Would Subsidizing a Food Pathogen Vaccine Upset the Food Policy Applecart?

Stephan Marette
UMR Economie Publique, INRA-AgroParisTech, 78850 Grignon, France
marette@agroparistech.fr

Brian Roe
AED Economics, Ohio State University, 2120 Fyffe Road, Columbus, OH 43210
roe.30@osu.edu

Mario Teisl
School of Economics, University of Maine, 5782 Winslow Hall, Orono, ME 04469
teisl@maine.edu

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Abstract: Vaccines against several common foodborne pathogens are being developed and could substantially alter the policy tools available to address foodborne illness. However, little analysis is available to suggest how social welfare would be affected by these new vaccines. To address this void, we use stated preference data to estimate consumer willingness to pay (WTP) for food safety vaccines and then simulate the welfare impacts on related commodity markets of subsidizing consumer purchases of the vaccine within a partial equilibrium framework. To obtain consumer demand for the vaccine from the stated preference data, we simultaneously estimate model parameters in an econometrically coherent manner that recognizes the recursive nature of responses to questions probing respondents' willingness to purchase vaccines and perceptions of the probability and severity of possible foodborne illness incidents and the joint distribution of unobservable components. Based on this econometric estimation, we integrate the average proportion of consumers purchasing the vaccine in a partial equilibrium model linked to a particular food product. Our simulation shows that subsidizing the vaccine is likely to lead to a higher welfare than stricter pathogens standards when the marginal cost of public funds is relatively low.

Introduction

Government agencies and private firms spend millions of dollars per year to improve the safety of food. While there are many debates about the best way to insure the safety of the nation's food supply (HACCP programs or public inspections), the development of vaccines to protect consumers against food pathogens is progressing rapidly (e.g., see Flynn [*E. coli* vaccine] and Stevens [*Salmonella* and *Campylobacter* vaccines]), which adds a new dimension to the food safety policy debate. For example, could a policy of promoting and subsidizing food safety vaccinations be more cost effective than current approaches? How would the presence of food safety vaccines alter the benefit/cost ratio of other programs?

In this paper, we provide a first analysis of the potential welfare impacts of vaccines against foodborne pathogens. Given the novelty of such vaccines and the critical role that consumer decisions to become vaccinated play in assessing the efficacy of vaccination policies, we use stated preference data to calibrate potential consumer response to the introduction of these vaccines and then simulate welfare effects of policies that alter the effective consumer prices of vaccines in a partial equilibrium framework of the US beef sector. The stated preference data, which is obtained from the Foodborne Diseases Active Surveillance Network (FoodNet) survey, allows us to estimate consumer response to food safety vaccines that would protect the individual from *Salmonella*, *E. coli* and/or *Listeria* across various time periods of protection (1-year, 5-years, 10-years, or lifetime of protection). We explicitly model three distinct aspects of the respondent's decision process: the choice of becoming vaccinated (Probit), the subjective estimate of the probability of contracting a foodborne illness (Tobit), and the subjective assessment of the severity of the foodborne illness (Ordered Probit).[1] We simultaneously estimate model parameters in an

[1] Outside of an earlier, much simpler presentation paper (Mukhopadhaya et al 2004), we know of no literature examining consumers' willingness to pay for a food safety vaccine; nor any paper examining the policy implications of such a vaccine.

econometrically coherent manner that recognizes the recursive nature of these elements and the joint distribution of unobservable components. Specifically, we account for the nonlinear nature of all equations while also accommodating the joint distribution of their disturbance terms. This process is important as we find that ignoring this jointness of the estimation leads to biased parameter estimates.

We show that consumer WTP for the vaccine differs significantly by demographics and food related perceptions. From the vaccine choice equation we show that choice is negatively influenced by vaccine price and positively influenced by the perceived risk of contracting a foodborne illness; it is unaffected by the perceived illness severity. Individuals were more likely to purchase the vaccine if it controlled for *E. coli* relative to *Listeria* or *Salmonella*. Other positive influences include the length of vaccine coverage (increasing at a decreasing rate), income and perceived work-days lost due to illness. Choice is negatively influenced by age and education.

We then use the consumer response parameters estimated from the stated preference data to simulate the average proportion of consumers accepting the vaccine (for a given price or a given length of vaccine coverage) by integrating this measure in a partial equilibrium model linked to a particular food product (beef). This partial equilibrium model for the US beef sector is calibrated with the integration of the stated preference results to evaluate the perceived damages by consumers linked to the pathogens. In this model, the perceived damages are a cost of ignorance since they are not internalized in the product demand. For the proportion of consumers accepting the vaccine, the cost of ignorance and the related damages disappear once they receive the shot. The vaccine positively impacts welfare via the damage reduction.

The public promotion of the vaccine (via a subsidy) can be compared to a stricter food standard imposed on firms (like HACCP). The related application compares the impact of the vaccine to a stricter standard to cap pathogens in the beef sector in the US. This calibrated model allows us to compare the impact of the vaccine subsidization and the stricter standard on producers' profits and domestic welfare defined as the sum of domestic beef producers' profits and beef consumers' surplus. Our simulation shows that the vaccine introduction leads to a slight increase in welfare within the beef market as it stimulates consumer beef demand by lowering the possibility of food-related damages without imposing higher costs on beef producers. The vaccine introduction is likely to be Pareto-improving (namely benefiting to all agents), since the price/quantity increases comes from the demand increase by consumers aware of food pathogens while the cost function of producers does not change. Eventually, subsidizing the vaccine is optimal when the marginal cost of public funds is relatively low. Simulated outcomes for a policy that involves tighter pathogen regulations does not increase welfare as the additional costs of beef production are not offset by increased demand under the parameters considered in the simulation.

Our contributions are both methodological and empirical. From a methodological point of view, this paper goes beyond the state preference approaches for estimating willingness to pay for the vaccine by instead using the stated preference data to help calibrate a partial equilibrium model of a sector that will be impacted by the introduction of the vaccine. In this model, the demand for the vaccine is integrated in the partial-equilibrium via the expected per-unit damage. This allows us to determine the indirect welfare impact of the vaccine that arises in one related market and paves the way for more complete studies combining stated preference work with traditional econometric estimations to derive welfare analyses.

Our paper also contributes to the debate about food safety. We provide the only estimates of consumer response in a food safety vaccine market of which we are aware and help structure how the introduction of a vaccine will have indirect impacts in markets for foods that might be complements to a foodborne pathogen vaccine. Previous studies on regulatory interventions concerning food safety focus on altering the production process for products via HACCP (Unnevehr, 2000), altering the inspections regime for products (Alberini et al., 2008) or introducing processes that alter the quality of single goods via irradiation (Fox et al., 1995). Vaccines are intriguing in that they are not physically tied to the products that carry the foodborne pathogen, which fundamentally alters the policy dynamics and the necessary framework for considering the associated welfare impacts of policies meant to stimulate vaccine production or use. Even if the vaccine development in the US is still in early stages, this study sheds light on how consumers' might respond once these vaccines become more widely available.

