Slaughterhouse Rules: Human Error, Food Safety, and Uniformity in Meat Packing

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Abstract

Meat retailers and processors express demand for a more uniform product, and technical innovations are allowing an increasingly uniform supply. Meat packers can promote uniformity through pre-slaughter sorting, or earlier through contractual procurement. Emphasizing human error and the efficacy of effort on the packing line, we develop a model whereby packers gain from expanding revenue and reducing processing costs when exogenously determined carcass uniformity increases. Line speed and occupational risk increase with uniformity. Whether optimally regulated or not, equilibrium food safety can decline with increased uniformity. Effort-saving automation also will have an adverse effect on occupational safety, and may have this effect on equilibrium food safety. Under endogenously chosen carcass uniformity, a line speed regulation may not support first-best because it distorts grower-level technology adoption incentives. We also provide a precise ordering on pre-slaughter lot sorts such that packing line capital efficiency increases.

Keywords: biotechnology, contract provisions, overload, safety regulation, value of information.

JEL classification: L5, Q1, D2

SLAUGHTERHOUSE RULES: HUMAN ERROR, FOOD SAFETY, AND UNIFORMITY IN MEAT PACKING

The packing line lies at the interface between production and consumption in meat markets. For various reasons, producers and consumers have keen interests in packer conduct and performance. Concerning quality, packers convey signals to producers regarding what consumers want, and also regarding what traits facilitate processing. Consumers seek consistent, safe, cheap meat that is derived from humane procedures. While the emphases many have changed over time, these interests are not new. Innovations in science have altered the incentives to achieve these goals. Biotechnology has allowed improved measurement of, and capacity to breed, consistent, high quality livestock for meat.

The focus of this paper is on understanding the economics of effort and of safety failures during packing. The issue has relevance for at least three reasons, two of which are the objects of our inquiry. The reason that is not studied here is animal welfare, a concern for many consumers. Retailers such as McDonald's Corporation and Burger King have acted to reassure consumers that the animal sources of their products were acceptably treated prior to and during slaughter (*South Florida Business Journal* 2002). More direct evidence of willingness to pay for improved animal welfare is provided in Bennett and Blaney 2002. One reason that is considered here is the very hazardous nature of meat packing occupations. The meat packing industry had the highest reported incidence rate of repeated trauma disorders in 1996 (Bureau of Labor Statistics 1999). It also had the highest reported incidence rate of nonfatal occupational injuries and illnesses in 2002, with the third highest in 2001 (Bureau of Labor Statistics 2002). The other reason considered in this paper is that the packing line is a primary source of food contamination. For over a century, governments in North America and Western Europe have reflected public concerns by intervening to secure the quality of food (Goodwin 1999).

These and other concerns have been articulated by Schlosser (2001), by Eisnitz (1997), and by many others. Among the complaints expressed is that slaughter activities are at excessive throughput rates, so that workers and food quality are at excessive risk. The goal of this paper is to model incentives in slaughterhouse activities to understand better the origin of demand for homogeneous livestock as inputs, the incentives for high throughput, and the equilibrium risks of failure in food and occupational safety.

While a failure can have many technical origins, it can largely be attributed to human error. This is especially true in meat packing. Although mechanization has greatly affected the industry, human intervention is required throughout. This is mainly because animals, more so than plastics, metals, and other commodities, are both heterogeneous and solid. These descriptions are especially applicable at earlier stages of processing. Animal conformations are still almost as variable as human physiques, and workers provide the intelligence required to adapt to carcass peculiarities. The central processing steps of evisceration and cutting are still heavily manual, with the knife as a primary tool.

Unlike many other industrial operations, the packing line can be quite chaotic as the animal and then carcass moves along the chain. It is in this kind of environment that mistakes are frequent. The probability of making a mistake is not exogenous. Two important features of the packing environment are endogenous. One is line speed relative to the speed at which the line was designed to perform best. The other is carcass uniformity, and it is economically feasible to alter the extent of uniformity among animals on the line.

Line speed is a concern for meat industry quality control professionals while, in so competitive an industry, line speed and line disruptions convert to forgone revenues. Roberts (1980, p. 8) asserts:

> The care taken by personnel must, obviously, be less effective the faster they work. Fast working increases the risk of undesirable hygienic accidents, such as failure to contain faeces when cutting out the anus; or liberation of gut contents into the carcass by accidental perforation of the gut with a too hasty knife. The greater liability to accidental cuts makes it more necessary for operatives to use protective guards (e.g., chainmail gloves) which increase hygienic problems. Above all the operative is not likely to spend time between carcasses in cleaning his

> tools, hand and clothing: operations not manifestly productive yet especially necessary to contain within the individual carcass the effects of hygienic accidents.

It is important to emphasize that it is not line speed in an absolute sense that matters but rather the speed relative to the way the line has been designed, the skills of the workers, and the nature of the materials. Sheridan (1998, p. 334) emphasizes: "The most important aspect is whether or not the operatives have sufficient time to carry out their jobs." Warrick's April 2001 press interview with Temple Grandin, assistant professor of animal science at Colorado State University and consultant for McDonald's Corporation, also suggests the dangers of excessive throughput. Grandin asserts: "It's like the 'I Love Lucy' episode in the chocolate factory. You can speed up a job and speed up a job, and after a while you get to a point where performance doesn't simply decline—it crashes." Empirical evidence to support the idea is provided in Bell 1997, in Prasai et al. 1995, and in Reagan et al. 1996, although factors such as the degree of labor specialization, efficiency in the management system, and the extent of size/sex/weight uniformity of animals complicate the relationship (Hogue et al. 1993, p. 113).

There are several specific tasks for which the consequences for food safety of stress on the line are very direct. For obvious reasons, animal cleanliness is known to affect the likelihood of contamination. Ridell and Korkeala (1993) have shown that dungy animals increase carcass bacterial counts for cattle in Finland. Factory owners manage the problem by separating dungy animals, to kill later in the day and at a slower line speed. Formal regulations to implement this procedure were adopted in Ireland in 1998 (Doherty 1999). Van Donkersgoed et al. (1997) note that North American abattoirs assign dirt (tag) scores to cattle lots. Management reduces line speed and adds dirt-removing workers to the line when processing these animals.

The removal of intestines is another critical point. Tying the bung (rectum) and additional care at evisceration are known to reduce the incidence of contamination in pigs (Nesbakken et al. 1994; Oosterom and Notermans 1983). Of especial concern is carelessness that leads to damaged intestines. Rivas, Vizcaíno, and Herrara (2000) remark that when working with larger Iberian pigs, skill and strength are required to succeed at evisceration. They note: "Moreover, the hygienic condition of the dressed carcass is largely determined by the skill with which workers remove the gut so that no rupture of the intestine occurs."

Worker hygiene is a further critical area. Bell (1997) has shown that hand washing and knife blade treatment are significant in limiting contamination. Guyon et al. (2001), studying *E. coli* O157:H7 in beef slaughtering, found three points of concern: the worker's hands at one stage, the worker's apron at another, and a footbridge the carcass came in contact with at a third. For the last of these, a regular decontamination procedure could not be readily implemented because of line speed.

