Ensuring a Safe Food Supply: The Importance of Heterogeneity

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Abstract

In this paper we develop a model of food safety regulation that considers the employment of a differentiated food market with two types of government certified quality standards: a minimum standard and a higher one. Individuals, heterogeneous in their susceptibility to food-related health risks, choose which safety-grade of food to consume based on price and their vulnerability. The model is then extended to the case where consumers misperceive their susceptibility to health risks associated with food consumption. The theoretical presentation is followed by an application of the model to examine campylobacteriosis and salmonellosis caused by consumption of beef, pork, and chicken. The paper demonstrates that the benefits from multiple quality standards hinges fundamentally on the distribution of vulnerabilities across the population and the associated distribution of population health risks for a given level of food quality. Uniform standards are generally preferred to differentiated ones under either stringent or lax regulations on population health risk. If the population distribution of vulnerabilities is unimodal and consumers misperceive their vulnerability, the value of a differentiated policy will depend on which quality standard is attracting the majority of consumers. The empirical results confirm the importance of the population distribution of vulnerability on the relative desirability of single versus multiple quality standards.

KEYWORDS: food safety, health, risk regulation

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1. Introduction

Health risks from consuming food contaminated with bacteria and other pathogens are omnipresent, potentially lethal, and a major concern. Recent outbreaks involving food contaminated with such pathogens as *E. coli* and *Salmonella* have provided policy makers with a renewed interest in the design of food quality standards (CAST, 1994; FSIS, 1996). Moreover, the Codex Alimentarius Commission, an intergovernmental body responsible for implementation of the FAO/WHO Food Standards Programme, has highlighted the importance of establishing food safety objectives that define a tolerable level of hazard in food to achieve appropriate levels of protection (WHO/FAO, 2005). Setting optimal standards, however, is quite challenging due to considerable variation across individuals in their susceptibility to food risks. In general, individuals with healthy immune systems will be far less sensitive to tainted food exposures than those with immature or compromised immune systems (Gerber et al., 1996). Surprisingly, this latter group, which includes children, the elderly, pregnant mothers, and people with various medical conditions, comprises nearly one-fifth of the current US population (Gerber et al., 1996). With the aging baby-boom generation, these numbers are expected to rise.

Setting food quality standards universally low in this heterogeneous setting will leave the most vulnerable citizens bearing a disproportionate and significant share of the population’s food-related health risks. On the other hand, setting standards universally high can protect those most sensitive to food-related health risks, but at significant costs to more hardy citizens who will face higher food prices with little additional health benefits. Higher standards may also increase regulation costs, as more stringent standards will generally require greater inspection and enforcement efforts.

In this paper, we develop a model of food safety regulation that considers the employment of a differentiated food market with two types of government certified quality standards: a minimum standard and a higher one. The use of differentiated standards can be viewed as a standard uniform regulatory approach combined with a government-sanctioned quality certification system. This regulatory framework is conceptually similar to the current system governing automobile safety in the US. In that setting, the National Highway Traffic Safety Administration sets mandatory minimum safety standards for vehicles and also employs a 5-star rating system to delineate higher levels of crash safety. A similar system governs product safety, where supra-minimum standards are defined by independent third-party organizations such as the Consumers Union.¹

¹ Defining and measuring food safety, like vehicle safety, requires considerable scientific knowledge and specialized equipment and is generally characterized by significant economies of scale, suggesting a limited role for third-party involvement.
Of course, the need for government (or third party) involvement presupposes that individuals are unable to easily discern quality themselves. As such, the establishment of multiple standards can be viewed as a tool to improve the efficiency of a market characterized by asymmetric information. Absent a clear quality signal, firms have little incentive to invest in improving their products and the heterogeneous consumer class is forced to consume goods that just satisfy minimum quality standards. In contrast, differentiated standards improve both consumer and producer welfare since individuals that prefer higher quality products can tailor their consumption to accommodate their preferences and producers can extract rent from providing these higher quality items. The value of such a signal will depend upon factors determining the supply of and demand for quality, as well as the costs of producing the signal.

In a health risk regulatory framework, the differentiated standards approach ensures baseline safety levels, but allows consumer preferences to determine individual safety consumption and thus population safety attainment. In our model, individuals are heterogeneous in their susceptibility to food-related health risks and choose which safety-grade of food to consume based on price and their vulnerability. Regulators, taking this consumer demand function as given, control population health risks by choosing both the minimum quality standard and the certified higher standard based on the distribution of vulnerabilities across the population. The model is then extended to the case where consumers misperceive their susceptibility to health risks associated with food consumption.

The approach taken in this paper employs a probabilistic model of the health risk generation process (contamination, exposure, and dose-response) in tandem with a safety-fixed decision rule. This approach is consistent with the conceptual framework for environmental health risk management laid out by Lichtenberg and Zilberman (1988) and its numerous applications (e.g. Lichtenberg et al., 1989; Sinding and Zivin, 2000 and 2002; and Graff Zivin and Zilberman, 2002). The model developed here is essentially an extension of the Graff Zivin and Zilberman (2002) study, which was the first to explicitly examine regulations when individuals are heterogeneous in their susceptibility to environmental health risks.

The present work departs from that study in several important dimensions. That study, in part due to its focus on municipal drinking water supplies, assumed that citizens would consume whichever quality of water was deemed appropriate for them, i.e. it ignored potentially important consumer preferences. As described above, we relax this assumption and address consumer demand directly. Incorporating consumer sovereignty in the regulatory framework adds considerable realism to the model, as it allows us to examine the case where consumers know more about their own susceptibility to food risks than policy makers do. It also addresses tradeoffs between product safety and price, tradeoffs that consumers are asked to make everyday (see, for example Viscusi, 1992).
Clearly, the option to employ differentiated standards when individuals are heterogeneous, while not always exercised, can only improve the regulator’s ability to meet target risk levels. Less clear are the conditions defining which approach, i.e. uniform versus differentiated, will be preferred. Graff Zivin and Zilberman (2002) demonstrated that the optimal deployment of differentiated standards depends significantly on scale effects in the production of safe products. The inclusion of incentive compatibility constraints, i.e. consumer responsiveness, in the regulatory framework allows us to identify a broader class of conditions under which each approach will be optimal. In addition, it allows us to address potentially important concerns about consumer misperceptions of their susceptibility to certain types of health risks.

