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Competitive planned obsolescence

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We provide a model of planned obsolescence in a competitive market. A feature of the model is that there are configurations where a firm cannot survive in the competitive market unless its product exhibits planned and known obsolescence. This form of obsolescence is complementary to that of existing models and arises from the ability of planned obsolescence to minimize the lemons problem.

1. Introduction

■ The incentives that durability offers to a monopolist to price discriminate over time and the related difficulties that secondhand markets create in these situations have been well recognized in the economics literature. The conventional problem for the monopolist is that, having sold a durable good, there is an incentive to reduce price later to bring into the market those consumers who would not pay the initial high price. However, consumers realize that the monopolist has such an incentive to reduce price once they have purchased, and those who value the good less highly wish to withhold their purchase until price falls. For this reason the monopolist is unable to extract as much money from the market as would be possible with precommitment. This notion was first discussed by Coase (1972) and has since been developed in several articles that consider the robustness of the basic observation (see, for example, Bagnoli, Salant, and Swierzbinski, 1989; Bulow, 1982; Gul, Sonnenschein, and Wilson, 1986; and Stokey, 1981).

The essential problem is that the monopolist's actions in the future provide competition for the company in the present market. If the monopolist is able to lease the good, distort technology, or implement buyback procedures, then more profit can be extracted from the market, since these strategies restrict the aftermarket (see, for example, Fudenberg and Tirole, 1998; Kahn, 1986; and Waldman, 1996, 1997). Failing this, the monopolist has an incentive to reduce durability or make the good obsolete after a period of time (see Bulow, 1986; Choi, 1994; Hendel and Lizzeri, 1999b; Rust, 1986; and Waldman, 1993).

Since the presence of some monopoly power is essential to their arguments, these articles almost invariably analyze monopoly markets. However, obsolescence appears to be a feature that

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also arises in industries that have competitive elements (even though they may not be perfectly competitive), such as the often-cited example of annual model changes in the automobile industry. It is attractive, therefore, to consider whether planned obsolescence could arise in a competitive market, and this is the purpose of our article. Indeed, a particular feature of the model is that there are configurations where a firm cannot survive in the competitive market unless its product exhibits planned and known obsolescence. The form of planned obsolescence here is complementary to that of existing models and arises from the ability of planned obsolescence to promote healthy secondary markets in this context.

The basic idea of the model is straightforward. Goods differ in basic quality, but this is private information to the owner. There are additional built-in attributes that are observable, have value, and change over time. As new products come onto the market with better attributes, consumers who value them highly may wish to trade in their old models but face a conventional "lemons" problem. But if the attributes of the new product are sufficiently superior to those of a particular old model-type, then the owners of these model-types will be more likely to trade in both the high-quality as well as the poor-quality products. For this reason, buyers in the secondhand market (who turn out to have low value for the additional attributes) may actually pay a higher price for model-types with low levels of attribute than model-types with higher levels. This then translates into a higher initial demand for models with lower attributes in the primary market, and firms that provide higher attributes cannot find a market even at the same price as the lower-attribute models. In this context the obsolescence is planned with the aim of enhancing the secondhand market rather than killing it off. Our article formalizes this idea and explores the characteristics of the equilibria.

An important feature of our model is the effect of the secondary market on the primary market, an interaction not considered in the original Akerlof (1970) article. Other articles that have dealt with this interaction are Johnson and Waldman (2003) and Hendel and Lizzeri (1999a, 2002). These models differ from ours in several respects. The main distinction is that they do not allow for the planned obsolescence that is our central concern here. Johnson and Waldman (2003) and Hendel and Lizzeri (2002) focus on leasing, which is excluded here (however, see Section 5). Hendel and Lizzeri (1999a) have a fixed supply of durable goods and do not consider production cost. The initial price is determined by demand conditions given the fixed supply. In our analysis, competition between producers determines initial price and planned obsolescence simultaneously.

The structure of the article is as follows. In Section 2 we outline the model and introduce the equilibrium notion to be used. The model has two periods, services are consumed in both periods, and the main good is durable. The good has two features: a basic feature and additional attributes. As a concrete example, it is useful to think of the mechanical ability of a car as being a basic feature and additional factors and add-ons such as safety equipment as attributes. The basic feature can be of high or low quality, but this is private information to the owner. Attributes are a feature of the product and common knowledge. For simplicity and clarity, when defining planned obsolescence we assume that costs are driven by basic features and that attributes can be included costlessly up to a ceiling. We define a situation of planned obsolescence as one in which a supplier deliberately withholds attributes that could be added costlessly to the good and provide positive utility. Because the level of additional attributes signals the expected basic quality in the secondary market, the model is subject to the typical problem of multiple equilibria. To overcome this problem, we formalize a version of the standard belief-based refinement by extending the concept of Cho and Kreps (1987) to our environment.

In Section 3 we present our main results. We show that for generic parameters, there is a unique equilibrium satisfying this refinement. We identify three categories of equilibria according to the speed of technological progress. If technical progress is rapid, then consumers demand the best model that can be produced, since the rapid technical progress prevents the lemons problem from arising, i.e., there is no need for planned obsolescence. However, if technical progress is moderate, then consumers are better off purchasing models that do not have the highest possible attributes. This is because the higher initial utility arising from these higher attributes is not sufficient to offset the consequent lower price in the secondhand market. One can think of the preference for the lower-attribute model as a precommitment device to ensure that *ex post* it is optimal to release both high- and low-quality units rather than just lemons. Thus equilibria with moderate growth exhibit planned obsolescence. If technical progress is slow, then there is insufficient benefit associated with replacing the item and so planned obsolescence is no longer optimal.

In Section 4 we show how the approach can be extended to an infinite-horizon framework in which the consumers are long-lived, while the durable good lasts only two periods. We show that planned obsolescence can arise in every period in an infinite-horizon model. Finally, Section 5 closes with some general remarks.

2. The environment

■ **Model.** We consider a simple two-period model in which competitive firms produce and sell units of a durable good in each period. All producers are identical. There is free entry with constant returns to scale, which implies that the units are sold at production cost. One unit of the durable good produced in period $t = 1, 2$ delivers service to its current owner in periods t and $t+1$ (if period $t+1$ exists). Each unit is characterized by two attributes that are determined at the time of production: the "basic" attribute Q and the "supplementary" attribute S. Q is a random variable assuming H and L with even probabilities where $H > L > 0$, regardless of the producer and the level of S. For a unit produced in period t, S is a choice variable to be selected from a closed interval $[0, \bar{S}_t]$. We assume that exogenous technological progress increases the ceiling $\bar{S}_t$, that is, $\bar{S}_2 \geq \bar{S}_1 > 0$. The production cost of a durable good is constant at C per unit regardless of the incorporated level of S.[1] There are two groups of consumers, A and B, who live for two periods. Each group consists of identical people of measure m_i, $i = A, B$. For presentational convenience, we analyze and report the case where $m_A < m_B$; however, the core results carry over to other cases.

The per-period service value of one unit of durable good with attribute levels S and Q is $S+Q$ for group-A consumers and Q for group-B consumers; consequently, the expected service value per period of a new unit with S is $S+M$ and M for group-A and group-B consumers respectively, where $M = (H+L)/2$ is the expected value of Q. That is, group-A consumers value both attributes of the durable good, whereas group-B consumers value only the basic attribute. Each consumer consumes either one or zero units of the durable good in each period. The good can be acquired in the primary or secondary markets (as explained below). The identity of consumers (i.e., the group they belong to) is private information, so the terms of transactions cannot be specified on the identity of traders.

In each period a primary market exists in which consumers buy new units of the durable good from producers. Since the production side is competitive with free entry, any level S_t $(\leq \bar{S}_t)$ of the supplementary attribute can be obtained from a supplier at the production cost, C. The level of S_t of each unit is publicly observable. However, the value of the random variable Q of the particular unit is unknown to either producer or the customer at the time of purchase and is revealed privately to the owner after purchase. We refer to the realized level of Q as the (basic) "quality" of the unit: $Q = H$ is referred to as "high quality" and $Q = L$ as "low quality." We refer to the selected level of S_t as the "model-type."