The inspection procedure, be it government run or self-policed, is important in determining line speed. While there are no formal line speed limits at the E.U. legislative level, Germany has had direct regulations in place on the rate of inspection (Roberts 1980). In the United States, the Federal Meat Inspection Act and the Poultry Products Inspection Act empower inspectors to reduce line speed if the inspection task cannot be adequately performed and include maximum line speed provisions. Canada has maximum line speed regulations in place, depending on line design and carcass attributes (e.g., heavy chickens). Bradley and Jericho (1997) observe that a head lymph node inspection at high line speeds requires the carcass to be railed out of the line, often causing costly delay. Watkins, Lu, and Chen (2000) evaluate an automated poultry inspection technology to find that much of the gain in profit arises from increased line speed. That human inspection slows throughput is a longstanding problem.[1]

Non-uniformities also slow throughput. In addition they lead to inconsistencies in the consumer experience, which restaurant franchises are particularly keen to avoid. The trend toward more uniform production processes is a central feature of agricultural industrialization (Boehlje 1996). The broiler industry has for many years emphasized uniformity in production and, if only to recapture lost market share, that emphasis is increasing in the hog and cattle sectors. Uniformity is commonly demanded in feed, medication, and animal inputs at the grow-out stage. Animal market integrators often require the grower to obtain these inputs from a central source. Protocols for the use of inputs are often stipulated in production contracts. For housing, too, the integrator often seeks to specify the type of building used. On the processing side, uniformity has facilitated automation, as in de-boning poultry (Schwartz 1991; Government Accounting

Office 1999). It is standard practice for packers to sort animals according to market destination; for example, cows, bull beef, steers, or heifers (Hogue et al. 1993).[2]

In pork production, technology firms such as Farmweld have developed systems to support increased uniformity among hogs during grow-out and as they leave the farm (Smith, 2002b). The advantages arise from mitigating management problems due to lot heterogeneity as well as from achieving the high price box in the packer's payment grid. A more speculative attempt at technology development to promote uniformity is by the company Prolinea, which intends to sell cloned cattle and hogs for meat production. Among parties interested in this venture is the world's largest hog producer, and major packer, Smithfield, which has made equity investments in the venture (Smith 2003). A uniformity-promoting technology that may not be as widely available in the future is the sub-therapeutic use of antibiotics. McDonald's, a trend-setter in retail-level demand for meat products, has declared its intention to curtail procurement of animal products grown with this technology. The European Union, with Denmark taking a firmer stance, has placed limits on such use. From their study of the issue, Hayes and Jensen (2003) suggest that the consequences will likely be slightly lower feed conversion efficiency and also an increase in the variance of slaughter weights.

The intent of the present work is to study consequences of the packing line environment for packing decisions and to connect these decisions to food and occupational safety consequences. The environmental parameters considered here are the level of carcass uniformity and the extent of labor-saving automation. The decisions we will look at are line speed and the level of effort required of workers. We arrive at some counterintuitive conclusions. In particular, more carcass uniformity and effort-saving automation will increase equilibrium effort required of workers as well as occupational safety risk. We then identify conditions under which food safety risk will increase with carcass uniformity. Stepping back a stage, a connection is made between the long-run determinants of the extent of uniformity and the packing line decision environment. We also inquire into the effects of regulation on food safety, and on the adoption of uniformity-promoting technologies. We then discuss the results.

Human Error

There are *M* carcass types of meat animal species moving in single file on a packing line. Types 1 through M differ, perhaps by breed or weight, and that is the only detail necessary about the non-uniformities. The fraction that is the *i*th type is $\theta_i \geq 0, i \in \Omega_M = \{1, 2, \ldots, M\}$, with $\sum_{i=1}^{M} \theta_i = 1$. The temporal sequence of carcasses is independent. Each carcass requires a baseline worker effort level of μ_1. In addition, a change in carcass type from the last carcass requires the worker to adjust, and so requires more effort.

The effort involved in adjustment is crucial in the analysis. If the present carcass is the *i*th type, then the probability that the next is not is $1-\theta_i$. Taking expectations, the unconditional expectation that a change occurs is

$$\delta = \sum_{i=1}^{M} \theta_i (1-\theta_i) = 1 - \sum_{i=1}^{N} \theta_i^2, \qquad \sum_{i=1}^{M} \theta_i = 1. \tag{1}$$

This is our index of type heterogeneity, and a decrease in δ represents an increase in type uniformity. A few comments are warranted on the index. If $\theta_i = 1$ for some $i \in \Omega_M$, then $\delta = 0$ because no change in type will ever occur along the line. If $\theta_i = M^{-1}\ \forall i \in \Omega_M$ then $\delta = (M-1)/M$ and this is the maximum value δ can assume over type simplex $\theta = (\theta_1, \theta_2, \ldots, \theta_M)$, $\theta_i \geq 0, \sum_{i=1}^{M} \theta_i = 1$. The function is symmetric and concave in the arguments of θ, and so it is Schur-concave (Marshall and Olkin 1979). As such, the majorization pre-ordering induces order across vectors θ, an ordering on type heterogeneity that was also applied in Hennessy, Miranowski, and Babcock (in press 2004).[3]

DEFINITION 1. [In Marshall and Olkin (1979, pp. 10 and 59)] Vector $Q' \in \mathbb{R}^n$ is *majorized* by $Q'' \in \mathbb{R}^n$ (written as $Q' \prec Q''$) if $\sum_{i=1}^{k} q'_{(i)} \geq \sum_{i=1}^{k} q''_{(i)}\ \forall k \in \Omega_n$ and $\sum_{i=1}^{n} q'_{(i)} = \sum_{i=1}^{n} q''_{(i)}$ where the $q_{(i)}$ are defined as order statistics, $q_{(1)} \leq q_{(2)} \leq \ldots \leq q_{(n)}$. A Schur-concave function $U(Q): \mathbb{R}^n \to \mathbb{R}$ satisfies the statement: $U(Q') \geq U(Q'')$ whenever $Q' \prec Q''$.

EXAMPLE 1. $(1/3, 2/3) \prec (3/4, 1/4)$ because $1/3 \geq 1/4$ and $1/3 + 2/3 = 1/4 + 3/4$. Also, $(0.2, 0.4, 0.4) \prec (0.5, 0.4, 0.1)$ because $0.2 \geq 0.1$, $0.2 + 0.4 \geq 0.1 + 0.4$, and $0.2 + 0.4 + 0.4 = 0.1 + \ 0.4 + 0.5$.

Applying the definition, the value of δ is smaller under θ'' than under θ' whenever $\theta' \prec \ \theta''$. Each type change involves additional effort level μ_2. Line speed is $N > 0$ per hour and so we have an index of expected (over the type sequence stochastic process) hourly worker effort $N \times (\mu_1 + \delta\mu_2)$.[4] To capture the idea that automation will alter required effort, we introduce an effort-saving automation parameter $\kappa > 0$ that scales back required effort. Cumulating, the hourly worker effort level is

$$e = \kappa^{-1} N \times \left(\mu_1 + \delta\mu_2\right). \tag{2}$$

Notice that $de / d\delta = \kappa^{-1} N \mu_2 \geq 0$. For a *given value* of N, effort is maximum when all types are equally represented on the line, $\theta_i = M^{-1} \ \forall i \in \Omega_M$. It is minimized when all are of the same type. We will hold that human error is a monotone increasing function of effort level e and so of δ, N, and κ^{-1}. Write $p(z) \in [0,1], z = \bar{e} - e$, as the probability of a human mistake per unit time on the packing line where $\bar{e}$ is the maximum effort that can be elicited, with $p_z(z) \leq 0$ and $p_{zz}(z) \geq 0$. The convexity requirement captures decreasing returns to a caretaking reduction in packing line exhertions.[5] Fraction $\phi \in (0,1)$ of mistakes pertains exclusively to food safety risk, while the remainder pertains exclusively to occupational safety risk.