The theoretical presentation is followed by an application of the model to examine campylobacteriosis and salmonellosis caused by consumption of beef, pork, and chicken. These pathogens account for a large share of annual foodborne illness, with a disproportionate amount of that risk being borne by sensitive populations who, for a given exposure, are considerably more likely to become ill than their non-sensitive counterparts. In particular, we examine consumer food quality choice under the hypothetical scenario, where the higher quality standard is food produced under the Hazard Analysis Critical Control Points (HACCP) approach. The analysis is then generalized to a continuum of food quality levels.

The paper demonstrates that the benefits from multiple quality standards hinges fundamentally on the distribution of vulnerabilities across the population and the associated distribution of population health risks for a given level of food quality. Depending on the marginal rates of technical substitution between the quality standards in producing safety, uniform standards may be preferred to differentiated ones under either stringent or lax regulations on population health risk. Similar ambiguities arise when examining consumer misperceptions. If the population distribution of vulnerabilities is unimodal, the value of a differentiated policy will depend on which quality standard is attracting the majority of consumers. When the majority of consumers are consuming the lower quality food, the benefits from a discriminatory approach are greatest when consumers significantly underestimate their risk. When the majority of citizens are consuming the higher quality food, a uniform policy will be preferred if consumers significantly underestimate their risk. The empirical results confirm the importance of the population distribution of vulnerability on the relative desirability of single versus multiple quality standards. When sensitive populations are five times more susceptible to foodborne disease, they will always consume the certified higher quality food, while the non-sensitive group will only consume the higher quality food if it is slightly less contaminated than the
minimum quality standard. As the sensitivity of the susceptible population decreases, so does the desirability of the higher quality food.

The paper is organized as follows. Section 2 presents the theoretical approach, progressing from the simple single-standard case to the two-standard case with consumer misperception. Section 3 presents the case study. Section 4 offers some concluding remarks.

2. The Model

Suppose that the consumption of food, through the presence of bacteria or other forms of contamination may lead the consumers of that food to become ill. We will denote the probability that an individual gets sick from consuming a unit of food as \(f(v,q)\), where \(q\) denotes the quality of the food, \(f'(q) < 0, f''(q) \leq 0\), and \(v\) denotes the individual's vulnerability to food risk. Food quality, in this context, should be viewed as a measure of safety. It is meant to describe the likelihood of a given concentration of pathogens per unit of food. In the models that will be developed, this quality level will be regulated through minimum quality standards, possibly in conjunction with a government certified higher quality standard.

Vulnerability, \(v\), describes the probability that an individual will become ill after a given pathogen exposure. This measure is perfectly analogous to what toxicologists refer to as a dose-response relationship. Individuals within the population are heterogeneous in their vulnerability such that some people are more likely to get sick than others after the same level of pathogen exposure. This is a common feature of many environmental health risks, which reflects differences in both genetic composition and immune system integrity across individuals (Grandjean, 1991; Gerber et al., 1996). For example, a healthy teenager may be able to eat a hamburger with no adverse health impacts, while an elderly person may become seriously ill from eating the same hamburger.

Let \(g(v)\) denote the distribution of vulnerabilities within the population, where the range of vulnerabilities is defined between zero and one. As such, \(g(v)\) simply indicates the number of individuals within the population at each level of vulnerability. The population risk of becoming ill after consuming food of purity level \(q\) can, therefore, be expressed as follows:

\[
R(v,q) = \int_0^1 g(v) \cdot f(v,q) dv.
\]

In other words, \(R\) represents the average individual risk of illness in the population or the expected percentage of the population consuming food of the same quality \(q\) that will experience a pre-defined adverse health outcome.

In the models that follow the policy maker will choose the food quality standard(s) such that population health risks are below some health risk target \(k\) in
the least cost fashion. Let \( cq \) represent the regulator’s costs of setting and enforcing the food quality standard \( q \). These regulation costs may also include consumer ‘complaint’ costs, which depend, in part, on the impacts of the safety standard on food prices. Thus, the cost function should be viewed as general enough to include the impacts of regulation on consumer and producer welfare, so far as regulators internalize such costs. The policy maker’s objective can formally be expressed as \( \min_q cq \) s.t. \( R \leq k \).

This formulation of the regulator’s problem is consistent with other economic models of environmental health risk management problems (Lichtenberg and Zilberman, 1988 and Graff Zivin and Zilberman, 2002). Essentially, it is the safety-fixed model introduced to the field of economics by Kataoka (1963). This approach, commonly referred to as ‘containment of risk,’ is the guiding principle behind much of the current health protection legislation (Grant and Jarabek, 1990). If the regulatory cost function includes the costs of the intervention as well as all impacts on consumer and producer surplus, the goal of the regulator can be viewed as social welfare maximization subject to a population health risk target. \(^2\) This health risk standard \( k \) is generally defined either legislatively or administratively as an allowable or a reasonable level of population risk. \(^3\)

2.1 One Quality Standard

In this case, we will only consider setting a single food quality standard. We assume that food has no close substitutes and thus over a reasonable range of prices, consumers do not alter the amount that they consume. In the multiple standard cases that we develop later, however, the policy maker will need to attend to consumer demand as a function of food quality and price. The policy maker’s objective is to ensure that the population health risk does not exceed the allowable level in the least-cost manner. Expressing this problem as a Lagrangian maximization, we obtain

\[
\max_q L = -cq + \lambda \left[ k - \int_0^1 g(v) f(v, q) dv \right],
\]

where \( \lambda \) is the shadow value of the government risk standard. This value measures the impact of maintaining the risk standard on the cost-minimizing objective and as such can be thought of as the value of health implicitly defined by the regulation.

\(^2\) It is interesting to note that, given the exogenous population risk standard, such a regulation will not necessarily pass a cost-benefit test.