The remainder of this paper is structured as follows. The next section presents the econometric estimation. The simple partial-equilibrium model is introduced in the third section. The empirical application to the US beef sector is provided in the fourth section. The last section concludes.

Estimation of consumer' acceptance for food safety vaccines

We use stated preference data obtained from the Foodborne Diseases Active Surveillance Network (FoodNet) survey to estimate consumer acceptance of food safety vaccines that would protect the individual from *Salmonella, E. coli* or *Listeria* across various time periods (1-year, 5-year, 10-year or lifetime protection). Following an approach used by Teisl and Roe (2009), we explicitly model three distinct aspects of the respondent's decision process: the choice of purchasing the vaccine (probit), the subjective estimate of the probability of contracting a foodborne illness (probit of whether they expect no illness), and the subjective assessment of the severity of the foodborne illness (ordered probit of a severity scale). We simultaneously estimate model parameters in an econometrically coherent manner that recognizes the recursive nature of the various elements and the joint distribution of unobservable components.

Data

The FoodNet data were collected by telephone over a 12-month period during 2002. Respondents were selected randomly for telephone interviews from nine Emerging Infections Program (EIP) sites which includes nine states (in 2002): California, Colorado, Connecticut, Georgia, New York, Maryland, Minnesota, Oregon and Tennessee. Although the chosen states are not representative of the whole country, our study includes a variety of geographic areas across the USA. In addition to the food vaccine choice scenario questions, the data also contain information on individual characteristics (e.g., gender, race, age and education); socio-economic characteristics (e.g., income, medical insurance); and health status, food safety awareness and expected risk and severity assessments.

Econometric Model

To formalize our model of a person's choice to buy a food safety vaccine, we assume an individual's probability of purchasing the vaccine is a linear function of the respondent's subjective assessment of their risk of getting sick, the respondent's subjective assessment of the severity of potential illness without the vaccine, the vaccine's attributes (price, duration of protection) and other respondent characteristics:

Prob(Purchase Vaccine) = θ_1Prob(No Illness) + θ_2Illness Severity + θ_3Cost of Vaccine + θ_4Salmonella+ θ_5Coli + θ_6Hamburger + θ_7Lettuce + θ_8Eggs + θ_9Vaccine duration + θ_{10} (Vaccine duration)^2 + θ_{11}Age < 25 + θ_{12}Age > 65 + θ_{13}Female +

$$\theta_{14}\text{Education} + \theta_{15}\text{Income} + \theta_{16}\text{Insure} + \theta_{17}\text{Loss} + \theta_{0}\text{Intercept} + e_j^i \quad (1)$$

where Prob(No Illness) equals one if the respondents reports a zero for either the probability of buying a food contaminated with a pathogen listed in the survey (rotated between *Listeria, e. Coli* and *Salmonella*) or for the probability that the person would become sick after eating food contaminated with that same pathogen. The probability of buying a contaminated food is based upon open-ended responses to the following question "In your opinion what percent of [FOOD] (rotated among chicken, hamburger, eggs and lettuce) found at grocery stores contains germs that could make you sick?" The individual's assessment of the probability that they would become sick after eating the food are based upon responses to the following "If you ate some [FOOD] that contains germs that could make you sick, how often do you think you would get sick?" Individuals were asked to choose one of the following categories: All of the time (coded 100 percent), Most of the time (coded 75 percent), About half of the time (coded 50 percent), Occasionally (coded 25 percent), and Never (coded 0 percent).

The individual's assessment of the severity of the illness is based upon responses to the following question "Suppose you did get sick after eating the [FOOD] containing [PATHOGEN]. How sick do you think you would get? Individuals were asked to choose one of the following categories: Become mildly sick (coded as 1); Become moderately sick (coded as 2) and Become severely sick (coded as 3).

The respondent is then posed with the question: "Imagine there were a safe vaccine against [PATHOGEN] (rotated among *Listeria, e. Coli* and *Salmonella*) that you could swallow. This vaccine would have no side effects and would last for TIME PERIOD (rotated among 1 year, 5 years, 10 years and lifetime where lifetime was coded as 100 minus the respondent's age). Would you be willing to pay $ DOLLAR (rotated among $25, $50, $75 and $100) for this vaccine (assume that this is not covered by your insurance)?" Responses are coded 1 if Yes, 0 if No.

The respondent's insurance status was based on the following question: "Do you have any medical insurance?" Responses are coded 1 if Yes, 0 if No. A loss of work time variable was based on responses to three questions asked of people who stated they had a bout of vomiting of diarrhea in the last month. In the first question we asked if the individual had been employed in the last month. If they were employed, then they were asked if they missed work due to this illness. If they said yes to this question we then asked the number of days of work they lost due to the illness. Note that individuals who were unemployed or did not miss work, this variable was coded as 0.

There were four possible foods stated in the scenarios concerning becoming sick and illness severity: hamburger, lettuce, raw chicken, eggs. Each respondent saw the same food listed in each of the questions (i.e., the food assignment was random and differed across people but not across questions). The three dummy variables are added to accommodate the food considered by the respondent; raw chicken is the omitted category.

Similarly the scenarios featured one of three possible pathogens: *Salmonella*, *e.Coli*, *Listeria*. Each respondent saw the same pathogen listed in each of these questions (i.e., the pathogen assignment differed across people but not across questions). Two dummy variables are used with *Listeria* as the omitted category.

Five demographic characteristics are included: dummy variables for Age < 25 and Age > 65 (middle aged is omitted); a dummy variable for gender (1= female; 0 = male); income (in tens of thousands of dollars); and education level (in years). e_j^i is an unobservable disturbance term.

Note that the variables denoting one's subjective risk of getting sick and their assessment of the severity of any resulting illness may be driven by the same unobservable components that drive their choice concerning vaccination. We model a recursive structure where respondents formulate their subjective risk of getting sick and their subjective assessment of the severity of any resulting illness prior to choosing whether to purchase a food safety vaccine. We hypothesize the respondent's subjective assessment of the likelihood of getting sick after eating a contaminated food (without the vaccine) is:

$$\text{Prob(No Illness)} = \delta_1\text{Hamburger} + \delta_1\text{Lettuce} + \delta_1\text{Eggs} + \delta_1\text{Age} < 25 + \delta_1\text{Age} > 65 + \delta_1\text{Female} + \delta_1\text{Education} + \delta_1\text{Income} + \delta_1\text{Vomit} + \delta_1\text{Advise} + \delta_1\text{Eat Out} + \delta_1\text{Eat Pink} + \delta_1\text{Raw Eggs} + \delta_1\text{Runny Eggs} + \delta\text{Intercept} + \omega_1 \quad (2)$$

where Vomit is meant to represent a person's recent experience with potential foodborne illness. Vomit is derived from the responses to the following question: "In the past month, have you had either vomiting or diarrhea?" Responses included Yes (coded as 1) and No, Don't remember, not sure (all coded as 0).