Goods purchased in period 1 can be sold at the start of period 2; however, because the value of Q for each unit is private information to its owner, an adverse-selection problem of the Akerlof-type (Akerlof, 1970) prevails in the secondary market. We assume that there is no effective information transmission device (such as warranty), so there exists only one price $p(S_1)$ for each model-type S_1 traded in the secondary market.

[1] Note that a higher S is available at no additional cost as long as $S \leq \bar{S}_t$ in period t. This assumption is not essential for our result but makes the identification of planned obsolescence particularly straightforward. A reduction of S below $\bar{S}_t$ reduces instantaneous utility and brings no cost saving, so it is clear that this is happening to ensure that the product is obsolete to the purchaser. If cost increases in S, we would need to define obsolescence in a more complex way to separate it from a reduction in quality that is the result of a conventional cost/utility tradeoff.

Individual consumers are atomless traders who make their trading decisions based on the market prices of products. To make the purchase decision they compare the costs of available model-types against their values, including anticipated market resale prices. The market resale prices of the various secondhand model-types are described by a price function[2]

$$p : [0, \bar{S}_1] \rightarrow \Re_{++}.$$

In equilibrium, p clears the secondary markets. Resale prices of model-types that are not traded are not realized in the secondary market. Nonetheless, their resale prices are important because the reason that they are not traded is that their resale prices (in conjunction with other factors) do not justify it.[3]

We assume that consumers in each group have identical, risk-neutral utility functions that are separable between wealth and the service value of the durable good, i.e., the per-period utility is the service value of the durable good owned minus the cost of acquiring it. The total utility of a consumer is the undiscounted sum of the utilities over the two periods and each consumer maximizes the *ex ante* (expected) total utility. As an example, consider the following strategy. A consumer buys one unit of model-type S_1 in period 1; if this unit turns out to be a "plum" or of high quality ($Q_1 = H$), she keeps it in period 2; if it turns out to be a "lemon" or of low quality ($Q_1 = L$), then she sells it at $p(S_1)$ and purchases a new unit of model-type $\bar{S}_2$ in the primary market. This strategy will provide an *ex ante* total utility of

$$U_A = S_1 + M - C + \frac{S_1 + H + p(S_1) + \bar{S}_2 + M - C}{2}$$

for a consumer in group A and

$$U_B = M - C + \frac{H + p(S_1) + M - C}{2}$$

for a consumer in group B.

The supply of secondhand units of various model-types is determined primarily by the market prices, $p(S_1)$, which may differ for different model-types. The demand, on the other hand, is directly affected by another factor, namely, the belief or the expected "average (basic) quality" of the secondhand units of the model-type in question that are offered for sale. This naturally varies across model-types; in particular, the lemons problem can be more severe for some model-types, lowering the expected average quality. We describe these beliefs for various model-types by a belief function[4]

$$\beta : [0, \bar{S}_1] \rightarrow [L, H],$$

which is shared by all consumers.

Being engaged in a competitive market, individual consumers make their own purchase/resale decisions taking the price function p and the belief function β as given. A (pure) strategy σ of a consumer consists of the following components: (i) the decision on the model-type to buy in period 1 (or not to buy at all), and (ii) the decision, contingent upon the realized quality of the unit

[2] Our main results can also be obtained by modelling a bargaining process in the secondhand market as follows (but the analysis is more complex): First, all sellers of secondhand units commit and post their asking prices. Then, buyers subscribe to their choice of model-type and posted price pair, and the offered units are allocated among subscribers (randomly if there is excess demand). If buyers remain who want to subscribe to the unallocated secondhand units, a second round (of subscription and allocation) takes place in the same manner. Further rounds continue (with no time lag, hence no discounting) until either the supply or the demand runs out.

[3] Later we check the plausibility of resale prices of untraded model-types to refine equilibria.

[4] Equivalently, we may define a belief profile $\mu : [0, \bar{S}_1] \rightarrow [0, 1]$ and a belief function β on the expected quality as $\beta(S_1) = \mu(S_1)H + (1 - \mu(S_1))L$, where $\mu(S_1)$ is the posterior probability that the supplied secondhand unit of model-type S_1 is of high quality.

purchased (if one was purchased) in period 1, whether to sell the old unit at the price prescribed by p, and the decision on the model-type to buy in period 2 from either the primary or the secondary market, or not to buy one. We assume that selling and buying decisions in the secondary market are simultaneous, but we allow that one can make a purchase in the primary market contingent on sale of her secondhand unit. We denote the set of all strategies by Σ.

For analytical and expositional convenience, attention is concentrated on the levels of C in the following range:

$$2M + \frac{M - L}{2} \ < \ C \ < \ 2M + \frac{\bar{S}_2 - H}{2}. \tag{1}$$

The first inequality means that C is high enough so that in equilibrium, group-B consumers will not buy a durable good in period 1. Lemma 3 will show why the inequality must have this form, but loosely it is the lowest C that makes it unprofitable for a group-B consumer to "free ride" on group-A consumers, by purchasing the same model-type as group-A consumers and holding if high quality but replacing, if low quality, with a secondhand unit of the same model-type (which is released by group-A consumers regardless of the quality). Setting C above the lower bound in (1) makes group-B consumers' purchasing behavior in the secondhand market straightforward and facilitates the analysis without affecting the essential forces.[5] On the other hand, if C is too large, it would not be sensible in a two-period model for the consumers to purchase a new unit in the second period. The second inequality ensures that C is not too high to preclude all equilibria with replacement purchases of new units in the second period.[6]

□ **Equilibrium.** Consumers in the same group may adopt different strategies. This is described by a strategy distribution that is a probability measure over the strategy space Σ. Let μ_A and μ_B denote the strategy distributions of groups A and B, respectively. To avoid unnecessary measure theoretic complications, we focus on strategy distributions that diversify the consumers over finitely many different strategies.

Consider a pair of strategy distributions, (μ_A, μ_B), referred to as a strategy profile. A model-type S_1 is said to be available (in the resale market) if the secondhand supply of the model-type S_1 has a strictly positive measure according to (μ_A, μ_B). A secondary market is said to clear for a specific model-type S_1 (available or not) if, according to (μ_A, μ_B), the demand for and the supply of the secondhand units of model-type S_1 have the same measure. The strategy distributions μ_A and μ_B are said to be compatible if the secondhand market clears for every model-type.

For each available model-type S_1, we can calculate the expected level of the basic attribute, or the "average basic quality," by means of Bayesian updating. μ_A and μ_B are Bayes consistent with a belief function β if $\beta(S_1)$ coincides with this Bayesian updating for every available model-type.

Given a price function p and a belief function β, we can calculate the *ex ante* utilities $U_A(\sigma)$ of group A and $U_B(\sigma)$ of group B for each strategy $\sigma \in \Sigma$. A strategy $\sigma \in \Sigma$ is a best response of group A given p and β if $U_A(\sigma) \geq U_A(\sigma')$ for all $\sigma' \in \Sigma$, and analogously for group B.

A standard equilibrium refers to a collection (μ_A, μ_B, p, β) such that (i) μ_A and μ_B are compatible and Bayes consistent with β, and (ii) the support of μ_A (μ_B) consists of best responses of group A (B) given p and β.

This notion, however, is not sufficiently restrictive to prevent certain implausible off-the-equilibrium-path beliefs. In particular, a certain model-type may remain unavailable in the resale market simply because the belief about the quality of that model-type is somehow trapped at an unreasonably low level (so that the potential resale price is very low, precluding supply), even though should anyone deviate to supply such a model-type, potential buyers would revise their beliefs upward, thereby enabling the deviator to secure a higher price. We eliminate such unstable

[5] The fundamental results extend to a broader range of C but the analysis becomes more complex, mainly because of the "swapping strategy" (described in Section 3) that can then be attractive to group-B consumers. An earlier version of this work (Grout and Park, 2001) includes this more complex case.