Packing Line Decisions

Consumers are willing to pay for more consistent, especially more tender, meat and we model this by the twice continuously differentiable unit revenue function $R(\delta)$, with $R_\delta(\delta) \leq 0$.[6] The cost of packing line effort is given by the twice continuously differentiable, increasing, and convex function $C(e)$. The packer is fully informed about worker effort and so there are no contractual information problems.[7] But increased effort requires an increase in the wage rate, as well as incurring the costs of losing and re-hiring workers due to the high turnover that accompanies physically demanding work. It also involves increased worker risk, and so cost $C(e)$ should include a labor market risk premium (Garen 1988).

The packer has one choice variable, line speed N, and seeks to maximize private surplus,[8]

$$V(N^*;\delta) = \max_N \; NR(\delta) - C(e), \tag{3}$$

with optimum choice N^*, associated effort level e^*, and optimality condition[9]

$$R(\delta) - \kappa^{-1} \times \left(\mu_1 + \delta\mu_2\right) C_e(e) = 0. \tag{4}$$

The effect of type heterogeneity on optimum line speed may be represented as

$$\frac{dN^*}{d\delta} = \frac{R_\delta(\delta) - \kappa^{-1}\mu_2 C_e(e^*)}{\kappa^{-2} \times \left(\mu_1 + \delta\mu_2\right)^2 C_{ee}(e^*)} - \frac{N^*\mu_2}{\left(\mu_1 + \delta\mu_2\right)} \leq 0. \tag{5}$$

This is as should be expected: the line slows to account for an increase in the extent of non-uniformity.

Turning to the effect on equilibrium elicited effort, e^*, from (2):

$$\frac{de^*}{d\delta} = \kappa^{-1} N^* \mu_2 + \kappa^{-1} \times \left(\mu_1 + \delta\mu_2\right) \frac{dN^*}{d\delta} = \frac{R_\delta(\delta) - \kappa^{-1}\mu_2 C_e(e^*)}{\kappa^{-1} \times \left(\mu_1 + \delta\mu_2\right) C_{ee}(e^*)} \leq 0. \tag{6}$$

In contrast to the N-fixed derivative in (2), effort increases with increased animal uniformity. Packer surplus function (3) also supports the envelope effect

$$\frac{dV(N^*;\delta)}{d\delta} = N^* R_\delta(\delta) - \kappa^{-1} N^* \mu_2 C_e(e^*) \leq 0, \tag{7}$$

so that more uniformity (i.e., δ decreases) increases packer surplus. To summarize:

RESULT 1. Let $\theta' \prec \theta''$. Absent regulation, equilibrium line speed, worker effort, and packer surplus are all larger under θ'' than under θ'.

More heterogeneity elicits more effort because the direct effect of heterogeneity on effort, $\kappa^{-1}N^*\mu_2$ in (6), or just under (2), is more than offset by the indirect effect through altered line speed. This excess substitution is not due to $R_\delta(\delta)\le 0$ alone as it can also be sourced in the positive cost of effort; set $R_\delta(\delta)=0$ in (6). An alternative way of posing problem (3) is as $\max_e R(\delta)\kappa e/(\mu_1+\delta\mu_2)-C(e)$. Revenue $R(\delta)\kappa/(\mu_1+\delta\mu_2)$ is the unit reward for effort purchased by the packer, and it is increasing in the degree of uniformity. Even for $R(\delta)$ a constant, the unit reward for purchased effort increases with uniformity because the bottom line is meat sold to retailers and non-uniformities necessitate more effort to that end. The driver behind the anomaly in Result 1 should be reconciled with intuition upon positing that more effort should be taken when effort becomes more effective.

Occupational safety is often measured as risk per unit time rather than as risk per unit output. For $p(\overline{e}-e)$ with $p_z(z)\le 0$, Result 1 holds that occupational safety risk per hour, $(1-\phi)p(\overline{e}-e^*)$, increases with the extent of animal uniformity. Food safety risk is best measured on a per-carcass basis. It arises not from $p(z)$ directly but from the ratio

$$L(e;\delta)=\frac{\phi\, p(z)}{N}=\frac{\phi\times(\mu_1+\delta\mu_2)\,p(\overline{e}-e)}{\kappa e}, \tag{8}$$

because it is the risk per carcass and not the risk per unit time that matters to consumers. Label $L(e;\delta)$ as the measure of food safety risk. Differentiating at the optimum,

$$\begin{aligned}\frac{dL(e^*;\delta)}{d\delta}&=\phi\mu_2\frac{p(\overline{e}-e^*)}{\kappa e^*}-\frac{\phi\times(\mu_1+\delta\mu_2)}{\kappa}\left(\frac{p(\overline{e}-e^*)+e^*p_z(\overline{e}-e^*)}{(e^*)^2}\right)\frac{de^*}{d\delta}\\&=\frac{\phi\, p(\overline{e}-e^*)}{\kappa e^*}\left[\mu_2-(\mu_1+\delta\mu_2)\frac{1+e^*p_z(\overline{e}-e^*)/p(\overline{e}-e^*)}{e^*}\frac{de^*}{d\delta}\right].\end{aligned} \tag{9}$$

The positive term $\phi\mu_2 p(\overline{e}-e^*)/(\kappa e^*)$ arises because more uniformity (δ low) facilitates expeditious completion of slaughter for a fixed stock of animals. From a food safety perspective, it is not errors per hour that matter but rather errors per carcass.

A necessary condition for derivative (9) to be negative is that $-1>e^*p_z(\overline{e}-e^*)/p(\overline{e}-e^*)$. Note though that, from (6), if

$$\frac{\mu_2 e^* C_{ee}(e^*)}{\kappa R_\delta(\delta) - \mu_2 C_e(e^*)} - 1 \geq -\frac{d\mathrm{Ln}\left[p(\bar{e}-e)\right]}{d\mathrm{Ln}(e)}\Big|_{e=e^*} \tag{10}$$

then the expression in (9) is negative. In that case, more uniformity in carcasses, $\theta' \to \theta''$ with $\theta' \prec \theta''$, increases effort and thus also the probability of a human mistake to such an extent that food safety risk increases.

RESULT 2. Let $\theta' \prec \theta''$. Absent regulation, equilibrium occupational risk per hour is larger under θ'' than under θ'. Equilibrium food safety risk per carcass is smaller under θ'' than under θ' whenever $-1 \leq e^* p_z(\bar{e}-e^*)/p(\bar{e}-e^*)$. It is larger under θ'' than under θ' whenever (10) applies.

Suppose that $R_\delta(\delta) = 0$ so that the only benefit to the industry from a decrease in δ is through cost, $-\kappa^{-1} N^* \mu_2 C_e(e^*) \leq 0$ in (7). Then (10) becomes

$$\frac{d\mathrm{Ln}\left[p(\bar{e}-e)\right]}{d\mathrm{Ln}(e)}\Big|_{e=e^*} \geq 1 + \frac{d\mathrm{Ln}\left[C_e(e)\right]}{d\mathrm{Ln}(e)}\Big|_{e=e^*}. \tag{11}$$

For an increase in uniformity to increase food safety risk per carcass, the elasticity of the failure probability with respect to effort must be larger than unity plus the own elasticity of marginal cost. Unity arises because of the direct benefits of uniformity, the term $\phi\mu_2 p(\bar{e}-e^*)/(\kappa e^*)$ in (9). The cost elasticity arises because if $[d\mathrm{Ln}\left[C_e(e)\right]/d\mathrm{Ln}(e)]|_{e=e^*} \to \infty$ then $de^*/d\delta \to 0$. In that case, expression (9) is assuredly positive and the substitution effect cannot overcome the direct benefits of more uniformity. Figure 1 illustrates a case where the failure probability is elastic with respect to effort, $-1 > e^* p_z(\bar{e}-e^*)/p(\bar{e}-e^*)$, and so the possibility arises that more uniformity increases food safety risk. The value of $p(\bar{e}-e^*)$ is low while both the absolute value of the derivative and the effort level are high.