Eat Out is a measure of the relative frequency that a respondent dines away from home; this measure is included as national studies indicate that U.S. residents view food that is eaten at home to be safer (FDA). This variable is the sum of seven variables measuring the frequency of away-from-home eating that occurred over the last seven days. Away-from-home eating includes eating at a regular sit-down restaurant (where food is brought to your table), a deli or sandwich shop, a fast-food chain (including take-away or drive-thru food), or a cafeteria or restaurant where the main course is from a buffet line (this includes school cafeterias). In addition, this variable includes ready-to-eat food served in a supermarket (such as a pre-made sandwich), street vended food or ready-to-eat food served in a convenience store. In each case each component variable is coded as 1 if the condition holds; 0 otherwise; the Eat Out variable is the sum of these and ranges from 0 to 7.

Advice is used to denote a person's level of awareness of food safety messages. Individual's exposure to food safety information is correlated with higher levels of risk perception; the direction of causality is unclear. The variable is constructed from the response to the following: “Have you seen or heard a food safety message called Fight-Bac?” A Yes response is coded as 1 and No is coded 0.

The Runny Eggs variable is based on those who stated they ate scrambled, fried, soft-boiled, or poached eggs in the last seven days and stated some of the eggs were runny (if the condition holds then coded as 1; 0 otherwise). The Raw Eggs variable is based on those who stated they ate items with raw egg in them such as raw cookie dough, cake batter, steak tartar or homemade eggnog (coded 1 if yes; 0 otherwise).

The Eat Raw variable is based on a summation of several questions. Respondents who stated they ate hamburger patties (made from either fresh or frozen raw ground beef) that were either formed at home or purchased preformed (but not precooked) or other forms of ground beef, such as in tacos, meatloaf or spaghetti sauce in the last seven days and that these beef products were pink when eaten. Each response was coded 1 if the condition applied; 0 otherwise. The Eat Raw variable ranges from 0 to 5. ω_I is an unobservable disturbance term; all other variables are previously defined. We model the dependent variable as a probit. While a continuous variable could be constructed, we found that versions of the model with a continuous variable had difficulty converging.

Finally, we model the respondent’s assessment of the severity of illness (mild, moderate or severe) as being:

$$\text{Severity Illness} = \mu_1\text{Salmonella} + \mu_2\text{Coli} + \mu_3\text{Hamburger} + \mu_4\text{Lettuce} + \mu_5\text{Eggs} + \mu_6\text{Age} < 25 + \mu_7\text{Age} > 65 + \mu_8\text{Female} + \mu_9\text{Education} + \psi_I \quad (3)$$

where ψ_i is an unobservable disturbance term; all other variables are previously defined.

The estimation procedure must account for the nonlinear nature of equations (1), (2) and (3) (a probit, a probit and an ordered probit, respectively), while also accommodating the joint distribution of their disturbance terms. We assume the disturbance terms ε^i, $\omega_I^{\,i}$, and ψ^i

are jointly normally distributed with mean zero and a covariance matrix characterized by diagonal elements σ_ε^2, σ_ω^2, $\sigma\psi^2$ and correlations of $\rho_{\varepsilon\omega}$, $\rho_{\varepsilon\psi}$, and $\rho_{\omega\psi}$. This estimation approach controls for nonlinearity and joint normality and is similar to that used by Teisl and Roe (2009) and Pitt and Kahndker (1998). We estimate the three equations jointly with the STATA® command CMP (conditional mixed process) written by Roodman (2009), which provides consistent and efficient estimates.

Results

Estimation results are presented in table 1. The estimated model has χ^2 goodness-of-fit statistics that are significant at the 0.001 level. The model also yields significant correlation coefficients among two of error terms, signifying that joint recursive estimation was important given the nature of the data.

[Insert Table 1]

For the probit equation of vaccine purchase the estimated parameters related to the cost of the vaccine and the probability of illness are consistent with expectations and statistically significant in all models: respondents are more likely to become vaccinated if the vaccine is less expensive and less likely to become vaccinated if they perceive that eating food will result in no illness.

Individuals were more likely to purchase the vaccine if it controlled for *e. Coli* relative to *Listeria* or *Salmonella*. Other positive influences include the length of vaccine coverage (increasing at a decreasing rate), income and perceived work-days lost due to illness. Choice is negatively influenced by age and education.

As the vaccine choice equation is significantly and negatively influenced by vaccine price and other parameters, we can use this measure in a partial equilibrium for simulating regulatory scenarios.

The simple partial-equilibrium model

We now use the econometric results within a partial equilibrium model to determine the welfare impact of the vaccine for a given product whose demand might be affected by the introduction of the vaccine. As the vaccine is effective against pathogens that might be consumed from many products, the proportion of vaccinated consumers are introduced in the partial equilibrium model taking into account the supply and demand for a given product (US beef for our example). We measure welfare within this market for both the introduction of a vaccine and for a reduction in the probability of foodborne pathogen contamination generated by another policy instrument (e.g., tighter testing standards). In order to focus on the main economic mechanisms and to keep the mathematical aspects as simple as possible, the analytical framework is admittedly simple.

Beef is assumed to be homogenous (i.e., same quality attributes) except that the density of foodborne pathogens can rise to potentially dangerous levels. The characterization of preferences largely follows Polinsky and Rogerson (1983). Demands are derived from quadratic preferences, and supply is derived from a quadratic cost function. Turning first to consumer preferences, the demand of each consumer $i=\{1,\ldots,N\}$ is derived from a quasi-linear utility function that consists of the quadratic preference for the market good of interest and an additive numeraire:

$$U_i(q_i, w_i) = aq_i - \bar{b}q_i^2/2 - I_i \times [1 - V_i(\rho)] \times \gamma \times r_i\, q_i + w_i \tag{4}$$

where the term $aq_i - \bar{b}q_i^2/2$ is the immediate satisfaction of consumer *i* from consuming a quantity q_i of the good and w_i is the numeraire good consumed by *i*. For simplicity $a, \bar{b}$ are the same for the *N* consumers. The advantage of (4) is its simplicity and tractability.

This approach accounts for damage and externalities as separable from consumption (Foster and Just, 1989 and Teisl et al., 2001). The effects of damage are captured by the term $-I_i \times [1 - V_i(\rho)] \times \gamma \times r_i\, q_i$. The parameter $r_i \geq 0$ is the per-unit damage and γ is the probability of having a contaminated product with a given policy (e.g., under HACCP) with $0 \leq \gamma \leq 1$. With a probability ($1-\gamma$), there is no damage. The parameter I_i represents consumer *i*'s knowledge that the product may contain foodborne pathogens. If consumers are not aware of potential foodborne pathogens, then I_i=0. Conversely, I_i=1 means that consumers are aware of the possibility that beef contains foodborne pathogens, and that may cause them to reduce their consumption.