\(^3\) In practice, the population over which this standard is defined depends upon the particular toxin and agency involved. For a more detailed discussion of this and related controversies see Graff Zivin and Zilberman (2002).
The solution to the maximization problem above is characterized by the following first-order conditions:

\[
\frac{\partial L}{\partial q} = -c - \lambda \int_0^1 g(v) \frac{\partial f}{\partial q} dv = 0
\]

(1)

\[
\frac{\partial L}{\partial \lambda} = k - \int_0^1 g(v) f(v, q) dv = 0.
\]

(2)

Equation (1) simply states that the marginal regulatory costs of the food quality standard equals the marginal benefit of reduced population morbidity times the value of health. Equation (2) merely restates the constraint. Together these two equations implicitly define the optimal food quality standard \(q^*\). Total differentiation and manipulation of equations (1) and (2) suggest, quite intuitively, that the optimal food quality level and the shadow value of health are both increasing in the stringency of the government health risk standard.

### 2.2 Two Food Quality Standards

Now we will suppose that the regulator can potentially employ two food quality standards: a minimum quality standard and a government-certified higher quality standard.\(^4\) We will denote the lower standard as \(q_L\) and the higher standard as \(q_H\). The health risk benefits from the two-standard case will depend, in part, on who consumes food from each group. An individual’s expected utility from consuming food of a given quality \(i\) can be expressed as:

\[
u(q_i, 1 - f(v, q_i)) - p(q_i) .
\]

(3)

The first term represents the health-adjusted expected utility from consuming food of quality \(q_i\), where the expression in parenthesis represents the probability that an individual with vulnerability \(v\) does not fall ill from consuming that food. Agents are assumed to be risk averse with respect to health, such that \(u'(q) > 0\) and \(u''(q) > 0\). The second term is simply the price the consumer must pay to consume food of quality \(q_i\).\(^5\) Price is assumed to increase with quality at an

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\(^4\) This problem could also be recast as one where safety standards are uniform, but there are multiple standards for assuring safety. In this case, we would view the higher quality standard as one corresponding to more careful testing and certification procedures to ensure that products are in compliance with the rules governing product safety. As long as the relationship between production techniques and product safety are not completely deterministic, all of our results would be qualitatively identical.

\(^5\) Note that we treat the disutility from food expenditure as equivalent across all individuals. When individuals differ in their wealth, this may not be a reasonable assumption. In that case, an accurate description of consumer demand would require information about the distribution of wealth across the population and its correlation with health risk vulnerability.
increasing rate, i.e. \( p'(q) > 0 \) and \( p''(q) > 0 \). Price increases are presumed sufficient to ensure that production levels for any food quality level will be sufficient to meet consumer demand at that quality level.

In the two-quality standards case, the consumer will simply choose to consume food from the category that provides them with the largest expected utility. For simplicity, we assume that the consumer cannot further purify or contaminate the food after it is purchased and does not alter the quantity of food that they consume.\(^6\) Thus, we can define \( \hat{v} \) as the vulnerability level at which an individual is indifferent between the two categories. It depends on food quality, prices, and consumer risk aversion. Formally, \( \hat{v} \) is defined by the following expression:

\[
\begin{align*}
 u(q_L, 1 - f(\hat{v}, q_L)) - p(q_L) &= u(q_H, 1 - f(\hat{v}, q_H)) - p(q_H). \\
 (4)
\end{align*}
\]

Taking consumer demand and the associated indifference level of vulnerability as given, the regulator’s goal is to choose quality standards that satisfy the population risk target in the least-cost manner. Equation (4) defines which type of food individuals (agents) of vulnerability \( v_i \) will consume and can be viewed as an incentive compatibility constraint for the regulator’s (principal’s) optimization problem. Costs of regulation are modeled as a cost per unit of quality for the minimum quality standard plus an additional cost based on the difference in quality between the two standards. Costs could be increasing with the quality standard due to additional inspection and enforcement costs or because the regulator has, at least partially, incorporated the impacts of the standards on producer welfare as a result of changes in food prices. Formally, this objective can be written as:

\[
\begin{align*}
 \max_{q_L, q_H} L &= -cq_L - \tilde{c}[q_H - q_L] + \lambda \left[ k - \int_0^{\hat{v}} g(v) f(v, q_L) dv - \int_{\hat{v}}^{\lambda} g(v) f(v, q_H) dv \right].
\end{align*}
\]

This regulator is now minimizing the costs of maintaining the minimum quality standard plus the costs of certifying the higher standard. The aggregate level of health risk in the population is defined as the sum of the risk to the less vulnerable individuals who consume the lower quality food and the high-risk individuals who consume the higher quality food. Again, \( \lambda \) represents the shadow value of health.

The solution to the maximization problem above is characterized by the following first-order conditions:

\(^6\) In reality, the manner in which consumers handle and prepare food does impact their ultimate exposure to foodborne pathogens and vulnerable individuals do alter the composition of various foods in their diet. Incorporating these impacts is beyond the scope of the present paper.
Equation (5) states that the marginal regulatory costs of the lower quality standard, which includes costs attributed to the minimum standard as well as costs due to the difference in the two standards, equals the marginal health risk reduction from the quality standard times the value of health. The benefits expression in brackets has two components. The first term reflects the change in risk to those already consuming the lower quality food from a slight change in food quality at the lower standard. The remaining terms capture the change in risk to those who switch from consuming at one quality standard to consuming at the other as a result of a small change in food quality at the lower standard. In other words, the first term in brackets represents the intensive margin of the change and the latter terms represent the extensive margin of the change in health risk. The interpretation of equation (6) is the same for the higher standard. The last equation simply restates our health risk constraint.

It is important to note that, in contrast to the single standard case, the impact on population risk from an increase in the minimum food quality standard (the bracketed term in equation (5)) can be positive or negative. This ambiguity arises because, while an increase in this standard makes those already consuming the lower quality food face less health risk, it also induces some people to switch from consuming the higher quality food to the lower quality food and thereby increases their risk. The overall impact will depend on whether the intensive effect dominates the extensive effect, which, in turn, depends on the population distribution of risk and consumer responses to price and associated health risk changes. For the remainder of the paper, we will assume that the net overall impact from an increase in the lower food quality standard is a decrease in population risk. No such assumption is needed for the impact of changes on the higher food quality standards as the intensive and extensive margins are reinforcing in this case.