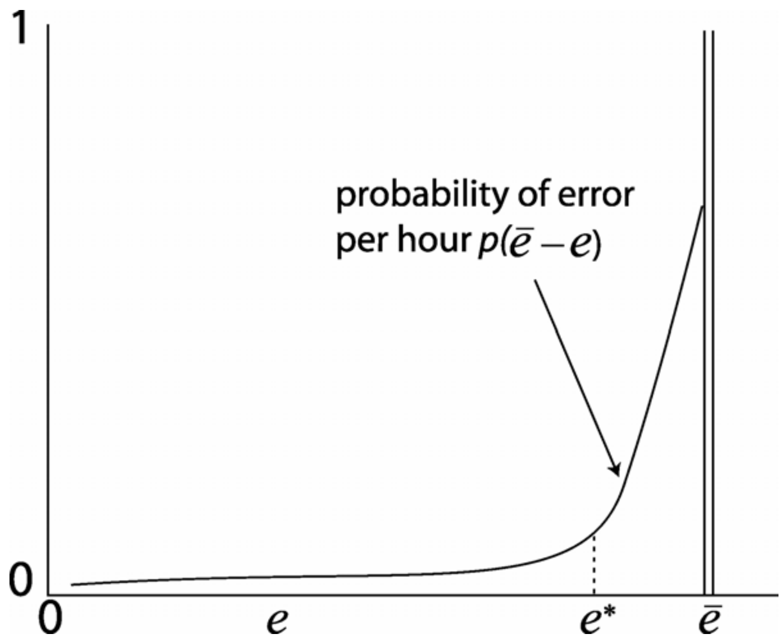

FIGURE 1. Elastic failure probability when more uniformity might increase food safety risk

Placing emphasis on effort-saving automation parameter κ the effect of a change on effort, from (4), is

$$\frac{de^*}{d\kappa} = \frac{R(\delta)}{(\mu_1 + \delta\mu_2)C_{ee}(e^*)} = \frac{C_e(e^*)}{\kappa C_{ee}(e^*)} = \frac{e^*}{\kappa}\left(\frac{d\mathrm{Ln}\left[C_e(e)\right]}{d\mathrm{Ln}(e)}\bigg|_{e=e^*}\right)^{-1} \geq 0, \tag{12}$$

so that occupational safety risk increases with the effort-saving technology. Equilibrium food safety risk is

$$\frac{dL(e^*;\delta)}{d\kappa} = -\frac{\phi \times (\mu_1 + \delta\mu_2)}{\kappa^2}\frac{p(\bar{e}-e^*)}{(e^*)^2}\left(e^* + \kappa \times [1 + e^* p_z(\bar{e}-e^*)/\,p(\bar{e}-e^*)]\frac{de^*}{d\kappa}\right). \tag{13}$$

The derivative is positive if and only if $e^* + \kappa \times [1 + e^* p_z(\bar{e}-e^*)/\,p(\bar{e}-e^*)]de^*/\,d\kappa \leq 0$. Substitute (12) into (13) to conclude that expression (13) is positive if and only if (11) is positive.

RESULT 3. Absent regulation, equilibrium occupational safety risk per hour increases with an effort-saving technology innovation. Equilibrium food safety risk per carcass decreases with the innovation whenever $-1 \le e^{*} p_z(\bar{e} - e^{*}) / p(\bar{e} - e^{*})$. It increases with the innovation if and only if (11) applies.

COROLLARY 3.1. If an effort-saving technology increases food safety risk per carcass, then so does an increase in uniformity, i.e., if (11) holds then so does (10).

The corollary arises because more uniformity increases food safety risk for two reasons, both of which concern the elicitation of effort. The marginal returns to effort arise through increased retail sales and through increased efficiency in effort. The effort-saving innovation gives rise only to the second of these effects.

Turning to the effects of first-best regulations, use (2) to confirm that excessive effort may be viewed as excessive line speed. With damage from a safety failure as $D > 0$ and probability of failure per carcass as $p(\bar{e} - e) / N$, assume that packers are fined D per failure. Packer surplus per hour is then[10]

$$W(N;\delta) = NR(\delta) - C(e) - Dp(z). \tag{14}$$

Optimal regulation supports line speed N^{**} and effort e^{**} as the solution to

$$R(\delta) - \kappa^{-1} \times \left(\mu_1 + \delta\mu_2\right) C_e(e) + \kappa^{-1} \times \left(\mu_1 + \delta\mu_2\right) Dp_z(z) = 0. \tag{15}$$

From the additional term relative to (4), line speed is too high. Additional work supports the following.

RESULT 4. Under optimal regulation, equilibrium food safety risk per carcass decreases with an increase in carcass uniformity when $-1 \le e^{**} p_z(\bar{e} - e^{**}) / p(\bar{e} - e^{**})$, and it increases when

$$\frac{\mu_2 e^{**} \times [C_{ee}(e^{**}) + Dp_{zz}(\bar{e} - e^{**})]}{\kappa R_\delta(\delta) - \mu_2 \times [C_e(e^{**}) - Dp_z(\bar{e} - e^{**})]} - 1 \ge -\frac{d\mathrm{Ln}\left[p(\bar{e} - e)\right]}{d\mathrm{Ln}(e)}\Big|_{e=e^{**}}. \tag{16}$$

The key point here is that the contrarian effects in results 2 and 3 have nothing to do with the existence of an externality. A simple derivation of (14) shows that

$$\frac{dW(N^{**};\delta)}{d\delta} = N^{**}R_{\delta}(\delta) - \kappa^{-1}N^{**}\mu_2 \times \left[C_e(e^{**}) - Dp_z(z^{**})\right] \leq 0, \tag{17}$$

and packer surplus still increases with more uniformity. But, under appropriate demand conditions, food safety risk per carcass could conceivably increase by so much that consumers receive no benefits while additional supply-side surplus is divided between packer and producer.

Equilibrium in Grower-Level Uniformity-Promoting Technologies

As has been previously discussed, animal uniformity when entering the slaughterhouse is not entirely exogenous. Uniformity can be changed at the outset through the use of genetic technologies in breeding, through production contracts, through intermediate-stage sorting, and through post-production sorting. We will consider post-production sorting first, and then turn to the other activities.

Define the *v*th carcass on the packing line as x_v and write $x_v = x_v(i)$ when it is the *i*th type. Describe the unconditional probability of this event as $P[x_v = x_v(i)]$, which has already been quantified as θ_i. The line successor conditional probabilities (conditional on $x_v = x_v(i)$) are given as $P[x_{v+1} = x_{v+1}(j) \mid x_v = x_v(i)],\ j \in \Omega_M$, and autocovariance is said to be positive whenever $P[x_{v+1} = x_{v+1}(i) \mid x_v = x_v(i)] > \theta_i\ \forall i \in \Omega_M$.

