TRACEABILITY, INSPECTION, AND FOOD SAFETY

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Abstract

Traceability exists in many food supply chains for valid economic reasons, one of which is improving food safety and quality. Some politicians and consumer groups are calling for increased identity preservation in systems where traceability has not yet been adopted. In this paper, we explore the implications of adding traceability to a food supply chain that already includes an inspection protocol. Our objective is to determine whether the addition of traceability will change the feasibility of a market for safer food and whether it will change the allocation of profits between producers and processors. We find that the addition of traceability to this system does influence whether or not the market will be feasible. If traceability is too high, then processors will not demand safer food, and if traceability is too low, then producers will not deliver safer food. We also show that the feasibility of the market depends on the sensitivity of the test used to inspect food.

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Product inspection and traceability are common elements of commercial transactions in the food supply chain. The practice of inspecting raw materials delivered by a supplier has been used for centuries to ensure the quality and safety of a vendor's product (see Juran for numerous examples). Traceability is a newer policy that is used to improve supply management, increase safety and quality, and to differentiate finished goods on the basis of credence attributes (Golan *et al*. (March 2004)). Government regulations requiring traceability or inspection exist in many markets. However, in most markets these practices made economic sense long before they made political sense.

One objective of product inspection and traceability is to improve food safety by identifying the existence and the source of unsafe product. Knowing that unsafe food exists, and where it came from, makes is possible to eliminate the root cause of the problem and to allocate the cost of food safety failures. The principal economic incentive for producing safer food is the cost associated with unsafe food. Unsafe food that reaches the consumer can result in "safety failure costs" like product liability costs (Buzby, Frenzen, and Rasco) and stock price declines (Salin and Hooker). To avoid these costs, inspection is used to sort out unsafe product before it reaches the consumer. If a lot fails inspection, the lot never reaches the consumer and so there is no chance of a safety failure cost. However, if a lot fails inspection, then the lot producer faces "inspection failure costs" that may include rework, rectification, or scrapping the unsafe food (see Campanella for a general description of inspection failure costs).

Because traceability and inspection are different policy mechanisms, their benefits, costs, and effectiveness are often evaluated independently. However, the two mechanisms are not independent in terms of their influence on producer behavior and food safety. For example, when inspection is used to filter product moving through the supply chain, the probability that the consumer is exposed to unsafe food declines. Lower probability of a food safety failure means lower food safety failure costs to allocate to party responsible for the unsafe food.

The effect of traceability and product inspection on food safety is not unambiguous. Too much traceability can lead to market failure because the buyer will not be motivated to demand safer food, and too little traceability will cause the market to fail because the supplier will not be motivated to deliver safer food (Starbird and Amanor-Boadu). Similarly, extraordinarily rigorous inspection can lead to market failure because the supplier will not be able to get product accepted and, as Akerlof shows, when the buyer knows nothing about quality (no inspection) the supplier has no motivation to deliver safer food. The challenge is to find the level of traceability that motivates the buyer to demand safe food and motivates the supplier to deliver safer food.

In this paper, we explore the impact of these two policies on food safety and the allocation of costs when they are used in isolation and when they are used to complement one another. We compare the effects of traceability and inspection policies on the level of food safety reaching the consumer, the price of a product that passes inspection, and the overall system profit. Our system is a two-stage, assembly-type supply chain in which the buyer is a food processor and the supplier is a first-level producer. We consider three cases. In the first case, inspection is used to evaluate product safety, but there is no traceability mechanism. In the second case, the source of the food can be traced back to the first-level producer, but there is no inspection. In the last case, both inspection and traceability are used to ensure food safety.

Model

We use a principal-agent model to represent the relationship between the processor and the producer in our food supply chain. The principal-agent model is designed to represent imperfect information in economic exchanges (see Macho-Stadler and Perez-Castrillo for a detailed description of principal-agent theory). In our model, the processor is the principal and the producer is the agent. We assume that the producer knows how safe the product is but the processor does not. The processor's objective is to offer a price that maximizes the processor's expected profit subject to motivating the producer to deliver safer food. Unfortunately, the processor does not know if the product delivered by the producer is safe because safety is a credence attribution, i.e., an attribute that is not directly or immediately observable (Golan *et al*.).

We measure food safety by the proportion of the producer's output that meets all government standards for safety and we define the contamination rate, q, as the proportion of product that fails to meet at least one government standard. Our definition implicitly assumes that the government standards truly differentiate safe and unsafe food. We chose this measure of safety instead of a particular pathogen density because it captures the effect of all pathogens that influence food safety.

