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R & D: Allocation: Reliability Vs. Customer Cost

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R&D ALLOCATION: RELIABILITY VS. CUSTOMER COST

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The paper considers a monopoly firm with two possible R&D projects, one improving the product's reliability and the second reducing the customers' costs associated with product failure. The firm must choose one project or the other, and has a fixed budget for R&D expenditures. A condition on parameters is derived which indicates which project should be chosen. Monte Carlo analysis suggests that for the firm's decision-making the most important parameter is a measure of the ambient level of technology. From society's point of view, the most important parameter in determining the effect of the R&D choice on society is the size of the market being served by the firm.

INTRODUCTION

Although the success of any firm, industry, or country depends on decision-makers getting many things right, the present paper argues that technology choices are particularly important. And, although good decisions need to be made at all levels, the firm is where technology creates a welfare-enhancing product. It hardly needs to be said that business leaders have recognized the connections between innovation, R&D spending, quality, and national welfare:

> *Nothing can do more for the U.S. economy and to help ensure America's global competitiveness than an enhanced focus on innovation and research by the public and private sectors.*
> F. Duane Ackerman, Chairman and Chief Executive Officer – BellSouth Corporation (Liebermann, 2005, 1)

> *U.S. leadership in technology has been the cornerstone of America's strategies for driving economic growth and ensuring national security.*
> George Scalise, President, Semiconductor Industry Association (Liebermann, 2005, 1)

The goal of the present paper is to explore the R&D decision making of a monopoly firm in the case that the firm has two competing R&D projects under consideration. Briefly, the first type of R&D project improves the product's reliability while the second type of R&D project improves the product in the sense that it reduces the customer cost of failure. It is assumed that the decision-maker in the firm must choose one project or the other, and has a fixed budget for R&D expenditures. The first major result of the paper is a condition on parameters (12) that indicates which project should be chosen. The second major result suggests that of these parameters, the one which measures the ambient level of technology is most important, as will be seen in Table 5. The third major result is that the most important parameter in determining the effect of R&D choice on society is the size of the market being served by the firm. See Table 6.

LITERATURE REVIEW

The standard survey of how the U.S. became the technological leader in the period following World War II may be Nelson and Wright (1992). They argue that one key source of this leadership was "the massive private and public investments in R&D and scientific and technical education that the United States made after World War II" (1992, 1933). Crescenzi, Rodrigues-Pose and Storper (2007) argue that the U.S. has greater innovative capacity than the E.U. because it has relatively more mobile capital, population and knowledge. More generally, Brezis, Krugman, and Tsiddon (1993) have an early paper arguing that "technological change tends to reinforce the position of leading nations" (1993, 1211), which is the starting point of the present paper. Although their paper has several advantages compared to the present paper, technological improvements in their model are essentially free and exogenous, which of course, obviates the major research question of the present paper. Furman and Hayes (2004) empirically investigate how countries that were previously imitators in technologies can become leaders. They find that "the development of innovation-enhancing policies and infrastructures are necessary for achieving innovative leadership, but that these are insufficient unless coupled with ever-increasing financial and human capital investments in innovation" (2004, 1329).

Not everyone agrees with the thesis that technological progress is either necessary or sufficient for improving economic welfare. Glass (1998) argues, for example, that "technological leadership does not necessarily contribute to national welfare" (1998, 252), but it appears that this result is driven by the assumption that improving "technological leadership" reduces the rate of innovation—which is by no means obvious. There are certainly those who argue that the means of achieving technological leadership itself are not simple or easily understood, even assuming technological leadership is a desirable goal. See Nelson (1999) who has a (discursive) study of several industries which he argues provides support for both sides of the "industrial policy" debate. Finally, there are those that argue the U.S.'s comparative advantage in high tech production is diminishing because of changes in the global market for science and engineering (Freeman, 2006).

