce their products, and the rate of technological progress is exogenously given. The paper in this literature closest to our analysis is Regibeau and Rockett, where the new generation of products is introduced later than would be socially optimal if products are perfectly compatible. Our basic argument is similar except that in our model buyers with different valuations could trade in secondary markets and the high-valuation buyers can purchase goods more than once. Also, we allow for intergenerational compatibility controlled by the same firm while these articles focus on the case of compatibility between competing firms.

3 The Model

Consider a two-period model of a durable goods monopolist with secondary market trade, similar to the one proposed by Waldman (1996). In period one, a monopolist produces output

[3] Miao (2011) also showed that with network effects planned obsolescence can alleviate the classical monopoly undersupply problem, and similarly Bond and Samuelson (1987) found that a durable-goods monopolist may spend too much in cost-reducing innovations to exploit the residual demand.

of quality l that lasts two periods. At the beginning of the second period, the monopolist can invest in R&D, where R denotes the amount invested and $p(R)$ is the probability that the R&D is successful. It is assumed that $p(0) = 0$, $p(\infty) < 1$, $p'(0) = \infty$, $p'(R) > 0$ and $p''(R) < 0$ for all $R \geq 0$. Specifically, there is a probability $p(R)$ that output in the second period is of quality h, and a probability $1 - p(R)$ that output in the second period is again of quality l. In addition, the monopolist can decide whether to make the new product compatible with the old product that was sold in period one. We assume that the two quality levels are exogenously given. (However, varying the levels of quality would not change our qualitative results.) The constant marginal cost of production is given by $c > 0$ for both products, and there is no fixed costs other than the R&D investment.

The demand side of the market is characterized by two groups of consumers, denoted 1 and 2, where each consumer lives for two periods. Consumer group i consists of a continuum of non-atomic consumers of mass n_i $(i = 1, 2)$. Consumers demand at most one unit of the good in each period. A representative consumer in group i derives a gross benefit $v_i^k + \alpha N$ per period from the consumption of a unit of quality k $(k = l, h)$, where v_i^k is increasing in quality k and αN measures the network benefit when the total mass of consumers using the same (or compatible) product is N. The parameter α measures the intensity of network effects in a given market.[4] Consumer group 2 comprises early adopters who have a higher valuation than group 1 consumers, so that $v_2^k > v_1^k$ for any $k = l, h$. We assume that in each period the monopolist offers all consumers the same price for a new unit of output.[5] The

[4]The intensity of network effect may depend on the quality of the product; that is, a higher quality product may have a feature that enhances consumer's network benefits. Relaxing this assumption (e.g., $\alpha^h > \alpha^l$) does not change any of our results although it would make the model more realistic.

[5]In contrast to Choi (1994), where the monopolist price discriminates the two consumer groups that differ in the timing of their arrival, in our paper both consumers are present from period one. Thus, if the

structure of the game is common knowledge, and the monopolist and all consumers are risk neutral and have a common discount factor $\delta < 1$.

In period one, the monopolist announces the price for a unit of quality l, and then all consumers simultaneously decide whether to buy the good. In period two, the monopolist decides how much to invest in R&D and whether to make the new product compatible with the old one. The monopolist then announces the price for a unit of quality h if the R&D investment is successful, while it announces the price for a unit of quality l if the innovation fails.[6] Consumers who do not purchase a unit directly from the monopolist may purchase an old unit in a secondary market, where prices are determined by supply and demand. For simplicity, we assume that a used good provides the same flow benefit to consumers as a new unit does without any depreciation. This assumption does not affect any of the qualitative results that follow.

Attention is restricted to parameterizations such that the monopolist never finds it profitable to sell a new product to group 1 consumers.[7] However, Nahm (2004) shows that in Waldman (1996)'s model if the firm wants to sell the old product to the low-type consumers in period two, then the price of the old product is the same whether or not the firm introduces the new product. That is, the new product introduction does not change the price path of the old product compared to the case without the new product. Abstracting from in-

monopolist price discriminates based on the purchase of the old unit, then the high-valuation consumer may delay purchase in order to take advantage of the lower price offered in the second period. That is, under a certain range of parameterization, separating equilibrium cannot exist in our setting; hence, the monopolist would not be able to price discriminate.

[6] A price announcement for a unit of quality l in the second period, when the R&D investment succeeds, does not matter in our model because group 2 consumers have no incentive to delay purchase.

[7] Under this circumstance, the Coase conjecture problem of a durable goods monopolist does not arise. This assumption is made in this literature in order to focus on the time inconsistency problem related to the frequency of new product introduction.

tertemporal price discrimination is further justified in this paper as Mason (2000) has shown that the Coase conjecture fails in its strongest sense with a broad class of network benefit functions. Therefore, we believe the Coase conjecture problem has only weak effect in our analysis.

To make the problem nontrivial, we assume that the monopolist wants to sell units of quality l to group 2 consumers in the first period. When indifferent, consumers are assumed to purchase goods. For the most part of our analysis, we assume that $n_1 > n_2$, which means that the price in the secondary market, when it opens up in the second period, will be positive. (We also consider the case $n_1 < n_2$ at the end of Section 4.) As usual in models with network externalities multiple equilibria may exist. Following the literature (e.g., Katz and Shapiro 1986), we focus on a Pareto optimal symmetric equilibrium.

4 Analysis

We start with the monopolist's R&D and compatibility decisions in the absence of commitment. Suppose first that the monopolist chooses full compatibility for the new product. Because consumers have unit demands, if a group 2 consumer wants to buy the new product, he will sell the old unit in a secondary market, where the equilibrium price for a unit of quality l is given by $v_1^l + 2\alpha n_2$. Note that only n_2 number of consumers in group 1 can purchase an old unit, so the network benefit is proportional to the sum of users in each group $2n_2$. Thus, the monopolist can sell a unit of quality h to group 2 consumers at the price that makes group 2 consumers indifferent between purchasing and not purchasing the new product:

$$p_c^h = (v_2^h - v_2^l + \alpha n_2) + (v_1^l + 2\alpha n_2),$$

where the subscript c refers to the fully compatible case. Notice that the first part in the parenthesis is the incremental value of the new product and the second part is the resale value of an old unit.

Suppose next that the monopolist develops a (only) backward-compatible product. This means that group 2 consumers who purchase the new product would benefit from the increased network size, but the network benefit of group 1 consumers who purchase old units from the secondary market is limited to the size of old network (i.e., αn_2 at most). The secondary market price is thus $v_1^l + \alpha n_2$, and by the same logic as above the monopolist would sell units of quality h to group 2 consumers at a price,

$$p_b^h = (v_2^h - v_2^l + \alpha n_2) + (v_1^l + \alpha n_2),$$

where the subscript b refers to the backward compatible case.

Now suppose the monopolist develops a (only) forward-compatible product in the second period. This happens, for instance, when old units can execute the new standard, but new products does not support the old standard. Buyers of the new product do not benefit from an increased network size, but users of the old product do. In this case, the new product price is given by

$$p_f^h = (v_2^h - v_2^l) + (v_1^l + 2\alpha n_2),$$

where the subscript f refers to the forward compatible case. Notice that the new product price p_f^h is the same as that of the backward compatible product, p_b^h. This is because the aggregate effect of an increased network size and increased resale value is the same in these two cases. (However, this need not hold when the network intensity depends on product quality; see also footnote 5)

The last possibility is that the monopolist develops a new product that is not compatible at all with the old product. It is easy to show that the new product price in this case is given by

$$p_n^h = (v_2^h - v_2^l) + (v_1^l + \alpha n_2),$$

where the subscript n refers to the non-compatible case.

At the beginning of the second period, where the monopolist decides R&D investments, the monopolist's problem is given by

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \pi_j = p(R_j) n_2 \left[p_j^h - c\right] - R_j, \tag{1}$$

where $j \in \{c, b, f, n\}$ denotes the monopolist's compatibility choice.

The optimal R&D investment, R_j^*, is characterized by the respective first-order conditions given p_j^h's from above; and the optimal compatibility choice is determined by comparing the resultant profits under each of the four compatibility choices. From above the new product price is the highest when the product is fully compatible, followed by the backward- and forward-compatible cases (a tie), and then the non-compatible case ($p_c^h > p_b^h = p_f^h > p_n^h$). This implies that the monopolist's second-period profits can be ordered as $\pi_c^* > \pi_b^* = \pi_f^* > \pi_n^*$. Hence, the monopolist would optimally chooses full compatibility between the old and new products.

On the other hand, suppose the monopolist can credibly commit to the level of R&D investment and the compatibility choice in period one. The monopolist would then set the price for the unit of quality l at a level equal to the discounted utility a group 2 consumer receives over the two periods. Specifically, the total discounted utility from purchasing a unit of quality l is the sum of period-one utility, $v_2^l + \alpha n_2$, plus the discounted period-two expected utility. In period two, group 2 consumers derive the same utility as in period one $(v_2^l + \alpha n_2)$ with probability $1 - p(R_j)$ or the resale value of an old unit with probability $p(R_j)$, which depends on the monopolist's compatibility choice.

The monopolist's problem in the commitment case is thus

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} \quad : \quad \Pi_j = n_2 \left\{ v_2^l + \alpha n_2 + \delta[p(R_j) r_j + (1 - p(R_j))(v_2^l + \alpha n_2)] - c \right\} + \delta \left\{ p(R_j) n_2 \left[p_j^h - c \right] - R_j \right\} \tag{2}$$

where r_j denotes the secondary market price of an old unit given compatibility choice j.

Let us denote the R&D investment in this benchmark case with a hat (i.e., $\hat{R}_j$). Comparing problem (1) and problem (2), it follows that what differentiates the two sets of first-order conditions that characterize R_j^* and $\hat{R}_j$, respectively, for each j is the difference between the resale value of the old unit and the utility from its continued use in the second period. That is, the difference, $r_j - (v_2^l + \alpha n_2)$, is what drives the wedge between the commitment and non-commitment solutions. Below, a time-inconsistency problem is said to exist from the standpoint of the monopolist's profitability when the monopolist's second-period choice is different from the commitment solution.

Time inconsistent problems in this model necessarily mean that the monopolist earns a smaller profit than it could have had it been able to credibly commit to its choices in the first period. On the other hand, the monopolist's time inconsistency problem can in fact be socially beneficial. This is because if the R&D investment is successful, the social planner would want to transfer old products to group 1 consumers. However, if the resale price fully captures this benefit, and the monopolist can extract all surplus, then the monopolist's new product price in the non-commitment case equals precisely the consumer surplus created. We summarize these results in Proposition 1.

Proposition 1. The following holds with respect to the monopolist's R&D and compatibility decisions:

(i) The monopolist chooses full compatibility regardless of commitment.

(ii) There is a time inconsistent behavior regarding R&D investment:

(a) If $\alpha n_2 > v_2^l - v_1^l$, the monopolist underinvests relative to the commitment case.

(b) If $\alpha n_2 < v_2^l - v_1^l$, the monopolist overinvests relative to the commitment case.

(iii) The monopolist's time inconsistent behavior yields socially optimal outcomes.

Proposition 1 tells us that generically a durable-goods monopolist does not maximize ex ante discounted profits because it invests either too much or too little in new product R&D once it has sold its old products to the high valuation consumers. More specifically, the monopolist underinvests in R&D when the additional network benefit from an increased network size outweighs the valuation difference for a unit of quality l across the two consumer groups; and it overinvests when the network benefit is smaller than the valuation difference. Our result partly confirms the previous results in the literature that a durable-goods monopolist has an incentive to practice a type of planned obsolescence by introducing new products too frequently (see, e.g., Choi 1994; Waldman 1996).