[6] The benefit of replacement purchase is limited in the two-period model because there is no scope for resale at the end of period 2. Hence, this inequality can be loosened in longer-horizon contexts (see Section 4).

equilibria by the same idea as the Intuitive Criterion of Cho and Kreps (1987), naturally extended to our context. Here we give an informal definition that we believe provides sufficient intuition. A formal definition is in the Appendix.

Fix a standard equilibrium (μ_A, μ_B, p, β) in which group-A (B) consumers obtain equilibrium *ex ante* utility U_A^* (U_B^*). Consider a model-type S' ($\leq \bar{S}_1$) that is not traded in the secondary market and consider a price $p' > p(S')$. Suppose a consumer, say in group A, makes a deviant offer (S', p'), i.e., supplies a unit of the model-type S' and asks p' for it. For some (S', p') it could be rational for a potential buyer to purchase this unit if (i) only group-A consumers would have an incentive to deviate this way and (ii) their interim rationality would ensure that the expected quality of this unit is high enough to make the offer attractive. An equilibrium is robust if no deviation of this type exists. More specifically, the deviant offer can be interpreted as carrying the following implicit speech to potential buyers in the spirit of Cho and Kreps (1987).[7]

"By deviating this way I ought to convince you that I am in group A and that the expected quality of this unit is high enough that you will prefer buying this unit to the alternatives in the market, for the following reasons:

(i) If I am in group B, I have no incentive to do this. In particular, I would never have wished to buy S' and deviate in this way because the best *ex ante* utility a group-B consumer could expect from doing so is strictly worse than U_B^* (which can be guaranteed by following the equilibrium path) even if one can surely sell this unit at p' regardless of its quality.

(ii) If I am in group A, however, and this deviant offer convinces you of this (as it should for the reasons I am explaining), then it is clearly in my interest to do so. To see this, first note that I would indeed prefer this deviation to the equilibrium outcome if I was confident (to be justified shortly) that this deviant offer would be accepted with sufficiently high a probability; second, note that once I purchased a unit of S' based on such confidence, I would strictly prefer to make this deviant offer to not making it and retaining the unit, regardless of its realized quality.

This should convince you that any possible rationalization of this deviant offer implies that the expected quality of this unit is M. Hence, you should buy this unit because it is a strictly better deal than your supposed equilibrium purchase, which in turn justifies my aforementioned confidence and, thereby, ensures that it is in my interest to deviate this way."

If the potential buyers can actually verify that claims (i) and (ii) above are true for the deviant offer (S', p'), it would be rational for them to accept this offer. Anticipating this, a group-A consumer would indeed pursue such a deviation, thus upsetting the supposed equilibrium. An equilibrium is robust if there exists no deviant offer that upsets the equilibrium in this sense. Note that the results preceding Theorem 1 below apply for standard equilibrium, while Theorem 1 characterizes the robust equilibrium.

3. Characterization of equilibria

■ When a consumer decides to purchase a durable good in period 2 (from either the primary or secondary market), she obviously wishes to sell the old unit (if one is currently held) because the resale price is positive. This is taken for granted in all strategies in this article. We start with some preliminary results.

[7] In the current treatment, deviant offers are surprise moves that are not included in the model, in the same spirit as "neologisms" (Farrell, 1993) and "announcements" (Matthews, Okuno-Fujiwara, and Postlewaite, 1991) were dealt with in the refinement literature of cheap-talk equilibria. In the alternative model described in footnote 2, they would be off-the-equilibrium-path moves and our refinement could be defined within the model. We opted for the current approach for expositional efficiency.

Lemma 1. In equilibrium, group-A consumers do not purchase secondhand goods.[8]

Proof. See the Appendix.

Corollary 1. If group-A consumers do not purchase durable goods in period 1, or if they sell their previous purchase, then they will always buy $\bar{S}_2$ in period 2.

The basic intuition for Lemma 1 is that if group-A consumers wish in period 2 to replace their old units with a particular secondhand model-type, then they would have done better had they purchased this model-type to start with in period 1 and held it for two periods. This result dramatically reduces the possible replacement behavior that needs to be examined. It implies that $\bar{S}_2$ is the only model-type that group-A consumers may buy in period 2, because they would only consider buying new durable goods, and among these $\bar{S}_2$ gives the best value. Since it gives a positive net value,[9] they will indeed buy it when they are without a durable good at the start of period 2, as stated in Corollary 1.

Lemma 1 also implies that group-B consumers are the only buyers of secondhand units. So, all secondhand model-types traded are equivalent options for them, i.e.,

$$\beta(S_1) - p(S_1) = \beta(S_1') - p(S_1') \quad \text{for all traded model-types } S_1 \text{ and } S_1', \tag{2}$$

since group-B consumers value only the basic quality of the good (not the model-type). Furthermore, the prices they pay for them do not exceed the expected qualities. The next lemma asserts that expected qualities cannot exceed M because any consumer willing to sell a model-type when it is a plum would definitely sell it when it turns out to be a lemon. Combined with Lemma 1, this gives Corollary 2.

Lemma 2. If group-A (B) consumers find it optimal to sell high-quality units of a model-type S_1 in the secondary market, then they will also sell low-quality units of S_1.

Proof. A group-A (B) consumer would sell a high-quality unit of S_1 only if there were an alternative (weakly) preferred to keeping it, such as replacing it with another unit or simply selling it off, which must be strictly preferred to keeping a low-quality unit. *Q.E.D.*

Corollary 2. If a secondhand model-type S_1 is traded in an equilibrium, then

$$p(S_1) \leq \beta(S_1) \leq M. \tag{3}$$

These results also have implications on group-B consumers' purchasing behavior in the primary market. Since $C > 2M$ from (1), they would not buy new durable goods in period 2, nor would they buy a new unit in period 1 with an intention of keeping it for two periods, because the cost would exceed the benefit. However, they could buy a new unit in period 1 with the expectation of recovering the cost via beneficial trading opportunities in period 2. In particular, group-B consumers could possibly buy a model-type S_1 in period 1, keep it in period 2 if it turns out to be a plum, and replace it with another secondhand unit (with a higher expected quality) if it turns out to be a lemon. This we refer to as a "swapping strategy." It turns out, as the next lemma implies, that in equilibrium, group-B consumers do not adopt swapping strategies.

Lemma 3. In equilibrium, group-B consumers do not buy new durable goods in either period, and so all secondhand units traded in period 2 are supplied by group-A consumers and are purchased by group-B consumers.

[8] For knife-edge parameter values, the following meaningless replacement behavior may be possible: some group-A consumers sell lemons of model-type $\bar{S}_1$ at the price $p(\bar{S}_1) = \bar{S}_1 + L$ and then buy back a secondhand unit of $\bar{S}_1$ (known to be a lemon) at the same price. In this case, a practically identical equilibrium exists in which these consumers simply keep their secondhand units. We treat "replacing a low-quality unit with another unit of the same model-type whose quality is known to be low" as "keeping it." This interpretation is more natural and does not affect the equilibrium conditions.

[9] The net value is $\bar{S}_2 + M - C > C + H - 3M > H - M > 0$, where the first and second inequalities come, respectively, from the second and first inequalities of (1).