The consumer theory in this paper falls in the general line of the Sutton and Shaked (1987) literature in the sense that a distributional foundation for customer behavior is assumed. This demand structure is especially common in the quality literature. See Herguera and Lutz (2003), Chaudhuri (2000), and Herguera, Kujal, and Petrakis (2000). A uniform distribution of reservation prices is formally similar to the linear demand function with no income of Brod and Shivakumar (1997), d'Aspremont and Jacquemin (1988), and Greenlee (2005). Conceptualizing quality as a probability of product failure is not new to the literature either, see, for example, Daughety and Reinganum (1995) and Matthews and Moore (1987). Nor is the concept of a customer cost new to the literature, Jung (2004), for example, has a cost of use function for the customer. Several papers have combined the two concepts as done in the present paper, see Gretz, Highfill, and Scott (2007) and (forthcoming), but as far as we are aware, this is the first attempt to choose between R&D projects as described above. Quadratic cost of quality or R&D functions, independent of the quantity produced, are common in the literature as well. (See Brod and Shivakumar (1997), d'Aspremont and Jacquemin (1988), Greenlee (2005), and Herguera and Lutz (2003).)

THE RESEARCH AND DEVELOPMENT PROJECTS

Nearly by definition research and development expenditures improve technology, for example, the technology used in a production process and/or the technology that is embodied in a product itself. The present paper considers the latter situation—where R&D expenditures improve the "quality" of the firm's product. Quality has many possible meanings; in the present paper we focus on two key notions. The first is "reliability," the probability that the product meets the customer's expectations without having to return or repair it. One minus this probability will be defined as "product failure." Consider, for example, mining trucks, the large dump trucks used in strip or open-pit mining operations to move rock and ore from the excavation site to the surface. Usually there are a number of trucks moving between the ore and the surface so that excavation is a continuous process. In this case the concept of product failure is straightforward—a truck "fails" when it cannot be used. For other examples (microwaves, coffee makers, hair dryers—the list is almost endless) the product fails when it does not meet the wants and needs of the customer—who then returns it for exchange or repair. The probability of product failure is denoted by T. (The exposition will assume that any given customer will experience at most one product failure, although this assumption is not required in the formal analysis.)

The first type of R&D project under consideration by the decision-maker improves the product in the sense that it reduces the probability of product failure. In the mining truck example, for instance, the R&D project may be to implement a new welding process which produces stronger welds and thus reduces the probability that any given truck will fail.

The second key concept is the "customer cost of product failure" or more simply, the "customer cost of failure." In general, product failure imposes costs on customers. In the mining truck example, such costs include not only the direct costs of fixing the truck, but also all the costs associated with shutting down or slowing the line, for example, the wages for other equipment operators whose productivity depends on the smooth operation of the trucking line. In extreme cases, the customer cost of failure might well be more than the cost of the mining truck itself. For examples like consumer goods, the customer cost of failure includes the expenses associated with returning the item, or perhaps costs associated with not being able to use a microwave for a few days.

The second type of R&D project under consideration by the decision-maker improves the product in the sense that it reduces the customer cost of failure. In this case the product is neither more nor less likely to fail, but if it does fail the costs for the customer are reduced. In the mining truck example, for instance, the R&D project may be to redesign the engine so that access to certain key parts is easier thus reducing repair time and the associated costs of the line being down. For consumer products the project may also be a redesign, for example, so that customers can make simple repairs (e.g., change a bulb or a filter) themselves using help available from a call center. The customer cost of failure is denoted by K.

It is assumed that customers (or potential customers) know the probability that a unit will fail, or equivalently, the expected return rate, but not whether the unit they purchase will fail. Thus their decision to purchase depends on the "expected cost of product failure" which is the customer cost of failure times the probability the product fails, i.e., KT.