RESULT 5. Absent regulation, let types be sorted just before slaughter so that the packing line type sequence autocovariance is positive. Then line speed and effort are higher than they would be were the type sequence independent. Equilibrium food safety risk per carcass decreases with the sorting activity if $-1 \leq e^* p_z(\bar{e} - e^*) / p(\bar{e} - e^*)$. It increases if (10) applies.

At this point we step back and endogenize carcass uniformity during production. Verification of on-farm sorting and uniformity-promoting activities may require contracts, or it may suffice to have better informal communications between the grower and the processor. In any case, the cost of obtaining heterogeneity level δ is held to be $F(\delta;\eta)$ per animal where $F_{\delta}(\delta;\eta) \le 0$. Scalar parameter η captures cost-reducing innovations, $F_{\eta}(\delta;\eta) \le 0$, that promote uniformity. Such an innovation could be in genetics or in reproductive physiology. Or it could be in medication technologies, such as antibiotics, that better control inter-animal differences. It could also be in feed or housing input controls that homogenize animal outputs across growers who deliver to a packer.

The joint-surplus maximizing problem across growers and packers becomes

$$V(e^*,\delta^*) = \max_{e,\delta} \left[R(\delta) - F(\delta,\eta)\right] \times \frac{\kappa e}{\mu_1 + \delta\mu_2} - C(e). \tag{18}$$

The problem may be decomposed into two stages. First, define

$$J(\eta) = \max_{\delta} \left[R(\delta) - F(\delta,\eta)\right] \times \frac{\kappa}{\mu_1 + \delta\mu_2}. \tag{19}$$

If $F_{\delta,\eta}(\delta;\eta) \ge 0$, so that an increase in η decreases the unit cost of more uniformity, then it is readily shown that $\delta^*(\eta)$ is decreasing.[11] Innovations that reduce the marginal cost of increasing uniformity can include data processing technologies in the feedlot and office, developments in feed mechanization, housing modifications, and artificial insemination. From the envelope theorem, $F_{\eta}(\delta,\eta) \le 0$ implies $J_{\eta}(\eta) \ge 0$.

In the second stage, problem (18) becomes

$$\max_{e} J(\eta)e - C(e), \tag{20}$$

so that, consistent with the law of supply, $e^*(\eta)$ can be seen to be increasing. Now equation (2) and the analysis after (18) lead to

$$\frac{dN^*}{d\eta} = \frac{\kappa}{\mu_1 + \delta\mu_2}\frac{de^*}{d\eta} - \frac{\kappa\mu_2 e^*}{(\mu_1 + \delta^*\mu_2)^2}\frac{d\delta^*}{d\eta} \ge 0. \tag{21}$$

From (8),

$$\frac{dL[e^*(\eta),\delta^*(\eta)]}{d\eta}=\frac{\phi\mu_2 p(\bar{e}-e^*)}{\kappa e^*}\frac{d\delta^*}{d\eta}-\frac{\phi\times(\mu_1+\delta^*\mu_2)}{\kappa}\left(\frac{p(\bar{e}-e^*)+e^* p_z(\bar{e}-e^*)}{(e^*)^2}\right)\frac{de^*}{d\eta}, \quad (22)$$

and the expression is negative if $-1\le e^* p_z(\bar{e}-e^*)/p(\bar{e}-e^*)$. To summarize:

RESULT 6. Under $F_{\delta,\eta}(\delta;\eta)\ge 0\ge F_\eta(\delta;\eta), 0\ge F_\delta(\delta;\eta)$, and absent regulation, then the maximization of joint-surplus across packers and growers supports the following assertions:

(a) $dN^*/d\eta\ge 0$;

(b) $de^*/d\eta\ge 0\ge d\delta^*/d\eta$;

(c) food safety risk per carcass decreases with an increase in uniformity-promoting technology index η if $-1\le e^* p_z(\bar{e}-e^*)/p(\bar{e}-e^*)$.

When the level of uniformity is endogenous, then the behavioral nature of the food safety inefficiency is quite structured.

RESULT 7. Absent regulation, there is too much effort and the line speed is too high. But the level of uniformity is correct.

As was previously mentioned, line speed regulations, be they explicit or implicit, have been enacted in an effort to strengthen quality control. We ask next what effects such a regulation will have on industry behavior and performance. There is a LeChatelier-effect restriction in the extent of uniformity index response (Milgrom and Roberts 1996).

RESULT 8. Assume $F_{\delta,\eta}(\delta;\eta)\ge 0\ge F_\eta(\delta;\eta), 0\ge F_\delta(\delta;\eta)$. Suppose a line speed constraint $N\le\hat{N}$ is imposed on objective (18), where the constraint need not bind. Then the responsiveness of equilibrium heterogeneity index δ^* to η increases as $\hat{N}$ increases.

Consider a perfectly competitive market such that joint-surplus maximization is supported. Then a line speed regulation will tend to decrease the extent to which a uniformity-promoting innovation converts to increased uniformity in the animals and animal products. For example, country A with a line speed regulation may adopt genetic technologies at the farm level less rapidly than would unregulated country B.

Under a binding line speed regulation, the industry may be viewed as having the maximization problem

$$\max_{\delta} \left[R(\delta) - F(\delta;\eta)\right]\hat{N} - C\left[\kappa^{-1} \times (\mu_1 + \delta\mu_2)\hat{N}\right]. \tag{23}$$

If $R_{\delta\delta}(\delta) < F_{\delta\delta}(\delta;\eta)$ and the solution is interior, then equilibrium δ satisfies

$$R_{\delta}(\delta) - F_{\delta}(\delta;\eta) - \kappa^{-1}\mu_2 C_e\left[\kappa^{-1} \times (\mu_1 + \delta\mu_2)\hat{N}\right] = 0, \tag{24}$$

with consequences:

RESULT 9. For objective function (23) concave in δ, a binding line speed regulation cannot be first-best when the level of uniformity is endogenous. The optimum line speed regulation reduces the chosen level of uniformity relative to first-best, i.e., δ^* is too high.

This result is in contrast with a line speed regulation with δ exogenous, as in (14). Then the chosen values of N and e are the same up to a scalar multiple, and the line speed constraint is equivalent to a maximum effort constraint as might be imposed by a workers' union.[12] When δ is endogenous, then an adjustment in δ can be a substitute for eliciting more effort, i.e., growers choose δ to be high, uniformity to be low, and so effort effectiveness to be low. The regulation will act to dampen demand for uniformity in packing plants because effort not expended at the lower line speed can be expended on processing non-uniform carcasses. Of course, there may be farm-level motives for uniformity, and these will still exist. Uniform production may increase the efficiency of feed conversion, reduce transactions costs in going to market, and save management time because the herd can be treated more like an aggregate rather than at the animal level. As explained in Hennessy, Miranowski, and Babcock (in press 2004), uniformity may also facilitate the capacity to innovate in a farm's production system.

Sorting and Capital Cost Efficiencies

To this point the analysis has emphasized the effects of uniformity on labor efficiency. We turn now to an effect on capital cost efficiencies. Consider an operation where batches of a given stock of raw materials are to be processed. Each of S batches, numbered $s \in \{1, 2, \ldots, S\}$, is comprised of n units and each unit $i \in \{1, 2, \ldots, n\}$ requires a processing time of $t_{s,i}$. The technology is *fixed* in that it is not conditioned on how the given stock of raw materials is partitioned into batches. The time for a batch to be processed is given in a Leontief manner by the largest $t_{s,i}$ among the batch. Total time taken to process the product is given by the sum of batch times, written as

$$\mathcal{L}_{\pi} = \sum_{s=1}^{S} \max[t_{s,1}, t_{s,2}, \ldots, t_{s,n}]. \tag{25}$$

Here the subscripted symbol π identifies the particular arrangement of the batches. This is just one among the $(nS)!/[(n!)^S S!]$ arrangements of nS units into S batches of n units.