Proof. As asserted above, if group-B consumers buy a unit of S_1 in period 1, they sell it in period 2. Due to Lemma 1, though, buying a secondhand unit of S_1 must be one of the best options for group B in period 2 after selling the used unit. If they sell a high-quality unit of S_1, therefore, the best they can do is to buy back another secondhand unit of S_1. This is clearly worse than keeping it because $\beta(S_1) \leq M$ by (3). So, we deduce that if they buy a unit of S_1 in period 1, they engage in a swapping strategy. This would mean that group-B consumers' equilibrium utility is $2M + \frac{\beta(S_1)-L}{2} - C$. Note that this is negative by (1) and (3), an impossibility. Hence, we conclude that they never buy new goods. The second part of the lemma follows from Lemma 1. *Q.E.D.*

The separation of the two groups into distinct sellers and buyers of secondhand units further restricts the equilibrium resale price level beyond those given in (3). Note that if $p(S_1) < \beta(S_1)$, every group-B consumer would demand one unit of the secondhand good. To meet this demand, the same number (measure) of group-A consumers must supply secondhand units, which is impossible because $m_A < m_B$. Therefore,

$$p(S_1) = \beta(S_1) \quad \text{for every traded model-type } S_1. \tag{4}$$

In light of Lemma 3 and equation (4), group-B consumers are indifferent between buying a secondhand unit and not buying at all. Consequently, group-B consumers' *ex ante* equilibrium utility is always $U_B^* = 0$. Nonetheless, their purchase facilitates secondhand trading and thereby promotes diverse replacement behavior of group-A consumers. Provided that they can sell their used units at a "fair" price as in (4), group-A consumers' replacement incentives are primarily determined by how much better the new products are relative to their current ones. In fact, they will have chosen their current product strategically, taking into account its influence on subsequent replacement incentives. Such forward-looking consideration generates distinct equilibrium purchase behavior of group-A consumers depending on the speed of technological growth, i.e., $\bar{S}_2 - \bar{S}_1$. This is summarized in our main theorem below, followed by an intuitive discussion. In the sequel, equilibrium refers to robust equilibrium, and two equilibria are considered equivalent if they coincide on on-the-equilibrium paths (i.e., differ only on off-the-equilibrium paths).

Theorem 1. Given any $\bar{S}_2$, Figure 1 characterizes the robust equilibrium for different ranges of $\bar{S}_1$. Planned obsolescence arises for all $\bar{S}_1$ between S^* and $\hat{S}$, where

$$S^* = \bar{S}_2 + 2M - H - C \qquad \text{and} \qquad \hat{S} = \bar{S}_2 + \frac{5M - 2H}{3} - C. \tag{5}$$

The robust equilibrium is unique for all $\bar{S}_1$ except at three boundary levels.[10] In all three growth regions of Figure 1,

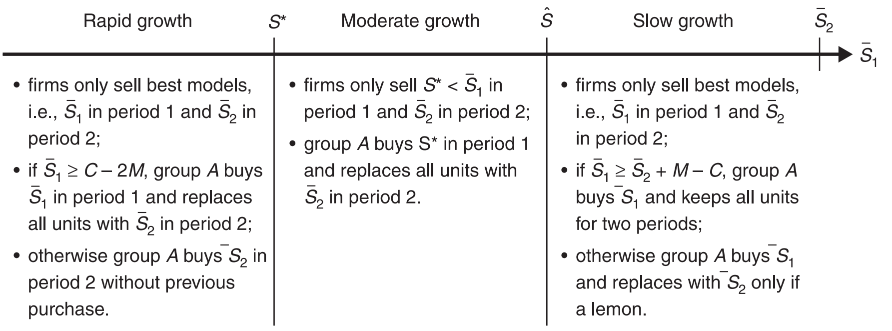
(i) $p(S) = \beta(S) = M$ if $S \leq S^*$, and $p(S) = \beta(S) = L$ if $S > S^*$;
(ii) group-B consumers buy all the used units supplied by group-A consumers.

Proof. See the Appendix.

□ **Slow growth.** If $\bar{S}_1$ is close to $\bar{S}_2$ (i.e., the growth $\bar{S}_2 - \bar{S}_1$ is slow), there is not sufficient technological progress to justify the sale of plum products. Indeed, if $\bar{S}_1$ is sufficiently close to $\bar{S}_2$, the product improvement is too little even to justify replacement of lemons, so group-A consumers simply buy the best model-type $\bar{S}_1$ in period 1 and keep it for two periods. It is obvious that in this case group-B consumers do without the durable good in both periods. However, for somewhat lower levels of $\bar{S}_1$ the product improvement will justify replacement of lemons, which will be sold to group-B consumers at the price $p(\bar{S}_1) = L$.

[10] These are $\bar{S}_1 = \hat{S}$, $C - 2M$, and $\bar{S}_2 + M - C$, each of which obviously sustains two equilibria, one conforming to each side of the boundary.

FIGURE 1



Group-A consumers prefer replacing a lemon to keeping it if

$$\bar{S}_1 + L \ \leq \ L + \bar{S}_2 + M - C, \tag{6}$$

i.e., (6) is an interim rationality constraint. So, they always keep their old unit if $\bar{S}_1$ is above $\bar{S}_2 + M - C$, while they keep it only if a plum if $\bar{S}_1$ goes below it. The *ex ante* equilibrium utility for group-A consumers is $U_A^* = 2(\bar{S}_1 + M) - C$ in the former case and $U_A^* = (3\bar{S}_1 + \bar{S}_2 + 5M - 3C)/2$ in the latter.

□ **Moderate growth (planned obsolescence).** Once $\bar{S}_1$ falls below a certain threshold, namely $\hat{S}$, the incentives change as follows. If group-A consumers buy $\bar{S}_1$ in period 1, the product improvement $(\bar{S}_2 - \bar{S}_1)$ is still not large enough to justify the replacement of a plum, so they would replace it with $\bar{S}_2$ in period 2 only if it turns out to be a lemon. However, they may buy a certain model-type, say $S^* < \bar{S}_1$, that is *just* sufficiently low to warrant replacement of an old unit regardless of its quality. Then, they would derive a lower value from using these units in period 1 but later will be able to convince the buyers (who are group B) that they release plums as well as lemons, i.e., $\beta(S^*) = M$, thereby extracting a resale price $p(S^*) = M$, higher than $p(\bar{S}_1) = L$. For this argument to be valid, replacing even a plum (of the model-type S^*) should indeed be *just* optimal (i.e., equivalent to keeping it) given the increased resale price.[11] From this we calculate the exact level of S^* as specified in (5).

If, as is indeed the case in this region, the total gain from the increased resale value more than compensates for the forgone service value in period 1, so that this behavior is preferable to buying $\bar{S}_1$ and replacing it only if it is a lemon, i.e.,

$$S^* + M - C + 2M + \bar{S}_2 - C \ \geq \ \bar{S}_1 + M - C + \frac{\bar{S}_1 + H + L + \bar{S}_2 + M - C}{2}, \tag{7}$$

then group-A consumers prefer this course of action. That is, they voluntarily elect to purchase a model-type that is less than the maximum available in period 1 even though they could buy higher model-types at the same price, a phenomenon we refer to as planned obsolescence. The *ex ante* equilibrium utility of group A is $U_A^* = S^* + \bar{S}_2 + 3M - 2C$. The threshold $\hat{S}$ that divides the slow-growth and moderate-growth regions, specified in (5), is the highest $\bar{S}_1$ subject to (7).

□ **Rapid growth.** Once the technological progress becomes sufficiently rapid ($\bar{S}_1 \leq S^*$), group-A consumers will wish to purchase a brand new model in the second period regardless.

For relatively higher $\bar{S}_1$ within this region, group-A consumers buy the best model-type $\bar{S}_1$ and replace it regardless of quality, passing on the secondhand units to group B at $p(\bar{S}_1) = M$. In

[11] It would not be robust if replacing a plum is strictly preferred to keeping it, for they could deviate and extract the same price with higher model-types.

this case, the *ex ante* equilibrium utility of group A is $U_A^* = \bar{S}_1 + \bar{S}_2 + 3M - 2C$. For even lower $\bar{S}_1$, however, purchase in period 1 is not justified at all. Then, group-A consumers simply do without the durable good in period 1 and buy $\bar{S}_2$ in period 2 only. This equilibrium occurs if

$$\bar{S}_1 + \bar{S}_2 + 2M - 2C \leq \bar{S}_2 + M - C \qquad \Longleftrightarrow \qquad \bar{S}_1 \leq C - 2M, \tag{8}$$

because only then is this behavior preferable to buying $\bar{S}_1$ and replacing regardless of the quality. The *ex ante* equilibrium utility of group A is $U_A^* = \bar{S}_2 + M - C$.