The impact of changes in the regulatory health risk standard on the optimal food quality standards can be obtained through comparative static analysis. Let $R$ denote total population health risk faced by the two groups consuming from each of the food quality groups. The proof is provided in the appendix.
Proposition 1:

\[
\frac{dq_L}{dk} < 0 \quad \text{if} \quad \frac{\partial R}{\partial q_L} > \frac{\partial^2 R}{\partial q_H^2} < \frac{\partial^2 R}{\partial q_L \partial q_H} \quad \text{(8a)}
\]

\[
\frac{dq_H}{dk} < 0 \quad \text{if} \quad \frac{\partial R}{\partial q_L} > \frac{\partial^2 R}{\partial q_H^2} < \frac{\partial^2 R}{\partial q_L \partial q_H} \quad \text{(8b)}
\]

Expression (8a) states that the impact of changing the government health-risk target on the minimum food quality standard is ambiguous. More stringent health standards may lead to either an increase or decrease in the minimum food quality standard. Which result obtains, depends on the marginal productivities of each of the food quality standards in reducing health risk, the rate of change in the marginal productivity of the high standard and the degree of substitutability/complementarity between the two standards. Each of these constituent impacts is rather complex. For example, the marginal productivity of the minimum-quality standard depends on the health impacts for those who continue to consume at this standard, as well as the health impacts for those who both switch into and out of the low standard. Switching, in turn, depends on the local properties of the vulnerability distribution as well as the impacts of the standard on food prices and consumers’ expected utility from food consumption. The degree to which changes in these minimum standards substitute for changes in the higher ones depends on the curvature of the consumer demand function, which is driven by price effects, risk aversion, and the distribution of vulnerabilities.

If we think of \( R \) as the output of a health risk production function and the food quality standards as inputs, then the interpretation of (8a) can be recast in the familiar language of production economics. Whether more stringent standards lead to a higher or lower standard depends on whether marginal rate of technical substitution between the two inputs is greater than or less than the marginal rate of technical substitution between the two inputs on the marginal productivity of the higher food quality standard. The impact of changes in the stringency of the government’s health risk standard on the higher food quality standard (8b) has a similar interpretation. The effect on the high-quality standard also depends on the marginal rate of technical substitution between the two inputs and on marginal rate of technical substitution on the marginal productivity of the minimum food quality standard.

While a more stringent health standard can lead to either increases or decreases in the optimal food quality level for either the minimum or high-quality food standard (the signs of 8a and 8b are ambiguous), it can never lead to a simultaneous decrease in both food quality standards. This observation is quite intuitive, as more stringent health standards could not be met if both food quality...
standards were reduced. As a result, we can imagine three possible scenarios arising in response to a change in the regulator’s health risk objective. The more stringent objective can 1) lead to increases in both food quality standards; 2) lead to an increase in the lower food quality standard and a decrease in the higher food quality standard; or 3) lead to a decrease in the lower food quality standard and an increase in the higher food quality standard. These scenarios have clear implications about the potential benefits from employing both a minimum and certified higher quality food standard, which can be summarized as follows:

Proposition 2:

As $k \to 0$, if $\frac{dq_L}{dk} < 0$ and $\frac{dq_H}{dk} < 0$, the standards may converge or diverge. \hfill (9a)

As $k \to 0$, if $\frac{dq_L}{dk} > 0$ and $\frac{dq_H}{dk} < 0$, the standards will converge. \hfill (9b)

As $k \to 0$, if $\frac{dq_L}{dk} < 0$ and $\frac{dq_H}{dk} > 0$, the standards will diverge. \hfill (9c)

Condition (9a) implies that impact of more stringent health risk targets on the desirability of two separate food quality standards will depend on the relative rates at which the two food quality standards increase in response to the policy change. If the minimum quality standard increases at a rate faster than the higher standard, the two will converge suggesting a preference for a single, uniform food quality standard when allowable population health risks are quite small. If the opposite is true and the higher standard increases at a faster rate, the two will diverge as health standards become more stringent, suggesting that standards will become more differentiated as risk standards become more stringent. In this case, a uniform quality standard may be preferred when health risk targets are rather lax. Condition (9b) indicates that in this scenario more stringent health regulations unambiguously lead to a uniform food quality standard. In the scenario that corresponds to condition (9c), more stringent health regulations lead to larger differences between the minimum and certified higher food quality standard.

Thus, we find that the adoption of a differentiated food quality standard will hinge on the health risk production function, the population distribution of vulnerabilities, and the stringency of the government health risk target. In some cases, the value of a differentiated policy approach will be greatest when allowable population health risk is low and in other cases the value will be greatest when allowable population health risk is high. In short, if the cost of

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7 A proof of this condition is provided in the Appendix under the heading Corollary to Proposition 1.
certifying an additional higher food quality standard is non-zero, employing multiple food quality standards when the population is heterogeneous in their susceptibility to food-related health risks is not necessarily advantageous.

2.3 Two Food Quality Standards with Consumer Misperception of Risks

In this section, we would like to consider the properties of our previous model when consumers misperceive their own health risks from consuming food of a given quality. This case is designed to represent the realistic scenario under which individuals do not accurately understand their likelihood of becoming ill after eating a particular item of food, i.e. they do not know their vulnerability. In particular, we will assume that individuals underestimate their own vulnerability, but that the regulator knows the true population distribution of vulnerabilities.\(^8\)

Let \(\alpha\), a positive fraction less than one, denote the degree to which individual’s misperceive their own food-related health risks. The expression defining indifference between the two types of food (4) can now be rewritten as:

\[
u(1 - \alpha f(\hat{\nu}, q_L)) - p(q_L) = u(1 - \alpha f(\hat{\nu}, q_H)) - p(q_H).\]

The important thing to note in this new expression is that the indifference level of vulnerability is now also a function of consumer misperception, i.e. \(\hat{\nu}(q_L, q_H, \alpha)\).\(^9\)

The first-order conditions for the regulator’s maximization problem are identical to (5) – (7) above with this new \(\hat{\nu}\) replacing the old one. The impacts of changes in the stringency of the government health risk standard are similar to those described in Propositions 1 and 2. In this case, risk misperception simply alters the relative magnitudes of optimal quality standard responsiveness. Three scenarios that define the desirability of differentiated versus uniform standards still arise, but the boundaries defining them now depend on the degree of risk misperception.