The parameter $V_i(\rho)$ takes into account consumer *i*'s choice of being vaccinated, where ρ is the price of the vaccine paid by consumers, where we assume (for simplicity) that the vaccine is supplied in a perfectly elastic fashion and priced at marginal cost . If $V_i(\rho) = 1$ the consumer is vaccinated and does not suffer from any damage (for simplicity). If the consumer chooses vaccination, the cost of ignorance and the related damages disappear upon receipt of the shot. The vaccine positively impacts welfare via damage reduction. If $V_i(\rho) = 0$, the consumer is not vaccinated and has a per-unit damage equal to $r_i = r$.

The utility function (4) is maximized subject to the budget constraint of $pq_i + \rho V_i(\rho) + w_i = y_i$, where y_i denotes the income of person *i*. This leads to the following inverse demand function: $p = a - \bar{b}q_i - I_i \times [1 - V_i(\rho)] \times \gamma \times r_i$. The demand for consumer *i* is $q_i\,(p, I_i, V_i(\rho)) = \left[a - p - I_i \times [1 - V_i(\rho)] \times \gamma \times r_i\right] / \bar{b}$. For consumer *i* the decision to become vaccinated depends upon a simple comparison of the price of the vaccine to the expected damages including all the sources of contamination (recall there may be other sources of contamination in addition to the good studied in this partial equilibrium setting).

Hence, the likelihood of vaccination by consumer i is decreasing in the price of vaccination (ρ) and the proportion of the foodborne illness originating with beef (δ) and increasing in the probability of foodborne contamination (γ), the per unit damage (r_i) and the quantity consumed (q_i). Note that, for simplicity, we assume no income effects, e.g., you never buy less meat because you have to pay for the vaccine. The function defined by (4) is used to calculate Marshallian welfare. Note that, for vaccine price ρ, we assume the proportion of those vaccinated is given by the econometric estimation $V(\rho)$ for average values of independent variables used in the estimation, where the subscript i is dropped to represent an aggregate proportion. This is a drastic simplification which means that the average value given by the econometric estimation is used and applied to all consumers. By simplicity, the per-unit damage is assumed identical for every buyer i with $r_i = r$.

Aggregate demand for the good is obtained by summing individual demand functions over all N consumers. Conceptually, total demand can be partitioned into three groups: (1) those who are vaccinated and are, therefore, assumed protected from damage, (2) those who are not vaccinated and aware of the damage and (3) those who are not vaccinated and unaware of the damage. The proportion $V(\rho)$ of consumers that is vaccinated and does not suffer from any damage has an individual demand denoted as $q_i(p, I_i, 1)$. With $b = \bar{b}/N$, the demand over the $V(\rho) \times N$ consumers is defined by

$$Q_1^D(p) = \sum_{i=1}^{V(\rho).N} q_i(p, I_i, 1) = \frac{V(\rho) \times N \times (a-p)}{\bar{b}} = \frac{V(\rho) \times (a-p)}{b}. \qquad (5)$$

The proportion $1 - V(\rho)$ of consumers is not vaccinated and may suffer damage equal to $r_i = r$. Among them, a proportion β of consumers is not aware of the damage; this group generates a cost of ignorance in the welfare analysis. A proportion $\beta\left(1-V(\rho)\right)$ of consumers that is not vaccinated and is not aware of the damage have an individual demand denoted as $q_i\,(p,0,0)$. The demand over the $\beta\left(1-V(\rho)\right)\times N$ consumers is defined by

$$Q_2^D(p)=\sum_{i=1}^{\beta\left(1-V(\rho)\right)N} q_i\,(p,0,0)=\frac{\beta\left(1-V(\rho)\right).N.(a-p)}{\bar{b}}=\frac{\beta\left(1-V(\rho)\right)(a-p)}{b}. \qquad (6)$$

The damage does not impact the demand because of this segment's lack of awareness. The cost of ignorance is: $\gamma\times r\times Q_2^D(p)$.

Eventually, a proportion $(1-\beta)\left(1-V(\rho)\right)$ of consumers that is not vaccinated and is aware of the per-unit damage $r_i=r$ will have an individual demand denoted as $q_i\,(p,1,0)$. The demand over the $(1-\beta)\left(1-V(\rho)\right)\times N$ consumers is:

$$Q_3^D(p)=\sum_{i=1}^{(1-\beta)\left(1-V(\rho)\right)N} q_i\,(p,1,0)=\frac{(1-\beta)\left(1-V(\rho)\right).N.(a-p-\gamma\times r)}{\bar{b}} \qquad (7)$$
$$=\frac{(1-\beta)\left(1-V(\rho)\right).(a-p-\gamma\times r)}{b}.$$

The damage is internalized and there is no cost of ignorance. The overall demand is:

$$Q^D(p)=Q_1^D(p)+Q_2^D(p)+Q_3^D(p)=\frac{a-p-(1-\beta)\left(1-V(\rho)\right)\times\gamma\times r}{b}, \qquad (8)$$

which is a relatively simple expression that can be calibrated for given values of β and $V(\rho)$.

The respective inverse demands are:

$$\begin{cases} p_1^D(Q) = Max\left[0, a - \dfrac{bQ}{V(\rho)}\right] & \text{vaccinated consumers} \\ p_2^D(Q) = Max\left[0, a - \dfrac{bQ}{\beta[1-V(\rho)]}\right] & \text{non-vaccinated and unaware consumers} \\ p_3^D(Q) = Max\left[0, a - \gamma \times r - \dfrac{bQ}{(1-\beta)[1-V(\rho)]}\right] & \text{non-vaccinated and aware consumers} \end{cases} \quad (9)$$

The proportion $V(\rho)$ influences the balance between demands. Note that a value of $V(\rho)$ tending towards 0 leads to $p_1^D(Q) =$ 0 (the same effect is valid for other inverse demands).