We make a number of assumptions in applying the principal-agent model to this problem. First we assume that there are multiple producers supplying each processor and that the producers' products are commingled. If there is only one supplier, then identify preservation is not an issue at this point in the supply chain. Second, for convenience, we assume that the producer and the processor are risk neutral. Third, we assume that traceability is measured by the proportion of the cost of a safety failure that is allocated to the producer. Full traceability means that all safety failure costs are allocated to the producer.

In the first case we consider, the product is inspected before the processor accepts delivery but there is no traceability. If the product fails inspection, the producer incurs an inspection failure cost, s. However, if an unsafe product passes inspection and causes a safety failure event when it reaches the consumer, the processor pays all of the safety failure costs. In Case II, the origin of the product can be traced back to the producer but the product is not inspected before it is delivered to the processor. If an unsafe product causes a food safety failure when it reaches the consumer, then the producer and the processor share the costs of the safety failure. Finally, in Case III, the product is inspected before the processor takes delivery and the source of the product can be traced back to the producer. In this case, the producer incurs inspection failure costs if the product does not pass inspection and shares the cost of the safety failure if an unsafe lot passes inspection. Figure 1 represents the product flow and the flow of expected revenue and costs through the supply chain.

Case I. <u>Inspection without Traceability.</u>

In this case the product is tested using an imperfect inspection procedure before the processor takes delivery. The inspection procedure is imperfect because there is a chance that an unsafe lot passes inspection and that a safe lot fails inspection. For the purposes of this analysis, we assume that every lot is inspected, but that the sensitivity (α) and specificity (β) of the test are less than one[1]. The producer's risk, the probability that a safe lot fails inspection, is 1-β and the consumer's risk, the probability that an unsafe lot passes inspection, is 1-α.

The processor's problem is:

$$
\begin{aligned}
&\underset{w}{\text{MAX}} && \lambda(p-w) - R\eta_I(q) \\
(1)\qquad &\textit{Subject to}: && w\lambda - \frac{c(q)\lambda}{P_a(q)} - \frac{1-P_a(q)}{P_a(q)} s\lambda \geq M \\
& && q \in \underset{\hat{q}}{\text{Argmax}} \left\{ w\lambda - \frac{c(\hat{q})\lambda}{P_a(\hat{q})} - \frac{1-P_a(\hat{q})}{P_a(\hat{q})} s\lambda \right\}
\end{aligned}
$$

where λ is the total number of lots purchased by the processor from this producer per year (lots/year)[2], p is the market price received by the processor (\$/lot), w is the price paid to the producer (\$/lot), $\eta_I(q)$ is the probability of a safety failure after the product reaches the consumer in a system that includes inspection, R is the expected cost of a safety failure (\$/event), q is the contamination rate, $c(q)$ is the production cost as a function of the contamination rate, and M is the minimum required profit that the producer must have in order to deliver this product. The value s is the inspection failure cost (\$/lot) and $P_a(q)$ is the probability that a lot passes inspection or the probability of acceptance. The inspection failure cost includes rework, repair, replacement, disposal, and any statutory penalties that might be imposed. The producer must make λ/P_a units in order to deliver λ units to the processor because some of the units will fail inspection.

The probability of acceptance and the probability of a food safety failure depend upon the contamination rate and the diagnostic accuracy of the inspection (sensitivity and specificity). We assume that the sensitivity and specificity include uncertainty associated with human and sampling errors. The details of the relationship between the contamination rate test specificity, test sensitivity, the probability of acceptance, and the probability of a food safety failure are provided in Appendix 1.

In the program shown in (1), the first constraint is called a participation constraint. The producer won't participate unless her expected profit is larger than M. The second constraint is the incentive compatibility constraint. This constraint means that the producer selects a contamination level that maximizes the producer's expected profit.

To simplify our analysis, we assume that there are two levels of contamination, q^L and q^H, corresponding to low contamination (safer food) and high contamination (less safe food), respectively. This simplification guarantees that our solution is a local optimum (See Macho-Stadler and Perez-Castrillo). There are cost levels, probabilities of acceptance and probabilities of a safety failure that correspond to these two contamination levels. We assume that $c^L > c^H$, $\eta_I^L < \eta_I^H$, and $P_a^L > P_a^H$ where, $c^L = c(q^L)$, $c^H = c(q^H)$, $\eta_I^L = \eta_I(q^L)$, etc.