However, the monopolist may also underinvest depending on the intensity of network benefit (α), size of the installed base (n_2), and the difference in consumer valuations ($v_2^l - v_1^l$). Holding the valuation difference constant, underinvestment is more likely to occur in an industry where the intensity of network benefit is larger, the installed base is larger, or both. One potential application of this result is to explain vaporware as the monopolist's time-inconsistent behavior. That is, suppose the monopolist announces in period one that it plans to make an R&D investment to develop a new product. However, if the monopolist underinvests in period two, then the new product development fails more often than it was expected because the monopolist invests less than it initially intended.

This contrasts to the earlier literature on vaporware, where the focus is mostly on the effects of strategic preannouncements vis-à-vis competitors (e.g., Farrell and Saloner 1986; Haan 2003; Dranove and Gandal 2003; Gerlach 2004; Choi et al. 2010). Our analysis shows another possibility that a durable goods monopolist faces a time-inconsistency problem, where the monopolist underinvests in markets where network effects are strong and the installed base is large. We suspect that these two explanations for vaporware are observationally indistinguishable. However, our explanation seems consistent with the fact that vaporware is more commonly observed in computer and gaming industries where there are significant network effects compared to other consumer durable markets.

We now consider a simple variant of this section's analysis. Until now, by assuming that the size of group 1 consumers is larger than that of group 2 consumers ($n_1 > n_2$), we gave all the bargaining power in the secondary market to the group 2 consumers. However, if we assume instead that the size of group 1 consumers is smaller than the size of group 2 consumers (or the the secondary market collapses due to some other factors that are external to the model), then the resale price for a unit of quality l in the second-hand market would be zero. Since then the monopolist cares only about the incremental benefit to the group 2 consumers, the monopoly solution is different from the social optimum. Further, both fully and backward compatible new products command the same new unit price in this case because the resale value to group 1 consumers is not internalized by the monopolist.

Proposition 2. Suppose $n_1 < n_2$ so that the resale price of old units drops to zero. Then the following holds:

(i) The monopolist is indifferent between full- and backward-compatibility both in the commitment and non-commitment cases.

(ii) The monopolist overinvests relative to the commitment level.

(iii) The monopolist underinvests relative to the socially optimal level.

Proposition 2 shows that the monopolist's overinvestment incentive holds more generally when the second-hand market collapses due to smaller residual demands and more competition between sellers. In particular, since the monopolist does not capture the resale value, the second period R&D expenditure exerts only negative externality on its first-period profit. The model also suggests that the monopolist may exhibit time-inconsistent behavior regarding the compatibility choice. That is, it may announce full (backward) compatibility in period one and then later choose to develop a backward only (full) compatible product. However, since the monopolist is indifferent in this case, a small cost advantage for supporting only backward compatibility would lead the monopolist to choose the latter.

Another subtle difference is that even though the monopolist overinvests in equilibrium, the level of its R&D investment now falls short of the socially optimal level. The reason is that the monopolist cannot capture the surplus created by the resale transaction in which units of quality l are transferred to group 1 consumers. Thus, new product introduction may appear too frequent (i.e., planned obsolescence), but in fact the frequency is lower than what is socially optimal without fully functioning secondary markets. We also know from Proposition 1 that the socially optimal compatibility choice is full compatibility. The monopolist may thus further decrease social welfare by choosing backward compatibility. Thus, in our model healthy secondary markets are desirable for network industries.

5 Extensions

In this section, we consider two extensions of the base model. First, we consider an entry of potential competitor at the beginning of the second period. Second, we consider a three-period model in which two sequential R&D investment opportunities exist.

5.1 R&D Competition

In Section 3's model, we considered the monopolist's incentive to upgrade its own product and ignored the possibility that another firm can compete against the incumbent by making an R&D investment. Assume everything is the same as in the base model with $n_1 > n_2$ except that at the beginning of the second stage an equally efficient firm can make an investment, R_e, in R&D and enter the market if it is successful, while the monopolist invests R_m. In the analysis that follows, to keep the argument more straightforward, we assume that the incumbent's and the entrant's marginal cost of production and the R&D success function are the same. The qualitative results would be similar even if we assumed asymmetric firms. Thus, for a given level of R&D expenditure, R_k, $k = e, m$, each firm develops a new product of quality h in the second period with probability $p(R_k)$.

Although the entrant may try to obtain a license to make its product compatible with the monopolist's, our discussion will be focused on the case where the potential entrant's product is not compatible with the incumbent's. An example may be the mobile phone standards, where there are currently two dominant technologies, the GSM standard and the CDMA2000 standard, which are completely incompatible. This assumption is supported by the analysis in Regibeau and Rockett (1996), where two firms decide when to introduce a new product and choose the degree of compatibility. They show that if firms make compatibility decisions when they introduce their products, then the follower prefers incompatibility; hence, the equilibrium degree of compatibility between the two firms would be zero if standardization requires the agreement of both firms.[8]

There are four possible equilibrium outcomes in the second period. First, with probability $(1 - p(R_e))(1 - p(R_m))$ neither firm succeeds in developing a new product. Then, no market transaction takes place. Second, with probability $(1 - p(R_e))p(R_m)$ the monopolist develops a new product while the entrant does not. In this case, the rest of equilibrium behavior is the same as described in Proposition 1 above. Third, with probability $p(R_e)(1 - p(R_m))$ only the entrant succeeds in R&D. Because the entrant's product is not compatible with the monopolist's units of quality l, group 2 consumers churning to the entrant's product cannot benefit from an increased network size. Likewise, group 1 consumers in the secondary

[8]A similar conclusion is reached by Katz and Shapiro (1992).

market would only be willing to pay up to $v_1^l + \alpha n_2$. Given this, the entrant will set $p_e^h = (v_2^h - v_2^l) + (v_1^l + \alpha n_2)$ and sell to group 2 consumers.

Finally, with probability $p(R_e)p(R_m)$ both firms succeed in developing a new product. In this case, group 2 consumers benefit from competition between the entrant and the incumbent. If the incumbent chooses noncompatibility for its new product, the incumbent's and the entrant's new products yield the same level of utility, and thus competition would drive the new product price down to the level of the marginal cost c.[9] However, for all the other compatibility choices, the monopolist's product yields a higher level of utility due to higher resale value, increased network benefit, or both. Therefore, a fully or one-way compatible monopolist's product will be priced strictly above the marginal cost, whereas the entrant's new product price will be driven down to the marginal cost c. Hence, the entrant earns a zero profit even though the product qualities are the same.

Proposition 3. Suppose a potential entrant can invest in R&D, and the entrant's product is not compatible with the monopolist's.

(i) The monopolist chooses full compatibility regardless of commitment.

(ii) There exists a range $\alpha \in [\alpha_{\min}, \alpha_{\max}]$, where $\alpha_{\min} \leq \frac{v_2^l - v_1^l}{n_2} \leq \alpha_{\max}$, such that the monopolist underinvests relative to the commitment case.

(iii) The monopolist underinvests, and the entrant overinvests relative to the socially optimal outcome.

The above proposition shows that our basic finding in Proposition 1 continues to hold

[9] We assume that when both the incumbent's and the entrant's products are not compatible with units of quality l, group 2 consumers chooce to buy a new unit from the incumbent monopolist when they are indifferent. This tie-breaking rule can be justified by an arbitrarily small switching cost (due to, e.g., brand loyalty).

when potential competition is taken into account. That is, there exists a range of parameter value α, in which R&D underinvestment occurs. However, outside of this range it turns out that the direction of bias depends on the R&D technologies of the two firms in a quite complex way. Further, it is shown that with potential competition the two firms' R&D investments tend to move away from the socially optimal level in the opposite directions. This is because the monopolist who cannot extract the whole surplus from consumers due to potential competition has a weaker R&D incentive, while the entrant who has no installed base spends too much in R&D from the standpoint of social welfare.

5.2 Successive R&D

So far, we have assumed that the monopolist can invest in R&D only once. In this subsection, we consider the more realistic case where there are successive R&D investments while the secondary market is fully operative. To be precise, assume everything is the same as in the base model except for the following. Instead of two periods, we now assume consumers live for three periods, and the monopolist has two R&D investment opportunities. The monopolist can first develop a medium-quality product ($k = m$) in period 2 and, if it is successful, can invest in period 3 to produce a high-quality product ($k = h$). Note that innovation is sequential in the sense that only if the monopolist succeeds in the first R&D it can invest in the second R&D. Hence, if the monopolist fails in the first R&D, it can only invest in R&D for the medium-quality product at the beginning of period 3.

On the demand side, there are now three groups of consumers (denoted $i = 1, 2, 3$). Group 3 is the highest valuation group. Group 2 has the next highest valuation, and group

1 has the lowest valuation. Let n_i denote the size of each consumer group. With two R&D opportunities and three consumer groups the analysis can be complicated because the secondary market prices crucially depend on the relative sizes of the consumer groups. Here we focus on the case where $n_1 = n_2 = n_3$ and give full bargaining power to higher types, which ensures that the resale price remains positive. As in our previous analysis, we assume that in any period the monopolist has an incentive to sell new units only to group 3 consumers. Let R denote the period 2 investment, and $T_{l(m)}$ denote the period 3 investment when the monopolist's current technology is $l(m)$ respectively. For simplicity, we assume that the R&D success functions are the same in all three cases, $p(R) = p(T_l) = p(T_m)$, where we make the usual technical assumptions as stated in Section 3.

Because the secondary market is operative, when both period 2 and period 3 R&D investments succeed, group 2 consumers will be able to sell old units of quality l to group 1 consumers who have not purchased anything so far, and buy old units of quality m from group 3 consumers who may want to purchase the new units of quality h. Similarly, if the monopolist succeeds in R&D in period 2, then the new product price should induce group 3 consumers to buy the new product and sell the old units in the resale market. We compare the equilibrium R&D investments in each of the two stages with those that would result if the monopolist could commit to a level of R&D investment only for the immediate next level of product development; that is, where the monopolist can commit to a level of R and T_l in period 1, and a level of T_m in period 2 (only if the first R&D investment succeeded).

Proposition 4. Suppose that the monopolist can invest twice in periods 2 and 3, and innovation results in a higher quality product.

(i) There is a time inconsistent behavior regarding the first R&D investment:

(a) If $\alpha n_3 > v_3^l - v_2^l$ and δ is smaller(larger) than a certain threshold, the monopolist underinvests(overinvests) relative to the commitment case.

(b) If $\alpha n_3 < v_3^l - v_2^l$, the monopolist overinvests relative to the commitment case.

(ii) There is a time inconsistent behavior regarding the second R&D investment, where $k = l(k = m)$ if the monopolist fails(succeeds) in the first R&D:

(a) If $\alpha n_3 > v_3^k - v_2^k$, the monopolist underinvests relative to the commitment case.

(b) If $\alpha n_3 < v_3^k - v_2^k$, the monopolist overinvests relative to the commitment case.

(iii) The monopolist chooses full compatibility regardless of commitment.

(iv) The equilibrium levels of R&D investments are socially optimal.

The above proposition shows that the initial results in Proposition 1 remain unchanged for the second R&D investment. That is, as long as the valuation difference between consumer groups is smaller than the additional network benefit from the secondary market trade, the monopolist underinvests in R&D relative the commitment case. What is different from the previous result is that in the first R&D investment unless the discount factor is sufficiently small the monopolist overinvests even if the network benefit is larger than the valuation difference. This occurs because if the monopolist is sufficiently patient, then it overinvest in the first R&D in order to exploit another profit opportunity from the second R&D investment, and this force weakens the monopolist's underinvestment incentive in the intermediate stage (i.e., period 2).