4. Extension to infinite horizon

■ The driving force behind planned obsolescence is to ensure that the future product is sufficiently superior to warrant replacement of a used good regardless of the realized quality. This force is not peculiar to the two-period models, and it can be naturally extended to longer-horizon settings in which planned obsolescence may arise in multiple periods. In fact, since a replacing unit itself can be resold in a future secondhand market (rather than the second half of its lifetime gets wasted, as in the two-period model), there are stronger incentives to replace and, as a consequence, planned obsolescence arises for slower technological growth than in the two-period model.

In this section we present a nondegenerate infinite-horizon model in which planned obsolescence takes place forever. For this to happen, on the one hand the technological growth needs to be sufficiently large between adjacent periods so that one does not have to sacrifice too much in the current attribute level to get a "fair" secondhand price; on the other hand, growth should not be too large to remove the need for planned obsolescence. We first identify the upper-bound growth rate that sustains planned obsolescence, Δ, derived in (12) below: if the technology grows at the rate of Δ or faster, the secondhand units command the fair price without planned obsolescence. If it grows at a constant rate smaller than Δ, however, a purchaser cannot continue upgrading her unit at the rate of Δ (which is required to sustain the fair secondhand price), because she would eventually desire a model-type above the technological ceiling. To sustain planned obsolescence forever, therefore, technology needs to grow more slowly than Δ but at an accelerating rate to catch up with Δ, as outlined below.

The two-period model described in Section 2 is extended as follows. Consumers live infinitely, but the durable good lasts for only two periods. In each period $t = 1, 2, \cdots$, competitive manufacturers supply, at production cost C, new durable goods of any model-type up to a maximum $\bar{S}_t$, where $\bar{S}_t < \bar{S}_{t+1}$. In each period, secondary markets operate in the same way as described earlier for units produced last period. Consumers maximize their discounted sum of utility stream where the discount factor is δ.

We first identify a benchmark environment with the aforementioned upper-bound growth rate that sustains planned obsolescence. Consider a sequence of constant technological progress, i.e., $\bar{S}_{t+1} - \bar{S}_t = \Delta > 0$ for all t. Note that the purchasing behavior of group-A consumers is governed by the relative improvement of the newly available products over the previous ones, which is the same every period for the case we are considering. Therefore, an equilibrium continuation strategy from period t onward also constitutes an equilibrium strategy from period $t + 1$ when the model-types of the durable good that is consumed and traded are upgraded by Δ in every period. We consider a stationary equilibrium in which continuation strategies are identical for every period subject to this upgrading. Let $V(\bar{S}_t)$ denote the continuation-equilibrium utility level of a group-A consumer at the point in period t when she needs to make a purchase decision. By stationarity, $V(\bar{S}_{t+1})$ is obtained from $V(\bar{S}_t)$ by adding Δ in every period, i.e.,

$$V(\bar{S}_{t+1}) - V(\bar{S}_t) = \frac{\Delta}{1 - \delta}. \tag{9}$$

We identify the value of Δ such that in the equilibrium, (i) group-A consumers continue to buy $\bar{S}_t$ and in the next period sell it regardless of the realized quality at price M (and buy $\bar{S}_{t+1}$), and (ii) in each period they are indifferent between replacing a high-quality secondhand unit and keeping it. These two conditions imply, respectively,

$$V(\bar{S}_t) = \bar{S}_t + M - C + \sum_{t' \geq t+1}^{\infty} \delta^{t'-t}(\bar{S}_t + (t'-t)\Delta + 2M - C) \tag{10}$$

and

$$\begin{aligned} M + V(\bar{S}_{t+1}) &= \bar{S}_t + H + \delta V(\bar{S}_{t+2}) \\ &= \bar{S}_t + H + \delta V(\bar{S}_{t+1}) + \frac{\delta\Delta}{1-\delta}, \end{aligned} \tag{11}$$

where the last equality follows from (9). Given the price functions $p_{t+1}(S_t) = M$ for all secondhand model-types $S_t \leq \bar{S}_t$ that may be available in period $t+1$, condition (ii) ensures that the behavior of group A proposed in (i) is indeed an equilibrium: they have no reason to buy a lower model-type because it would simply reduce the use value without any benefits. This is compatible with the behavior of group-B consumers, too: since the swapping strategy is not an attractive option for them, they find it optimal to buy secondhand units of $\bar{S}_{t-1}$ for price M in each period $t \geq 2$. Simultaneously solving (10) and (11), we can pin down the upper-bound growth rate we are seeking as

$$\Delta = H - (2+\delta)M + C. \tag{12}$$

Let $\bar{\mathcal{S}}^b = (\bar{S}_1^b, \bar{S}_2^b, \cdots)$ denote a technological path that grows at this rate, i.e., $\bar{S}_{t+1}^b - \bar{S}_t^b = \Delta$ for all $t = 1, 2, \cdots$.

Taking the sequence $\bar{\mathcal{S}}^b$ as a benchmark, we now construct other environments that exhibit planned obsolescence. Specifically, consider a sequence of technological progress $\bar{\mathcal{S}}' = (\bar{S}_1', \bar{S}_2', \cdots)$ such that

$$\bar{S}_1' - \bar{S}_1^b = \varepsilon > 0, \quad \bar{S}_t' - \bar{S}_t^b > \bar{S}_{t+1}' - \bar{S}_{t+1}^b > 0 \;\; \forall t, \quad \text{and} \quad \lim_{t\to\infty}(\bar{S}_t' - \bar{S}_t^b) = 0.$$

This is a sequence that increases from a slightly higher initial point than $\bar{\mathcal{S}}^b$ but at a slower rate; however, the speed of increase accelerates gradually to catch up with that of $\bar{\mathcal{S}}^b$, so that the gap $\bar{S}_t' - \bar{S}_t^b$ reduces and eventually converges to zero.

We now verify that for this technological progress, $\bar{\mathcal{S}}'$, there exists an equilibrium that exhibits planned obsolescence in every period. Specifically, we show that the equilibrium behavior of group A is to continue to buy $S_t^* = \bar{S}_t^b < \bar{S}_t'$ in period t and in the next period sell it regardless of the realized quality at price M (and buy $\bar{S}_{t+1}^b$). The price functions in this equilibrium are $p_{t+1}(S_t) = M$ for all secondhand model-types $S_t \leq S_t^*$ and $p_{t+1}(S_t) = L$ for $S_t > S_t^*$. Note that, for sufficiently large δ (e.g., $\delta > 1/3$), the technological progress in $\bar{\mathcal{S}}'$ is less than that needed for planned obsolescence in the two-period model, $\bar{S}_2 - \hat{S}$ in Section 3.

To verify this equilibrium, we show that no alternative behavior would be better for group A. Since they have no reason to buy a model-type lower than S_t^* (because it would simply reduce the use value without any benefits), if there was a better alternative, it must involve purchasing a new unit of model-type higher than S_t^* in some period t. If a consumer did purchase such a model-type, in the next period she would keep it if it turns out to be a plum and replace it if a lemon (since for sufficiently small ε she still prefers to replace a lemon even at a resale price L). Note that the effect of this purchase lasts only until the consumer disposes of it (either by resale or by end of its lifetime). Hence, the gain from this would be an increased use value of a magnitude less than ε for one and a half periods; the loss is a drop in resale value by $M - L$, which realizes with a probability of one-half (i.e., when a lemon). Since the loss is bounded away from zero while the gain converges to zero as ε tends to zero, there is a critical level of ε below which the alternative behavior does not pay off. This proves that the proposed behavior that exhibits planned obsolescence in every period is indeed an equilibrium.[12]

We emphasize that the rather narrowly specified path of technological growth in the constructed example is needed to ensure sustained planned obsolescence forever. (Note that, nonetheless, it is not a knife-edge example, i.e., we identified an "open" set of environments in which planned obsolescence takes place forever.) Generally, planned obsolescence may arise in different patterns in a wider class of environments. For instance, consider technological progress that alternates between spells of periods of growth faster than $\bar{S}^b$ and other spells of growth slower than $\bar{S}^b$. Then, planned obsolescence may arise when the growth is slower while it does not when the growth accelerates.