The market for safer food exists only if the processor demands safer food and the producer is willing to deliver safer food. For Case I, the processor demands safer food if,

(2) $$\lambda(p - w^L) - R\eta_I^L \geq \lambda(p - w^H) - R\eta_I^H$$

where w^L is the price that the processor must offer in order to induce the producer to deliver q^L and w^H is the price that the processor must offer in order to induce the producer to deliver q^H. Equation (2) can also be written:

(3) $$w^L - w^H \leq \frac{R(\eta_I^H - \eta_I^L)}{\lambda}$$

This condition, the processor's participation constraint, implies that the processor demands safer food only if the incremental increase in the cost of the safer food (LHS) is less than the incremental decrease in the expected cost of a food safety failure (RHS). If the increase in cost is too large, or the incremental decline in the expected food safety failure cost is too small, then the processor will not demand safer food.

The other necessary condition for the exchange of safer food is that the producer is willing to deliver safer food. The supplier delivers safer food if the incentive compatibility constraint is satisfied. With two safety levels, this constraint reduces to:

$$\frac{c^L}{P_a^L} - \frac{c^H}{P_a^H} \leq s\left(\frac{1}{P_a^H} - \frac{1}{P_a^L}\right). \tag{4}$$

This condition means that the increase in the expected cost of producing the safer food (LHS) must be less than the incremental decline in the expected cost of failing inspection (RHS). The better the inspection procedure at distinguishing between low and high contamination, the greater the RHS, and the greater the cost that the supplier is willing to pay in order to produce safer food.

Case II. <u>Traceability without Inspection</u>

In Case II, the origin of the food product is traceable and so a portion of the safety failure costs can be allocated to the producer. The proportion of the safety failure costs allocated to the producer is called the traceability factor and is represented by π. The proportion of safety failure costs paid by the processor is $(1-\pi)$. The processor's problem is:

$$\begin{aligned} & \underset{w}{\text{MAX}} && \lambda(p-w)-(1-\pi)R\eta_{II}(q) \\ (5) \qquad & \textit{Subject to}: && \lambda(w-c(q))-\pi R\eta_{II}(q)\geq M \\ & && q\in \underset{\hat{q}}{\text{Argmax}}\ \{\lambda(w-c(\hat{q}))-\pi R\eta_{II}(\hat{q})\} \end{aligned}$$

where $\eta_{II}(q)$ is the probability of a food safety failure if no inspection is used. Some sampling inspection procedures have no effect on the probability that a unit is unsafe in the lots that pass inspection, in which case $\eta_I(q)=\eta_{II}(q)$ (see Mood). Assuming that there are only two levels of safety, q^L and q^H, the processor will demand safer food if,

$$(6) \qquad \lambda(p-w^L)-(1-\pi)R\eta_{II}^L \geq \lambda(p-w^H)-(1-\pi)R\eta_{II}^H$$

where w^L is the price at which the producer delivers q^L and w^H is the price at with the producer delivers q^H. This condition can be written:

$$(7) \qquad w^L-w^H \leq \frac{(1-\pi)R(\eta_{II}^H-\eta_{II}^L)}{\lambda}.$$

Equation (7) defines the maximum difference in the offer price that will motivate the processor to demand safer food. The RHS of (7) is less than the RHS of (3) because some of the food safety failure costs are allocated to the producer as a result of identity preservation, and so the processor realizes less economic benefit from safer food.

The producer will provide safer food if her incentive compatibility constraint is satisfied. Rewriting this constraint yields:

$$(8) \qquad c^L-c^H \leq \frac{\pi R(\eta_{II}^H-\eta_{II}^L)}{\lambda}.$$

This condition requires that the incremental increase in the cost of providing the safer food (LHS) is less than the incremental decline in the food safety failure cost allocated to the producer (RHS). If the cost of delivering the safer food is too high, or the benefit is too low, then she has no incentive to deliver safer food.

Case III. Inspection and Traceability.

In the final case, we combine the two policies. The processor's problem becomes:

$$\text{(9)} \qquad \begin{aligned} &\underset{w}{\text{MAX}} && \lambda(p-w)-(1-\pi)R\eta_I(q) \\ &\textit{Subject to}: && w\lambda-\frac{c(q)\lambda}{P_a(q)}-\frac{1-P_a(q)}{P_a(q)}s\lambda-\pi R\eta_I(q)\geq M \\ & && q\in \underset{\hat{q}}{\text{Argmax}}\left\{w\lambda-\frac{c(\hat{q})\lambda}{P_a(\hat{q})}-\frac{1-P_a(\hat{q})}{P_a(\hat{q})}s\lambda-\pi R\eta_I(\hat{q})\right\} \end{aligned}$$