Label the set of all possible batch arrangements as Π. Suppose now that the units are sorted, and label the nS units in increasing order according to time taken for processing. Unit (i) has processing time $t_{(i)}$ so that $t_{(1)} \le t_{(2)} \le \ldots \le t_{(Sn)}$. Define partition $\hat{\pi}$, called the full sorting partition, as the ordered partition with batches $\{(t_{(1)}, t_{(2)}, \ldots, t_{(n)}),$ $(t_{(n+1)}, t_{(n+2)}, \ldots, t_{(2n)}), \ldots, (t_{(nS-n+1)}, t_{(nS-n+2)}, \ldots, t_{(nS)})\}$. Of course, such sorting must be supported by the information available to the sorter.

In particular, complete information on raw material types, together with zero sorting costs, would make the full sorting partition feasible. This sorting partition is of interest because it has been demonstrated by Minc (1971) that

$$\mathcal{L}_{\hat{\pi}} = \min_{\pi \in \Pi} \mathcal{L}_{\pi}. \tag{26}$$

To summarize:[13]

RESULT 10. For a processing technology that is Leontief and fixed, the full sorting partition of raw materials minimizes processing time.

EXAMPLE 2. Let $t_{1,1} = 1 = t_{(1)}, t_{1,2} = 2 = t_{(2)}, t_{2,1} = 4 = t_{(3)}$, and $t_{2,2} = 5 = t_{(4)}$. With two batches of two animals, then $\mathcal{L}_{\hat{\pi}} = \max[1,2] + \max[4,5] = 7$. There are $4!/[(2!)^2 2!] - 1 = 2$ other ways of sorting the raw materials. These lead to times $\mathcal{L}_{\pi'} = \max[1,4] + \max[2,5] = 9$ and $\mathcal{L}_{\pi''} = \max[1,5] + \max[2,4] = 9$.

The objective in (26) points to the plant's vulnerability to the weakest link. The packer does not want the high order statistics $t_{(nS)}$, $t_{(nS-1)}$, … , scattered through the batches. It is better to hold them off as a batch at the end, as is done with dungy animals in Finland (Ridell and Korkeala 1993) and Ireland (Doherty 1999). It bears emphasis that the packer has not been allowed to condition the technology to the batch, perhaps by introducing dirt-removing employees onto the line. Were this possible, then the finding in Result 10 would likely be reinforced in practice because it likely would be easier to condition the technology to a relatively homogeneous batch than a heterogeneous batch. When compared with Result 1, on labor efficiency, Result 10 identifies a capital efficiency motive for sorting so that line speed becomes batch-conditioned. In reality, it would be hard to separate the motives because a worker who receives a problematic carcass will be stressed by the effort while other workers will be idle.

Discussion

Uniformity in materials, be it through contracts or the use of newer biotechnologies, is an important indicator of the industrialization phenomenon. This paper has clarified some of the economics concerning the benefits of uniformity in production, safety issues that are affected, and regulation to mitigate excessive equilibrium food safety risk. It is important to clarify some features not captured in the model. Uniformity likely will increase the effectiveness of the inspection process and should induce more automation of that process. The inspection process is important just as a screening device. In addition, it will provide information for technology improvements. And it should sharpen incentives earlier in production and processing phases. An automation innovation that removes workers from the line will increase occupational safety.

The paper has dealt with several issues concerning the extent of available information, although we have not emphasized that aspect of the problem. A feature of our findings is that more information on animal inputs can be bad in that it can increase food safety risk. The reason is the absence of information on the risk itself, so that equilibrium is second-best. The processing technology sits between incomplete information on inputs and incomplete information on outputs. A better understand of the normative and positive aspects of processing technology choices in the face of such interacting partial information sets should be relevant when considering the determinants of food safety.

The analysis of the environment assumed in this paper does support the idea that sorting and uniformity-promoting biotechnology innovations should quicken the privately optimum rate of processing and the level of occupational risk. But it does not necessarily support the thesis that food safety risk will increase. An empirical analysis of the issue should be possible, but economists likely will have to interact closely with research microbiologists working to identify the technology of safer practices in meat processing. In addition, economists may be able to complement the body of microbiology studies by providing a better factory-level understanding of the importance of hard financial incentives and softer social incentives to which workers and inspectors respond.

Endnotes

1. See Chapter 3 in Wellford 1972.

2. Many packers slaughter animals from premium quality assurance programs in the same batch. AIBP, a very large Irish beef packer, has done so for Aberdeen Angus producers.

3. A related pre-ordering has been used extensively in stochastic modeling by Chambers and Quiggin (2000). The use of the idea here is different because majorization is applied to order a deterministic decision environment heterogeneity, and the modeling of uncertainty is distinct.

4. Under standard law-of-large-numbers assumptions, the empirical mean number of changes per hour converges to δ as the sequence length extends to infinity. We will heretofore suppress the term "expected" when referring to functions of δ.

5. This is a standard assumption in caretaking models. See, e.g., Innes 1999.

6. See Smith 2002a; Boleman et al. 1997; Lusk et al. 2001; or Miller et al. 2001.

7. This is a reasonable assumption given the nature of packing lines.

8. When the model emphasis shifts, we will re-identify the emphasized arguments in value function $V(\cdot)$.

9. The objective function is concave in N as $C_{ee}(e) \geq 0$.

10. There is a cancellation when risk per carcass is multiplied by the number of carcasses.

11. The objective function in (19) is submodular in (δ, η). This suffices to ensure that $\delta^*(\eta)$ is decreasing. See Milgrom and Shannon 1994 or Topkis 1998, p. 76, on response effects when optimizating over submodular and supermodular functions.

12. In some meat packing lines, workers are given a bonus that depends on the number of processed animals. In that case, management concerned about quality tests by food retailers may be keener than workers to maintain a slow rate of throughput.

13. A complete characterization of order on partitions to reduce processing time is provided by the multivariate arrangement increasing order, as developed in Boland and Proschan 1988.

14. We do not dwell on the second-order conditions in system (A3) because these conditions are not necessary. The payoff in (18) with $-Dp(\bar{e}-e)$ appended is supermodular in $(e,-D)$, and so the comparative statics are robust. See Milgrom and Shannon 1994.

Appendix: Proofs

Proof of Result 5: View equation (6) and Result 2. Result 5 is confirmed if it can be shown that positive autocovariance decreases the value of δ relative to independence where the value of δ must now be conditioned on the present type in the sequence, i.e., $\delta(x_v)$. Adapting equation (1),

$$\begin{aligned}
&\delta[x_v = x_v(i)] = \sum\nolimits_{i=1}^{M} \theta_i P[x_{v+1} \neq x_{v+1}(i) \mid x_v = x_v(i)] \\
&= \sum\nolimits_{i=1}^{M} \theta_i \times \left(1 - P[x_{v+1} = x_{v+1}(i) \mid x_v = x_v(i)]\right) \\
&= 1 - \sum\nolimits_{i=1}^{M} \theta_i P[x_{v+1} = x_{v+1}(i) \mid x_v = x_v(i)] \leq 1 - \sum\nolimits_{i=1}^{M} \theta_i^2,
\end{aligned} \tag{A1}$$

so that positive autocovariance reduces the expectation that a change occurs.

