Incorporating behavioral effects in the valuation of medical research and improvements to public safety
(*preliminary version - please do not quote*)

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March 14, 2006

Abstract

We analyze a framework in which the probability that an individual experiences a loss depends both on the individual's own level of care and on the average level of care of other agents. Important applications of this framework are HIV/AIDS and other infectious diseases, traffic accidents, worker's compensation, and environmental safety.

Within this framework, we analyze the social value of research that influences or provides information about the probability or the severity of a loss. We show that behavioral effects are essential to take into account when calculating the social value of such research, and characterize when this leads to an increased or decreased optimal level of research. We also show that it is possible to have an innovation that, for any exogenous level of care, reduces the probability or the severity of a loss, but that leads to a lower level of welfare in equilibrium.

For safety enhancements that can be purchased by individuals, an individual will generally expend too much on reducing the size of loss but, depending on conditions that we specifiy, either too much or too little on features that reduce the individual's probability of loss.

Keywords: Value of research, externalities.

1 Introduction

We analyze a framework in which the probability that an individual experiences a loss depends both on the individual's own level of care and on the average level of care of other agents. Important applications of this framework are diseases like HIV/AIDS or other infectious diseases, traffic accidents, worker's compensation, and environmental safety.

Within this framework, we show how the assessment of the social value of new loss prevention and loss mitigation technology is affected by consideration of behavioral responses. For example, suppose that research can lead to a treatment for a disease such as HIV and this treatment mitigates the consequences of acquiring the disease (e.g., consider the antiviral drugs that have lead to a significantly higher life expectancy for people infected with HIV). If prevention behavior that influences the probability of contracting the illness reduces people's utility, they will respond to this innovation by lowering their level of care as noted, for example, by Geoffard and Philipson (1996). In some cases, this might still be efficient as care is costly. However, we also show that, even when we include the reduction of the cost of care in social welfare, it is possible to have an innovation that, for any exogenous level of care, reduces the severity of the illness but also leads to a lower level of welfare in equilibrium.

We also analyze a different type of research that does not affect the severity of a loss, but rather the probability of having a loss (for any given level of care of the individual). For example, consider an immunization that is only effective with some probability, or anti-lock brakes for cars. Depending on the specific functional form, such research can either increase or decrease the level of individual care.

We then show that behavioral effects are essential to take into account when calculating the social value of research for a cost-benefit analysis that determines the efficient level of said research. We characterize when the possibility that behavior changes as a result of the new technology leads to an increased or decreased optimal level of research relative to the case without behavioral effects having been accounted for. The decisive condition turns out to be whether the level of care that individuals exert, measured by how costly it is for individuals to be careful, increases or decreases. In the former case, the optimal level of research increases, and vice versa.

A few remarks here will help to explain how our analysis fits into the existing literature, most specifically that on road safety and control of infectious diseases. When we refer to the individual's level of care we mean things such as attentiveness to road hazards while driving or use of safer sex practices. These are assumed unobservable to the social planner (or government). Our analysis is designed to consider how such choices create externalities for others[1] and how these choices are affected by other safety measures, whether these are

[1] Our paper is essentially an application of the phenomenon of *moral hazard in teams*. See Holmstrom,

observable features purchased by individuals themselves or are publicly provided. We do not consider many of the indirect measures used for imperfectly observing (and controlling) such choices such as experience rating by insurers, liability through negligence enforced through the legal system, or imperfect monitoring such as police enforcement of traffic regulations that others have studied (e.g., Boyer and Dionne, 1987). Our reason is twofold: (1) in some instances such instruments are very costly or impossible to effect and (2) we wish to emphasize in isolation of other issues how the externality created by moral hazard that affects other agents impacts on social welfare. We recognize that even without this externality individual moral hazard can create a negative externality for an insurance pool (e.g., see Gossner and Picard, 2005). We leave aside these sorts of issues in this paper.

2 The model

We consider a society with many individuals who are all subject to the possibility of suffering a loss $L(\lambda)$. As in the motivating examples described in the introduction, L can be thought of as catching a disease or having a car accident. The parameter λ describes the state of the loss mitigation technology that influences how severe a loss is if it occurs. In the examples given in the introduction, think of a treatment for a disease that reduces the mortality rate or increases the quality of life of affected patients; or a car safety device like an airbag that mitigates the health consequences of an accident. We assume that higher knowledge λ corresponds to a smaller loss size for the individual, so that $L(\lambda)$ is a decreasing function.