The impact of changes in risk misperception on optimal food quality standards can be characterized by the following expressions. See the appendix for the proof.

\(^8\) Alternatively, we could assume that people overperceive their risk, but in that case all of the costs of misperception are borne by the individuals through excessive food expenses. A more realistic approach could impose a distribution of heterogeneous risk perceptions that transform actual risk into perceived risk. Such an approach would add considerably computational complexity and is beyond the scope of the present work.

\(^9\) Here we assume that consumers are completely unaware of misperception. If consumers knew the population distribution of misperception, but not the specifics of their own case, misperception would further complicate matters as additional uncertainty would be imposed upon risk-averse agents. Since food prices are deterministic in our framework, this would push consumers toward the higher quality food.
Proposition 3:
\[ \frac{dq_L}{d\alpha} \geq 0 \quad \text{if} \quad \frac{dg}{d\hat{v}} \geq 0 \]  \hspace{1cm} (11a)
\[ \frac{dq_H}{d\alpha} \geq 0 \quad \text{if} \quad \frac{dg}{d\hat{v}} \leq 0 . \]  \hspace{1cm} (11b)

A change in consumers’ misperception of their vulnerability to food risks has an ambiguous effect on optimal food quality standards. The results depend on the shape of the vulnerability distribution and, in particular, whether the slope of the distribution at the indifference vulnerability level is increasing or decreasing. If we imagine a unimodal distribution of vulnerability, the impact will depend on whether \( \hat{v} \) is to the left or the right of the maximum. In other words, are the majority of individuals consuming the minimum quality food or the higher quality food? If the majority of people are consuming the minimum-quality food (i.e. \( g'(\hat{v}) < 0 \)), then the minimum food quality standard will be reduced and the higher food quality standard will be increased. If the majority of people are consuming the high-quality food (i.e. \( g'(\hat{v}) > 0 \)), the opposite is true. This implies the following:

As \( \alpha \to 0 \), if \( \frac{dg}{d\hat{v}} < 0 \), the standards diverge \hspace{1cm} (12a)

As \( \alpha \to 0 \), if \( \frac{dg}{d\hat{v}} > 0 \), the standards converge. \hspace{1cm} (12b)

Condition (12a) indicates that, if the number of people evaluated at the threshold vulnerability is decreasing in vulnerability, differentiated food quality standards are most attractive when consumers dramatically underestimate their vulnerability to food risks. Condition (12b) states the opposite. When the number of people evaluated at the threshold vulnerability is increasing in vulnerability, a uniform food quality standard appears most attractive when consumers dramatically under-perceive their vulnerabilities.

Thus, when consumers misperceive their own health risks, the benefits from employing a minimum food quality standard as well as a certified higher quality standard will depend on panoply of factors. They will continue to depend on all the conditions discussed in the previous section as well as the properties of the vulnerability distribution at the indifference vulnerability and the degree to which consumers under-perceive their vulnerabilities. It is interesting to note that, contrary to intuition, the impact of informational campaigns to educate consumers about their health risks can lead to the adoption of either a uniform or a differentiated standards approach. The strategy that prevails will depend on which food market is the dominant one.
3. Case Study

In this section, we develop an application of the conceptual model to examine food quality improvements in the beef, chicken, and pork industries. Due to data limitations, the case study will not be able to replicate the maximization problems described earlier in their entirety. Rather, using some basic toxicological and epidemiological data as well as data on the effectiveness and expected price impacts of a recent federal food safety initiative, we will illustrate the conditions under which consumers will prefer two quality standards and when they prefer one. The presentation that follows is quite stylized and is designed to illuminate salient features of the theoretical model. While we hope that this analysis will draw attention to the importance of risk heterogeneity in policy making, it should not be interpreted as a prescription for food safety policy.

The first intervention examined in this case study is the adoption of the Hazard Analysis Critical Control Points (HACCP) approach to controlling food quality. HACCP is a federally mandated program that requires all meat and poultry plants to identify points in the production process where pathogens may enter and establish methods to control those hazards. The regulatory system also calls for periodic testing for *salmonella* to ensure that pathogen-reduction standards are being met and testing for *E. coli* to verify adequate removal of fecal contamination. The implementation date was graduated from January 1998 to January 2000, depending on the size of the processing plant. More details on the HACCP regulations can be found in FSIS (1996).

For the purposes of our case study, we examine the hypothetical case where HACCP is treated as a second, higher food quality standard, rather than a mandatory program that all must adopt. Indeed, one should imagine pre-1998 standards as those which all must meet and the HACCP standards as an optional higher standard that is certified by the government. The benefits from the higher standard derive from reductions in a suite of pathogen levels, which in turn yield reductions in the incidence of numerous foodborne diseases. Two pathogens, *Campylobacter jejuni* or *coli* and non-typhoid *Salmonella*, account for more than one-half of all foodborne disease (Buzby and Roberts, 1996). For simplicity, their reduction and the ensuing reduction in disease will serve as our benefits measure.\(^{10}\)

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\(^{10}\) Of course, the true benefits of any food quality improvement program will be the sum total of all disease avoidance as a result of pathogen reduction. In principal, this is difficult to measure as it requires detailed information on the effectiveness of the intervention in reducing each pathogen as well as a dose-response function for each and every pathogen that is being reduced.
3.1 The Dose-Response Relationship

The relationship between pathogen levels and the manifestation of clinical disease is characterized by the dose-response function. Dose-response functions have been estimated for both campylobacter and salmonella, with the Weibull-Gamma providing the best fit (Holcomb et al., 1999). The Weibull-Gamma model has the following form:

\[
\Omega(d) = 1 - \left[1 + \frac{d^\Psi}{\omega}\right]^{-\varepsilon},
\]

where \(\Omega(d)\) represents the probability of infection, \(d\) represents the dose, and \(\Psi\), \(\omega\), and \(\varepsilon\) are parameters affecting the shape of the curve. In this model, host/pathogen heterogeneity is described by the Gamma distribution with parameters \(\omega\) and \(\varepsilon\) for the Weibull parameter \(\Psi\) (Farber et al., 1996). The parameter estimates for campylobacter are \(\Psi=2.56\), \(\omega=9.99\), and \(\varepsilon=0.05\) while the estimates for salmonella are \(\Psi=0.24\), \(\omega=1.87E+10\), and \(\varepsilon=3.56E+8\). Together, these imply that the infectious dose required to cause illness in 1 percent of the population is 1.4 and 0.07 colony forming units, respectively (Holcomb et al., 1999). It is important to note that these parameter values are derived from human experiments with healthy volunteers, and therefore do not accurately describe health risks to sensitive populations.