Proof of Result 7: The first-order conditions on (18), when the first-best fine $Dp(\bar{e} - e)$ is levied, are

$$\begin{aligned}
&\frac{[R(\delta) - F(\delta;\eta)]\kappa}{\mu_1 + \delta\mu_2} - C_e(e) + Dp_z(\bar{e} - e) = 0, \\
&(\mu_1 + \delta\mu_2)[R_\delta(\delta) - F_\delta(\delta;\eta)] - [R(\delta) - F(\delta;\eta)]\mu_2 = 0.
\end{aligned} \tag{A2}$$

Now increase the magnitude of the externality from 0 to true value *D*, yielding system effects

$$\begin{pmatrix} -[C_{ee}(e^{**}) + Dp_{zz}(\bar{e} - e^{**})] & 0 \\ 0 & (\mu_1 + \delta\mu_2)[R_{\delta\delta}(\delta^{**}) - F_{\delta\delta}(\delta^{**};\eta)] \end{pmatrix} \begin{pmatrix} \dfrac{de^{**}}{dD} \\ \dfrac{d\delta^{**}}{dD} \end{pmatrix} = -\begin{pmatrix} p_z(\bar{e} - e^{**}) \\ 0 \end{pmatrix}. \tag{A3}$$

The system is block separable so that $d\delta^{**}/dD = 0$ and $de^{**}/dD = p_z(\bar{e} - e^{**})/[C_{ee}(e^{**}) + Dp_{zz}(\bar{e} - e^{**})] \leq 0$, i.e., the first-best effort is smaller than the unregulated effort (when $D = 0$).[14] Using (2),

$$\frac{dN^{**}}{dD} = \frac{\kappa}{\mu_1 + \delta\mu_2}\frac{de^{**}}{dD} - \frac{\kappa e^{**}\mu_2}{(\mu_1 + \delta\mu_2)^2}\frac{d\delta^{**}}{dD} = \frac{\kappa}{\mu_1 + \delta\mu_2}\frac{de^{**}}{dD} \leq 0. \tag{A4}$$

Proof of Result 8: From Result 6, part (a), when η is sufficiently low then $\hat{N}$ does not bind. There are three cases: where the initial smaller value $\eta = \eta'$ and the final value $\eta = \eta'' > \eta'$ are both such that the line speed constraint does not bind in either case, where the initial and final values are such that the constraint binds in both cases, and where the values are such that the constraint binds when $\eta = \eta''$ but not when $\eta = \eta'$. The first case is trivial while the second may be viewed as a special case of the third so only the third case is analyzed. Write $\delta^*(\eta)|_{N \leq \hat{N}}$ as the optimal value of δ^* for technology index evaluation η and under constraint $N \leq \hat{N}$. Apply part (b) of Result 6 with $\hat{\eta}$ as the η value such that $N^* = \hat{N}$:

$$\delta^*(\eta'')|_{N \leq \hat{N}} - \delta^*(\eta')|_{N \leq \hat{N}} = \int_{\eta'}^{\hat{\eta}} \frac{d\delta^*(\eta = s)}{d\eta}|_{N \leq \hat{N}}\, ds + \int_{\hat{\eta}}^{\eta''} \frac{d\delta^*(\eta = s)}{d\eta}|_{N \leq \hat{N}}\, ds. \tag{A5}$$

Observe that the objective in (18) may be written as $V = [R(\delta) - F(\delta;\eta)]N - C[\kappa^{-1}N \times (\mu_1 + \delta\mu_2)]$ with cross-derivatives $\partial^2 V/\partial\delta\partial N \leq 0, \partial^2 V/\partial\delta\partial\eta \leq 0, \partial^2 V/\partial N\partial\eta \geq 0$ so that it is supermodular in $(-\delta, N, \eta)$. Now by Theorem 2, page 176 in Milgrom and Roberts 1996,

$$\frac{d\delta^*(\eta)}{d\eta}|_{N \leq \hat{N}} \geq \frac{d\delta^*(\eta)}{d\eta}. \tag{A6}$$

This is the LeChatelier effect that unconstrained δ^* is more parameter responsive than constrained δ^*. Insert (A6) into (A5) to obtain

$$\delta^*(\eta'') - \delta^*(\eta') = \int_{\eta'}^{\hat{\eta}} \frac{d\delta^*(\eta = s)}{d\eta} ds + \int_{\hat{\eta}}^{\eta''} \frac{d\delta^*(\eta = s)}{d\eta} ds \leq \delta^*(\eta'')|_{N \leq \hat{N}} - \delta^*(\eta')|_{N \leq \hat{N}} . \tag{A7}$$

In general, from the monotonicity of N^* in η, obtain

$$\delta^*(\eta'')|_{N \leq \hat{N}^a} - \delta^*(\eta')|_{N \leq \hat{N}^a} \leq \delta^*(\eta'')|_{N \leq \hat{N}^b} - \delta^*(\eta')|_{N \leq \hat{N}^b} \tag{A8}$$

whenever $\hat{N}^b \leq \hat{N}^a$.

Proof of Result 9: Re-present the first-best conditions in (A2) as

$$C_e(e^{**}) = Dp_z(\overline{e} - e^{**}) + \frac{[R(\delta^{**}) - F(\delta^{**};\eta)]\kappa}{\mu_1 + \delta^{**}\mu_2} = Dp_z(\overline{e} - e^{**}) + \frac{[R_\delta(\delta^{**}) - F_\delta(\delta^{**};\eta)]\kappa}{\mu_2}. \tag{A9}$$

But (24) asserts $C_e(e^*) = [R_\delta(\delta^*) - F_\delta(\delta^*;\eta)]\kappa / \mu_2$, a contradiction for $e^* = e^{**}$ when $Dp_z(\overline{e} - e^{**}) \neq 0$. Effort must change to reconcile the two expressions for marginal cost. Decrease e^*, $e^* \to \hat{e} < e^*$, so that $C_e(\hat{e}) < [R_\delta(\delta) - F_\delta(\delta;\eta)]\kappa / \mu_2$ and $\hat{e}$ becomes a candidate for e^{**}. That is, $e^* > e^{**}$. From (2), with line speed fixed at $\hat{N}$, the equilibrium level of uniformity index δ^* must be too high.

References

Bell, R.G. 1997. “Distribution and Sources of Microbial Contamination on Beef Carcasses.” *J. Appl. Microbiol.* 82(March): 292–300.

Bennett, R., and R. Blaney. 2002. “Social Consensus, Moral Intensity and Willingness to Pay to Address a Farm Animal Welfare Issue.” *J. Econ. Psych.* 23(August): 501–20.

Boehlje, M. 1996. “Industrialization of Agriculture: What Are the Implications?” *Choices* vol. 11, First Quarter, pp. 30–34.

Boland, P.J., and F. Proschan. 1988. “Multivariate Arrangement Increasing Functions with Applications in Probability and Statistics.” *J. Multivar. Anal.* 25(May): 286–98.

Boleman, S.J., S.L. Boleman, R.K. Miller, J.F. Taylor, H.R. Cross, T.L. Wheeler, et al. 1997. “Consumer Evaluation of Beef of Known Categories of Tenderness.” *J. Anim. Sci.* 75(June):1521–24.

Bradley, J.A., and K.W.F. Jericho. 1997. “Risk Assessment: Abscessation of Head Lymph Nodes and Carcass Inspection at Two High-Line-Speed Beef Abattoirs in Western Canada.” *J. Food Protect.* 60(February): 157–60.