Again assuming two safety levels, the processor demands safer food if,

$$\text{(10)} \qquad w^L-w^H\leq\frac{(1-\pi)R(\eta_I^H-\eta_I^L)}{\lambda}$$

which is the same as the result for case II. The producer will deliver safer food if,

$$\text{(11)} \qquad \frac{c^L}{P_a^L}-\frac{c^H}{P_a^H}\leq s\left(\frac{1}{P_a^H}-\frac{1}{P_a^L}\right)+\frac{\pi R(\eta_I^H-\eta_I^L)}{\lambda}.$$

Equation (11) implies that the increase in the cost of delivering safer food must be less than or equal to the incremental decline in inspection failure cost and safety failure costs allocated to the producer.

Analysis

In this section we examine the impact of the traceability and inspection on the existence of a market for safer food and on the price of safer food.

Too Much or Too Little Traceability

The conditions under which the producer supplies and processor demands safer food are dependent upon the traceability factor in Cases II and III. We can rearrange (7) we get:

$$\pi \leq 1 - \frac{\lambda\left(w^L - w^H\right)}{R\left(\eta_{II}^H - \eta_{II}^L\right)} \tag{12}$$

And if we rearrange (10) we get,

$$\pi \leq 1 - \frac{\lambda\left(w^L - w^H\right)}{R\left(\eta_{I}^H - \eta_{I}^L\right)} \tag{13}$$

Equation (12) defines the maximum value of π that motivates the buyer to demand safer food in Case II and equation (13) defines the maximum π for Case III. If the traceability factor is greater than the RHS of (12) or (13), then the processor has no incentive to demand safer food because the producer is paying a large portion of the safety failure costs. When the processor can push safety failure costs on to the producer, the processor's financial risk decreases and so does his incentive to demand safer food.

Traceability also influences the producer's willingness to deliver safer food as well. For Case II, we can rearrange equation (8) to get,

$$\frac{\lambda\left(c^L - c^H\right)}{R\left(\eta_{II}^H - \eta_{II}^L\right)} \leq \pi \tag{14}$$

which defines the minimum traceability factor that will motivate the producer to deliver safer food. If condition (14) is not true , then the producer does not face enough of the safety failure costs to motive her to deliver q^L. The corresponding condition for Case III is:

$$(15) \qquad \frac{\lambda\left(c^L + s\right)/P_a^L - \lambda\left(c^H + s\right)/P_a^H}{R\left(\eta_I^H - \eta_I^L\right)} \le \pi.$$

The conditions described above show that the market for safer food can fail if the traceability factor is too close to zero or too close to one. If π is one, then all of the food safety failure costs are passed on to the producer and the processor has no incentive to demand safer food. If π is zero, then all of the safety failure costs are paid by the processor and the producer has no incentive to deliver safer food. The values of π at which safer food will be exchanged are defined by (12) and (14) if there is no inspection and by (12) and (15) if there is inspection.

The Price of Safer Food.

In order to evaluate the economic impact of traceability and inspection, we need to examine the bid price for safer food, w^L, under the different policy options and compare them. For this part of the analysis, we assume that the producer's participation constraint is exactly satisfied at q^H (i.e. the market for less safe food exists) and that the producer's incentive compatibility constraint is exactly satisfied (i.e. the producer is indifferent to delivering safe or less food). Given these two assumptions, we define w_I^L, w_{II}^L, and w_{III}^L as the bid prices that satisfy both the producer's participation constraints and the processor's participation constraints ((3), (7), and (10)) under Cases I, II, and III, respectively.

For Case I, the maximum price that the producer can charge is the highest price that satisfies the processor's participation constraint when a market exists for less safe food and the producer is economically indifferent to producing safe or less safe food. The minimum price that the processor can bid is the lowest price that satisfies the producer's participation constraint when the producer is indifferent between producing at q^L or at q^H. For Case I, this range of prices is:

(16) $$\frac{c^L + s\left(1 - P_a^L\right)}{P_a^L} \le w_I^L \le \frac{c^L + s\left(1 - P_a^L\right)}{P_a^L} + \frac{R\left(\eta^H - \eta^L\right)}{\lambda}$$

At prices below the minimum, the market will fail because the producer's participation constraint will not be satisfied. At prices above the maximum, the market will fail because the processor's expected profit at q^H will be higher, even if the producer is willing to deliver q^L.