The research and development decision for the manager is conceptualized as follows. The firm (or profit center, etc.) has a fixed amount of some key resource so that both possible R&D projects cannot be done. A profit center, for example, has enough engineers to do one of the proposed R&D projects, but not both. The engineers themselves are assumed to be flexible resources in the sense that they can successfully conclude either project. (See Scott, Highfill, and Sattler (1988).) The decision maker has a fixed number of dollars to spend on R&D, denoted RDE, "research and development expenditure." Even though in the economic literature R&D expenditure is usually endogenous, our observation of firm behavior leads us to believe firms usually have an exogenous constraint for R&D expenditure. We speculate that this may be a means of controlling risk. If he or she chooses the project to reduce the failure rate, the project to reduce the customer cost of failure will not be done, and the customer cost of failure remains at its "ambient level," denoted by $K_0 > 0$, the "initial customer cost of failure." On the other hand, if the manager chooses the project to reduce the customer cost of failure, then the project reducing the failure rate will not be done, the probability of failure remaining at its ambient level, denoted by $0 < T_0 \le 1$.

The relationship between R&D expenditures on the probability of product failure and the customer cost of failure are assumed to be respectively

$$RDE = z_T (T_0 - T)^2 \text{ or } T = T_0 - \sqrt{\frac{RDE}{z_T}} \qquad (1)$$

$$RDE = z_K (K_0 - K)^2 \text{ or } K = K_0 - \sqrt{\frac{RDE}{z_K}} \qquad (2)$$

where $z_T > 0$ and $z_K > 0$. Notice that in both cases the R&D expenditure is designed to *reduce* the probability of failure or the customer cost of failure.

CUSTOMER BEHAVIOR

Suppose customers' reservation prices (denoted v) for a perfect product (or product of the highest possible quality) are uniformly distributed on the interval $(0, V)$, defining V as the highest reservation price any potential customer would have for the product; alternatively, V is the intercept of the indirect demand function for a perfect product. Defining P as the usual concept of price, i.e., the price paid by the customer when the product is originally purchased, the "full quality price" of the product is $P + KT$, the price plus the expected cost of product failure. For a perfect good $T = 0$ and the price and full quality price are the same. Recall that a *lower* quality product is thus associated with a higher value of T and vice versa. Similarly, the customer benefits from a low customer cost of failure, so small values of K are better for the customer.

Customers whose reservation price is greater than the full quality price will buy the product. Customers are indifferent between buying the product and not buying it when

$$v = (P + KT). \qquad (3)$$

Assume the population distribution function is $1/V$ and the quantity demanded is the proportion of potential customers who buy it times the number of potential buyers, denoted N. Quantity demanded, Q, is thus

$$Q = N \int_{P+KT}^{V} \frac{1}{V} dv = N\left(1 - \frac{P+KT}{V}\right).$$

The indirect demand function for the innovator is

$$P = V - KT - \frac{V}{N} Q. \qquad (4)$$

THE FIRM'S OPTIMIZATION PROBLEM

The firm (profit center, etc.) is assumed to be a simple profit maximizer. It is assumed that the manager first picks which R&D project is done, and then the firm chooses the optimal quantity. Production costs are constant per unit. The profit function is

$$\Pi = (P - mc(1+T))Q - RDE(1-S)$$

where mc is the (constant) marginal cost of production (note that the firm expects to pay this cost $(1+T)$ times as the firm must fully replace units that fail) and S is a government subsidy of private R&D expenditures. We include S for generality, however we set $S = 0$ in the Monte Carlo simulations below since the focus of this paper is on R&D project choice and not government subsidies of R&D. Substituting from (4) the profit function is

$$\Pi = (V - KT - \frac{V}{N} Q - mc(1+T))Q - RDE(1-S).$$

The profit function captures a key difference between the two proposed R&D projects. Both projects benefit customers by reducing the expected customer cost of product failure, KT. This reduction in the full quality cost implies that more customers will purchase the product at a given price P, or equivalently, the price the firm will receive for a given quantity of sales will increase. But the R&D project that reduces the probability of failure helps the firm in a second way because it reduces the number of replacement units that have to be produced.