5. Concluding remarks

■ We have explored an additional motivation for planned obsolescence to that analyzed in the existing literature. The most intriguing feature of the form of planned obsolescence analyzed here is that for certain configurations it is the dominant mode of delivery in a competitive environment and in this sense is not driven by the exploitation of monopoly power.[13] This section discusses some extensions to the model.

Planned obsolescence in this article takes the form of customers wishing to purchase only products that withhold some attributes (relative to what could be supplied) in the common knowledge that the market will soon offer more up-to-date models with higher levels of attributes. That is, competitive behavior implies that their models become obsolete sooner than is necessary. It is useful to conjecture what will happen if for some reason it is only feasible to provide models that incorporate all the potential attributes that are available at the time. In this case it appears that a similar notion of planned obsolescence could arise if the firms are able to manipulate the speed of arrival of new attributes, since consumer demand may be greatest for the output of those firms that embark on an excessive R&D program. This planned obsolescence through advance R&D has similarities to that found in monopoly-based models (e.g., Waldman, 1996), although in our context it is a feature of competitive markets and is present to enhance the aftermarket, not weaken it.

Following the literature on planned obsolescence, we have excluded leasing from the model, but it is instructive to consider whether this can resolve the need for planned obsolescence. Even in the absence of moral hazard problems it appears that conventional leases would not resolve the problem.[14] For example, if firms could lease their products but could not preclude the possibility of retention by the owner, then owners of good-quality units could negotiate to retain their units and the lemons problem would reappear.[15]

For simplicity of presentation and for the reasons given in footnote 1, we have assumed that the attributes can be added at zero cost and that group-B consumers attach zero value to the attribute. However, these extreme assumptions provide rather extreme predictions, basically that whenever there is planned obsolescence we will find that cars with a higher level of attributes would sell for less than cars with a lower level. In practice we would expect attributes to have

[12] It is straightforward that this equilibrium is robust. Since no deviant offer asking a price higher than M may be accepted, due to Lemma 2, deviation by purchasing $S_t < S_t^*$ is dominated by purchasing S_t^* because $p_{t+1}(S_t) = M$ for all $S_t \leq S_t^*$. Deviation by purchasing $S_t > S_t^*$ would get a secondhand price of at most L because group-A customers prefer retaining the unit even at the best possible price M and hence is not beneficial. Furthermore, one can verify that this is the unique robust equilibrium in the same manner as in the proof of Theorem 1.

[13] Note that since this is a competitive equilibrium, the obsolescence is not planned in the sense that producers are forcing it on the consumers, but it is in the sense that producers are induced to supply such products by consumers' forward-looking demand behavior.

[14] In addition to conventional moral hazard problems, there could also be difficulties of incomplete lease contracts in some circumstances. In such cases inefficiencies will arise for the conventional reasons. (See, for example, Grout, 1984, and Hart and Holmström, 1987).

[15] See Johnson and Waldman (2003). Note, however, that Hendel and Lizzeri (2002) have shown, in a model that has similarities with Johnson and Waldman (2003), that it is never optimal to offer contracts that make all consumers return their cars at lease expiration.

TABLE 1

Variable	Coefficient	Standard Error
Time since purchase (years)	.06	.012
Fixed effect:		
Ford Taurus	.81	.052
Honda Accord	1.03	.058
Toyota Camry	1.02	.052

some value to all users and that attributes were costly to add. At the most general level, we see the main insight arising from our approach being that the value of attributes in the secondary market is "damaged" because more attributes exacerbate the lemons problem. In contrast, one would tend to think from general pricing theory that it is the units that do not offer attributes that become least valuable over time, since they fail to offer what will increasingly be seen as standard add-ons. Therefore, although not a definitive test of our model, it is useful to see if attributes depreciate faster or slower than the basic unit. Other things being equal, the more truth there is in our theory, the more likely it is that attributes will depreciate more quickly.

To provide a simple test, we examined data in buyer's guides on equipment adjustment rates (i.e., increments on the basic price to reflect additional specifications). In particular, we have taken data from Car Wizard on the depreciation of add-ons and basic units over six years for three of the most popular models in the United States.[16] The depreciation of each add-on is divided by the depreciation of the basic unit and regressed on a model dummy (one for each of the three cars) and the year since purchase. The results are summarized in Table 1. All coefficients are significant at 1%. The ratio of depreciation of add-on to base unit is larger the older the car. This is greater than one at all times for the Honda Accord and Toyota Camry and becomes greater than one for the Ford Taurus for all models that are just over three years old or older. That is, the evidence suggests that add-ons depreciate more quickly than the price of a basic unit. In contrast, in markets such as secondhand computers or televisions, where core product reliability is high, it is the most basic models that are most discounted. Some caution is required, however, when pushing this observation too far in the computer market, since the lack of functional compatibility may be at least as important for the destruction of value of the low-facility models as the presence of core product reliability.

Finally, in our equilibrium, lower levels of (added) attributes assure high (unobserved) quality. However, in a more general model where the attribute is costly to produce, high-valuation consumer types may be able to signal their type by purchasing higher-attribute models and hence suffer less from adverse selection. While for certain groups the damage from the lemons problem may be reduced, it is still essential that *ex post* they have an incentive to release both high- and low-quality models into the market, and so, for relevant parameter values, in equilibrium they will still elect to purchase model-types lower than those they would purchase in a full-information environment. In this sense, this additional signalling consideration is compatible with the link between attributes and lemons explored in this article.

Appendix

■ A formal definition of robust equilibrium, and proofs of Lemma 1 and Theorem 1 follow.

Fix a standard equilibrium (μ_A, μ_B, p, β) in which group-A (B) consumers obtain an equilibrium *ex ante* utility U_A^* (U_B^*). Let S' ($\leq \bar{S}_1$) be a model-type not traded in the secondary market and let $p' > p(S')$. Consider a hypothetical consumer (in either group) who takes p and β as given and, in addition, believes that a deviant offer (S', p') will be accepted in

[16] The data were taken from www.carwizard.com as of March 2001. The cars are Ford Taurus, Honda Accord, and Toyota Camry, and the add-ons are air conditioning, cruise control, power door locks, power steering, power windows, tilt wheel, leather interior, dual power seats, power seats, moon roof, sliding sun roof, alloy wheels, and premium wheels.

the market with probability $r > 0$. Let Σ' be the set of all strategies that this hypothetical consumer perceives: Σ' is the union of Σ, the set of standard pure strategies given (p, β), and the set of strategies involving the deviant offer (S', p'). The latter set consists of all strategies according to which (i) she buys a unit of S', (ii) depending on the realized quality she either makes the deviant offer (S', p') or not, and (iii) depending on whether this offer is accepted or not (if one was made), she either makes a purchase in the primary or secondary market, or not.

Given $r \in [0, 1]$, we can calculate the *ex ante* expected utility of each strategy $\sigma' \in \Sigma'$ for this hypothetical consumer, which we denote by $U_A(\sigma')$ if she is in group A and $U_B(\sigma')$ if in group B. A strategy $\sigma' \in \Sigma'$ is a best response of group A given (p, β, S', p', r) if $U_A(\sigma') \geq U_A(\sigma'')$ for all $\sigma'' \in \Sigma'$, and analogously for group B.