For Case II, the range of prices for safer food is:

(17) $$c^L + \frac{\pi R \eta_{II}^L}{\lambda} \le w_{II}^L \le c^L + \frac{\pi R \eta_{II}^L}{\lambda} + \frac{(1-\pi)R(\eta_{II}^H - \eta_{II}^L)}{\lambda}$$

And for Case III, the range is:

(18) $$\frac{c^L + s\left(1 - P_a^L\right)}{P_a^L} + \frac{\pi R \eta_I^L}{\lambda} \le w_{III}^L \le \frac{c^L + s\left(1 - P_a^L\right)}{P_a^L} + \frac{\pi R \eta_I^L}{\lambda} + \frac{(1-\pi)R(\eta_I^H - \eta_I^L)}{\lambda}$$

The producer's and processor's profits depend on the processor's bid price. Naturally, the lower the bid price the lower the profit for the producer and the greater the profit for the processor. We can compare the maximum and minimum expected profit for the processor by incorporating these price limits in the original programs. Table 1 shows the minimum and maximum expected profit for the processor assuming that the minimum expected profit for the producer is $M = 0$. The maximum producer profit is simply the difference between the maximum and minimum processor profit, since all profit is shared by the two parties.

It is difficult to draw conclusions about the relative profit from systems without inspection (Case II) and systems with inspection (Case I and Case III) because the value of $\eta_I(q)$ can vary dramatically from the value of $\eta_{II}(q)$. We can conclude that the maximum profit from inspection alone (Case I) is equal to the maximum profit from inspection and traceability (Case III) and that the minimum profit from Case III is greater than the minimum profit from Case I. The relative position of traceability alone and systems with inspection depends on the difference in the probabilities of a food safety failure.

Example

To illustrate how the addition of traceability affects a system with inspection, consider the delivery of beef trimmings in combo bins to a ground beef manufacturer like Texas American Foodservice Corporation (Golan *et al* (April 2004)). The Texas American Foodservice Corporation uses a food safety monitoring program called the Bacterial Pathogen Sampling and Testing Program. This safety protocol requires that combo bins (approximately one ton of beef trim) delivered by suppliers are sampled based on type, supplier and supplier performance record, but that not less than every 50 tons is sampled.

Suppose that the buyer uses a BAX PCR test to monitor combo bins for the presence of *E. coli*. Hochberg *et al.* show that the sensitivity and specificity of the BAX PCR test for *E. coli* are both about 99%. Suppose also that the combo bin supplier can use one of two decontamination procedures for combo bins. The less rigorous system results in a contamination rate of $q^H = 0.8\%$ and the more rigorous system results in a contamination rate of $q^L = 0.2\%$. Using the relationships identified in Appendix I, we can determine the probability of acceptance and the probability that a unit is contaminated given it passes inspection, which we denote θ.

Contamination level	Low	High
q	.002	.008
$\Pr\{\text{Pass}\} = P_a(q)$	.98804	.98216
$\Pr\{\text{Unsafe}\vert\text{Pass}\} = \theta$	2.0242 X 10^{-5}	8.1453 X 10^{-5}

The probability of a food safety failure depends on the volume. If we assume that the processor purchases $\lambda = 500$ combo bins per year, the probability that at least one will be contaminated is $1-(1-\theta)^{\lambda}$, so $\eta_I^L = 0.01007$, and $\eta_I^H = 0.03991$.

Suppose that the cost of a more safe combo bin is $800, the cost of a less safe combo bin is $780, the cost of inspection failure is *s* = $160 for scrap and goodwill losses (about 20% of the cost of the bin). We also assume that the cost of a food safety failure is $500,000 per event which includes liability, stock market losses, market share losses, etc.

One of the important elements common to each of our conditions on the traceability factor is the difference between the probability of a food safety failure at high contamination and the probability of a food safety failure at low contamination, $\eta_I^H - \eta_I^L$. As this difference increases, the maximum traceability factor increases and the minimum traceability factor decreases. Figure 2 shows the maximum and minimum values of π for different values of $\eta_I^H - \eta_I^L$ assuming that the bid price differential is based on the prices that satisfy the producer's participation constraints in Case I. Figure 2 indicates that there is a minimum threshold for improvement that must be reached for a market to be feasible. The minimum threshold is the value of $\eta_I^H - \eta_I^L$ at which (13) and (15) are satisfied. The solution to this problem is difficult to find analytically because $\eta_I^H - \eta_I^L$, P_a^L, and P_a^H all depend on the contamination rate, sensitivity, and specificity. Using numerical methods we find that, for this example, the threshold value is about 2.93% meaning that the reduction in contamination must be enough to reduce the probability of a food safety failure by 2.9% for the safe food market to be feasible with traceability

Even if the market is feasible, the market will fail if traceability is too close to 0 or too close to 1. If π is one, the all the food safety failure costs are passed back to the producer and the processor's incentive to demand safer food disappears. If π is zero, the none of the food safety failure cost are passed back to the producer and the producer's incentive to deliver safer food disappears. As the incremental improvement in the probability of a food safety failure increases, so does the difference between the maximum and minimum values of π.