To find the optimal behavior, recalling that the level of R&D spending is exogenous, it is sufficient that the firm maximize variable profits

$$VP = (V - KT - \frac{V}{N} Q - mc(1+T))Q. \qquad (5)$$

In the case that the manager chooses the R&D project that improves quality (reduces the expected return rate), using (1) and (5) variable profits, denoted VPT, are with a slight rearrangement

$$VPT = \left(V - (K_0 + mc)\left(T_0 - \sqrt{\frac{RDE}{z_T}}\right) - mc - \frac{V}{N} Q\right) Q \cdot \qquad (6)$$

Recall that since the R&D funds are spent on T it follows that $K = K_0$, as shown in (6).

Similarly, in the case that the manager chooses the R&D project that reduces the customer cost of failure, using (2) and (4) variable profits, denoted VPK, are

$$VPK = \left(V - T_0\left(K_0 - \sqrt{\frac{RDE}{z_K}} + mc\right) - mc - \frac{V}{N} Q\right) Q \cdot \qquad (7)$$

In this case the R&D funds are spent on K so that $T = T_0$, as shown in (7).

Equilibrium variable values as well as conditions for an internal solution for both cases are derived in the

Computational Appendix. Comparing (A2) to (A6), the decision maker should choose the R&D project which improves reliability if and only if

$$\left(mc+K_0\right)\sqrt{\frac{RDE}{z_T}} > T_0\sqrt{\frac{RDE}{z_K}}. \qquad (8)$$

To interpret (8) notice from (A1) that the marginal increase in sales from a dollar increase in R&D funding to reduce the probability of failure is

$$\frac{dQ}{d\,RDE}=\frac{N}{4V}\left(mc+K_0\right)\sqrt{\frac{1}{z_T}}\frac{1}{\sqrt{RDE}}. \qquad (9)$$

Similarly from (A5) that the marginal increase in sales from a dollar increase in R&D funding to reduce the customer cost of failure is

$$\frac{dQ}{d\,RDE}=\frac{N}{4V}T_0\sqrt{\frac{1}{z_K}}\frac{1}{\sqrt{RDE}}. \qquad (10)$$

Factoring out the terms (9) and (10) have in common, the left-hand side of (8) gives the benefit of R&D spending on reducing the probability of failure while the right-hand side of (8) gives the benefit of R&D spending on reducing the customer cost of failure. Noting the relationship between quantity and profit in (A2) and (A6), the decision maker should choose the project that has the greater marginal impact on sales and profits.

The Computation Appendix contains analytical solutions to all important variables, as well as the conditions for an interior solution. Analytical solutions lend themselves to qualitative analysis, but quantitative results are often useful as well. Condition (8) gives a relatively straightforward decision rule for managers. But quantitative results can suggest how much a firm gains by choosing the right project (and avoiding the mistake of choosing the wrong one), not to mention the gains to consumers and society at large. A Monte Carlo analysis is useful in addressing these kinds of questions. The parameter sets and simulation choices for the Monte Carlo analysis are found in the Numerical Appendix.

MONTE CARLO SIMULATIONS

Table 1 is designed to compare the outcomes of the cases when no R&D is done, the "No R&D" column, when the optimal R&D choice is made, the "Profit Maximizing R&D" column, and finally, when managers make the wrong R&D choice, the "Non-Profit Maximizing R&D" column. The first two columns are virtually self-explanatory, giving the outcomes for society and the firm in the cases described. The optimal R&D strategy as compared to no R&D at all increases social surplus on average by about 134% (17821.1/7602.8 –1), consumer surplus by about 147% (6260.4/2534.3 –1), and profits by about 128% (11560.6/5068.5 – 1) which suggests that quite a lot is at stake in the R&D decision for the firm, its customers, and society.