The above result in Proposition 4 is related to Fishman and Rob (2000). Fishman and Rob consider multiple, sequential innovations by a durable goods monopolist, and show that the monopolist invests too little in comparison with the social optimum. This is because in their model the monopolist, not being able to capture the consumer utility from a new product when a higher quality product is introduced, waits for a longer period during which consumers pay for the services of the initial product. In Fishman and Rob's model, however, there is no secondary market trade, so the surplus created by innovations cannot be captured by the resale value. Recall that in Section 3 we found that when the secondary market collapses the monopolist underinvests relative to the social optimum, which is consistent with Fishman and Rob's finding.

6 Conclusion

Although network effects play a central role in industries such as computer and telecommunications, relatively little is known about how they affect a durable goods monopolist's innovation incentives. The current paper is an attempt to clarify how network effects affect the monopolist's R&D incentive under time-inconsistency problems. The existing literature on planned obsolescence has emphasized that the monopolist's incentive to introduce new products is too high. We have shown that this result can be overturned if network effects are strong and the firm can choose compatibility between old and new products. It has been also showed that the monopolist may invest too little from the social welfare standpoint if the secondary market is inactive or there exists a potential competitor. The underinvestment result continues to hold under sequential innovations.

There are a few policy implications that can be drawn from our analysis. First, when the secondary market is fully operative and there is little competition, the frequency of new product introduction is socially optimal. Hence, whether the observed frequency in an industry is thought to be too high or too low, the government need not intervene. Second, the government should try to boost the firm's R&D investments in markets where secondary markets do not function well. Third, apart from product diversity the government need to encourage the incumbent's R&D investment and discourage the entrant's R&D investment in network industries. Finally, as discussed above, vaporware or underinvestment in new product development need not be a strategic (mis)behavior. In particular, vaporware is more likely to be observed at later generations of products.

7 Appendix

Proof of Proposition 1. Consider first the monopolist's problem in the second period:

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \pi_j = p(R_j) n_2 \left[p_j^h - c \right] - R_j,$$

where $p_c^h = v_2^h - v_2^l + v_1^l + 3\alpha n_2$, $p_b^h = p_f^h = v_2^h - v_2^l + v_1^l + 2\alpha n_2$, and $p_n^h = v_2^h - v_2^l + v_1^l + \alpha n_2$ as shown in the text.

The first-order condition with respect to R_j is

$$\begin{aligned} p'(R_j^*) n_2 [v_2^h - (v_2^l - v_1^l) + 3\alpha n_2 - c] &= 1 \text{ for } j = c, \\ p'(R_j^*) n_2 [v_2^h - (v_2^l - v_1^l) + 2\alpha n_2 - c] &= 1 \text{ for } j = b,\ f, \\ p'(R_j^*) n_2 [v_2^h - (v_2^l - v_1^l) + \alpha n_2 - c] &= 1 \text{ for } j = n, \end{aligned}$$

respectively.

Since $\partial \pi_j / \partial p_j^h > 0$ by the envelope theorem and $p_c^h > p_b^h = p_f^h > p_n^h$, it follows that the second-period profit can be ranked as $\pi_c^* > \pi_b^* = \pi_f^* > \pi_n^*$. Thus, the monopolist chooses full compatibility in the second period.

Now consider the commitment solution, which can be reduced to

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \Pi_j = p(R_j) n_2 [r_j - (v_2^l + \alpha n_2) + (p_j^h - c)] - R_j,$$

where the resale prices are $r_c = r_f = v_1^l + 2\alpha n_2$ and $r_b = r_n = v_1^l + \alpha n_2$ under each compatibility choice.

Here the set of first-order conditions are

$$\begin{aligned}
p'(R_j^*) n_2 [v_2^h - 2(v_2^l - v_1^l) + 4\alpha n_2 - c] &= 1 \text{ for } j = c, \\
p'(R_j^*) n_2 [v_2^h - 2(v_2^l - v_1^l) + 2\alpha n_2 - c] &= 1 \text{ for } j = b, \\
p'(R_j^*) n_2 [v_2^h - 2(v_2^l - v_1^l) + 3\alpha n_2 - c] &= 1 \text{ for } j = f, \\
p'(R_j^*) n_2 [v_2^h - 2(v_2^l - v_1^l) + 1\alpha n_2 - c] &= 1 \text{ for } j = n.
\end{aligned}$$

Since $p_c^h > p_b^h = p_f^h > p_n^h$ and $r_c = r_f > r_b = r_n$, it follows again from the envelope theorem that the discounted profits for each j can be ranked as $\Pi_c^* > \Pi_f^* > \Pi_b^* > \Pi_n^*$. Therefore, the monopolist chooses full compatibility in the first period.

Next, compare the two first-order conditions under each regime when $j = c$. Notice that $v_2^h - (v_2^l - v_1^l) + 3\alpha n_2 - c > v_2^h - 2(v_2^l - v_1^l) + 4\alpha n_2 - c$ if and only if $v_2^l - v_1^l > \alpha n_2$. Because $p(R)$ is concave, it follows that $R_c^* \gtreqless \hat{R}_c$ if $v_2^l - v_1^l \gtreqless \alpha n_2$ as claimed.

Finally, consider the problem of a social planner who maximizes social surplus:

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : p(R_j) n_2 [s_j - c] - R_j,$$

where s_j denotes the consumer surplus created by the R&D investment with compatibility choice j.

If the R&D investment is successful, then it is optimal to produce n_2 units of quality h because only group 2 consumer's valuation is higher than c. On the other hand, consumers have unit demands, so it is efficient to have the existing n_2 units of quality l transferred to group 1 consumers. However, since the resale price fully captures utility benefit from a group 1 consumer and the monopolist price for the new units of quality h is the sum of resale price and the incremental benefit group 2 consumers receive, it follows that $s_j = p_j$ for all j. Therefore, the planner's problem is the same as that of the monopolist's in the second period, and the monopolist's choices must be socially optimal. ∎

Proof of Proposition 2. Due to competition, the resale value of the old unit of quality l is driven down to zero regardless of the compatibility between the old and new units. Hence, the monopoly price for a unit of quality h equals the incremental benefit to the group 2 consumers, which is $p_c^h = p_b^h = v_2^h - v_2^l + \alpha n_1$ and $p_f^h = p_n^h = v_2^h - v_2^l$. Notice that under full and backward compatibility, group 2 consumers receive additional network benefit of αn_1. The monopolist's problem in the second period is the same as above,

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \pi_j = p(R_j) n_2 \left[p_j^h - c\right] - R_j.$$

Therefore, we obtain $\pi_c^* = \pi_b^* > \pi_f^* = \pi_n^*$.

The monopolist's problem under commitment reduces to

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \Pi_j = p(R_j) n_2 [(p_j^h - c) - (v_2^l + \alpha n_2)] - R_j,$$

where the first-order condition is

$$p'(R_j) n_2 [(p_j^h - c) - (v_2^l + \alpha n_2)] = 1 \text{ for each } j.$$

Since $p_c^h = p_b^h > p_f^h = p_n^h$, it follows that $\Pi_c^* = \Pi_b^* > \Pi_f^* = \Pi_n^*$. Because the two programs differ only in the additional negative term in the latter, it is straightforward that $R_j^* > \hat{R}_j$ for each j.

On the other hand, the consumer surplus s_j created by the introduction of new product is the sum of the utility group 1 consumers get from the old units of quality l and the incremental utility of group 2 consumers. Since the monopolist cannot capture the utility of group 1 consumers through its pricing of new product, $p_j^h < s_j$ for all j, it underinvests relative to the socially optimal level in all cases of j. ■

Proof of Proposition 3. The potential entrant's problem is as follows:

$$\max_{R_e \geq 0} : \pi_e = n_2 p(R_e)(1 - p(R_{m,j}))[(v_2^h - v_2^l) + (v_1^l + \alpha n_2) - c] - R_e.$$

The first-order condition is

$$n_2 p'(R_e)(1-p(R_m))[(v_2^h - v_2^l) + (v_1^l + \alpha n_2) - c] = 1, \tag{3}$$

which tells us that, other things being equal, the entrant's optimal reaction $R_e^*(R_m)$ is a decreasing function of the monopolist's R&D investment R_m.

The monopolist's problem in the second period is given by

$$\max_{R_{m,j} \geq 0, j \in \{c,b,f,n\}} \quad : \quad \pi_{m,j} = n_2(1-p(R_e))p(R_{m,j})[p_{m,j}^h - c]$$
$$+ n_2 p(R_e) p(R_{m,j})[q_{m,j}^h - c] - R_{m,j},$$

where $p_{m,j}^h$ is the price the monopolist charges when the entrant fails to innovate; hence, $p_{m,j}^h$ is the same as in the proof of Proposition 1, and $q_{m,j}^h$ denotes the price the monopolist charges when it faces competition from the entrant. Following the argument in the main text, $q_{m,c}^h = c + 2\alpha n_2$, $q_{m,b}^h = q_{m,f}^h = c + \alpha n_2$, and $q_{m,n}^h = c$. Since $p_{m,c}^h > p_{m,b}^h = p_{m,f}^h > p_{m,n}^h$, it follows from the envelope theorem that $\pi_{m,c}^* > \pi_{m,b}^* = \pi_{m,f}^* > \pi_{m,n}^*$. The first-order condition is

$$n_2(1-p(R_e))p'(R_{m,j})[p_{m,j}^h - c] + n_2 p(R_e) p'(R_{m,j})[q_{m,j}^h - c] - 1 = 0. \tag{4}$$

Now consider group 2 consumers' willingness to pay for a unit of quality l in period one. With probability $(1-p(R_e))(1-p(R_{m,j}))$, a group 2 consumer will continue to use the old units of quality l. With complementary probability, a group 2 consumer anticipates to resell old units to group 1 consumers in the second period. Thus, the monopolist's problem under commitment is given as

$$\max_{R_{m,j}\geq 0, j\in\{c,b,f,n\}} : \Pi_j = n_2\{v_2^l + \alpha n_2 + \delta[(p(R_{m,j}) + p(R_e) - p(R_{m,j})p(R_e))r_j$$
$$+(1 - p(R_{m,j}) - p(R_e) + p(R_{m,j})p(R_e))(v_2^l + \alpha n_2)]\}$$
$$+\delta\{n_2(1 - p(R_e))p(R_{m,j})[p^h_{m,j} - c] + n_2 p(R_e)p(R_{m,j})[q^h_{m,j} - c] - R_{m,j}\},$$

where the resale prices are $r_c = r_f = v_1^l + 2\alpha n_2$ and $r_b = r_n = v_1^l + \alpha n_2$. Thus, it follows that $\Pi_c^* > \Pi_f^* > \Pi_b^* > \Pi_n^*$. The first-order condition is

$$n_2\left\{(p'(R_{m,j}) - p'(R_{m,j})p(R_e)) + [(p'(R_e) - p(R_{m,j})p'(R_e))]\frac{\partial R_e^*}{\partial R_{m,j}}\right\}(r_j - (v_2^l + \alpha n_2))$$
$$-n_2 p'(R_e)p(R_{m,j})\{p^h_{m,j} - q^h_{m,j}\}\frac{\partial R_e^*}{\partial R_{m,j}}$$
$$+n_2(1 - p(R_e))p'(R_{m,j})[p^h_{m,j} - c] + n_2 p(R_e)p'(R_{m,j})[q^h_{m,j} - c] - 1$$
$$= 0.$$

The first-order condition of the commitment problem differs from that of the noncommitment problem by the following term,

$$n_2\left\{(p'(R_{m,j}) - p'(R_{m,j})p(R_e)) + [(p'(R_e) - p(R_{m,j})p'(R_e))]\frac{\partial R_e^*}{\partial R_{m,j}}\right\}(r_j - (v_2^l + \alpha n_2))$$
$$-n_2 p'(R_e)p(R_{m,j})\{p^h_{m,j} - q^h_{m,j}\}\frac{\partial R_e^*}{\partial R_{m,j}}.$$

Note that the last term is positive since $j^* = c$ and therefore $p^h_{c,j} > q^h_{c,j}$, and $\frac{\partial R_e^*}{\partial R_{m,j}} < 0$ as shown above. On the other hand, the sign of the first bracketed term is ambiguous because $r_c - (v_2^l + \alpha n_2) = v_1^l - v_2^l + \alpha n_2 \gtreqless 0$. In particular, there exists a range of α, including

$\alpha = \frac{v_2^l - v_1^l}{n_2}$, where the first term is made sufficiently small and so the whole expression above becomes positive.