Numerous groups of individuals are more susceptible to a wide range of water and foodborne pathogens, including the very young, the elderly, pregnant women, and the immunocompromised. These groups presently comprise roughly 20% of the US population (Gerber et al., 1996). While the degree to which this group is more susceptible to infection due to campylobacter and salmonella exposure is not known, other pathogens have been shown to be 3-9 times more infective in this population than in the ‘healthy’ population (Perz et al., 1998; Farber et al., 1996). Based on these data, we will assume in our base case that susceptible populations are five times more likely to become infected from a given dose than their healthy counterparts. Later in this section, this assumption will be changed to examine the desirability of uniform versus differentiated standards when the infectivity difference is smaller.

11 As a general rule, sensitive populations are more likely to become infected and, conditional on becoming infected, tend to develop more intense illness. For the purposes of our simple case study, we will simply focus on the infectivity difference, abstracting from the fact that not all illnesses are equivalent.

12 Note that this assumption is equivalent to saying that the \((\Psi,\omega,\varepsilon)\) triple for the vulnerable population is such that a given dose yields an infection rate in the vulnerable population that if five times as large as that in the healthy population. In reality, this infectivity difference is probably not constant, but rather would vary with dose in a manner that depends on the exact composition of the triple. We are assuming that at the low range of doses that we are considering the assumption of constancy is reasonable.
3.2 Effectiveness, Costs, and Demand for Food Safety

Given these dose-response functions, data on the annual incidence of foodborne campylobacteriosis and salmonellosis (see Buzby and Roberts, 1996), and data on annual per capita meat and chicken consumption (USDA) we can infer pre-HACCP contamination levels. The adoption of HACCP is presumed to reduce these contamination levels by 20% (Knutson et al., 1995). Thus, to calculate the number of foodborne illnesses that would result from consuming meat and poultry using HACCP, we plug the new reduced pathogen levels of campylobacter and salmonella in the dose-response functions for the non-sensitive (80% of total) and sensitive (20% of total) populations to predict the total number of illnesses. These figures are summarized in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Pre-HACCP</th>
<th>HACCP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average Pathogen Levels</strong> (colony forming units)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Campylobacter</td>
<td>1.64</td>
<td>1.31</td>
</tr>
<tr>
<td>Salmonella</td>
<td>0.034</td>
<td>0.027</td>
</tr>
<tr>
<td><strong>Illness Probability</strong> (Non-sensitive)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>campylobacteriosis</td>
<td>0.0150</td>
<td>0.0090</td>
</tr>
<tr>
<td>salmonellosis</td>
<td>0.0086</td>
<td>0.0081</td>
</tr>
<tr>
<td>Total</td>
<td>0.0236</td>
<td>0.0172</td>
</tr>
<tr>
<td><strong>Illness Probability</strong> (Sensitive)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>campylobacteriosis</td>
<td>0.0750</td>
<td>0.0452</td>
</tr>
<tr>
<td>salmonellosis</td>
<td>0.0432</td>
<td>0.0409</td>
</tr>
<tr>
<td>Total</td>
<td>0.1182</td>
<td>0.0862</td>
</tr>
<tr>
<td><strong>Food Expenditure</strong> ($/person/year)</td>
<td>$144.47</td>
<td>$160.40</td>
</tr>
</tbody>
</table>
Adopting HACCP will also change the price of food. Average beef prices are expected to rise from $1.15 per pound to $1.32, average pork prices are expected to rise from $0.79 per pound to $0.83 per pound, and chicken prices are expected to rise from $0.60 to $0.66 per pound (Antle, 2000). Based on annual per capita meat and chicken consumption figures from the USDA (64.4 lbs. Beef, 52.9 lbs. chicken, and 47.7 lbs. pork in 2000), average annual expenditure on meat and poultry will rise from $144.47 to $160.40. These figures are also summarized in Table I.

Now, all that is needed to calculate the incidence of foodborne illness in the two-standard case is a characterization of consumer demand. Here we make the simplifying assumption that consumers are risk neutral, where the benefits from consuming food of a given quality is equal to a maximum potential consumption benefit, $\beta$, times the probability that an individual does not contract foodborne illness $u(i) = \beta \cdot [1 - f(v, q_i)]$ minus the cost of food. We have already described illness probabilities and price effects. All that is required is an assumption about the potential consumption benefit. We set this benefit equal to $2400 per year, which implies consumer responsiveness to food safety consistent with the empirical literature (Eom, 1994; Ready et al., 1996). The price elasticity of food safety for the non-sensitive population is roughly 0.36 and for the sensitive population is approximately 1.8.

### 3.3 The Results

Given this characterization of consumer demand, only the susceptible fraction of the population would purchase food certified at the higher standard. The reason for this is quite intuitive. Consuming the higher quality food is equally costly for all consumers, but the vulnerable segment of the population is willing to bear this additional financial burden in exchange for a sizable reduction in the risk of foodborne illness, roughly 3 percentage points. In contrast, the change in foodborne health risks for the non-sensitive segment of the population is only about 0.5 percentage points. Non-sensitive citizens do not find this small risk reduction worth the additional expenditure. Thus, the additional risk standard reduces the population level annual rate of foodborne illness (due to both campylobacteriosis and salmonellosis) from 14.18% to 10.98%. If the high quality standard were mandated for all producers, the incidence of foodborne illness would drop to 10.3%.