Table 1: Average Endogenous Variable Values from Monte Carlo Simulations when no R&D is Conducted, when the Profit Maximizing R&D Project is Chosen, and when the Non-Profit Maximizing R&D Project is Chosen

	No R&D [1]	Profit Maximizing R&D[2]		Non-Profit Maximizing R&D[3]	
		Mean	Average % Change*	Mean	Average % Change*
Social Surplus (SS)	7602.8	17821.1	237.89%	11605.7	144.79%
Consumer Surplus (CS)	2534.3	6260.4	335.56%	4188.6	61.46%
Profit (Π)	5068.5	11560.6	189.05%	7417.1	47.12%
Variable Profit (VP)	5068.5	12520.9	335.56%	8377.3	144.79%
Purchase Price (P)	404.1	434.0	12.89%	419.4	6.17%
Full Quality Price: $P+KT$	611.1	571.8	-6.66%	591.2	-3.30%
Quantity (Q)	43.2	72.2	77.41%	57.5	39.12%
Improve Reliability		45.01%		54.99%	
Reduce Customer Cost		54.99%		45.01%	

Averages based on 8740 observations.
[1] Variable values calculated with no R&D project chosen.
[2] Variable values calculated with the profit maximizing R&D project chosen.
[3] Variable values calculated with the non-profit maximizing R&D project chosen.
* Average percent change in variable from the no R&D case.

The percentage gain to consumers, regardless of which R&D project is chosen, is greater than the gain to the firm on average. While purchase price increases on average after the quality improvement, full quality price, $P + KT$, decreases. Consumers are better off even though they are paying a higher purchase price on average. The factors which determine the effect of R&D on profits will be explored further below, but notice that the profit maximizing R&D project choice for the firm is to improve the reliability of its product about 45% of the time and reduce the customer cost of product failure about 55% of the time, this is in spite of the fact (as explained in the Numerical Appendix) that the parameter sets were chosen so that *a priori* neither solution is favored in the simulations.

The third column of Table 1 shows the effect of the firm making the wrong R&D choice—i.e., improving reliability when it should be reducing customer cost of failure or vice versa. The firm's opportunity cost of choosing the wrong R&D project is large; on average the percentage increase in profit is approximately 2.7 times greater ((11560.6/5068.5 – 1)/(7417.1/5068.5 –1)) when the firm chooses the profit maximizing R&D project rather than the wrong R&D project. The opportunity cost of the wrong R&D for society is the same order of magnitude ((17821.1 /7602.8 – 1)/(11605.7/7602.8 –1)).

Next we investigate how the parameters affect R&D choice and which parameters are most important. The natural logs of the parameters are used as the independent variables to ensure comparable scale and a logit analysis is done. Marginal effects are included in Table 2 because logit coefficients do not easily lend themselves to interpretation. The elasticity of the probability of the firm choosing to improve reliability with respect to the non-logged parameters is included in the last column to show the effect of these base values. (The descriptive statistics for the independent variables are found in the Numerical Appendix.)

Table 2 shows that all parameters are important in determining which R&D projects are chosen. Note particularly that the parameters in inequality (8), the manager's decision rule, are significant and have the expected sign. However, the most interesting result in Table 2 is the size and sign of the elasticity coefficient on the ambient expected number of exchanges, T_0. The absolute value of the elasticity coefficient is more than twice the next largest elasticity which suggests that T_0 is the most important determinant of R&D project choice. The sign is negative which suggests that firms are less likely to invest in improving product failure as the ambient rate of product failure becomes *larger*. After all, spending the money to reduce the expected return rate from 20% to 10% decreases the number of expected returns by 50%, however spending the same amount of money to reduce the expected return rate from 50% to 40% only decreases the number of expected returns by 20%. The former quality improvement clearly has a bigger relative impact on firm profit. But if the ambient quality is pretty bad, it makes more sense to focus on reducing the cost of failure for customers.

As an example, often when new software is introduced (say Windows Vista) the firm and consumers both expect there to be many bugs in the program. Instead of focusing R&D resources on finding and fixing the bugs before launch, the firm can decrease the cost of product failure by improving the efficiency of its customer support call center—which helps the customer whose product fails and increases profits for the firm. The implication for R&D project managers is clear; the most important factor to consider when deciding between projects is the existing level of product reliability.