In the beginning of the game, players all simultaneously choose their level of precaution, p. The probability that individual i suffers a loss is given by the function $D(p_i, \bar{p}, \theta)$ that depends on the level of care of individual i, p_i, the average level of care that everybody else in the society exerts, $\bar{p}$, and the state of knowledge θ that parameterizes the function D.

We assume the following signs of derivatives: First, $D_1 \equiv \frac{\partial D}{\partial p_i} < 0$, so that a higher level of care of individual i strictly decreases the probability that individual i suffers a loss. Second, $D_2 \equiv \frac{\partial D}{\partial \bar{p}} \leq 0$, so that a higher level of care by everybody else also (at least weakly) diminishes an individual's loss probability. A strictly negative derivative is intuitively plausible for the traffic application as well as for communicable diseases, while other diseases like cancer or heart attacks would have a zero derivative in the second argument. Third, we parameterize the state of knowledge θ such that a higher level of θ corresponds to a smaller loss probability for all levels of precaution larger than 0:

1982) for a general characterization of this problem and Cooper and Ross (1985), Lanoie (1991), Pedersen (2003), and Risa (1992, 1995) for specific applications.

$D_3 \equiv \frac{\partial D}{\partial \theta} \leq 0$. An example of θ would be an anti-lock brake system (ABS) or advice about how diet influences the probability of getting some type of cancer. Furthermore, we assume that all first derivatives of the function D are continuous, and that $D_{11} > 0$ so that there are decreasing returns to scale in the level of care.

Being more careful involves a direct utility cost for the individual, given by the function $c(p_i)$. We assume the usual conditions that guarantee an interior optimum for p_i: $c'(p_i) > 0$ and $c''(p_i) > 0$ for all p_i and $c'(0) = 0$.

Individual i's objective function is

$$\min_{p_i} D(p_i, \bar{p}, \theta)L(\lambda) + c(p_i), \tag{1}$$

that is, individual i minimizes the sum of the expected loss and the cost of care.

Before the individuals make their choice, a social planner can choose the level of research that generates technical knowledge (λ, θ) at a per capita cost of $K(\lambda, \theta)$. The social planner knows how the state of (λ, θ) will influence the players' decisions on their care level, which can be summarized by the function $p(\lambda, \theta)$. Taking this behavioral effect into account, the social planner maximizes per capita utility plus some externality effect captured by the term E:

$$-D(p(\lambda, \theta), p(\lambda, \theta), \theta)[L(\lambda) + E] - c(p(\lambda, \theta)) - K(\lambda, \theta). \tag{2}$$

Here, we assume that each loss event also generates externalities of size $E \geq 0$ that the individuals do not take into account when deciding on their level of care, but that the social planner cares about. This appears important in many applications: For example, if the illness causes not only discomfort or a decreased life expectancy for the individual, but also medical treatment costs that are covered by public health insurance programs, the social planner will want to take this into account.

For much of the analysis we set $E = 0$ since the externality that we want to focus on occurs due to $D_2 < 0$. The model is also kept simple by summarizing the effect of all other individuals' precaution (p_j, $j = 1, 2, ..., i-1, i+1, ..., n$) by the average probabilty. Since we assume homogeneous agents and a symmetric equlibrium in our base model, this is not problematic. However, it will be interesting to consider at least two types of agents who take different levels of precaution due, for example, to differences in the cost of effort. We leave this for future work.

3 Results

3.1 Choice of the optimal level of care

The first order condition of the minimization problem (1) is

$$D_1(p_i, \bar{p}, \theta)L(\lambda) + c'(p_i) = 0. \tag{3}$$

Since D_{11} and c'' are assumed to be positive, this first order condition is also a sufficient condition for a minimum of the individual's cost.