This comparison of pre-HACCP food quality to HACCP food quality can be extended to examine a larger range of interventions using additional data from

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13 Note all figures are based on price impacts on large producers (who are the majority producers in each market) and the assumption that the base safety level is 50%. See Antle (2000) for more details.
Antle (2000). In that paper, safety cost elasticities were estimated for beef, pork, and poultry plants using data on plant cost functions. They were estimated to be 0.728, 0.263, and 0.506 respectively. Using these figures we can calculate price impacts for a continuum of pathogen reduction levels. Coupled with dose-response functions for vulnerable and non-vulnerable populations, we can calculate the net benefit to each group from consuming the higher quality food. The results indicate that the net benefits from a higher food quality standard for the non-sensitive population remain positive for all interventions that yield pathogen reduction levels less than or equal to roughly 13%. After the 13% level, the increased food prices begin to outweigh the additional health benefits, a result that is driven, in part, by the steep curvature of the dose-response function at low-doses. On the other hand, the net benefits to the sensitive population are always increasing in pathogen reduction, albeit at a decreasing rate. These net benefits curves are depicted in Figure 1.

All of the previous analysis can be repeated for alternative assumptions about the dose-response function for sensitive populations. If, for example, we conservatively assume that vulnerable populations are only 1.5 times more likely to develop foodborne disease than their non-vulnerable counterparts, we still find that the vulnerable subgroup would choose to consume food produced under HACCP. Of course, the resulting reductions in poisonings as a result of this choice are considerably smaller. We also find that the net benefits to this group from adopting interventions that are progressively more effective in reducing pathogen levels is not monotonic. It is increasing at low levels of effectiveness, but begins to decline at mid-levels of effectiveness, eventually yielding negative net benefits at around 78% effectiveness. In other words, if the vulnerable subgroup is only 1.5 times more susceptible to disease than the non-sensitive population, they will not prefer the higher quality standard if it dramatically reduces pathogen levels because at very high reduction levels the higher food costs outweigh the additional health benefits. This net benefit curve is also depicted in Figure 1.

The impacts of risk misperception on consumer decisions can be examined in an entirely analogous manner. If both vulnerable and non-vulnerable populations under-perceive their ‘true’ risk of developing foodborne disease, then the threshold intervention effectiveness level below which consumers will choose to purchase the higher quality food will fall. The importance of this threshold as well as the thresholds discussed earlier will depend fundamentally on the goals of the regulator. While we did not attempt to address these goals in our case study, we have illustrated the conditions that demarcate the boundaries of vulnerability-driven consumer choice for our empirical problem. Consumer demand, a function

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14 Again, all figures are based on large producers.
Figure 1: Net Benefits from Pathogen Reduction
of the price of food and the heterogeneous health risks associated with consuming it, dictates the terms of trade between the two regulatory approaches. Government health targets may not always be commensurate with the health outcomes implied by consumer choice. In this case, high uniform quality standards may be preferred to the two-standard approach.

4. Conclusions

This paper examines food safety standard setting in a population where individuals are heterogeneous in their vulnerability to foodborne illness. A particular focus is placed on the joint implementation of a regulated minimum quality standard and a certified higher quality standard, which may appeal to certain subsets of the population. Our analytic results suggest that the optimal employment of multiple quality standards depends critically on consumer demand for food, which, in part, depends on how accurately consumers perceive their vulnerability to food risks. The attractiveness of uniform versus differentiated standards also hinges critically on the distribution of vulnerabilities across the population.

The paper also includes a stylized case study to illustrate the salient features of the theoretical model and the importance of risk heterogeneity and consumer demand in food safety policy making. The case study confirms the importance of consumer demand and the population distribution of vulnerability. Examining policies to control meat and poultry contamination with Campylobacter and Salmonella, we find that non-sensitive populations would only be willing to consume higher quality food that contains up to 13% less pathogens than the minimum quality standard. At purity levels higher than this, the benefits from reduced illness do not outweigh the accompanying rise in food prices. In contrast, we find that the benefits from consuming the higher quality food for the sensitive population is monotonically increasing in food purity, albeit at a decreasing rate. When the vulnerable population is made less sensitive, two quality standards only makes sense if the higher food quality standard is 80% more pure than the minimum standard or less.

The model developed here could be extended in several directions. First, the modeling of consumer demand for safe food could be expanded to incorporate wealth effects, changes in the quantity of food consumed (rather than simply change in type), substitutions across broad food categories, and explicitly recognizing the consumers role in mitigating pathogen exposure after the food is purchased. In this case, consumer demand for a given food product will no longer simply depend on price and quality, but on complex interactions with the composition of their entire diet, heterogeneous income elasticities, and the degree to which consumers can engage in the household production of food safety. Second, a more detailed model of the regulatory cost function for mandating
minimum quality standards and certifying higher standards would allow one to expand the research question to examine the optimal number of certified food quality standards. The modeling approach could also be usefully extended, by moving beyond heterogeneity in susceptibility to foodborne illness to include heterogeneity in the intensity of illness, conditional on infection. Together, these comprise a future research agenda.
Appendix

Proposition 1:

Let $R$ denote the total population health risk faced by the two groups consuming from each of the food quality groups. Totally differentiate Eqs. (5), (6), and (7) and apply Cramer’s Rule and the implicit function theorem to obtain the following:

$$
\frac{dq_L}{dk} = \left\{ -\lambda \frac{\partial^2 R}{\partial q_L \partial q_H} \frac{\partial R}{\partial q_H} + \lambda \frac{\partial^2 R}{\partial q_H^2} \frac{\partial R}{\partial q_L} \right\} / |H|,
$$

$$
\frac{dq_H}{dk} = \left\{ -\lambda \frac{\partial^2 R}{\partial q_L \partial q_H} \frac{\partial R}{\partial q_L} + \lambda \frac{\partial^2 R}{\partial q_L^2} \frac{\partial R}{\partial q_H} \right\} / |H|,
$$

where the determinant of the bordered Hessian $|H|$ is defined as

$$
|H| = \left[ \lambda \frac{\partial^2 R}{\partial q_L^2} \right] \left[ \frac{\partial R}{\partial q_H} \right]^2 + \left[ \lambda \frac{\partial^2 R}{\partial q_H^2} \right] \left[ \frac{\partial R}{\partial q_L} \right]^2 - 2\lambda \frac{\partial^2 R}{\partial q_L \partial q_H} \frac{\partial R}{\partial q_L} \frac{\partial R}{\partial q_H}
$$

and must be positive to ensure an interior solution.