An interesting extension of this result involves the effect of test sensitivity on the feasibility of a market for safer food. The difference between η_I^H and η_I^L depends on the test sensitivity (α), among other things, and Figure 3 shows the maximum and minimum levels of traceability if we vary α . As sensitivity approaches 1, the probability that an unsafe unit passes inspection approaches zero at both high and low contamination. As these probabilities approach zero, they get closer together and the difference between η_I^H and η_I^L gets smaller and smaller. As we have already seen, when the difference between η_I^H and η_I^L is small, the market fails. This result suggests that the extremely high test sensitivity may not be desirable in systems that include traceability.

Conclusions

Our analysis leads to several results about the impact of adding traceability to a food supply chain that already includes inspection. In any supply chain, the existence of a market for safer food depends on the processor's willingness to demand safer food and the producer's willingness to deliver safer food. When traceability is added to a food supply chain, the ability of the market to function depends on the traceability factor. If the traceability factor is too high, then the processor will not demand safer food and if the traceability factor is too low, then the producer will not deliver safer food. The challenge facing regulators seeking to require traceability in a supply chain that does not have it is how to make sure there is neither too much nor too little traceability.

We also found that the existence of the market is influenced by the diagnostic accuracy of the test used for inspection. Contrary to what intuition suggests, more sensitive tests may make it impossible for a safe food market function. The reasons are similar to the results associated with traceability. Extremely sensitive tests make it impossible for any food to pass inspection regardless of the contamination level. As the probability of acceptance at q^L and q^H approaches zero, the distinction between q^L and q^H is lost and so is all motivation to demand, and to deliver safer food.

ENDNOTES

[1]In this context, sensitivity is the probability that a test indicates that a lot is contaminated given that the lot is contaminated. Specificity is the probability that a test indicates that a lot is not contaminated given that the lot is not contaminated.

[2]If we assume that all the producers are identical and that the processor offers one price to all producers, then λ is the processor's annual demand from all producers.

APPENDIX I

The relationship between the contamination rate, sensitivity, specificity, the probability of acceptance, and the probability of a food safety failure.

The probability of acceptance and the probability of a food safety failure are functions of the sensitivity (α), specificity (β), and contamination rate, q . α is the conditional probability that a unit fails inspection given it is contaminated. β is the conditional probability that a unit passes inspection given it is not contaminated. The contamination rate, q, can be interpreted as the marginal probability that a unit is contaminated. The following table shows the relationship between these and other important joint and marginal probabilities:

	True Condition		
Test Result	*Contaminated (Unsafe)*	*Not Contaminated (Safe)*	**Total**
Contaminated (Fails inspection)	αq	$(1-\beta)(1-q)$	$(1-\beta)(1-q)+S_e q$
Not Contaminated (Passes inspection)	$(1-\alpha)q$	$\beta(1-q)$	$(1-\alpha)q+\beta(1-q)$
Total	q	$1-q$	1.0

The probability that a lot passes inspection is the marginal probability:

$$P_a(q) = (1-\alpha)q + \beta(1-q) \, .$$

Bayes' Theorem tells us that the probability that any one unit is contaminated given it passes inspection is the probability that a unit is contaminated and it passes inspection divided by the probability that a unit passes inspection:

$$\Pr\left\{\text{Unsafe} \mid \text{Passes}\right\} = \theta = \frac{(1-\alpha)q}{(1-\alpha)q+\beta(1-q)}$$

The processor purchases λ units from the producer each year. The probability that at least one of the λ units purchased by the processor is contaminated is:

$$\eta_I(q) = 1 - (1-\theta)^{\lambda}$$

This is the probability of a food safety failure if every unsafe unit that passes inspection causes a food safety failure. If some unsafe units do not cause a food safety failure, then this probability would need to be reduced, or the expected food safety failure cost, *R*, would need to be adjusted.

If there is no inspection to filter out unsafe product, then all of the contaminated products are passed on to the processor who passes them on to the consumer. In this case the probability that at least one of the λ units purchased from the producer are contaminated is:

$$\eta_{II}(q) = 1 - (1-q)^{\lambda}$$

This probability can be quite a bit higher than $\eta_I(q)$.