The social planner's problem is given by

$$\max_{R_e, R_{m,j} j \in \{c,b,f,n\}} : n_2 p(R_{m,j}) \left[s_{m,j} - c\right] - R_{m,j} + n_2(1 - p(R_{m,j}))p(R_e) \left[s_e - c\right] - R_e.$$

It is only when the monopolist fails that the entrant's R&D investment is socially useful. Note that the consumer surplus $s_{m,j}$ is maximized with full compatibility for the monopolist's products. Thus, from above discussion it is easy to see that $s_{m,c} = v_2^h - v_2^l + v_1^l + 3\alpha n_2$ and $s_e = v_2^h - v_2^l + v_1^l + \alpha n_2$. The first-order conditions are then

$$n_2(1 - p(R_{m,j}))p'(R_e) \left[v_2^h - v_2^l + v_1^l + \alpha n_2 - c\right] = 1, \quad (5)$$

$$n_2 p'(R_{m,c}) \left[v_2^h - v_2^l + v_1^l + 3\alpha n_2 - c\right] = 1. \quad (6)$$

Note that conditions (3) and (5) are the same. On the other hand, conditions (4) and (6) are different because, the incumbent monopolist cannot extract the whole surplus from group 2 consumers when both firms are successful in R&D. Therefore, the monopolist's equilibrium R&D investment $R_{m,c}^*$ is smaller than the socially optimal level. Then, it is immediate from the strategic substitutability between R_e^* and $R_{m,c}^*$ that the equilibrium R&D investment by the entrant is greater than the social optimum. ■

Proof of Proposition 4. It is straightforward to show that the monopolist always chooses full compatibility in both commitment and noncommitment cases, so we fix $j = c$ in this proof.

First, consider the monopolist's R&D decision in the last period. If the monopolist has failed in the first R&D, it can now invest T_l to develop products of quality m. In this case, the monopolist's problem is given by

$$\max_{T_l \geq 0} : p(T_l) n_3 \left[v_3^m - v_3^l + v_2^l + 3\alpha n_3 - c \right] - T_l.$$

The first-order condition is

$$p'(T_l) n_3 \left[v_3^m - v_3^l + v_2^l + 3\alpha n_3 - c \right] = 1.$$

If the monopolist has succeeded in the first R&D, it can invest T_m to develop products of quality h in period three. When the R&D is successful, the monopolist will sell quality h to group 3 consumers. In this process, group 2 consumers will be induced to sell old units of quality l to group 1 consumers and buy old units of quality m from group 3 consumers in the secondary market. Group 2 consumers' gross utility from such transactions is $v_2^m + 3\alpha n_3 + (v_1^l + 3\alpha n_3)$, while their utility in the last period is $v_2^l + 2\alpha n_3$ if they choose to keep their old units of quality l. Then, the resale price of quality m must be equal to $v_2^m + 3\alpha n_3 + (v_1^l + 3\alpha n_3) - (v_2^l + 2\alpha n_3) = v_2^m - v_2^l + v_1^l + 4\alpha n_3$. Given the incremental value of quality upgrade for group 3 is $v_3^h - v_3^m + \alpha n_3$, the price for quality h is given by $v_3^h - v_3^m + v_2^m - v_2^l + v_1^l + 5\alpha n_3$. The monopolist's problem is then

$$\max_{T_m \geq 0} : p(T_m) n_3 \left[v_3^h - v_3^m + v_2^m - v_2^l + v_1^l + 5\alpha n_3 - c \right] - T_m,$$

and the first-order condition is given by

$$p'(T_m)n_3\left[v_3^h - v_3^m + v_2^m - v_2^l + v_1^l + 5\alpha n_3 - c\right] = 1.$$

Second, consider the monopolist's R&D decision in the second period. Suppose the monopolist has succeeded in developing quality m. The monopoly price p^m for units of quality m must satisfy the following inequality:

$$\begin{aligned} v_3^l + \alpha n_3 + \delta u_3^l \quad \leq \quad & v_3^m + 2\alpha n_3 + (v_2^l + 2\alpha n_3) - p^m \\ & + \delta[p(T_m)(v_2^m + 3\alpha n_3) + (1 - p(T_m))(v_3^m + 2\alpha n_3)], \end{aligned}$$

where $u_3^l = v_2^l + 2\alpha n_3$ if the monopolist succeeds in R&D in period three and $u_3^l = v_3^l + \alpha n_3$ otherwise. Note that the left-hand side is group 3 consumers' continuation utility when they continue to use a unit of quality l in period two. The right-hand side is group 3 consumers' continuation utility when they buy a unit of quality m: the sum of the current-period utility, the resale value of a unit of quality l, and the expected utility of quality m in the next period. The monopolist's problem is then given by

$$\max_{R\geq 0} : p(R)n_3\left[p^m - c\right] - R,$$

where $p^m = v_3^m - v_3^l + v_2^l + 3\alpha n_3 + \delta[p(T_m)(v_2^m + 3\alpha n_3) + (1 - p(T_m))(v_3^m + 2\alpha n_3) - (v_2^l + 2\alpha n_3)]$.

Now suppose the monopolist's R&D decision when it can commit to a level of investment. Consider first the case where the monopolist can commit to a level of T_m in period two. Note that the wedge between the commitment and the noncommitment solution comes from the additional term in the commitment first-order condition created by taking a derivative of p^m with respect to T_m, which is

$$\delta p'(T_m)[v_2^m - v_3^m + \alpha n_3].$$

Thus, the commitment R&D investment $\widehat{T}_m$ is larger than the noncommitment investment T_m^* if $\alpha n_3 > v_3^m - v_2^m$, and the opposite holds otherwise.

Next consider the case where the monopolist can commit to a level of R and T_l in period one. Similarly, the difference between the commitment solution and the noncommitment solution comes from the expression of the price of unit of quality l,

$$\begin{aligned} p^l &= v_3^l + \alpha n_3 + \delta[p(R)(v_2^l + 2\alpha n_3) + (1-p(R))(v_3^l + \alpha n_3)] \\ &\quad + \delta^2(1-p(R))[p(T_l)(v_2^l + 2\alpha n_3) + (1-p(T_l))(v_3^l + \alpha n_3)]. \end{aligned}$$

Taking a derivative of p^l with respect to R and T_l respectively, we get the following additional term in the first-order condition in the commitment case:

$$\begin{aligned} \text{w.r.t. } R &: \quad \delta p'(R)(v_2^l - v_3^l + \alpha n_3) - \delta^2 p'(R)[p(T_l)(v_2^l + 2\alpha n_3) + (1-p(T_l))(v_3^l + \alpha n_3)], \\ \text{w.r.t. } T_l &: \quad \delta^2(1-p(R))p'(T_l)[v_2^l - v_3^l + \alpha n_3]. \end{aligned}$$

From the second expression we can easily see that the commitment R&D investment $\widehat{T}_l$ is larger than the noncommitment investment of T_l^* if $\alpha n_3 > v_3^l - v_2^l$, and the opposite holds otherwise.

On the other hand, from the first expression we can see that for δ being sufficiently small the commitment level of R would be larger than the noncommitment level if $\alpha n_3 > v_3^l - v_2^l$, and the opposite holds otherwise. If δ is larger than a certain threshold, however, the sign of the above expression is ambiguous.

Finally, it can be readily verified that the monopolist's problem under noncommitment coincides with the social planner's problem. Since the argument is the same as in the base model, we omit this part of the proof. ■

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Monopoly R&D and Compatibility Decisions in Network Industries

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Abstract

In network industries, we often observe frequent upgrades of existing products as well as delayed introductions of new products. In order to explain these contrasting phenomena, this paper examines a durable-good monopolist's incentive for R&D investment in new product development in a market with network effects. We show that if the network effect is strong the monopolist underinvests in R&D compared to the commitment level, whereas overinvestment occurs when the network effect is weak. The monopolist also chooses full intergenerational compatibility between products. We then extend the analysis to the cases of potential entry and successive innovations, and examine how the results change in these extensions.

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1 Introduction

The past decades have seen the introduction of successive generations of innovative products in the computer, telecommunications, and consumer electronics industries, such as smart phones, game consoles and audio/visual equipment, in a relatively short period of time. New products have been often developed by firms with significant market power, and the business strategy to produce new products replacing old ones too often came to be known as 'planned obsolescence.' On the other hand, in some other markets especially computer software or video games new products are often released after a long delay or released with little improvement over existing products. Such products are labelled as 'vaporware,' and the term has been used in a wide range of industries by the press. Economists have typically analyzed one of these two issues at a time. That is, in the former case manufacturers bring out new products too often whereas in the latter case product developments are too slow or insufficient. The traditional view is that vaporware are strategic preannouncements vis-à-vis competitors although there is little conclusive evidence to support this claim.[1]

The purpose of this paper is to show that these two phenomena (i.e., over- and under-investments in R&D) can be explained in a coherent framework. To be more specific, we focus on the interplay between the time-inconsistency problem and network effects in determining the firm's R&D investment and intergenerational compatibility decisions. In contrast to some of the papers in the literature on network compatibility (e.g., Katz and Shapiro 1986,

[1] For instance, the Untied States Government first accused Microsoft in 1994 of anti-competitive licensing practicess, where the district judge focused on the allegation that Microsoft engaged in vaporware. Judge Sporkin refused to approve a consent decree that did not address vaporware allegations whereas Microsoft explained that it preannounces products because software vendors need such early notification to begin developing compatible applications software. The review was dismissed for lack of proof.

1992), we endogenize the monopolist's decision on new product introduction through R&D investments and the compatibility choices between the new and the old products. Also, in our model there is a fully operative secondary market for used goods, so resale values are explicitly considered in our analysis. A similar approach has been taken by Waldman (1996) in a model without network effects. In this respect, our model extends the analysis of Waldman to a market with network effects and endogenous compatibility choices. Later we enrich our base model by considering extensions to the introduction of a potential entrant and sequential innovations.

Our main finding is that the monopolist generally prefers full compatibility between the new and the old products, and it may underinvest in new product R&D relative to the commitment level if the network effect is sufficiently strong. With network externalities, the introduction of a new product induces low-valuation buyers to purchase old units via the secondary market at a higher price, and this increases the high-valuation buyers' surplus from the secondary market trade under full compatibility. However, the firm does not take into account this positive externalities once old units are sold. If this effect outweighs the standard overinvestment tendency (see, e.g., Waldman 1996), then the monopolist's overall R&D incentive becomes smaller than the commitment solution. We also show that the monopolist's decisions are socially optimal in this setting. On the other hand, if the secondary market is eliminated (due to, say, excess supply or other technological measures), then the monopolist invests less than the social optimum, even though the non-commitment level of R&D investment would be always larger than the profit-maximizing (commitment) solution.