The proportion $V(\rho)$ of consumers buying the vaccine is estimated by the average probability of buying the vaccine based on the econometric estimation presented in table 1. In this simple framework, the vaccination is exogenously given by the econometric estimation and is not driven by the individual level of consumption of the market good, which would be realistic. It means that consumers take their vaccine decision first based on a perception linked to the consumption of many goods that might carry foodborne pathogens and adjust their consumption for each good after the vaccine decision is made. Note that we do not have the consumption quantity variables necessary to test if a consumer's decision to receive vaccination is sensitive to consumption levels of certain foods.[2]

For every consumer $i=\{1,\ldots,N\}$, the average probability $V(\rho)$ of buying the vaccine, which determines the proportion of population receiving the vaccine, comes from the

[2] Our model is recursive (as is our estimation, which excludes quantity demanded), but one estimation could consider $V(\rho, Q)$ that is fully simultaneous (vaccination and quantity of food demanded is fully endogenous). The model would get much more complicated as $V(\rho)$ becomes $V(\rho, Q)$ where Q is the demanded quantity of the good, which would turn our linear demand functions non-linear.

econometric estimation detailed in the previous section. As the probit model is very close to the logit model in terms of assumptions concerning the unobserved components and in terms of predicted proportions, the average probability is given by the more tractable logit value:

$$V(\rho) = \frac{1}{1 + \exp\left[-(\theta_0 + \theta_1 \rho + \Theta^T \overline{X}) \right]} \tag{10}$$

where θ_0 is the estimated intercept and θ_1 is the estimated coefficient linked to the price ρ. The transposed vector Θ^T integrates all the other estimated coefficients and $\overline{X}$ is the vector of the average values of the other independent variables used in the estimation. This price ρ can vary and be taken into account in the simulations since the price coefficient β_1 in the estimation of table 1 is statistically significant. The price variation will significantly impact the shift in demand. The vaccine price ρ will vary in our simulations and will be accounted in the welfare calculations.

On the supply side, a perfectly competitive industry with price taking firms is assumed both with or without HACCP. There are *M* firms. Firms' cost functions are quadratic in output, and they choose output to maximize profits:

$$\pi_j = pq_j - fq_j - \tfrac{1}{2}cq_j^2 - K_j \text{ for } j = \{1,\ldots,M\} \tag{11}$$

where *f* and *c* are parameters defining the variable cost and K is the sunk cost linked to the firm's market entry and compliance with regulations. The profit maximization yields individual firm supply functions which can be added up to yield overall industry supply[3]:

$$Q^S = \frac{M(p-f)}{c} \tag{12}$$

[3]Individual supply functions are only defined for prices exceeding average costs, because otherwise firms would obviously cease production.

The parameter c and f will vary with HACCP enforcement. In particular, $c_H > c$ means that producers with HACCP incur higher marginal cost than producers without HACCP. This reflects a situation where a producer under HACCP incurs a costly effort to reduce foodborne pathogen risks, while producers without HACCP do not bear these additional costs. To simplify further it is assumed that sunk costs K_j are equal to zero; this means that firm exit and entry can be ignored.

For both simplicity and ease of exposition, the profits and surpluses are described graphically. Figure 1 represents the baseline scenario with the quantity on the horizontal axis and the prices on the vertical axis.

[Insert figure 1]

With the baseline scenario, there is no vaccine (i.e., $\rho \rightarrow \infty$) and HACCP is not required. As a result, $V(\rho)$ is zero and $p_1^D(Q)$ defined in (6) is equal to zero. For the unaware consumers, the demand $p_2{}^D(Q)$ with $V(\rho)=0$ is represented by D_2 and for the aware consumers, the demand $p_3{}^D(Q)$ with $V(\rho)=0$ is represented by D_3. In figure 1, the baseline scenario is represented by the equilibrium price p^E that equalizes the overall demand $D_2 + D_3$ and the overall supply S based on equation (12). For unaware consumers, the demand $p_2(Q)$ is represented by D_2 and implies a cost of ignorance because of the absence of internalization of the damage r. The value of the overall cost of ignorance is $\gamma \times r \times Q_2^E$, where Q_2^E is the consumption by the proportion β of unaware consumers at the price p^E. The consumer surplus with the cost of ignorance for the unaware consumers is defined by the area $p^E Eva$- $0(\gamma \times r)tQ_2^E$ in figure 1. The producer profit is defined by the area $OkEp^E$.

Requiring HACCP for all firms leads to an upward supply (S) shift linked to the cost increase, with the new supply curve represented by the bold line S' in figure 1. Implementing HACCP decreases the probability of contamination to $\bar{\gamma} < \gamma$. The cost of ignorance decreases for the unaware consumers. The aware consumers increase their demand to D_3' since the expected per-unit damage $\bar{\gamma} r$ is internalized in this demand. Under HACCP, the new-equilibrium H leads to a price p^H and a quantity Q^H. The consumer surplus with the cost of ignorance for unaware consumers is defined by the area $p^H Hwa$- $0(\bar{\gamma} \times r)uQ_2^H$ in figure 1. The producer profit is defined by the area $OmHp^H$. The welfare effect of HACCP implementation characterized by the comparison of welfare in E and H depends on the relative change of the supply curve and the probability of contamination. If the proportion of unaware consumers β is large relatively to other parameters, the equilibrium quantity Q^H in H is lower than the equilibrium quantity Q^E in E because of the supply shift.

We now turn to the case where the vaccine is introduced and promoted by firms, doctors and hospitals. Figure 2 represents the impact of the vaccine with $V(\rho) > 0$ on the market allocation compared to baseline scenario in point E (with the demand represented by the dashed curves). For the vaccinated consumers, the demand defined by equation (9) is $p_1(Q)$ and represented by D_{1v} in figure 2. Compared to the baseline scenario E, the curves of unvaccinated consumers decrease with $D_{2v} < D_2$ and $D_{3v} < D_3$ because $V(\rho) > 0$. The number of aware consumers with a demand depending on the damage decreases when the number of vaccinated consumers increases.

[Insert Figure 2]

With the vaccine, the new equilibrium V leads to a price p^V and a quantity Q^V. The proportion $[1 - V(\rho)]$ of unvaccinated consumers given by the previous econometric estimation influences the cost of ignorance of the unaware consumers defined by the area $0(\gamma\times r)nQ_2^V$. The consumer surplus including the cost of ignorance is defined by the area p^VVza- $0(\gamma\times r)nQ_2^V$ in figure 2. The producer profit is defined by the area OVp^V. As the vaccine purchase and its demand are not detailed in our framework, we do not integrate the vaccine cost in our analysis of the welfare variation. Clearly, the effects on firms or consumers are different under HACCP and vaccine policies.

Subsidizing the Vaccine

Subsidizing the vaccine leads to a decrease in ρ paid by the consumer and to an increase in the proportion of consumers purchasing the vaccine $V(\rho)$ and to a decrease of $[1-V(\rho)]$, implying a decrease of Q_2^V and $0(\gamma\times r)nQ_2^V$ in figure 2. With a proportion *s* of the vaccine price financed by the taxpayer, the vaccine price paid by consumers is $(1-s)\rho$, and the part $s\rho$ is paid by the tax payer. The vaccine demand is $V\left((1-s)\rho\right)$. The overall cost of the subsidization included in the welfare is $\rho\times N\times V\left((1-s)\rho\right)\left[1+s\times CP\right]$, where N is the number of inhabitants in the country and $CP > 0$ is the marginal cost of the public funds.