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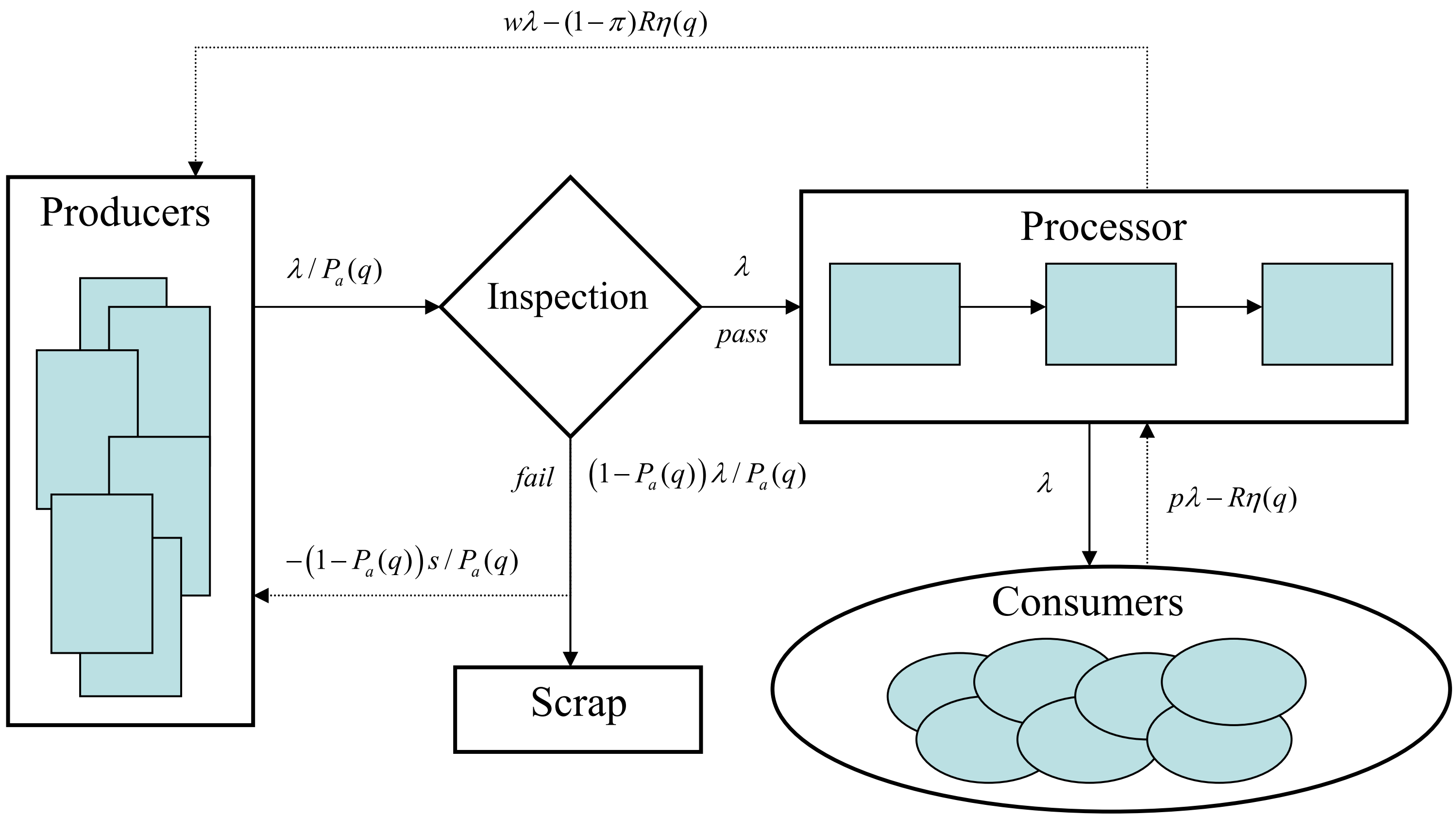
Table 1. Minimum and Maximum Processor Profits based on Range of Feasible Bid Prices.