We then extend our analysis in two ways. In our first extension, we consider the effect of potential entry on the behavior of the incumbent monopolist. The entrant and the monopolist can both invest in new product development, where the R&D success probabilities are symmetric and the entrant's product is incompatible with the monopolist's. We show that there exists a range of moderate network intensity where the underinvestment result continues to hold. Further, the monopolist underinvests and the potential entrant overinvests relative to the socially optimum level. In our second extension, we introduce two successive R&D opportunities for the monopolist, where the first innovation is required to undertake the second. Here we show that a similar conclusion holds for both the first and the second R&D investments. That is, as long as the high-valuation consumers exploit network benefits via the secondary market trade, the monopoly may underinvest in R&D relative to the commitment solution for sufficiently strong network intensity; however, the underinvestment incentive is weaker for the first R&D.

The outline for the paper is as follows. Section 2 discusses the relevant literatures. Section 3 sets forth our basic model. Section 4 analyzes the monopolist's compatibility and R&D decisions. Section 5 extends the analysis to the cases of potential entry and sequential innovation. Sections 6 contains concluding remarks. All formal proofs can be found in the Appendix.

2 Related Literature

There are broadly two types of literature on research and development. One is regarding perishable goods (see, e.g., Reinganum 1989 for a survey), while the other is concerned with durable goods. Understanding R&D incentives in a durable goods market is complicated by the time-inconsistency problem à la Coase (1972). Coase in his seminal article suggested that the monopoly seller has an incentive to introduce new products that make old units obsolete, known as planned obsolescence. Earlier literature focused on the monopolist's durability choice.[2] However, there has been a growing literature concerning the monopolist's incentive to introduce new versions of its products, which may be (in)compatible with the old unit. This paper contributes to this strand of literature by investigating how the monopoly's R&D incentive interacts with network effects.

As mentioned earlier, our analysis is related to Waldman (1996). In a two-period model, Waldman shows that a durable-goods monopolist invests too much in developing a new product relative to the profit-maximizing solution. That is, the monopolist faces a time-inconsistency problem, where the R&D investment that maximizes profits from now onwards does not maximize overall profits. This happens because the firm does not internalize the negative externality the new product exerts on the future value of the old product. In a related study, Nahm (2004) shows that when the buyer type is continuous there is a time-inconsistency problem in the monopolist's R&D decisions when the firm buys back old units in period two. The difference is that in our baseline model we focus on the interaction between the time-inconsistency problem and the intensity of network effects.

Other papers on planned obsolescence in network industries include Waldman (1993), Choi (1994), Ellison and Fudenberg (2000), and Miao (2010). Waldman and Choi focus on the monopolist's incentive to introduce a new product that is incompatible with old units. In particular, Choi finds that the monopolist may want to make the new product compatible

[2] Swan (1970, 1972) famously argued that a monopolist would not distort the optimal level of durability; however, a number of authors demonstrated that Swan's independence result breaks down in various circumstances (see, e.g., Bulow 1982; Liebowitz 1982; Rust 1986). In particular, Grout and Park (2005) and Strausz (2009) showed that planned obsolescence may occur even in competitive markets if some quality attributes are unobservable.

with the old one when it wants to sell only to new consumers. Ellison and Fudenberg show that the monopolist may supply upgrades excessively assuming that the new technology is only backward compatible. Miao (2010) considers the monopolist's incentive to tie a competitively-supplied add-on product that is only backward compatible.[3] In contrast to our paper, all these works assume exogenous technological improvements and find only excessive incentives to adopt new incompatible technologies.

Also related is the literature on the interaction between new product introduction and compatibility choices (see, e.g., Katz and Shapiro 1992; Regibeau and Rockett 1996; Kristiansen 1998). In this literature, two firms decide when to introduce their products, and the rate of technological progress is exogenously given. The paper in this literature closest to our analysis is Regibeau and Rockett, where the new generation of products is introduced later than would be socially optimal if products are perfectly compatible. Our basic argument is similar except that in our model buyers with different valuations could trade in secondary markets and the high-valuation buyers can purchase goods more than once. Also, we allow for intergenerational compatibility controlled by the same firm while these articles focus on the case of compatibility between competing firms.

3 The Model

Consider a two-period model of a durable goods monopolist with secondary market trade, similar to the one proposed by Waldman (1996). In period one, a monopolist produces output

[3] Miao (2011) also showed that with network effects planned obsolescence can alleviate the classical monopoly undersupply problem, and similarly Bond and Samuelson (1987) found that a durable-goods monopolist may spend too much in cost-reducing innovations to exploit the residual demand.

of quality l that lasts two periods. At the beginning of the second period, the monopolist can invest in R&D, where R denotes the amount invested and $p(R)$ is the probability that the R&D is successful. It is assumed that $p(0) = 0$, $p(\infty) < 1$, $p'(0) = \infty$, $p'(R) > 0$ and $p''(R) < 0$ for all $R \geq 0$. Specifically, there is a probability $p(R)$ that output in the second period is of quality h, and a probability $1 - p(R)$ that output in the second period is again of quality l. In addition, the monopolist can decide whether to make the new product compatible with the old product that was sold in period one. We assume that the two quality levels are exogenously given. (However, varying the levels of quality would not change our qualitative results.) The constant marginal cost of production is given by $c > 0$ for both products, and there is no fixed costs other than the R&D investment.

The demand side of the market is characterized by two groups of consumers, denoted 1 and 2, where each consumer lives for two periods. Consumer group i consists of a continuum of non-atomic consumers of mass n_i $(i = 1, 2)$. Consumers demand at most one unit of the good in each period. A representative consumer in group i derives a gross benefit $v_i^k + \alpha N$ per period from the consumption of a unit of quality k $(k = l, h)$, where v_i^k is increasing in quality k and αN measures the network benefit when the total mass of consumers using the same (or compatible) product is N. The parameter α measures the intensity of network effects in a given market.[4] Consumer group 2 comprises early adopters who have a higher valuation than group 1 consumers, so that $v_2^k > v_1^k$ for any $k = l, h$. We assume that in each period the monopolist offers all consumers the same price for a new unit of output.[5] The

[4]The intensity of network effect may depend on the quality of the product; that is, a higher quality product may have a feature that enhances consumer's network benefits. Relaxing this assumption (e.g., $\alpha^h > \alpha^l$) does not change any of our results although it would make the model more realistic.

[5]In contrast to Choi (1994), where the monopolist price discriminates the two consumer groups that differ in the timing of their arrival, in our paper both consumers are present from period one. Thus, if the

structure of the game is common knowledge, and the monopolist and all consumers are risk neutral and have a common discount factor $\delta < 1$.

In period one, the monopolist announces the price for a unit of quality l, and then all consumers simultaneously decide whether to buy the good. In period two, the monopolist decides how much to invest in R&D and whether to make the new product compatible with the old one. The monopolist then announces the price for a unit of quality h if the R&D investment is successful, while it announces the price for a unit of quality l if the innovation fails.[6] Consumers who do not purchase a unit directly from the monopolist may purchase an old unit in a secondary market, where prices are determined by supply and demand. For simplicity, we assume that a used good provides the same flow benefit to consumers as a new unit does without any depreciation. This assumption does not affect any of the qualitative results that follow.

Attention is restricted to parameterizations such that the monopolist never finds it profitable to sell a new product to group 1 consumers.[7] However, Nahm (2004) shows that in Waldman (1996)'s model if the firm wants to sell the old product to the low-type consumers in period two, then the price of the old product is the same whether or not the firm introduces the new product. That is, the new product introduction does not change the price path of the old product compared to the case without the new product. Abstracting from in-

monopolist price discriminates based on the purchase of the old unit, then the high-valuation consumer may delay purchase in order to take advantage of the lower price offered in the second period. That is, under a certain range of parameterization, separating equilibrium cannot exist in our setting; hence, the monopolist would not be able to price discriminate.

[6] A price announcement for a unit of quality l in the second period, when the R&D investment succeeds, does not matter in our model because group 2 consumers have no incentive to delay purchase.

[7] Under this circumstance, the Coase conjecture problem of a durable goods monopolist does not arise. This assumption is made in this literature in order to focus on the time inconsistency problem related to the frequency of new product introduction.

tertemporal price discrimination is further justified in this paper as Mason (2000) has shown that the Coase conjecture fails in its strongest sense with a broad class of network benefit functions. Therefore, we believe the Coase conjecture problem has only weak effect in our analysis.

To make the problem nontrivial, we assume that the monopolist wants to sell units of quality l to group 2 consumers in the first period. When indifferent, consumers are assumed to purchase goods. For the most part of our analysis, we assume that $n_1 > n_2$, which means that the price in the secondary market, when it opens up in the second period, will be positive. (We also consider the case $n_1 < n_2$ at the end of Section 4.) As usual in models with network externalities multiple equilibria may exist. Following the literature (e.g., Katz and Shapiro 1986), we focus on a Pareto optimal symmetric equilibrium.

4 Analysis

We start with the monopolist's R&D and compatibility decisions in the absence of commitment. Suppose first that the monopolist chooses full compatibility for the new product. Because consumers have unit demands, if a group 2 consumer wants to buy the new product, he will sell the old unit in a secondary market, where the equilibrium price for a unit of quality l is given by $v_1^l + 2\alpha n_2$. Note that only n_2 number of consumers in group 1 can purchase an old unit, so the network benefit is proportional to the sum of users in each group $2n_2$. Thus, the monopolist can sell a unit of quality h to group 2 consumers at the price that makes group 2 consumers indifferent between purchasing and not purchasing the new product:

$$p_c^h = (v_2^h - v_2^l + \alpha n_2) + (v_1^l + 2\alpha n_2),$$

where the subscript c refers to the fully compatible case. Notice that the first part in the parenthesis is the incremental value of the new product and the second part is the resale value of an old unit.

Suppose next that the monopolist develops a (only) backward-compatible product. This means that group 2 consumers who purchase the new product would benefit from the increased network size, but the network benefit of group 1 consumers who purchase old units from the secondary market is limited to the size of old network (i.e., αn_2 at most). The secondary market price is thus $v_1^l + \alpha n_2$, and by the same logic as above the monopolist would sell units of quality h to group 2 consumers at a price,

$$p_b^h = (v_2^h - v_2^l + \alpha n_2) + (v_1^l + \alpha n_2),$$

where the subscript b refers to the backward compatible case.

Now suppose the monopolist develops a (only) forward-compatible product in the second period. This happens, for instance, when old units can execute the new standard, but new products does not support the old standard. Buyers of the new product do not benefit from an increased network size, but users of the old product do. In this case, the new product price is given by

$$p_f^h = (v_2^h - v_2^l) + (v_1^l + 2\alpha n_2),$$

where the subscript f refers to the forward compatible case. Notice that the new product price p_f^h is the same as that of the backward compatible product, p_b^h. This is because the aggregate effect of an increased network size and increased resale value is the same in these two cases. (However, this need not hold when the network intensity depends on product quality; see also footnote 5)

The last possibility is that the monopolist develops a new product that is not compatible at all with the old product. It is easy to show that the new product price in this case is given by

$$p_n^h = (v_2^h - v_2^l) + (v_1^l + \alpha n_2),$$

where the subscript n refers to the non-compatible case.

At the beginning of the second period, where the monopolist decides R&D investments, the monopolist's problem is given by

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \pi_j = p(R_j) n_2 \left[p_j^h - c \right] - R_j, \tag{1}$$

where $j \in \{c, b, f, n\}$ denotes the monopolist's compatibility choice.

The optimal R&D investment, R_j^*, is characterized by the respective first-order conditions given p_j^h's from above; and the optimal compatibility choice is determined by comparing the resultant profits under each of the four compatibility choices. From above the new product price is the highest when the product is fully compatible, followed by the backward- and forward-compatible cases (a tie), and then the non-compatible case ($p_c^h > p_b^h = p_f^h > p_n^h$). This implies that the monopolist's second-period profits can be ordered as $\pi_c^* > \pi_b^* = \pi_f^* > \pi_n^*$. Hence, the monopolist would optimally chooses full compatibility between the old and new products.