Calibration

The parameters *a* and *b* defined in the baseline scenario can be determined by standard calibration methods using existing data on price elasticity of the demand and equilibrium prices and quantities of beef. There is no vaccine today in the US and the demand can be calibrated for a given proportion β of unaware consumers. Using existing data on the quantity $\hat{Q}_E$ of the regular product sold over a period, the average price $\hat{p}^E$ observed over the period, and the direct price elasticity $\varepsilon\ =(dQ_E\,/\,dP^E)(P^E\ \ /\,Q_E))$ obtained from time-series econometric estimates, the calibration of $Q^D(p)$ given by (8) leads to estimated values for the demand equal to $1/\tilde{b} = -\varepsilon \hat{Q}_E / \hat{p}^E$ and $a = \tilde{b}\hat{Q}_R + \hat{p}^E + (1-\beta) \times \gamma \times r$. The calibration of the demand is made for initial situations where the vaccine is not existing so $V(\rho) = 0$.

The parameters β and γ are exogenously given for this paper because of the difficulty obtaining credible information. For estimating the damage r, it is possible take results given by the experimental economics. If the average willingness to pay for a safe product is ϕ, the per unit damage calibrated for the specific product is defined by $r_2 = \phi \times \hat{p}^E$. The variation of the parameter γ that is the probability of having a contaminated product will be exogenously given. By integrating the proportion of vaccinated consumers coming from table 1 in the calibrated model, it is possible to assess the costs and benefits of a vaccine promotion versus a stricter standard imposed on the supply chain via a more stringent HACCP procedure. Eventually, the calibration of the supply function is also made with this method. We now turn to estimations with the beef example based on equations (4) and (12).

The Ground Beef Example

Parameters of the model are initially calibrated so as to replicate prices and quantities for the year 2007 in the United States. It is assumed that the initial proportion of unaware consumers is β = 0.2, which is similar to results of the 2001 Food Safety Survey where 88% of respondents had reported hearing of *e. Coli*.

For estimating the per-unit damage r, we take results given by the experimental economics. In an experimental economics study, Hayes *et al*. (1995) found respondents willing to pay 15% to 30% more for food that is essentially completely safe from five pathogens found in ground beef. This willingness to pay, which includes the cost of illness plus averting behavior, is often used as the social value of non-contamination and is widely cited. This experiment did not include *Listeria* and participants were students, which is a limitation. The value of 30% is clearly a lower bound in the context of health risks related to *Listeria*, *Salmonella* and *e. Coli*[4]. The per unit damage is $r = 0.3 \times \hat{p}^E$. Table 2 details other parameters used for calibrating the baseline scenario. We consider an initial probability γ =0.01 in equation (4) for characterizing the cost of ignorance under the baseline scenario.

[Insert Table 2]

To measure the efficiency of the HACCP policy, we assume a new probability $\bar{\gamma}$ =0.005 since the possible risks are reduced via the HACCP procedure. It is also assumed a cost $c_H = 1.1 \times c$ with c defined in equation (12) when HACCP is introduced, which corresponds to a small variation. Regarding the vaccine scenario, it is assumed that the vaccine price is $\rho = 50$. From (10) and the probit estimation of table 1, the estimated parameters are $\theta_0 + \Theta^T \overline{X} = 0.79$ and $\theta_1 = -0.0086$.

Table 3 presents estimations of welfare variation for the year 2007 in the United States given these parameter values. Note that in table 3 there is no subsidy for promoting the vaccine.

[Insert table 3]

Table 3 presents the price and quantity variations, the variation in domestic beef consumers' surplus (including the cost of ignorance), the variation in beef producers' profits and the variation in welfare for the beef market. Table 3 shows that the welfare variation is positive only under the vaccine introduction scenario. The vaccine case (second column) is more profitable for beef consumers compared to the HACCP case (first column) because the

[4] This approach differs from the case where we would estimate magnitude of damage from *ex post* cost of illness estimates. For instance, we could consider ERS estimates in 2006 that the average cost of suffering an *e. Coli* related illness was $6,067 and suffering *Salmonella* related illness was $1,766. See data available at http://www.ers.usda.gov/data/foodborneillness/.

price increase is much lower with the vaccine case compared to the HACCP case (see the difference between figures 1 and 2). Under HACCP, the beef price increase is very large compared to the reduction in the damage, which explains a negative impact of the welfare. The profit variation for beef producers is negative with the HACCP case (first column) due to the increased costs of production necessary to achieve the higher standard. Under the vaccine scenario (second column), profit variation for beef producers is positive because the price and quantity increase is only driven by vaccine-stimulated demand for more beef.

The welfare change associated with the vaccine (second column) is the only positive policy simulated here. This result is observed for a wide range of parameters, except when the cost increase coming from HACCP is very low (robustness was checked for different values of parameters). Adding the HACCP procedure to the vaccine introduction is likely to be socially counterproductive because HACCP lowers the contamination probability in beef, which diminishes demand for the vaccine. The vaccine introduction alone (second column) is likely to be Pareto-improving (namely benefiting to all agents), since the price/quantity increases comes from the demand increase by beef consumers aware of food pathogens while the cost function of beef producers does not change.

We now turn to the possibility of subsidizing the vaccine (as described above). With a proportion s of the vaccine price financed by the taxpayer, the vaccine price paid by consumers is $(1-s)\rho$. The number of US consumers is N=280,000,000. In figure 3, the welfare with the subsidized vaccine is presented. Keep in mind that we present the welfare with a subsidy in figure 3 while the results for vaccine welfare in table 3 consider no subsidy.

[Insert figure 3]

Figure 3 shows that fully subsidizing the vaccine is optimal when the marginal cost of public funds is zero, while partial subsidization is warranted when the cost of these public funds is higher (e.g., as in figure 3, it is optimal to subsidize at 28% when the cost of public funds is 7 cents on the dollar). However, any recommendations to introduce or subsidize vaccines against foodborne pathogens will require a more realistic and subtle model of the sector of interest than that introduced above.

Extensions and Conclusion

In this paper we take the first steps towards evaluating the possible indirect welfare impacts of introducing vaccines that can prevent illness due to foodborne pathogens. Such an analysis requires both an understanding of the potential demand for such vaccines and for the complementary impact on the demand for foods afflicted by the foodborne pathogens addressed by vaccination. To address the potential demand for vaccination, we use stated preference data gathered from US consumers that responded to a phone survey where the price and coverage of the vaccination was randomly assigned. We then used this data to help calibrate a simple, partial equilibrium model of the US beef sector that incorporates demand shifts linked to the availability and uptake of human vaccination against *e. Coli*. Our stylized, calibrated model suggests that introducing and subsidizing a vaccine against foodborne pathogens may improve both consumer and firm welfare in markets for products that can carry these pathogens. For example, we found it stimulated demand for beef without imposing additional costs on firms. However, the robustness and magnitude of these market-specific impacts must be further explored in light of the simplistic and exploratory nature of the model developed and the difficulty of calibrating key parameters.