Bureau of Labor Statistics. 1999. “Meat Packing Plants Have the Highest Rate of Repeated Trauma Disorders.” *Monthly Labor Review: The Editor’s Desk*, August 5. Washington, DC.

———. 2002. “Workplace Injuries and Illnesses in 2001.” News Release, December 19. Washington, DC.

Chambers, R.G., and J. Quiggin. 2000. *Uncertainty, Production, Choice, and Agency: The State-Contingent Approach*. Cambridge, UK: Cambridge University Press.

Doherty, A.M. 1999. “Cattle Cleanliness and Its Effect on Carcass Contamination.” *Hygiene Rev. 1999* (online publication of the Society of Food Hygiene Technology) http://www.sofht.co.uk/isfht/irish_99_cattle.htm (accessed October 2003).

Eisnitz, G.A. 1997. *Slaughterhouse: The Shocking Story of Greed, Neglect, and Inhumane Treatment Inside the U.S. Meat Industry*. Amherst, NY: Prometheus Books.

Garen, J. 1988. “Compensating Wage Differentials and the Endogeneity of Job Riskiness.” *Rev. Econ. Stat.* 70(February): 9–16.

Goodwin, L.S. 1999. *The Pure Food, Drink, and Drug Crusaders, 1879-1914*. Jefferson, NC: McFarland.

Government Accounting Office. 1999. *Pork Industry: USDA’s Reported Prices Have Not Reflected Actual Sales*. Report GAO/RCED-00-26. Washington, D.C. December.

Guyon, R., F. Dorey, J.P. Malas, and A. LeClercq. 2001. “Hazard Analysis of *Escherichia coli* O157:H7 Contamination during Beef Slaughtering in Calvados, France.” *J. Food Protect.* 64(September): 1341–45.

Hayes, D.J., and H.H. Jensen. 2003. "Lessons Can Be Learned from Danish Antibiotic Ban." *Feedstuffs* vol. 75, September 15, pp. 1, 16.

Hennessy, D.A., J.A. Miranowski, and B.A. Babcock. 2004. "Genetic Information in Agricultural Productivity and Product Development." *Amer. J. Agr. Econ.*, in press (February 2004).

Hogue, A.T., D.W. Dreesen, S.S. Green, R.D. Ragland, W.O. James, E.A. Bergeron, et al. 1993. "Bacteria on Beef Briskets and Ground Beef: Correlation with Slaughter Volume and Antemortem Condemnation." *J. Food Protect.* 56(February): 110–113, 119.

Innes, R. 1999. "Self-Policing and Optimal Law Enforcement When Violator Remediation Is Valuable." *J. Polit. Econ.* 107(December): 1305–25.

Lusk, J.L., J.A. Fox, T.C. Schroeder, J. Mintert, and M. Koohmaraie. 2001. "In-Store Valuation of Steak Tenderness." *Amer. J. Agr. Econ.* 83(August): 539–50.

Marshall, A.W., and I. Olkin. 1979. *Inequalities: Theory of Majorization and Its Applications*. San Diego, CA: Academic Press.

Milgrom, P., and J. Roberts. 1996. "The LeChatelier Principle." *Amer. Econ. Rev.* 86(March): 173–79.

Milgrom, P., and C. Shannon. 1994. "Monotone Comparative Statics." *Econometrica* 62(January): 157–80.

Miller, M.F., M.A. Carr, C.B. Ramsey, K.L. Crockett, and L.C. Hoover. 2001. "Consumer Thresholds for Establishing the Value of Beef Tenderness." *J. Anim. Sci.* 79(December): 3062–68.

Minc, H. 1971. "Rearrangements." *Trans. Amer. Math. Soc.* 159(September): 497–504.

Nesbakken, T., E. Nerbrink, O.J. Røtterud, and E. Borch. 1994. "Reduction of *Yersinia enterocolitica* and *Listeria* spp. on Pig Carcasses by Enclosure of the Rectum During Slaughter." *Int. J. Food Microbiol.* 23(October): 197–208.

Oosterom, J., and S. Notermans. 1983. "Further Research into the Possibility of Salmonella-Free Fattening and Slaughter of Pigs." *J. Hygiene* 91(August): 59–69.

Prasai, R.K., R.K. Phebus, C.M. Garcia Zepeda, C.L Kaster, A.E. Boyle, and D.Y.C. Fung. 1995. "Effectiveness of Trimming and/or Washing on Microbiological Quality of Beef Carcasses." *J. Food Protect.* 58(October): 1114–17.

Reagan, J.O., G.R. Acuff, D.R. Budge, M.J. Buyck, J.S. Dickson, C.L. Kastner, et al. 1996. "Trimming and Washing of Beef Carcasses as a Method of Improving the Microbiological Quality of Meat." *J. Food Protect.* 59(July): 751–56.

Ridell, J., and H. Korkeala. 1993. "Special Treatment during Slaughtering in Finland of Cattle Carrying an Excessive Load of Dung: Meat Hygienic Aspects." *Meat Sci.* 35(2): 223–28.

Rivas, T., J.A. Vizcaíno, and F.J. Herrara. 2000. "Microbial Contamination of Carcasses and Equipment from an Iberian Pig Slaughterhouse." *J. Food Protect.* 63(December): 1670–75.

Roberts, T.A. 1980. "The Effects of Slaughter Practices on the Bacteriology of the Red Meat Carcass." *Royal Soc. Health J.* 100(February): 3–9.

Schlosser, E. 2001. *Fast Food Nation: The Dark Side of the All-American Meal*. Boston: Houghton Mifflin.

Schwartz, M. 1991. *Tyson: From Farm to Table*. Fayetteville, AK: University of Arkansas Press.

Sheridan, J.J. 1998. “Sources of Contamination during Slaughter and Measures for Control.” *J. Food Safety* 18(December): 321–39.

Smith, R. 2002a. “Pharmacia Introduces ‘Opportunity’ to Help Producers Manage Consistency.” *Feedstuffs* vol. 74, September 23, p. 8.

———. 2002b. “Automated Hog Sorting Technology Offers Chance to Play in New Ballgame.” *Feedstuffs* vol. 74, July 22, pp. 10, 13.

———. 2003. “Cloning to Select Superior Cattle, Hogs as Process May Make Livestock Markets ‘Very Different.’” *Feedstuffs* vol. 75, March 10, pp. 20–21.

South Florida Business Journal. 2002. “USDA to Look at Slaughterhouse Rules.” January 23. http://southflorida.bizjournals.com/southflorida/stories/2002/01/21/daily41.html (accessed October 2003).

Topkis, D.M. 1998. *Supermodularity and Complementarity*. Princeton, NJ: Princeton University Press.

Van Donkersgoed, J., K.W.F. Jericho, H. Grogan, and B. Thorlakson. 1997. “Preslaughter Hide Status of Cattle and the Microbiology of Carcasses.” *J. Food. Protect.* 60(December): 1502–8.

Warrick, J. 2001. “They Die Piece by Piece: In Overtaxed Plants, Humane Treatment of Cattle is Often a Battle Lost.” *Washington Post*. April 10, p. A01.

Watkins, B., Y-C. Lu, and Y-R. Chen. 2000. “Economic Feasibility Analysis for an Automated On-Line Poultry Inspection Technology.” *Poultry Sci.* 79(February): 265–74.

Wellford, H. 1972. Sowing the Wind: A Report from Ralph Nader’s Center for Study of Responsive Law on Food Safety and the Chemical Harvest. New York: Grossman Publishers.