On the other hand, suppose the monopolist can credibly commit to the level of R&D investment and the compatibility choice in period one. The monopolist would then set the price for the unit of quality l at a level equal to the discounted utility a group 2 consumer receives over the two periods. Specifically, the total discounted utility from purchasing a unit of quality l is the sum of period-one utility, $v_2^l + \alpha n_2$, plus the discounted period-two expected utility. In period two, group 2 consumers derive the same utility as in period one $(v_2^l + \alpha n_2)$ with probability $1 - p(R_j)$ or the resale value of an old unit with probability $p(R_j)$, which depends on the monopolist's compatibility choice.

The monopolist's problem in the commitment case is thus

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \; \Pi_j = n_2 \left\{ v_2^l + \alpha n_2 + \delta [p(R_j) r_j + (1 - p(R_j))(v_2^l + \alpha n_2)] - c \right\} + \delta \left\{ p(R_j) n_2 \left[p_j^h - c \right] - R_j \right\} \tag{2}$$

where r_j denotes the secondary market price of an old unit given compatibility choice j.

Let us denote the R&D investment in this benchmark case with a hat (i.e., $\hat{R}_j$). Comparing problem (1) and problem (2), it follows that what differentiates the two sets of first-order conditions that characterize R_j^* and $\hat{R}_j$, respectively, for each j is the difference between the resale value of the old unit and the utility from its continued use in the second period. That is, the difference, $r_j - (v_2^l + \alpha n_2)$, is what drives the wedge between the commitment and non-commitment solutions. Below, a time-inconsistency problem is said to exist from the standpoint of the monopolist's profitability when the monopolist's second-period choice is different from the commitment solution.

Time inconsistent problems in this model necessarily mean that the monopolist earns a smaller profit than it could have had it been able to credibly commit to its choices in the first period. On the other hand, the monopolist's time inconsistency problem can in fact be socially beneficial. This is because if the R&D investment is successful, the social planner would want to transfer old products to group 1 consumers. However, if the resale price fully captures this benefit, and the monopolist can extract all surplus, then the monopolist's new product price in the non-commitment case equals precisely the consumer surplus created. We summarize these results in Proposition 1.

Proposition 1. The following holds with respect to the monopolist's R&D and compatibility decisions:

(i) The monopolist chooses full compatibility regardless of commitment.

(ii) There is a time inconsistent behavior regarding R&D investment:

(a) If $\alpha n_2 > v_2^l - v_1^l$, the monopolist underinvests relative to the commitment case.

(b) If $\alpha n_2 < v_2^l - v_1^l$, the monopolist overinvests relative to the commitment case.

(iii) The monopolist's time inconsistent behavior yields socially optimal outcomes.

Proposition 1 tells us that generically a durable-goods monopolist does not maximize ex ante discounted profits because it invests either too much or too little in new product R&D once it has sold its old products to the high valuation consumers. More specifically, the monopolist underinvests in R&D when the additional network benefit from an increased network size outweighs the valuation difference for a unit of quality l across the two consumer groups; and it overinvests when the network benefit is smaller than the valuation difference. Our result partly confirms the previous results in the literature that a durable-goods monopolist has an incentive to practice a type of planned obsolescence by introducing new products too frequently (see, e.g., Choi 1994; Waldman 1996).

However, the monopolist may also underinvest depending on the intensity of network benefit (α), size of the installed base (n_2), and the difference in consumer valuations ($v_2^l - v_1^l$). Holding the valuation difference constant, underinvestment is more likely to occur in an industry where the intensity of network benefit is larger, the installed base is larger, or both. One potential application of this result is to explain vaporware as the monopolist's time-inconsistent behavior. That is, suppose the monopolist announces in period one that it plans to make an R&D investment to develop a new product. However, if the monopolist underinvests in period two, then the new product development fails more often than it was expected because the monopolist invests less than it initially intended.

This contrasts to the earlier literature on vaporware, where the focus is mostly on the effects of strategic preannouncements vis-à-vis competitors (e.g., Farrell and Saloner 1986; Haan 2003; Dranove and Gandal 2003; Gerlach 2004; Choi et al. 2010). Our analysis shows another possibility that a durable goods monopolist faces a time-inconsistency problem, where the monopolist underinvests in markets where network effects are strong and the installed base is large. We suspect that these two explanations for vaporware are observationally indistinguishable. However, our explanation seems consistent with the fact that vaporware is more commonly observed in computer and gaming industries where there are significant network effects compared to other consumer durable markets.

We now consider a simple variant of this section's analysis. Until now, by assuming that the size of group 1 consumers is larger than that of group 2 consumers ($n_1 > n_2$), we gave all the bargaining power in the secondary market to the group 2 consumers. However, if we assume instead that the size of group 1 consumers is smaller than the size of group 2 consumers (or the the secondary market collapses due to some other factors that are external to the model), then the resale price for a unit of quality l in the second-hand market would be zero. Since then the monopolist cares only about the incremental benefit to the group 2 consumers, the monopoly solution is different from the social optimum. Further, both fully and backward compatible new products command the same new unit price in this case because the resale value to group 1 consumers is not internalized by the monopolist.

Proposition 2. Suppose $n_1 < n_2$ so that the resale price of old units drops to zero. Then the following holds:

(i) The monopolist is indifferent between full- and backward-compatibility both in the commitment and non-commitment cases.

(ii) The monopolist overinvests relative to the commitment level.

(iii) The monopolist underinvests relative to the socially optimal level.

Proposition 2 shows that the monopolist's overinvestment incentive holds more generally when the second-hand market collapses due to smaller residual demands and more competition between sellers. In particular, since the monopolist does not capture the resale value, the second period R&D expenditure exerts only negative externality on its first-period profit. The model also suggests that the monopolist may exhibit time-inconsistent behavior regarding the compatibility choice. That is, it may announce full (backward) compatibility in period one and then later choose to develop a backward only (full) compatible product. However, since the monopolist is indifferent in this case, a small cost advantage for supporting only backward compatibility would lead the monopolist to choose the latter.

Another subtle difference is that even though the monopolist overinvests in equilibrium, the level of its R&D investment now falls short of the socially optimal level. The reason is that the monopolist cannot capture the surplus created by the resale transaction in which units of quality l are transferred to group 1 consumers. Thus, new product introduction may appear too frequent (i.e., planned obsolescence), but in fact the frequency is lower than what is socially optimal without fully functioning secondary markets. We also know from Proposition 1 that the socially optimal compatibility choice is full compatibility. The monopolist may thus further decrease social welfare by choosing backward compatibility. Thus, in our model healthy secondary markets are desirable for network industries.

5 Extensions

In this section, we consider two extensions of the base model. First, we consider an entry of potential competitor at the beginning of the second period. Second, we consider a three-period model in which two sequential R&D investment opportunities exist.

5.1 R&D Competition

In Section 3's model, we considered the monopolist's incentive to upgrade its own product and ignored the possibility that another firm can compete against the incumbent by making an R&D investment. Assume everything is the same as in the base model with $n_1 > n_2$ except that at the beginning of the second stage an equally efficient firm can make an investment, R_e, in R&D and enter the market if it is successful, while the monopolist invests R_m. In the analysis that follows, to keep the argument more straightforward, we assume that the incumbent's and the entrant's marginal cost of production and the R&D success function are the same. The qualitative results would be similar even if we assumed asymmetric firms. Thus, for a given level of R&D expenditure, R_k, $k = e, m$, each firm develops a new product of quality h in the second period with probability $p(R_k)$.

Although the entrant may try to obtain a license to make its product compatible with the monopolist's, our discussion will be focused on the case where the potential entrant's product is not compatible with the incumbent's. An example may be the mobile phone standards, where there are currently two dominant technologies, the GSM standard and the CDMA2000 standard, which are completely incompatible. This assumption is supported by the analysis in Regibeau and Rockett (1996), where two firms decide when to introduce a new product and choose the degree of compatibility. They show that if firms make compatibility decisions when they introduce their products, then the follower prefers incompatibility; hence, the equilibrium degree of compatibility between the two firms would be zero if standardization requires the agreement of both firms.[8]

There are four possible equilibrium outcomes in the second period. First, with probability $(1-p(R_e))(1-p(R_m))$ neither firm succeeds in developing a new product. Then, no market transaction takes place. Second, with probability $(1-p(R_e))p(R_m)$ the monopolist develops a new product while the entrant does not. In this case, the rest of equilibrium behavior is the same as described in Proposition 1 above. Third, with probability $p(R_e)(1-p(R_m))$ only the entrant succeeds in R&D. Because the entrant's product is not compatible with the monopolist's units of quality l, group 2 consumers churning to the entrant's product cannot benefit from an increased network size. Likewise, group 1 consumers in the secondary

[8] A similar conclusion is reached by Katz and Shapiro (1992).

market would only be willing to pay up to $v_1^l + \alpha n_2$. Given this, the entrant will set $p_e^h = (v_2^h - v_2^l) + (v_1^l + \alpha n_2)$ and sell to group 2 consumers.

Finally, with probability $p(R_e)p(R_m)$ both firms succeed in developing a new product. In this case, group 2 consumers benefit from competition between the entrant and the incumbent. If the incumbent chooses noncompatibility for its new product, the incumbent's and the entrant's new products yield the same level of utility, and thus competition would drive the new product price down to the level of the marginal cost c.[9] However, for all the other compatibility choices, the monopolist's product yields a higher level of utility due to higher resale value, increased network benefit, or both. Therefore, a fully or one-way compatible monopolist's product will be priced strictly above the marginal cost, whereas the entrant's new product price will be driven down to the marginal cost c. Hence, the entrant earns a zero profit even though the product qualities are the same.

Proposition 3. Suppose a potential entrant can invest in R&D, and the entrant's product is not compatible with the monopolist's.

(i) The monopolist chooses full compatibility regardless of commitment.

(ii) There exists a range $\alpha \in [\alpha_{\min}, \alpha_{\max}]$, where $\alpha_{\min} \leq \frac{v_2^l - v_1^l}{n_2} \leq \alpha_{\max}$, such that the monopolist underinvests relative to the commitment case.

(iii) The monopolist underinvests, and the entrant overinvests relative to the socially optimal outcome.

The above proposition shows that our basic finding in Proposition 1 continues to hold

[9] We assume that when both the incumbent's and the entrant's products are not compatible with units of quality l, group 2 consumers chooce to buy a new unit from the incumbent monopolist when they are indifferent. This tie-breaking rule can be justified by an arbitrarily small switching cost (due to, e.g., brand loyalty).

when potential competition is taken into account. That is, there exists a range of parameter value α, in which R&D underinvestment occurs. However, outside of this range it turns out that the direction of bias depends on the R&D technologies of the two firms in a quite complex way. Further, it is shown that with potential competition the two firms' R&D investments tend to move away from the socially optimal level in the opposite directions. This is because the monopolist who cannot extract the whole surplus from consumers due to potential competition has a weaker R&D incentive, while the entrant who has no installed base spends too much in R&D from the standpoint of social welfare.

5.2 Successive R&D

So far, we have assumed that the monopolist can invest in R&D only once. In this subsection, we consider the more realistic case where there are successive R&D investments while the secondary market is fully operative. To be precise, assume everything is the same as in the base model except for the following. Instead of two periods, we now assume consumers live for three periods, and the monopolist has two R&D investment opportunities. The monopolist can first develop a medium-quality product ($k = m$) in period 2 and, if it is successful, can invest in period 3 to produce a high-quality product ($k = h$). Note that innovation is sequential in the sense that only if the monopolist succeeds in the first R&D it can invest in the second R&D. Hence, if the monopolist fails in the first R&D, it can only invest in R&D for the medium-quality product at the beginning of period 3.