Nonetheless, these results can instruct qualitative discussions of the impacts of *ex ante* regulatory measures which could streamline debate. This methodology of combining stated-preference calibration of novel demand elements with pre-existing estimates of supply and demand parameters derived from market data may be systematically mobilized for cost-benefit analyses that can enlighten decision-makers on the best way to improve food safety.

In order to focus on the main economic mechanisms and to keep the mathematical aspects as simple as possible, the analytical framework was admittedly simple. In order to fit different problems coming from various contexts, some extensions should be integrated into the model presented here. For instance, other products affected by the outbreaks could be integrated in the analysis.

Furthermore, a general equilibrium model including the demand for all types of food with their probabilities of contamination, income effects and vaccine demand with a complete specification of health preferences could be developed. Note also that the promotion of the vaccine may negatively influence the proportion β of consumers that is not aware of the damage, which could also alter welfare assessments. Finally we note that our welfare calculations focus on the impacts in the secondary market, i.e., the market for products whose demand might be enhanced via the introduction of the vaccine. A full analysis will integrate the welfare impacts in these markets as well as the welfare impacts in the market for vaccine as well.

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Table 1. Estimated Model Coefficients

	Mean (Standard Deviation)	Probit Purchase Vaccine	Probit Prob(No Illness)	Ordered Probit Severity Illness
No Illness	0.121 (0.326)	-0.660** (0.301)	--	--
Severity Illness	2.352 (0.724)	-0.104 (0.238)	--	--
Cost of Vaccine	61.948 (28.166)	-0.0088*** (0.0007)	--	--
Salmonella	0.540 (0.498)	0.017 (0.070)	--	0.258*** (0.048)
e. Coli	0.297 (0.457)	0.248*** (0.075)	--	0.365*** (0.048)
Hamburger	0.247 (0.431)	-0.087 (0.068)	0.451*** (0.012)	-0.288*** (0.042)
Lettuce	0.249 (0.433)	0.074 (0.103)	-0.252*** (0.012)	-0.546*** (0.044)
Eggs	0.249 (0.433)	0.054 (0.080)	0.594*** (0.065)	-0.306*** (0.048)
Vaccine duration	17.979 (23.306)	0.026*** (0.004)	--	--
Vaccine duration^2	866.328 (1680.134)	-0.0002*** (0.00005)	--	--
Age < 25	0.117 (0.322)	0.208*** (0.068)	-0.230*** (0.082)	-0.085* (0.047)
Age > 65	0.159 (0.366)	-0.305*** (0.064)	0.182*** (0.062)	0.080* (0.044)
Female	0.582 (0.493)	-0.016 (0.055)	-0.284*** (0.043)	0.240*** (0.030)
Education	14.027 (3.206)	-0.017** (0.007)	0.014* (0.008)	0.002 (0.005)
Income	5.669 (3.666)	0.019*** (0.005)	0.006 (0.006)	--
Insure	0.906 (0.292)	-0.067 0.064)	--	--
Loss	0.263 (2.991)	0.010* (0.006)	--	--
Vomit	0.142 (0.349)	--	-0.154** (0.065)	--
Advise	0.053 (0.224)	--	-0.069 (0.097)	--
Eat Out	0.168 (0.113)	--	-0.030 (0.197)	--
Eat Pink	0.079 (0.334)	--	0.177*** (0.057)	--
Raw Eggs	0.072 (0.259)	--	0.027 (0.084)	--
Runny Eggs	0.114 (0.318)	--	-0.035 (0.067)	--
Intercept		0.889* (0.535)	-1.648*** (0.127)	--[a]

	Mean (Standard Deviation)	Probit Purchase Vaccine	Probit Prob(No Illness)	Ordered Probit Severity Illness
ρ (vaccine, prob)		0.167 (0.004)		
ρ (vaccine, severity)		0.210 (0.193)		
ρ (prob, severity)		-0.111*** (0.025)		
N		6937		
Log Likelihood		-11514.10		
$\chi^2(41)$		925.19***		

Table 2. Values of parameters for the calibrated model of beef in 2007 in the USA

	Value
Beef consumption in 2006 (lbs)	8 248 630 614
Beef Price in 2006 (US $)	2.73
Own-price elasticity of demand	-0.504
Own-price elasticity of supply	0.9

Notes: We abstract away from quality differences linked to the leanness because, to the best of our knowledge, there is no data on quantities differing by fat content at the retail level - only prices varying by fat content. As a percentage of beef purchases, 43% are of lower fat and remaining 57% is of higher fat products. Thus, the weighted average price would be 0.43*3.26 + 0.57*2.34 = 2.73.

Table 3. Variation in the U.S. beef market due to HACCP and vaccine authorization compared to the baseline scenario (in $)

	HACCP	Vaccine	HACCP+Vaccine
Price variation	0.33	0.01	0.33
	(12%)	(0.05%)	(12%)
Quantity variation	- 511 431 431	3 821 436	- 509 586 926
	(-6%)	(0.04%)	(-6%)
Consumer surplus variation	- 2 677 192 366	28 791 178	- 2 664 029 958
	(-11%)	(0.10%)	(-11%)
Profit variation	- 281 976 463	11 594 374	- 276 202 867
	(-2%)	(0.09%)	(-2%)
Welfare variation	-2 959 168 829	40 385 552	-2 940 232 826
	(-8%)	(0.10%)	(-8%)