The final goal of this section is to understand what types of R&D projects are correlated with the largest gains to society. To this end we regress the percentage increase in social surplus on the exogenous parameters using a log-log specification to obtain elasticity estimates. Descriptive statistics are shown in the Numerical Appendix and the regression results are shown in Table 3. The importance column in Table 3 is the regression coefficient multiplied by the standard deviation of the variable because the standard deviation of the natural log measures the average percentage change in the variable. This multiplied by the elasticity tells how much change in the variable is coming from a given independent variable. For example, the importance of K_0 is 0.405 indicating that initial customer cost of failure is causing about 41% variation in social surplus.

Our results suggest that the most important parameter is market size, N. This has intuitive appeal; a larger market size implies the gains from innovation are experienced by more agents. Other variables that deserve mention are K_0, mc, and V with sign and importance similar to previous studies of this kind (see Gretz, Highfill, and Scott (2007)). And while the sign on V may seem counter intuitive, the incremental benefit on R&D is not as large when the product already has a very high value.

CONCLUSION

The primary innovation of the paper has been to weigh the advantages for the firm of two different kinds of R&D projects. The first R&D project improves the reliability of the firm's product; the second R&D project changes the customer's experience of the product rather than the product itself. The firm's decision on which R&D project to pursue depends on parameters measuring the effectiveness of R&D spending on either project, the quality of the product in the absence of any R&D spending, and the customer's experience, also in the absence of any R&D spending. Our results suggest that the consequences when the decision maker chooses the wrong project can be substantial. Another striking result is that when the ambient reliability is quite bad, the firm does not improve the product but instead

Journal of Business & Leadership: Research, Practice, and Teaching (2005-2012), Vol. 4 [2008], No. 2, Art. 9
Journal of Business & Leadership: Research, Practice and Teaching
2008, Vol. 4, No. 2, 68-77

reduces the customer's cost of failure. This result is a consequence of the R&D function which assumes a perfectible product as in the software example. (Given enough time the software designers could find all the bugs.) In cases where the product is not perfectible we anticipate the results would be quite different. Future research might investigate the sensitivity of these results to the structure of R&D spending.

Table 2: Logit Regression Results

The Dependent Variable Takes the Value 1 if it is Profit Maximizing for the Firm to Choose the R&D Project to Improve Reliability, 0 Otherwise

Variable	Logit Estimation Beta	Logit Estimation Std. Error	Marginal Effects Beta	Marginal Effects Std. Error	Elasticity[1]
Constant	11.839*	2.235	2.650*	(0.496)	
$\ln T_0$	-8.983*	0.268	-2.011*	0.063	-5.945
$\ln K_0$	2.975*	0.110	0.666*	0.024	1.969
$\ln z_T$	-4.173*	0.202	-0.934*	0.045	-2.761
$\ln z_K$	3.824*	0.129	0.856*	0.028	2.531
$\ln mc$	1.130*	0.071	0.253*	0.015	0.748
$\ln RDE$	-0.060*	0.023	-0.014*	0.005	-0.040
$\ln V$	2.304*	0.192	0.516*	0.044	1.525
$\ln N$	0.476*	0.107	0.107*	0.013	0.315
Number of Observations	8740				
Log Likelihood	-1260.258				

* indicates significance at the 1% level.

[1] This is the elasticity with respect to the base variable (not logged). The formula reduces to $\beta(1-\alpha)$ where β is the coefficient in the logit estimation and α is the estimated probability of Improve T_0 calculated at the means.

Table 3: OLS Regression Results

Dependent Variable: Natural Log of Percentage Change in Social Surplus from Undertaking No R&D to Undertaking the Profit Maximizing R&D Project

Variable	Coefficient	Standard Error	Importance
Constant	1.801*	0.421	
$\ln T_0$	0.660*	0.019	0.545
$\ln K_0$	0.500*	0.014	0.405
$\ln z_T$	-0.298*	0.033	-0.092
$\ln z_K$	-0.120*	0.011	-0.121
$\ln mc$	0.450*	0.011	0.524
$\ln RDE$	0.145*	0.004	0.429
$\ln V$	-1.188*	0.031	-0.495
$\ln N$	0.636*	0.009	0.820
Improve Reliability Dummy	-0.006	0.031	-0.003
Number of Observations	8740		
R^2	0.686		

* indicates significance at the 1% levels.