On the demand side, there are now three groups of consumers (denoted $i = 1, 2, 3$). Group 3 is the highest valuation group. Group 2 has the next highest valuation, and group

1 has the lowest valuation. Let n_i denote the size of each consumer group. With two R&D opportunities and three consumer groups the analysis can be complicated because the secondary market prices crucially depend on the relative sizes of the consumer groups. Here we focus on the case where $n_1 = n_2 = n_3$ and give full bargaining power to higher types, which ensures that the resale price remains positive. As in our previous analysis, we assume that in any period the monopolist has an incentive to sell new units only to group 3 consumers. Let R denote the period 2 investment, and $T_{l(m)}$ denote the period 3 investment when the monopolist's current technology is $l(m)$ respectively. For simplicity, we assume that the R&D success functions are the same in all three cases, $p(R) = p(T_l) = p(T_m)$, where we make the usual technical assumptions as stated in Section 3.

Because the secondary market is operative, when both period 2 and period 3 R&D investments succeed, group 2 consumers will be able to sell old units of quality l to group 1 consumers who have not purchased anything so far, and buy old units of quality m from group 3 consumers who may want to purchase the new units of quality h. Similarly, if the monopolist succeeds in R&D in period 2, then the new product price should induce group 3 consumers to buy the new product and sell the old units in the resale market. We compare the equilibrium R&D investments in each of the two stages with those that would result if the monopolist could commit to a level of R&D investment only for the immediate next level of product development; that is, where the monopolist can commit to a level of R and T_l in period 1, and a level of T_m in period 2 (only if the first R&D investment succeeded).

Proposition 4. Suppose that the monopolist can invest twice in periods 2 and 3, and innovation results in a higher quality product.

(i) There is a time inconsistent behavior regarding the first R&D investment:

(a) If $\alpha n_3 > v_3^l - v_2^l$ and δ is smaller(larger) than a certain threshold, the monopolist underinvests(overinvests) relative to the commitment case.

(b) If $\alpha n_3 < v_3^l - v_2^l$, the monopolist overinvests relative to the commitment case.

(ii) There is a time inconsistent behavior regarding the second R&D investment, where $k = l(k = m)$ if the monopolist fails(succeeds) in the first R&D:

(a) If $\alpha n_3 > v_3^k - v_2^k$, the monopolist underinvests relative to the commitment case.

(b) If $\alpha n_3 < v_3^k - v_2^k$, the monopolist overinvests relative to the commitment case.

(iii) The monopolist chooses full compatibility regardless of commitment.

(iv) The equilibrium levels of R&D investments are socially optimal.

The above proposition shows that the initial results in Proposition 1 remain unchanged for the second R&D investment. That is, as long as the valuation difference between consumer groups is smaller than the additional network benefit from the secondary market trade, the monopolist underinvests in R&D relative the commitment case. What is different from the previous result is that in the first R&D investment unless the discount factor is sufficiently small the monopolist overinvests even if the network benefit is larger than the valuation difference. This occurs because if the monopolist is sufficiently patient, then it overinvest in the first R&D in order to exploit another profit opportunity from the second R&D investment, and this force weakens the monopolist's underinvestment incentive in the intermediate stage (i.e., period 2).

The above result in Proposition 4 is related to Fishman and Rob (2000). Fishman and Rob consider multiple, sequential innovations by a durable goods monopolist, and show that the monopolist invests too little in comparison with the social optimum. This is because in their model the monopolist, not being able to capture the consumer utility from a new product when a higher quality product is introduced, waits for a longer period during which consumers pay for the services of the initial product. In Fishman and Rob's model, however, there is no secondary market trade, so the surplus created by innovations cannot be captured by the resale value. Recall that in Section 3 we found that when the secondary market collapses the monopolist underinvests relative to the social optimum, which is consistent with Fishman and Rob's finding.

6 Conclusion

Although network effects play a central role in industries such as computer and telecommunications, relatively little is known about how they affect a durable goods monopolist's innovation incentives. The current paper is an attempt to clarify how network effects affect the monopolist's R&D incentive under time-inconsistency problems. The existing literature on planned obsolescence has emphasized that the monopolist's incentive to introduce new products is too high. We have shown that this result can be overturned if network effects are strong and the firm can choose compatibility between old and new products. It has been also showed that the monopolist may invest too little from the social welfare standpoint if the secondary market is inactive or there exists a potential competitor. The underinvestment result continues to hold under sequential innovations.

There are a few policy implications that can be drawn from our analysis. First, when the secondary market is fully operative and there is little competition, the frequency of new product introduction is socially optimal. Hence, whether the observed frequency in an industry is thought to be too high or too low, the government need not intervene. Second, the government should try to boost the firm's R&D investments in markets where secondary markets do not function well. Third, apart from product diversity the government need to encourage the incumbent's R&D investment and discourage the entrant's R&D investment in network industries. Finally, as discussed above, vaporware or underinvestment in new product development need not be a strategic (mis)behavior. In particular, vaporware is more likely to be observed at later generations of products.

7 Appendix

Proof of Proposition 1. Consider first the monopolist's problem in the second period:

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \pi_j = p(R_j) n_2 \left[p_j^h - c \right] - R_j,$$

where $p_c^h = v_2^h - v_2^l + v_1^l + 3\alpha n_2$, $p_b^h = p_f^h = v_2^h - v_2^l + v_1^l + 2\alpha n_2$, and $p_n^h = v_2^h - v_2^l + v_1^l + \alpha n_2$ as shown in the text.

The first-order condition with respect to R_j is

$$\begin{aligned} p'(R_j^*) n_2 [v_2^h - (v_2^l - v_1^l) + 3\alpha n_2 - c] &= 1 \text{ for } j = c, \\ p'(R_j^*) n_2 [v_2^h - (v_2^l - v_1^l) + 2\alpha n_2 - c] &= 1 \text{ for } j = b,\ f, \\ p'(R_j^*) n_2 [v_2^h - (v_2^l - v_1^l) + \alpha n_2 - c] &= 1 \text{ for } j = n, \end{aligned}$$

respectively.

Since $\partial\pi_j/\partial p_j^h > 0$ by the envelope theorem and $p_c^h > p_b^h = p_f^h > p_n^h$, it follows that the second-period profit can be ranked as $\pi_c^* > \pi_b^* = \pi_f^* > \pi_n^*$. Thus, the monopolist chooses full compatibility in the second period.

Now consider the commitment solution, which can be reduced to

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \Pi_j = p(R_j)n_2[r_j - (v_2^l + \alpha n_2) + (p_j^h - c)] - R_j,$$

where the resale prices are $r_c = r_f = v_1^l + 2\alpha n_2$ and $r_b = r_n = v_1^l + \alpha n_2$ under each compatibility choice.

Here the set of first-order conditions are

$$\begin{aligned}
p'(R_j^*)n_2[v_2^h - 2(v_2^l - v_1^l) + 4\alpha n_2 - c] &= 1 \text{ for } j = c, \\
p'(R_j^*)n_2[v_2^h - 2(v_2^l - v_1^l) + 2\alpha n_2 - c] &= 1 \text{ for } j = b, \\
p'(R_j^*)n_2[v_2^h - 2(v_2^l - v_1^l) + 3\alpha n_2 - c] &= 1 \text{ for } j = f, \\
p'(R_j^*)n_2[v_2^h - 2(v_2^l - v_1^l) + 1\alpha n_2 - c] &= 1 \text{ for } j = n.
\end{aligned}$$

Since $p_c^h > p_b^h = p_f^h > p_n^h$ and $r_c = r_f > r_b = r_n$, it follows again from the envelope theorem that the discounted profits for each j can be ranked as $\Pi_c^* > \Pi_f^* > \Pi_b^* > \Pi_n^*$. Therefore, the monopolist chooses full compatibility in the first period.

Next, compare the two first-order conditions under each regime when $j = c$. Notice that $v_2^h - (v_2^l - v_1^l) + 3\alpha n_2 - c > v_2^h - 2(v_2^l - v_1^l) + 4\alpha n_2 - c$ if and only if $v_2^l - v_1^l > \alpha n_2$. Because $p(R)$ is concave, it follows that $R_c^* \gtreqless \hat{R}_c$ if $v_2^l - v_1^l \gtreqless \alpha n_2$ as claimed.

Finally, consider the problem of a social planner who maximizes social surplus:

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : p(R_j) n_2 [s_j - c] - R_j,$$

where s_j denotes the consumer surplus created by the R&D investment with compatibility choice j.

If the R&D investment is successful, then it is optimal to produce n_2 units of quality h because only group 2 consumer's valuation is higher than c. On the other hand, consumers have unit demands, so it is efficient to have the existing n_2 units of quality l transferred to group 1 consumers. However, since the resale price fully captures utility benefit from a group 1 consumer and the monopolist price for the new units of quality h is the sum of resale price and the incremental benefit group 2 consumers receive, it follows that $s_j = p_j$ for all j. Therefore, the planner's problem is the same as that of the monopolist's in the second period, and the monopolist's choices must be socially optimal. ■

Proof of Proposition 2. Due to competition, the resale value of the old unit of quality l is driven down to zero regardless of the compatibility between the old and new units. Hence, the monopoly price for a unit of quality h equals the incremental benefit to the group 2 consumers, which is $p_c^h = p_b^h = v_2^h - v_2^l + \alpha n_1$ and $p_f^h = p_n^h = v_2^h - v_2^l$. Notice that under full and backward compatibility, group 2 consumers receive additional network benefit of αn_1. The monopolist's problem in the second period is the same as above,

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \pi_j = p(R_j) n_2 \left[p_j^h - c\right] - R_j.$$

Therefore, we obtain $\pi_c^* = \pi_b^* > \pi_f^* = \pi_n^*$.

The monopolist's problem under commitment reduces to

$$\max_{R_j \geq 0, j \in \{c,b,f,n\}} : \Pi_j = p(R_j)n_2[(p_j^h - c) - (v_2^l + \alpha n_2)] - R_j,$$

where the first-order condition is

$$p'(R_j)n_2[(p_j^h - c) - (v_2^l + \alpha n_2)] = 1 \text{ for each } j.$$

Since $p_c^h = p_b^h > p_f^h = p_n^h$, it follows that $\Pi_c^* = \Pi_b^* > \Pi_f^* = \Pi_n^*$. Because the two programs differ only in the additional negative term in the latter, it is straightforward that $R_j^* > \hat{R}_j$ for each j.

On the other hand, the consumer surplus s_j created by the introduction of new product is the sum of the utility group 1 consumers get from the old units of quality l and the incremental utility of group 2 consumers. Since the monopolist cannot capture the utility of group 1 consumers through its pricing of new product, $p_j^h < s_j$ for all j, it underinvests relative to the socially optimal level in all cases of j. ■

Proof of Proposition 3. The potential entrant's problem is as follows:

$$\max_{R_e \geq 0} : \pi_e = n_2 p(R_e)(1 - p(R_{m,j}))[(v_2^h - v_2^l) + (v_1^l + \alpha n_2) - c] - R_e.$$

The first-order condition is

$$n_2 p'(R_e)(1-p(R_m))[(v_2^h - v_2^l) + (v_1^l + \alpha n_2) - c] = 1, \tag{3}$$

which tells us that, other things being equal, the entrant's optimal reaction $R_e^*(R_m)$ is a decreasing function of the monopolist's R&D investment R_m.