Case	**Minimum Processor Expected Profit (Expected Profit at Maximum w^L)**	**Maximum Processor Profit (Expected Profit at Minimum w^L)**
I Inspection	$\lambda\left(p-\frac{c^L+s(1-P_a^L)}{P_a^L}\right)-R\eta_I^H$	$\lambda\left(p-\frac{c^L+s(1-P_a^L)}{P_a^L}\right)-R\eta_I^L$
II Traceability	$\lambda(p-c^L)-\pi R\eta_{II}^L-(1-\pi)R\eta_{II}^H$	$\lambda(p-c^L)-R\eta_{II}^L$
III Inspection & traceability	$\lambda\left(p-\frac{c^L+s(1-P_a^L)}{P_a^L}\right)-\pi R\eta_I^L-(1-\pi)R\eta_I^H$	$\lambda\left(p-\frac{c^L+s(1-P_a^L)}{P_a^L}\right)-R\eta_I^L$

Figure 1. Product, Revenue, and Expense Flowchart*



* Solid lines represent the flow of product. Dotted lines represent the flow of revenue and expenses.

Figure 2. Incremental Change in the Probability of a Food Safety Failure and Traceability

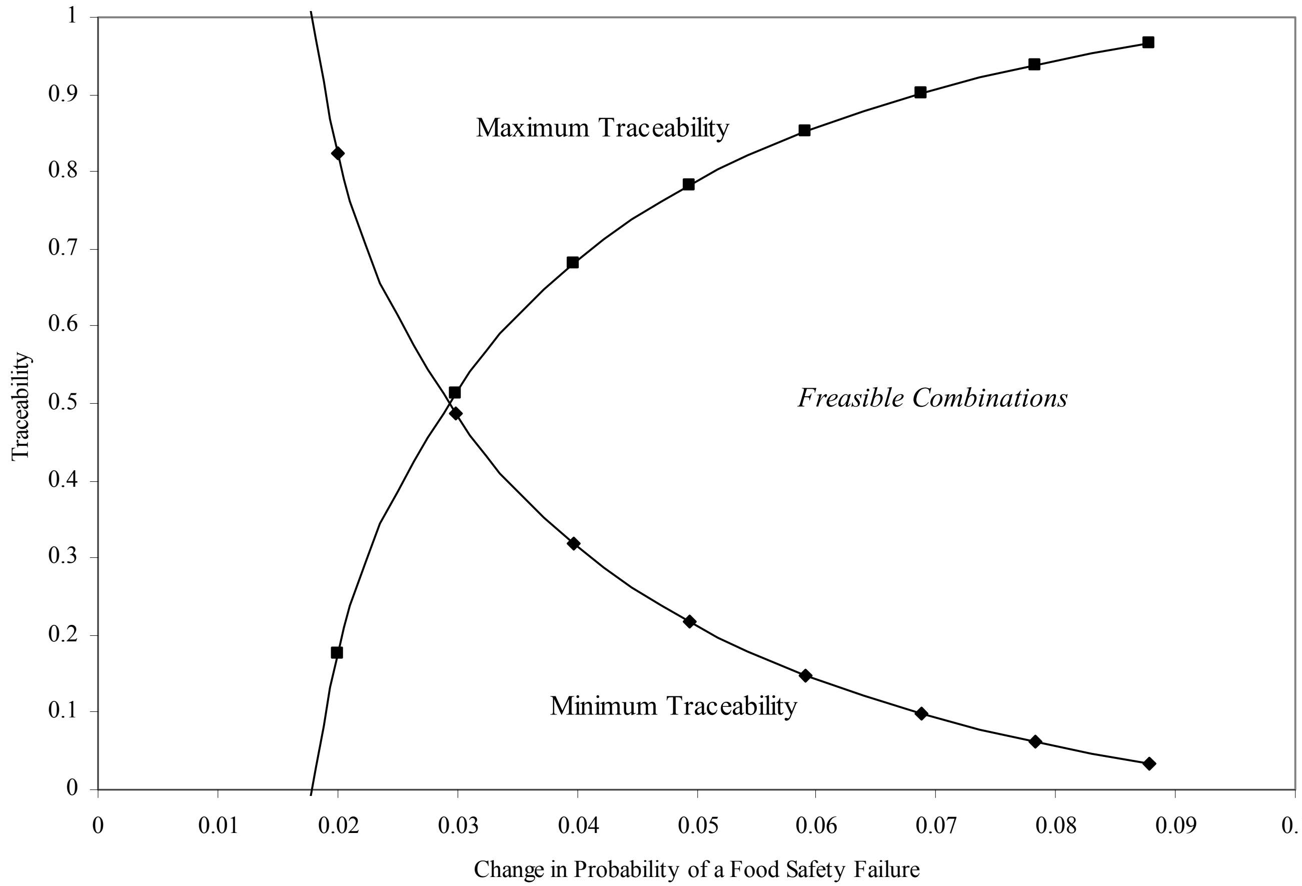


Figure 3. Diagnostic Sensitivity and Minimum and Maximum Traceability