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COMPUTATIONAL APPENDIX

For each case, either where the firm chooses to improve reliability or reduce customer cost, the goal is to obtain equilibrium variable values as well as conditions for an internal solution. We examine the case where the firm chooses to improve reliability first.

Solve the first order condition for improving reliability from (6) for Q to yield

$$Q = \frac{N}{2V}\left(V - \left(K_0 + mc\right)\left(T_0 - \sqrt{\frac{RDE}{z_T}}\right) - mc\right). \tag{A1}$$

Journal of Business & Leadership: Research, Practice and Teaching
2008, Vol. 4, No. 2, 68-77

Substitute Q from (A1) and T from (1) into (4) and let $K = K_0$ to find equilibrium price:

$$P = \frac{1}{2}\left(V - \left(K_0 - mc\right)\left(T_0 - \sqrt{\frac{RDE}{z_T}}\right) + mc\right).$$

Subtracting RDE from (6) and substituting Q from (A1) gives equilibrium profit:

$$\Pi = \frac{N}{4V}\left(V - \left(K_0 + mc\right)\left(T_0 - \sqrt{\frac{RDE}{z_T}}\right) - mc\right)^2 - RDE. \qquad (A2)$$

Consumer surplus is

$$CS = N\int_{P+KT}^{V} \frac{(v-(P+KT))}{V}dv = \frac{(V-(P+KT))^2}{2V} = \frac{V}{2N}Q^2 \qquad (A3)$$

where the latter equality uses (4). Substituting (A1) gives

$$CS = \frac{N}{8V}\left(V - \left(K_0 + mc\right)\left(T_0 - \sqrt{\frac{RDE}{z_T}}\right) - mc\right)^2$$

Finally, social surplus is the sum of profit and consumer surplus:

$$SS = \frac{3N}{8V}\left(V - \left(K_0 + mc\right)\left(T_0 - \sqrt{\frac{RDE}{z_T}}\right) - mc\right)^2 - RDE.$$

The second order condition found from (6), $\frac{\partial^2 VPT}{\partial Q^2} = -2\frac{V}{N} < 0$, always holds for positive values of V and N. However, we require profit to be non-negative for an internal solution. This occurs when

$$V - \left(K_0 + mc\right)\left(T_0 - \sqrt{\frac{RDE}{z_T}}\right) - mc \geq \sqrt{\frac{4V\ RDE}{N}}. \qquad (A4)$$

Notice that when (A4) holds it is also the case that quantity is positive and $P > mc$. Since consumer surplus is unambiguously positive, (A4) also guarantees positive social surplus. Finally, we require non-negative expected returns, $T_0 \geq \sqrt{\frac{RDE}{z_T}}$.

Now we examine the case where the firm chooses to reduce customer cost. Solve the first order condition for reducing customer cost from (7) for Q to yield

$$Q = \frac{N}{2V}\left(V - T_0\left(K_0 + mc - \sqrt{\frac{RDE}{z_K}}\right) - mc\right). \qquad (A5)$$

Substitute Q from (A5) and K from (2) into (4) and let $T = T_0$ to find equilibrium price:

$$P = \frac{1}{2}\left(V - T_0\left(K_0 - mc - \sqrt{\frac{RDE}{z_K}}\right) + mc\right).$$

Subtracting RDE from (7) and substituting Q from (A5) gives equilibrium profit:

$$\Pi = \frac{N}{4V}\left(V - T_0\left(mc + K_0 - \sqrt{\frac{RDE}{z_K}}\right) - mc\right)^2 - RDE. \qquad (A6)$$

Substitute (A5) into (A3) to obtain consumer surplus:

$$CS = \frac{N}{8V}\left(V - T_0\left(K_0 + mc - \sqrt{\frac{RDE}{z_K}}\right) - mc\right)^2 .$$

Finally, social surplus is the sum of profit and consumer surplus:

$$SS = \frac{3N}{8V}\left(V - T_0\left(K_0 + mc - \sqrt{\frac{RDE}{z_K}}\right) - mc\right)^2 - RDE .$$