Note: relative variation (%) compared to the baseline scenario in parentheses

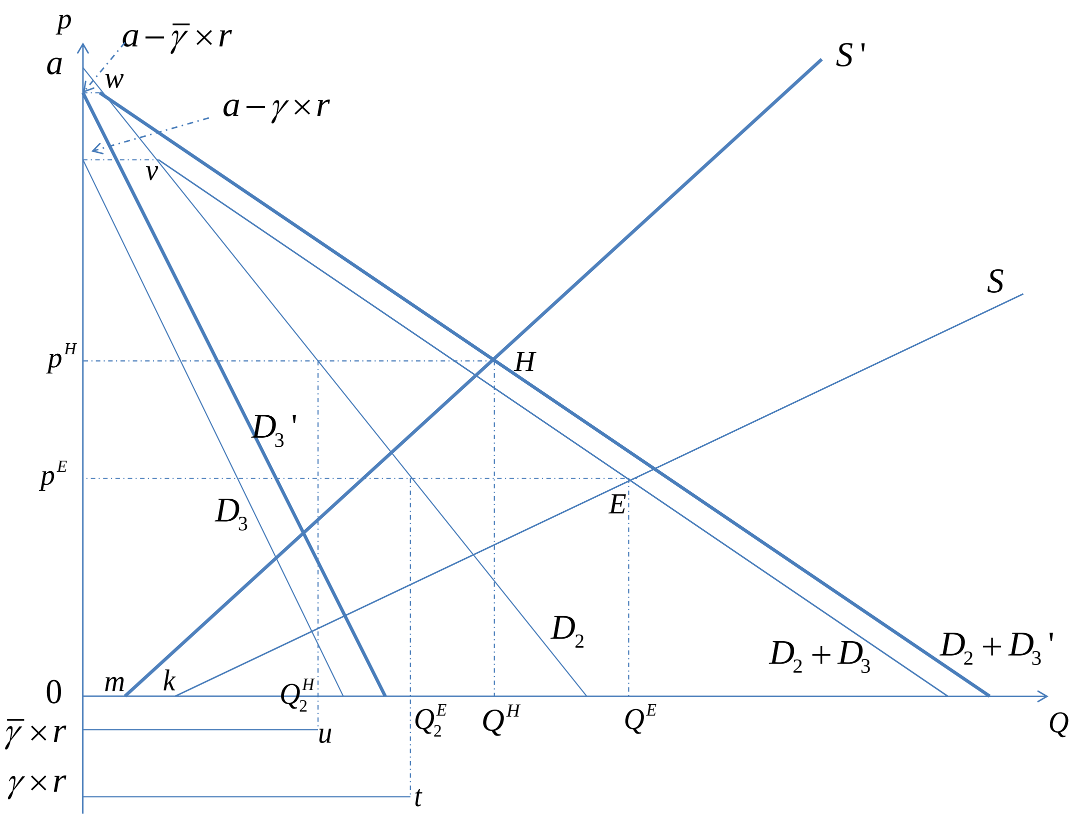

Figure 1. Baseline scenario and HACCP scenario

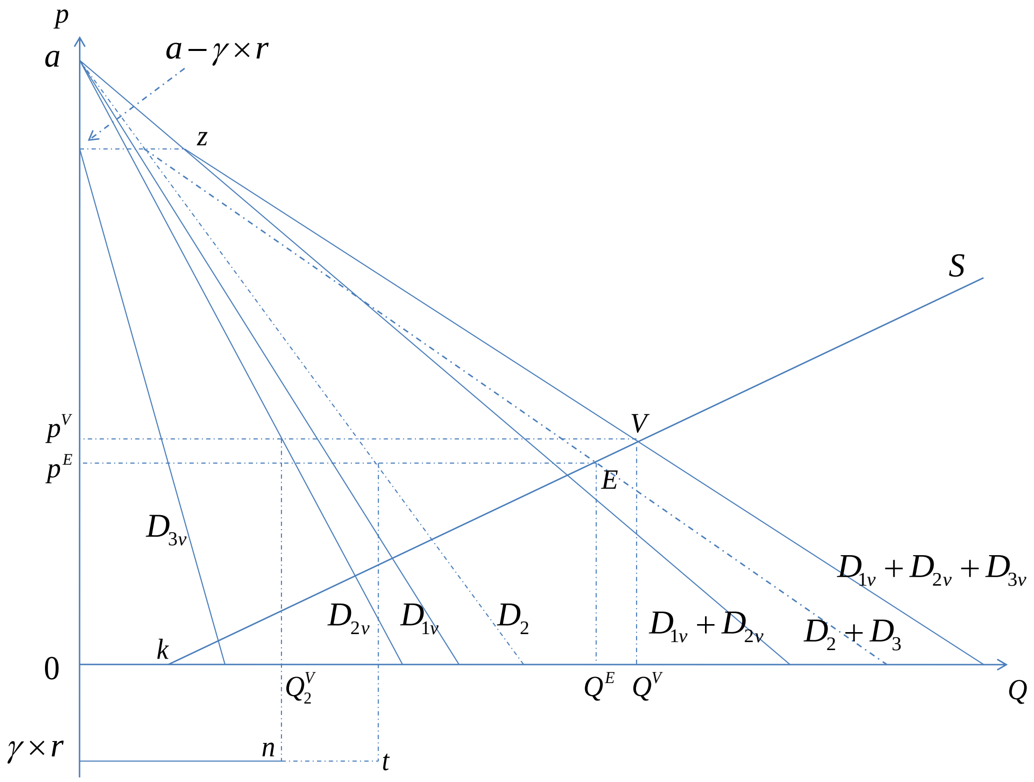

Figure 2. Baseline scenario and vaccine scenario

Welfare with the vaccine
Marginal cost of public funds *CP*=0

Welfare with the vaccine
Marginal cost of public funds *CP*=0.07

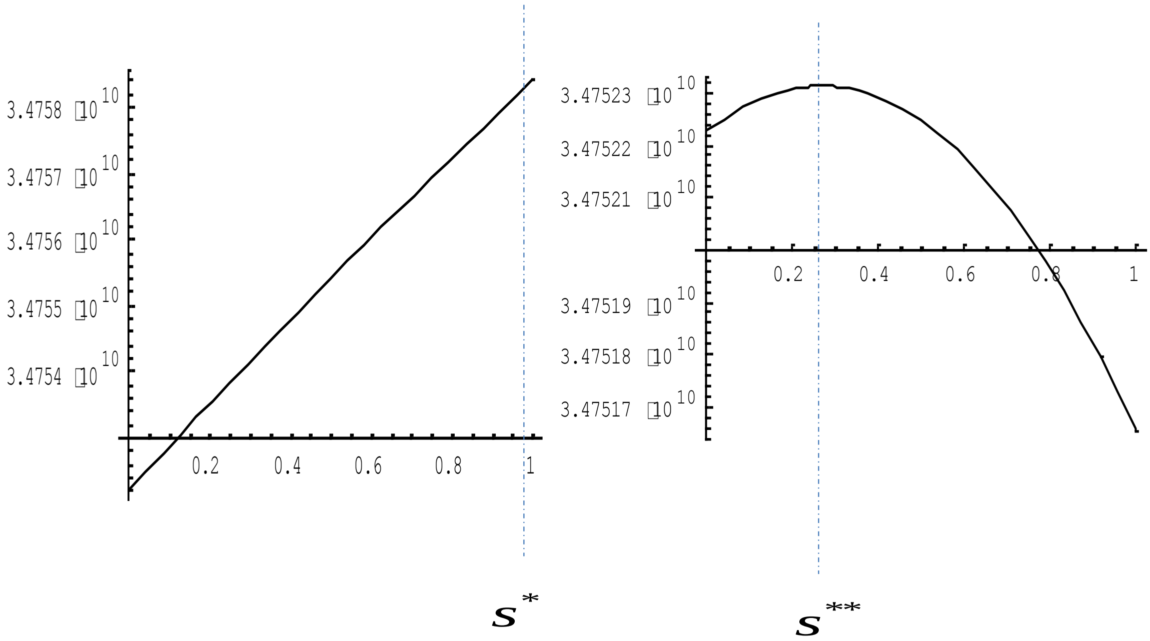

Figure 3. Vaccine Subsidy