Applying the implicit function theorem to (3) yields

$$\frac{\partial p_i}{\partial \lambda} = -\frac{D_1(p_i, \bar{p}, \theta)L'(\lambda)}{D_{11}(p_i, \bar{p}, \theta)L(\lambda) + c''(p_i)} < 0 \tag{4}$$

and

$$\frac{\partial p_i}{\partial \theta} = -\frac{D_{13}(p_i, \bar{p}, \theta)L(\lambda)}{D_{11}(p_i, \bar{p}, \theta)L(\lambda) + c''(p_i)}, \tag{5}$$

which can be positive or negative, depending on the sign of D_{13}. Hence, we have

Proposition 1. *The individual's optimal level of care is decreasing in λ, the technology parameter that reduces the size of a loss. An increase in θ increases (decreases) the individual's optimal level of care if and only if $\frac{\partial^2 D}{\partial p_i \partial \theta} < (>)0$.*

These results are intuitive. First, as the severity of a loss decreases, it becomes optimal to invest less in being cautious. Second, if an increase in θ increases the marginal effect of being careful (i.e., makes $\frac{\partial D}{\partial p_i}$ more negative), then the optimal level of care increases and vice versa.[2]

Let us now turn to the measure of the benefit of a marginal increase in λ and θ. Let an individual's equilibrium utility be denoted by

$$V(\lambda, \theta) = -D\left(p(\lambda, \theta), \bar{p}(\lambda, \theta), \theta\right) L(\lambda) - c(p(\lambda, \theta)). \tag{6}$$

Using the envelope theorem, the effect of an increase in λ is given by

$$\frac{dV}{d\lambda} = -D(p, \bar{p}, \theta)L'(\lambda) - \frac{\partial D}{\partial \bar{p}}\frac{\partial \bar{p}}{\partial \lambda}. \tag{7}$$

The first term on the right hand side is positive and a measure of the benefit if there were no behavioral response to the increase in λ: that is, simply the probability of a loss multiplied with the decrease in loss severity. The second term captures the effect of a

[2] A sufficient condition that guarantees stability must be developed here; i.e., to ensure the new symmetric equilibrium characterized by $p(\lambda, \theta) \equiv \bar{p}(\lambda, \theta)$ also exhibits these comparative static properties. We expect this can be achieved following Diamond (1974) and Boyer and Dionne (1987). However, we have not completed a detailed analysis.

behavioral response by other players: that is, an increase in λ decreases everybody's level of care, and the effect that this decrease in care has on the individual's utility level is given by $D_2 = \frac{\partial D}{\partial \bar{p}}$. Hence, the effect on the behavior of other people diminishes the social equilibrium value of research relative to the case of no behavioral effects.

Note that a change in λ also affects the individual's own level of care. However, by the envelope theorem, we can ignore this indirect effect (equal to $-D_1 L \frac{\partial p}{\partial \lambda} - c'(p) \frac{\partial p}{\partial \lambda} = 0$ by the first order condition) for small changes in λ.

The effect of an increase in θ is given by

$$\frac{dV}{d\theta} = -\frac{\partial D(p, \bar{p}, \theta)}{\partial \theta} L - \frac{\partial D}{\partial \bar{p}} \frac{\partial \bar{p}}{\partial \theta}. \tag{8}$$

Again, the first term is the benefit of increased research if there were no behavioral effects: It is equal to the decrease in probability of a loss times the value of the loss. The second term is the effect that arises because of the change in the equilibrium level of care of the other individuals. (Again, the envelope theorem allows us to ignore the indirect effect of the changed care level of the individual himself).

Note that the second term is ambiguous in sign, as it depends on $\frac{\partial p}{\partial \theta}$ which can be positive or negative according to Proposition 1. Therefore, the equilibrium value of research may be larger or smaller than without behavioral effects, depending on whether $\frac{\partial^2 D}{\partial p_i \partial \theta}$ is negative or positive.

3.2 Examples

We now show that an increase in λ that leads to a decrease in the size of the potential loss L can be counter-productive from a welfare point of view. Suppose that the probability of a loss is given by

$$D(p, \bar{p}) = \kappa - bp - (1 - b)\bar{p}, \tag{9}$$

so that b measures the extent to which the loss probability is influenced by the individual's own level of care, while $(1 - b)$ measures the extent that this probability is influenced by the average level of care of other players.

Furthermore, assume that the cost of care is given by $c(p) = cp^2$. The individual then chooses p to minimize

$$[\kappa - bp - (1 - b)\bar{p}]L + cp^2, \tag{10}$$

which yields $p = \frac{bL}{2c}$, and, of course, this is also the average level of care of everybody else in equilibrium. Note that, in order for this solution to make sense, we have to restrict parameters such that the probability of a loss is non-negative and less than one in equilibrium: $\frac{bL}{2c} < \kappa < 1 + \frac{bL}{2c}$.