As in the case where the firm improves reliability, the second order condition from (7), $\frac{\partial^2 VPK}{\partial Q^2} = -2\frac{V}{N} < 0$, always holds for positive values of V and N. Again, we require profit to be non-negative for an internal solution:

$$V - T_0\left(mc + K_0 - \sqrt{\frac{RDE}{z_K}}\right) - mc \geq \sqrt{\frac{4V\ RDE}{N}} . \tag{A7}$$

When (A7) holds it is also the case that quantity is positive and $P > mc$. Further, (A7) guarantees positive social surplus since consumer surplus is always unambiguously positive. Finally, we require non-negative customer cost of failure, $K_0 \geq \sqrt{\frac{RDE}{z_K}}$.

NUMERICAL APPENDIX

This section presents parameter sets used for the Monte Carlo simulations discussed in Section 6 as well as some preliminary results. There were 8,740 observations that yielded internal solutions out of 100,000 possible attempts. The descriptive statistics for parameter sets that yielded internal solutions are presented in Table A1. The descriptive statistics for the natural logs of parameter values are displayed in Table A2 to complement the logit and regression results.

We construct ranges for parameter sets used in the simulations to have no pre-existing bias towards improving reliability or reducing customer cost. In order to accomplish this it should be the case that the inequality shown in (12) bind on average, or formally

$$\frac{(mc + K_0)}{T_0} = \sqrt{\frac{z_T}{z_K}} . \tag{A8}$$

Gretz, Highfill, and Scott (2007) show that z_T has to be orders of magnitude larger than the other parameters to generate internal solutions. As such, the average z_T is set to 100,000. Further, in keeping in line with the mining truck situation described in Section 3, the initial customer cost of failure is allowed to be large relative to the maximum value of the product. Also, the ambient expected number of exchanges is bound by 0 and 1, inclusively. This seems reasonable as it is highly unlikely that markets where consumers expect to return the product more than once would be sustained over time. Finally, plugging in the averages of these three parameters into (A8) and solving yields $z_K = 0.025$.

Table A1: Descriptive Statistic of Parameters that Yielded Internal Solutions in Monte Carlo Simulations (8740 Observations)

Parameter	Mean	St. Dev.	Minimum	Maximum
T_0	0.43	0.27	0.00	1.00
K_0	496.36	264.30	0.47	999.79
z_T	100007.68	28812.84	50010.07	149984.61
z_K	0.03	0.01	0.00	0.05
mc	236.98	184.26	0.07	951.96
RDE **	960.22	2087.39	0.00	29596.76
V	696.59	218.59	28.88	999.96
N	439.68	313.41	0.03	999.91

* All parameters randomly selected using a uniform distribution over a range which closely follows the minimum and maximum reported. The range for K_0, mc, V, and N is 0 to 1000; the range for T_0 is 0 to 1; the range for z_K is 0 to 0.05; the range for z_T is 50,000 to 150,000.

** Constrained to make overinvestment impossible.

Table A2: Descriptive Statistics for Independent Variables used in Statistical Analysis (8740 Observations)

	Mean	St. Dev.	Minimum	Maximum
Improve Reliability Dummy (takes the value 1 if the profit maximizing R&D project choice is to improve reliability, 0 otherwise)	0.450	0.498	0.000	1.000
Natural Log of Percent Change in Social Surplus from undertaking no R&D project to choosing the Profit Maximizing R&D project	-0.079	1.655	-11.257	7.322
$\ln T_0$	-1.097	0.826	-5.538	0.000
$\ln K_0$	5.982	0.809	-0.765	6.908
$\ln z_T$	11.468	0.307	10.820	11.918
$\ln z_K$	-3.998	1.009	-11.770	-2.996
$\ln mc$	5.023	1.163	-2.663	6.859
$\ln RDE$	4.685	2.963	-16.367	10.295
$\ln V$	6.477	0.416	3.363	6.908
$\ln N$	5.589	1.290	-3.522	6.908