The monopolist's problem in the second period is given by

$$\begin{aligned} \max_{R_{m,j}\geq 0, j\in\{c,b,f,n\}} \quad : \quad \pi_{m,j} &= n_2(1-p(R_e))p(R_{m,j})[p_{m,j}^h - c] \\ &+ n_2 p(R_e)p(R_{m,j})[q_{m,j}^h - c] - R_{m,j}, \end{aligned}$$

where $p_{m,j}^h$ is the price the monopolist charges when the entrant fails to innovate; hence, $p_{m,j}^h$ is the same as in the proof of Proposition 1, and $q_{m,j}^h$ denotes the price the monopolist charges when it faces competition from the entrant. Following the argument in the main text, $q_{m,c}^h = c+2\alpha n_2$, $q_{m,b}^h = q_{m,f}^h = c+\alpha n_2$, and $q_{m,n}^h = c$. Since $p_{m,c}^h > p_{m,b}^h = p_{m,f}^h > p_{m,n}^h$, it follows from the envelope theorem that $\pi_{m,c}^* > \pi_{m,b}^* = \pi_{m,f}^* > \pi_{m,n}^*$. The first-order condition is

$$n_2(1-p(R_e))p'(R_{m,j})[p_{m,j}^h - c] + n_2 p(R_e)p'(R_{m,j})[q_{m,j}^h - c] - 1 = 0. \tag{4}$$

Now consider group 2 consumers' willingness to pay for a unit of quality l in period one. With probability $(1-p(R_e))(1-p(R_{m,j}))$, a group 2 consumer will continue to use the old units of quality l. With complementary probability, a group 2 consumer anticipates to resell old units to group 1 consumers in the second period. Thus, the monopolist's problem under commitment is given as

$$\begin{aligned}\max_{R_{m,j}\geq 0, j\in\{c,b,f,n\}} &: \Pi_j = n_2\{v_2^l + \alpha n_2 + \delta[(p(R_{m,j}) + p(R_e) - p(R_{m,j})p(R_e))r_j \\ &+(1 - p(R_{m,j}) - p(R_e) + p(R_{m,j})p(R_e))(v_2^l + \alpha n_2)]\} \\ &+\delta\{n_2(1-p(R_e))p(R_{m,j})[p_{m,j}^h - c] + n_2 p(R_e)p(R_{m,j})[q_{m,j}^h - c] - R_{m,j}\},\end{aligned}$$

where the resale prices are $r_c = r_f = v_1^l + 2\alpha n_2$ and $r_b = r_n = v_1^l + \alpha n_2$. Thus, it follows that $\Pi_c^* > \Pi_f^* > \Pi_b^* > \Pi_n^*$. The first-order condition is

$$\begin{aligned}& n_2\left\{(p'(R_{m,j}) - p'(R_{m,j})p(R_e)) + [(p'(R_e) - p(R_{m,j})p'(R_e))]\frac{\partial R_e^*}{\partial R_{m,j}}\right\}(r_j - (v_2^l + \alpha n_2)) \\ & -n_2 p'(R_e)p(R_{m,j})\{p_{m,j}^h - q_{m,j}^h\}\frac{\partial R_e^*}{\partial R_{m,j}} \\ & +n_2(1-p(R_e))p'(R_{m,j})[p_{m,j}^h - c] + n_2 p(R_e)p'(R_{m,j})[q_{m,j}^h - c] - 1 \\ = \;& 0.\end{aligned}$$

The first-order condition of the commitment problem differs from that of the noncommitment problem by the following term,

$$\begin{aligned}& n_2\left\{(p'(R_{m,j}) - p'(R_{m,j})p(R_e)) + [(p'(R_e) - p(R_{m,j})p'(R_e))]\frac{\partial R_e^*}{\partial R_{m,j}}\right\}(r_j - (v_2^l + \alpha n_2)) \\ & -n_2 p'(R_e)p(R_{m,j})\{p_{m,j}^h - q_{m,j}^h\}\frac{\partial R_e^*}{\partial R_{m,j}}.\end{aligned}$$

Note that the last term is positive since $j^* = c$ and therefore $p_{c,j}^h > q_{c,j}^h$, and $\frac{\partial R_e^*}{\partial R_{m,j}} < 0$ as shown above. On the other hand, the sign of the first bracketed term is ambiguous because $r_c - (v_2^l + \alpha n_2) = v_1^l - v_2^l + \alpha n_2 \gtreqless 0$. In particular, there exists a range of α, including

$\alpha = \frac{v_2^l - v_1^l}{n_2}$, where the first term is made sufficiently small and so the whole expression above becomes positive.

The social planner's problem is given by

$$\max_{R_e, R_{m,j} j \in \{c,b,f,n\}} : n_2 p(R_{m,j}) \left[s_{m,j} - c\right] - R_{m,j} + n_2(1 - p(R_{m,j}))p(R_e) \left[s_e - c\right] - R_e.$$

It is only when the monopolist fails that the entrant's R&D investment is socially useful. Note that the consumer surplus $s_{m,j}$ is maximized with full compatibility for the monopolist's products. Thus, from above discussion it is easy to see that $s_{m,c} = v_2^h - v_2^l + v_1^l + 3\alpha n_2$ and $s_e = v_2^h - v_2^l + v_1^l + \alpha n_2$. The first-order conditions are then

$$\begin{aligned} n_2(1 - p(R_{m,j}))p'(R_e) \left[v_2^h - v_2^l + v_1^l + \alpha n_2 - c\right] &= 1, & (5) \\ n_2 p'(R_{m,c}) \left[v_2^h - v_2^l + v_1^l + 3\alpha n_2 - c\right] &= 1. & (6) \end{aligned}$$

Note that conditions (3) and (5) are the same. On the other hand, conditions (4) and (6) are different because, the incumbent monopolist cannot extract the whole surplus from group 2 consumers when both firms are successful in R&D. Therefore, the monopolist's equilibrium R&D investment $R_{m,c}^*$ is smaller than the socially optimal level. Then, it is immediate from the strategic substitutability between R_e^* and $R_{m,c}^*$ that the equilibrium R&D investment by the entrant is greater than the social optimum. ■

Proof of Proposition 4. It is straightforward to show that the monopolist always chooses full compatibility in both commitment and noncommitment cases, so we fix $j = c$ in this proof.

First, consider the monopolist's R&D decision in the last period. If the monopolist has failed in the first R&D, it can now invest T_l to develop products of quality m. In this case, the monopolist's problem is given by

$$\max_{T_l \geq 0} : p(T_l) n_3 \left[v_3^m - v_3^l + v_2^l + 3\alpha n_3 - c \right] - T_l.$$

The first-order condition is

$$p'(T_l) n_3 \left[v_3^m - v_3^l + v_2^l + 3\alpha n_3 - c \right] = 1.$$

If the monopolist has succeeded in the first R&D, it can invest T_m to develop products of quality h in period three. When the R&D is successful, the monopolist will sell quality h to group 3 consumers. In this process, group 2 consumers will be induced to sell old units of quality l to group 1 consumers and buy old units of quality m from group 3 consumers in the secondary market. Group 2 consumers' gross utility from such transactions is $v_2^m + 3\alpha n_3 + (v_1^l + 3\alpha n_3)$, while their utility in the last period is $v_2^l + 2\alpha n_3$ if they choose to keep their old units of quality l. Then, the resale price of quality m must be equal to $v_2^m + 3\alpha n_3 + (v_1^l + 3\alpha n_3) - (v_2^l + 2\alpha n_3) = v_2^m - v_2^l + v_1^l + 4\alpha n_3$. Given the incremental value of quality upgrade for group 3 is $v_3^h - v_3^m + \alpha n_3$, the price for quality h is given by $v_3^h - v_3^m + v_2^m - v_2^l + v_1^l + 5\alpha n_3$. The monopolist's problem is then

$$\max_{T_m \geq 0} : p(T_m) n_3 \left[v_3^h - v_3^m + v_2^m - v_2^l + v_1^l + 5\alpha n_3 - c \right] - T_m,$$

and the first-order condition is given by

$$p'(T_m)n_3\left[v_3^h - v_3^m + v_2^m - v_2^l + v_1^l + 5\alpha n_3 - c\right] = 1.$$

Second, consider the monopolist's R&D decision in the second period. Suppose the monopolist has succeeded in developing quality m. The monopoly price p^m for units of quality m must satisfy the following inequality:

$$\begin{aligned} v_3^l + \alpha n_3 + \delta u_3^l \quad \leq \quad & v_3^m + 2\alpha n_3 + (v_2^l + 2\alpha n_3) - p^m \\ & + \delta[p(T_m)(v_2^m + 3\alpha n_3) + (1 - p(T_m))(v_3^m + 2\alpha n_3)], \end{aligned}$$

where $u_3^l = v_2^l + 2\alpha n_3$ if the monopolist succeeds in R&D in period three and $u_3^l = v_3^l + \alpha n_3$ otherwise. Note that the left-hand side is group 3 consumers' continuation utility when they continue to use a unit of quality l in period two. The right-hand side is group 3 consumers' continuation utility when they buy a unit of quality m: the sum of the current-period utility, the resale value of a unit of quality l, and the expected utility of quality m in the next period. The monopolist's problem is then given by

$$\max_{R\geq 0} : p(R)n_3\left[p^m - c\right] - R,$$

where $p^m = v_3^m - v_3^l + v_2^l + 3\alpha n_3 + \delta[p(T_m)(v_2^m + 3\alpha n_3) + (1 - p(T_m))(v_3^m + 2\alpha n_3) - (v_2^l + 2\alpha n_3)]$.

Now suppose the monopolist's R&D decision when it can commit to a level of investment. Consider first the case where the monopolist can commit to a level of T_m in period two. Note that the wedge between the commitment and the noncommitment solution comes from the additional term in the commitment first-order condition created by taking a derivative of p^m with respect to T_m, which is

$$\delta p'(T_m)[v_2^m - v_3^m + \alpha n_3].$$

Thus, the commitment R&D investment $\widehat{T}_m$ is larger than the noncommitment investment T_m^* if $\alpha n_3 > v_3^m - v_2^m$, and the opposite holds otherwise.

Next consider the case where the monopolist can commit to a level of R and T_l in period one. Similarly, the difference between the commitment solution and the noncommitment solution comes from the expression of the price of unit of quality l,

$$\begin{aligned} p^l &= v_3^l + \alpha n_3 + \delta[p(R)(v_2^l + 2\alpha n_3) + (1 - p(R))(v_3^l + \alpha n_3)] \\ &\quad + \delta^2(1 - p(R))[p(T_l)(v_2^l + 2\alpha n_3) + (1 - p(T_l))(v_3^l + \alpha n_3)]. \end{aligned}$$

Taking a derivative of p^l with respect to R and T_l respectively, we get the following additional term in the first-order condition in the commitment case:

$$\begin{aligned} \text{w.r.t. } R &: \quad \delta p'(R)(v_2^l - v_3^l + \alpha n_3) - \delta^2 p'(R)[p(T_l)(v_2^l + 2\alpha n_3) + (1 - p(T_l))(v_3^l + \alpha n_3)], \\ \text{w.r.t. } T_l &: \quad \delta^2(1 - p(R))p'(T_l)[v_2^l - v_3^l + \alpha n_3]. \end{aligned}$$

From the second expression we can easily see that the commitment R&D investment $\widehat{T}_l$ is larger than the noncommitment investment of T_l^* if $\alpha n_3 > v_3^l - v_2^l$, and the opposite holds otherwise.

On the other hand, from the first expression we can see that for δ being sufficiently small the commitment level of R would be larger than the noncommitment level if $\alpha n_3 > v_3^l - v_2^l$, and the opposite holds otherwise. If δ is larger than a certain threshold, however, the sign of the above expression is ambiguous.

Finally, it can be readily verified that the monopolist's problem under noncommitment coincides with the social planner's problem. Since the argument is the same as in the base model, we omit this part of the proof. ■

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