An equilibrium (μ_A, μ_B, p, β) is *upset by* a deviant offer (S', p') *by group* A if

(i) A best response of group A (B, resp.) given $(p, \beta, S', p', 1)$ generates an expected utility strictly greater than U_A^* (lower than U_B^*, resp.).
(ii) If σ'_A is a best response of group A given (p, β, S', p', r) and $U_A(\sigma'_A) \geq U_A^*$ for some $r \in [0, 1]$, then σ'_A specifies that the deviant offer (S', p') always be made regardless of the realized quality of the purchased unit of S'.
(iii) Some consumers (in either group) strictly improve upon the supposed equilibrium path by accepting the deviant offer (S', p') given that the expected quality of this unit is M.

In the same manner we define an equilibrium to be upset by a deviant offer *by group* B. An equilibrium is robust if it is not upset by any deviant offer by either group.

Proof of Lemma 1. In a given equilibrium, let $T^1 < \cdots < T^m$ be all the model-types that group-A consumers buy in period 1 and $S^1 < \cdots < S^n$ be those (if exist) for group-B consumers. We use Lemma 2 because it is proved independently.

From (1), group-B consumers do not buy a durable good in period 1 to keep it for two periods. From Lemma 2, therefore, we deduce that

Remark 1. In period 2, group-B consumers sell low-quality units of S^i that they purchased earlier.

Due to this resale motive, they must buy model-types with the highest resale price because they do not value the supplementary attribute:

$$p(S^1) = \cdots = p(S^n) = \hat{p} \geq p(S) \qquad \forall S \leq \bar{S}_1.$$

For an individual consumer in group A, buying a unit of $S < S^n$ in period 1 is dominated by buying S^n because S^n carries a higher use value and at least as high a resale value. Hence,

$$S^n \leq T^1.$$

Note further that if some group-A consumers sell high-quality units of T^j in period 2, then it is not optimal for them to buy back the same model-type in the secondary market, because doing so would amount to exchanging a high-quality unit of T^j with another unit whose expected quality is at most M from Lemma 2. Stated equivalently,

Remark 2. If some group-A consumers buy secondhand units of T^j, then group-A consumers do not sell high-quality units of T^j and, therefore, (i) $\beta(T^j) = L$ if $T^j > S^n$, and (ii) if $\beta(T^j) = L$, the equilibrium strategy is equivalent to buying and keeping a unit of T^j for two periods, hence $T^j = \bar{S}_1$.

A stronger argument applies to group-B consumers: since they do not value the supplementary attribute, they would not exchange a plum with any other unit of unknown quality. Stated equivalently,

Remark 3. If some group-B consumers buy secondhand units of *some* S^i, then they do not sell high-quality units of *any* S^i, hence $\beta(S^i) = L$ if $S^i < T^1$. This implies that no group-B consumer with a previous purchase buys secondhand units of $S^i < T^1$.

The second assertion of Remark 3 follows because such behavior would at best be equivalent to keeping a durable good for two periods. Now we prove Lemma 1 by three claims.

Claim 1. If $S^n = T^1$, group-B consumers do not sell high-quality units of S^n.

To reach a contradiction, suppose to the contrary. Then, Lemma 2 says that group-B consumers sell low-quality units of S^n as well, so their equilibrium utility is

$$U_B^* = M - C + \hat{p} + \beta(R) - p(R) \geq 0, \tag{A1}$$

where R is an optimal model-type to purchase after selling their old units ($\beta(R) - p(R) = 0$ if no purchase is optimal).

First, suppose no purchase is uniquely optimal for group B after selling old units. Then, group-B consumers generate a strictly positive net supply of secondhand goods. To generate net demand for market clearing, therefore, some group-A consumer must buy secondhand units of S^i without previous purchase. For this to be preferred to buying $\bar{S}_1$ and keeping for two periods, we need $S^n + \beta(S^n) - \hat{p} \geq 2\bar{S}_1 + 2M - C$, so that $\hat{p} < C - M$, contradicting (A1).

Next, suppose there is an optimal model-type R for group B to purchase after selling old units. By Remark 3, $R = T^j > S^n$ and group-A consumers should buy secondhand units of S^n, in particular, $S^n + \beta(S^n) - \hat{p} \geq R + \beta(R) - p(R)$, but this contradicts (A1) because $M < C - M$ from (1) while $\beta(S^n) \leq M$. This proves Claim 1.

Claim 2. Group-A consumers do not buy secondhand units of T^j.

Suppose to the contrary that they buy T^j in period 2, so that $\beta(T^j) = L$ by Remark 2 and Claim 1. Moreover, by part (ii) of Remark 2, $T^j = \bar{S}_1$ and the equilibrium utility for group A is $U_A^* = 2\bar{S}_1 + 2M - C$.

We now show $T^j = T^1 = \bar{S}_1$. If a group-A consumer buys $T^i < \bar{S}_1$, she needs to sell her used unit to obtain U_A^*. Note $p(T^i) \leq p(\bar{S}_1) + \beta(T^i) - L$: otherwise a used unit of T^i would be inferior to a used unit of $\bar{S}_1$. A straightforward calculation then leads to a contradictory conclusion that she cannot achieve U_A^*. Hence $T^1 = \bar{S}_1$.

Consider group-A consumers who buy secondhand units of $\bar{S}_1$. If they all had a previous purchase (i.e., had bought $T^1 = \bar{S}_1$), their behavior would be equivalent to no secondhand trading, as discussed in footnote 8. Hence, we consider the case that some of them buy secondhand units of $\bar{S}_1$ without previous purchase. This behavior must be equivalent to U_A^* and (weakly) better than buying $\bar{S}_2$ in period 2, from which we get $p(\bar{S}_1) < L$ due to (1). Then, group-B consumers who sell the low-quality units of their previous purchase (if these exist; see Remark 1) should buy secondhand units of $\bar{S}_1$ (see Remark 3). Likewise, group-B consumers without previous purchase should do the same. Note that $S^n < \bar{S}_1$, because $S^n = \bar{S}_1$ would imply that group-B consumers' equilibrium behavior is equivalent to buying $\bar{S}_1$ and keeping it for two periods. Therefore, the secondhand demand for $\bar{S}_1$ from group B is at least $m_B/2$. To meet this demand, all group-A consumers must buy $\bar{S}_1$ in period 1 and release it when low quality. So, no group-A consumers may demand secondhand $\bar{S}_1$ without previous purchase, contradicting our supposition. Claim 2 is proved.

Claim 3. Group-A consumers do not buy secondhand units of S^i.

By Claim 2, we only need to show this for $S^i < T^1$. Suppose to the contrary that they buy secondhand S^i. First, suppose they buy it without previous purchase, so that

$$S^i + \beta(S^i) - \hat{p} \geq S^i + U_B^*, \tag{A2}$$

where U_B^* is the equilibrium utility of group B and so the right-hand side of (A2) is the lower bound of the *ex ante* utility of group-A consumers when they follow the equilibrium behavior of group B. Note that (A2) cannot hold as a strict inequality because it would mean that group B would be better off buying S^i without previous purchase than the equilibrium path. Moreover, (A2) may hold as an equality only if group-B consumers sell secondhand units of S^i regardless of the quality and do not purchase anything afterward, because otherwise group A could do strictly better than the right-hand side of (A2) by following the equilibrium strategy of group B. This implies $\hat{p} \geq H$, but then (A2) is violated because $U_B^* \geq 0$.