Substituting the optimal value for both p and $\bar{p}$ in (10) above yields that the equilibrium total cost T (i.e., expected loss plus cost of care) is

$$T = \left[\kappa - \frac{bL}{2c}\right] L + c\left(\frac{bL}{2c}\right)^2. \tag{11}$$

Differentiating with respect to L gives

$$\frac{dT}{dL} = \kappa - \frac{bL}{2c}(2-b). \tag{12}$$

If $b = 1$, i.e. the probability of a loss depends only on the individual's own behavior, then a decrease in L always helps the individual, as the expression in (12) becomes $\kappa - \frac{L}{2c} > 0$. (The sign follows from the assumption above that $\kappa > \frac{bL}{2c}$). This result makes sense, since $b = 1$ implies that there are no externalities and thus each individual is not negatively affected by the fact that all other individuals behave less carefully when L decreases.

However, this result changes when b is small and κ is not much larger than $\frac{bL}{2c}$. Then, the derivative in (12) is negative, which means that a decrease in L actually *increases* the total cost T to individuals. Intuitively, a decrease in L induces all individuals to reduce their level of care. Just by itself (keeping other people's level of care constant), this is a beneficial effect for the individual, as his cost of care decreases by more than the expected cost of a loss increase. However, since the level of care of the other individuals is not fixed but also decreases in equilibrium, an additional negative externality is generated by the decrease in L, which outweighs the positive direct effect.

We now consider an example in which an increase in θ enables individuals to be more effective when they are careful, in the sense that for any given level of p, θ increases the marginal benefit of being careful. Let $D(p, \bar{p}) = [\kappa - b\theta p - (1-b)\theta\bar{p}]$, so that each individual minimizes

$$[\kappa - b\theta p - (1-b)\theta\bar{p}]\, L + cp^2, \tag{13}$$

which yields $p = \frac{b\theta L}{2c}$, and, of course, this is equal to the equilibrium level of care by everybody else. Note that an increase in θ here increases the equilibrium level of care. Hence, an increase of θ has two positive effects on the individual: First, a direct one that comes through the higher effectiveness of the individual's own p. Second, this direct effect is reinforced by a positive externality effect, since all other people increase their level of care and so also reduce the loss probability for everybody else.

Formally, substituting the equilibrium level of care into the objective function yields

$$T = \left[\kappa - \theta\frac{b\theta L}{2c}\right] L + c\left(\frac{b\theta L}{2c}\right)^2. \tag{14}$$

Differentiating T with respect to θ yields

$$\frac{\partial T}{\partial \theta} = \frac{bL^2}{c}\left(\frac{b}{2} - 1\right)\theta < 0. \tag{15}$$

More generally, an increase in θ is always beneficial for the individual if $\frac{\partial D}{\partial p \partial \theta} < 0$, i.e. if an increase in θ increases the marginal effectiveness of being careful.

The next example shows that an increase in θ can also be counterproductive, if it makes people less careful in equilibrium. Assume now that $D(p, \bar{p}) = (1-\theta)\left[\kappa - bp - (1-b)\bar{p}\right]$. An interpretation of this function is an immunization or a treatment that however only works for a proportion θ of the population and prevents or heals the illness for them, while the immunization (or treatment) has no effect on the remainder of the population. Furthermore, individuals are not sure whether they personally belong to the group that is positively affected by the treatment. With this loss probability function, each individual minimizes

$$(1-\theta)\left[\kappa - bp - (1-b)\bar{p}\right] L + cp^2. \tag{16}$$

This yields $p = \frac{b(1-\theta)L}{2c}$, which also equals the equilibrium level $\bar{p}$. Furthermore, for this example to have a reasonable solution, we have to assume that $\kappa \geq \frac{b(1-\theta)L}{2c}$ (to ensure that the equilibrium loss probability is non-negative). Substituting the equilibrium values of p and $\bar{p}$ in the objective function and simplifying yields

$$T = \kappa(1-\theta)L - \frac{b(1-\theta)^2 L^2}{4c}(2-b). \tag{17}$$

We can differentiate this with respect to θ to yield

$$\frac{\partial T}{\partial \theta} = L\left[\frac{b(1-\theta)L}{2c}(2-b) - \kappa\right]. \tag{18}$$

If b is smaller than 1, then this expression may be positive, indicating that the total cost for individuals may go up with an increase in θ. If, instead, $b = 1$, then our assumption on κ guarantees that $\frac{\partial T}{\partial \theta} < 0$, which implies that an increase in θ is beneficial for individuals.