Thus the signs of $dq_L / dk$ and $dq_H / dk$ will depend on the signs of the numerators in the expressions described above. Algebraic manipulation yields the following conditions:

$$
\frac{dq_L}{dk} < 0 \text{ if } \frac{\partial R}{\partial q_L} > \frac{\partial^2 R}{\partial q_H} < \frac{\partial^2 R}{\partial q_L} \frac{\partial R}{\partial q_L}
$$

$$
\frac{dq_H}{dk} < 0 \text{ if } \frac{\partial R}{\partial q_L} > \frac{\partial^2 R}{\partial q_L} \frac{\partial R}{\partial q_H} < \frac{\partial^2 R}{\partial q_H} \frac{\partial R}{\partial q_H}
$$

**Corollary to Proposition 1:**

While the impact of more stringent standards can either increase or decrease each of the quality standards, it cannot simultaneously decrease both. Substituting the expressions for $dq_L / dk$ and $dq_H / dk$, the Hessian can be re-expressed as

$$
|H| = dq_L / dk \cdot |H| \cdot \frac{\partial R}{\partial q_H} + dq_H / dk \cdot |H| \cdot \frac{\partial R}{\partial q_L}
$$

Since $\partial R / \partial q_L$ and $\partial R / \partial q_H$ are both negative, this expression cannot hold true if both $dq_L / dk$ and $dq_H / dk$ are positive.
Proposition 3:

Totally differentiate the analogous expressions to Eqs. (5), (6), and (7) which now contain the risk misperception parameter and apply Cramer’s Rule and the implicit function theorem to obtain the following:

\[
\frac{dq_L}{d\alpha} = \left\{ -\lambda \frac{\partial^2 R}{\partial q_L \partial \alpha} \left[ \frac{\partial R}{\partial q_L} \right]^2 + \lambda \frac{\partial^2 R}{\partial q_H \partial \alpha} \left[ \frac{\partial R}{\partial q_L} \frac{\partial R}{\partial q_H} \right] \right\} / |H|.
\]

\[
\frac{dq_H}{d\alpha} = \left\{ -\lambda \frac{\partial^2 R}{\partial q_H \partial \alpha} \left[ \frac{\partial R}{\partial q_L} \right]^2 + \lambda \frac{\partial^2 R}{\partial q_L \partial \alpha} \left[ \frac{\partial R}{\partial q_L} \frac{\partial R}{\partial q_H} \right] \right\} / |H|.
\]

Since the determinant of the bordered Hessian is positive, the sign of each of these derivatives can be characterized as follows:

\[
\frac{dq_L}{d\alpha} > 0 \quad \text{if} \quad \frac{\partial^2 R}{\partial q_H \partial \alpha} \frac{\partial R}{\partial q_L} - \frac{\partial^2 R}{\partial q_L \partial \alpha} \frac{\partial R}{\partial q_H} > 0
\]

\[
\frac{dq_H}{d\alpha} > 0 \quad \text{if} \quad \frac{\partial^2 R}{\partial q_L \partial \alpha} \frac{\partial R}{\partial q_H} - \frac{\partial^2 R}{\partial q_H \partial \alpha} \frac{\partial R}{\partial q_L} < 0.
\]

The sign of these derivatives will depend on the sign of the cross-partial derivatives with respect to the risk misperception variable. Expanding these cross-partial derivatives into their constituent components by breaking down the aggregate risk measure \( R \) yields:

\[
\frac{\partial^2 R}{\partial q_L \partial \alpha} = g(\hat{v}) \frac{\partial \hat{v}}{\partial \alpha} \frac{\partial f_L}{\partial q_L} + \frac{\partial \hat{v}}{\partial q_L} \left( \frac{\partial f_L}{\partial \hat{v}} - \frac{\partial f_H}{\partial \hat{v}} \right) + g(\hat{v}) \frac{\partial^2 \hat{v}}{\partial q_L \partial \alpha}
\]

\[
\frac{\partial^2 R}{\partial q_H \partial \alpha} = g(\hat{v}) \frac{\partial \hat{v}}{\partial \alpha} \frac{\partial f_L}{\partial q_H} + \frac{\partial \hat{v}}{\partial q_H} \left( \frac{\partial f_L}{\partial \hat{v}} - \frac{\partial f_H}{\partial \hat{v}} \right) + g(\hat{v}) \frac{\partial^2 \hat{v}}{\partial q_H \partial \alpha}
\]

where \( f_L \) represents \( f(\hat{v}, q_L) \) and \( f_H \) represents \( f(\hat{v}, q_H) \).

Recognizing that each of the derivatives of the threshold vulnerability \( \hat{v} \) above are implicitly defined in equation (4), substitution and tedious algebraic manipulation yields the following:

\[
\frac{\partial^2 R}{\partial q_L \partial \alpha} = -\frac{\partial \hat{v}}{\partial \alpha} \frac{\partial^2 \hat{v}}{\partial q_L^2} \left( \frac{f_L - f_H}{\partial \hat{v}} \right)
\]

\[
\frac{\partial^2 R}{\partial q_H \partial \alpha} = -\frac{\partial \hat{v}}{\partial \alpha} \frac{\partial^2 \hat{v}}{\partial q_H^2} \left( \frac{f_L - f_H}{\partial \hat{v}} \right)
\]
The signs of each of these expressions depend on the slope of the vulnerability distribution around \( \hat{v} \). If \( \frac{\partial g}{\partial \hat{v}} < 0 \), then \( \frac{\partial^2 R}{\partial q_L \partial \alpha} > 0 \) and \( \frac{\partial^2 R}{\partial q_H \partial \alpha} > 0 \), which, in turn, implies that \( \frac{dq_L}{d\alpha} < 0 \) and \( \frac{dq_H}{d\alpha} > 0 \). If \( \frac{\partial g}{\partial \hat{v}} > 0 \), then the opposite is true and \( \frac{dq_L}{d\alpha} > 0 \) and \( \frac{dq_H}{d\alpha} < 0 \).
References