Next, suppose that some group-A consumers who buy S^i had a previous purchase, say T^j. For it to be optimal for them to replace T^j of quality Q_1 with S^i,

$$T^j + Q_1 \;\leq\; p(T^j) + S^i + \beta(S^i) - \hat{p}. \tag{A3}$$

The released units of T^j, then, must be sold to group-B consumers by Claim 2, so

$$\beta(T^j) - p(T^j) \;\geq\; \beta(S^i) - \hat{p}. \tag{A4}$$

If $\beta(T^j) = L$, then (A3) must hold for $Q_1 = L$, which contradicts (A4) because $T^j > S^i$. If $\beta(T^j) > L$, then (A3) must hold for $Q_1 = H$, which again contradicts (A4) because $\beta(T^j) \leq M$. This completes the proof of Lemma 1. *Q.E.D.*

Proof of Theorem 1. Recall from Lemma 1 that group-A consumers buy only new goods. Obviously they would buy the maximum available model-type unless they planned to sell it in the next period. Therefore, in equilibrium they use one of the following four categories of strategies, (i)–(iv), because all other strategies are dominated by one of these and, hence, we need only compare these strategies to find the optimal one:

(i) buy $\bar{S}_1$ in period 1 and keep it for two periods;
(ii) buy a model-type $T \leq \bar{S}_1$ in period 1 and keep it in period 2 if the realized quality $Q_1 = H$ and replace it with $\bar{S}_2$ if $Q_1 = L$;
(iii) buy a model-type $T \leq \bar{S}_1$ in period 1 and replace it with $\bar{S}_2$ regardless of Q_1;
(iv) do not buy in period 1 and buy $\bar{S}_2$ in period 2.

Recall from Lemma 3 and equation (4) that group-B consumers may buy secondhand units only at a price equal to the expected quality, so their equilibrium utility is $U_B^* = 0$. Therefore,

$$p(S_1) \geq L \quad \text{for all } \; S_1 \leq \bar{S}_1 \tag{A5}$$

in equilibrium because otherwise there would be excess demand for the secondhand model-types with the highest value of $\beta(S_1) - p(S_1)$.

To prove the theorem, we first identify, for each category (i)–(iv), an upper bound on the expected utility level that group-A consumers may derive from a strategy in that category in equilibrium. Then, we show that for each level of $\bar{S}_1$ the strategy that achieves the maximum of these upper bounds actually constitutes an equilibrium presented in Figure 1 and that there is no other equilibrium.

We calculate the upper bounds for the four categories below. In doing so, we use the following fact observed in Section 3:

Remark 4. Since group-A consumers prefer keeping a high-quality unit of $T > S^*$ even at the maximum possible equilibrium resale price M, it follows that $p(T) = L$ for all traded secondhand model-types $T > S^*$.

(i) The expected utility from this strategy is precisely $U_A([i]) = 2(\bar{S}_1 + M) - C$.

(ii) Taking the maximum possible resale price $p(T) = M$ for $T \leq S^*$ and $p(T) = L$ for $L > S^*$, there is a threshold $\tilde{S}$ between S^* and $\hat{S}$ such that (a) if $\bar{S}_1 \geq \tilde{S}$, then buying $T = \bar{S}_1$ and selling at $p(T) = L$ if it is a lemon generates maximum utility $U_A([ii]) = (3\bar{S}_1 + \bar{S}_2 + 5M - 3C)/2$, and (b) otherwise, buying $T = \min\{S^*, \bar{S}_1\}$ and selling at $p(T) = M$ if it is a lemon generates maximum utility $U_A([ii]) = (3T + \bar{S}_2 + 4M + H - 3C)/2$.

(iii) Since this category is obviously not viable if $T > S^*$ from Remark 4, it suffices to consider group-A consumers buying a model-type up to S^* under this category. Then, the best model-type to purchase is S^* if $S^* \leq \bar{S}_1$ and $\bar{S}_1$ otherwise. So, the expected utility from this strategy has an upper bound: $U_A([iii]) = S^* + \bar{S}_2 + 3M - 2C$ if $S^* \leq \bar{S}_1$ and $U_A([iii]) = \bar{S}_1 + \bar{S}_2 + 3M - 2C$ otherwise.

(iv) The expected utility from this strategy is precisely $U_A([iv]) = \bar{S}_2 + M - C$.

For each level of $\bar{S}_1$, one can find the strategy that actually achieves the maximum of the upper bounds identified above, which we refer to as the "maximal" strategy. It is straightforward to verify that the maximal strategy for each $\bar{S}_1$ is the equilibrium strategy described in Figure 1. We now prove that this indeed constitutes a robust equilibrium and there is no other robust equilibrium.

We prove the equilibrium properties for the following equilibrium price and belief functions: $\beta(S_1) = p(S_1) = M$ for all $S_1 \leq S^*$ and $\beta(S_1) = p(S_1) = L$ for all $S_1 > S^*$. It is straightforward (hence omitted here) to show (a) the maximal strategy for each $\bar{S}_1$ is indeed a best response of group A to p and β, (b) group B's strategy (either buy a secondhand unit at the specified resale price or not buy at all) is a best response, and (c) the secondary market clears.

We now show that the equilibria in Figure 1 are robust. First, consider the range for slow growth, $\bar{S}_1 \geq \hat{S}$. Consider an arbitrary deviant offer (S', p') where $p' > p(S')$. If $p' > M$, however, no one would accept the offer: since the expected quality of S' cannot exceed M due to Lemma 2, the deviant offer is even less attractive than a unit of S' at the equilibrium $p(S')$ and $\beta(S')$, which was not demanded in the first place. Hence, we only need to consider deviant offers (S', p') where $S' > S^*$ and $L < p' \leq M$. Note that a group-B consumer would not deviate in this way regardless of the acceptance rate r, because it would generate a negative expected utility. For a group-A consumer, interim rationality implies that she would make such an offer, if she ever does, only if a it is a lemon. Hence, the posterior belief on the expected quality of this deviation is $L < p'$. So, it will not be accepted in the market. Therefore, the equilibrium is not upset by any deviant offer and, so, is robust. Finally, we conclude that there is no other equilibrium because, given (A5), group-A consumers can unilaterally implement the maximal strategy, which is the best that can be sustained in equilibrium.

Next, consider the range for moderate growth, $S^* \leq \bar{S}_1 \leq \hat{S}$. Robustness of the specified equilibrium can be proved in the same manner as above. To prove uniqueness is more involved. Since the specified strategy is the best response of group A as long as $p(S^*) = M$, if there is another equilibrium in which group-A consumers behave differently, the associated price function specifies $\tilde{p}(S^*) < M$ and the associated equilibrium utility is $\tilde{U}_A^* < U_A^*$. Note that $\tilde{U}_A^* \geq U_A([iv])$ because the strategy (iv) is autonomously implementable. Let $\tilde{T}$ be the model-type that generates an *ex ante* utility equal to $\tilde{U}_A^*$ if bought under category (iii). ($\tilde{T}$ uniquely exists because $U_A([iii])$ ranges from $\tilde{U}_A^*$ to U_A^* monotonically.) We show that the supposed equilibrium will be upset by a deviant offer (S', p') where $S' = \tilde{T} + \varepsilon$ and $p' = M - \varepsilon/2$ for sufficiently small $\varepsilon > 0$. Note that group-B consumers would never derive positive utility from this deviation for any acceptance rate r. Next, note that for sufficiently small ε, the only way for group A to do better than $\tilde{U}_A^*$ even when $r = 1$ is to buy S' and replace regardless of quality. Therefore, for any r such that group A can do better than $\tilde{U}_A^*$, they can do so only by offering (S', p') regardless of quality, hence the posterior belief must be M. Then, group-B consumers improve upon the equilibrium path by accepting this deviant offer, upsetting the supposed equilibrium.

Lastly, consider the range for rapid growth, $\bar{S}_1 \leq S^*$. Again, robustness can be shown analogously to the previous cases. Furthermore, for $C - 2M < \bar{S}_1 \leq S^*$, an argument exactly analogous to the moderate case applies to prove the uniqueness. For $\bar{S}_1 \leq C - 2M$, uniqueness follows because the specified strategy is the best that can be sustained in equilibrium and group-A consumers can implement it unilaterally.

As a final point, we note that the maximal strategy is unique except at the three boundary levels $\bar{S}_1 = \hat{S}, C - 2M$, and $\bar{S}_2 + M - C$. At each of these three levels, there are exactly two maximal strategies and, so, exactly two equilibria. This completes the proof of Theorem 1. *Q.E.D.*

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