The interpretation is similar to that in the first example. An increase in θ is directly beneficial for individuals as it reduces their loss probability and also allows them to reduce their cost of care. However, since everybody reduces his level of care, a negative externality arises that may more than offset the positive effect. The only case in which this cannot happen is if $b = 1$, as then an individual's loss probability depends only on his own actions.

4 Applications

There is a wide range of applications to this model. In this section we address some of these and, in so doing, link the model to the existing literature that concerns itself with the assessment of improvements to knowledge and practice concerning safety (prevention) and reduction in severity of accidents, disease, and other related phenomenon (loss mitigation). We are particularly interested in linking the impact of such improvements in public knowledge when these have an impact on the behavior of individuals who exert some precautionary effort themselves in an environment where the precautionary effort of others is also relevant. The spread of HIV/AIDS and other infectious diseases and traffic accidents are obvious examples.

4.1 Traffic Safety

Several empirical papers have found evidence for offsetting behavior resulting from safety improvements made in road and automobile safety (see for example, Peltzman (1975) and Harless and Hoffer (2003) and references therein). Our welfare analysis has demonstrated that under certain conditions the presence of this offsetting behaviour may lead to a reduction in social welfare that would not be recognized if behavioral effects were not taken into account.[3] This reduction in welfare may occur even if there is no direct cost of providing the *safety improvement*. In this section we will review how our results apply to road safety and also use our simple model to address some other specific aspects of the regulation of traffic safety.

The general results derived in section 3 provide insight into the value of publicly provided improvements in road safety as captured by items that reduce the probability of accidents occurring (e.g., rumble strips along the edge of the road) and those that reduce the severity of accidents (e.g., improved crash barriers). In particular, we saw that a costless reduction in L leads to a reduction is self-protection. This in itself does not imply a reduction in welfare since each individual responds optimally to this improved environment and so despits the off-setting effect welfare rises. However, the individual does not take into account the impact this reduced level of self-protection has on others' well-being through the increased accident probability for others. Thus, if this externality effect is strong enough, welfare will actually be reduced by such a *safety improvment*. We also saw that the welfare effect of a publicly provided improvement in safety that reduces the probability of an accident depends on whether the feature provided increases or decreases the marginal productivity of drivers' own self-protection efforts (e.g., attention paid to potential accident hazards as they arrive, speed, etc.). Since rumble strips alert drivers should they wander off the road onto the shoulder, this feature reduces the value of maintaining a high level of alertness. This would presumably translate into a reduction in the marginal productivity of alertness and encourage drivers to reduce their level of care. The externality effect would then reduce the value of such a *safety improvement* and we have shown that if this effect is strong enough then welfare may be reduced even if the feature is costless. On the other hand, safety improvments that enhance the marginal

[3] We emphasize that this general recognition is not a new finding but rather that our contribution is to point out how the functional form of $D(p_i, \overline{p}, \theta)$ impacts on this result.

productivity of drivers own self-protection efforts have an added advantage through this external effect.

Our model can also be used to analyze the welfare implications of safety features that can be purchased by individuals. In particular, we investigate whether such individual choices will be socially optimal and, if not, whether government should make certain features mandatory. It is well established that the likelihood and consequences of automobile accidents are characterized by factors that include:

- Individual choices regarding care taken in driving. These choices would include nonmonetary items such as degree of attention and care taken in driving, speed, etc., which we will refer to as *driving habits*. We will represent the impact of such choices by the effect of p_i, and hence $\overline{p}$, on $D(p_i, \overline{p}, \theta)$.

- Besides driving habits, there are individual self-protection decisions that are exercised in the form of monetary expenses for automobile features such as improved brakes (e.g., disc versus drum), improved braking systems (e.g., ABS), automatic stability packages, et cetera. Although up to now we have suggested an interpretation for the variable θ that is consistent with publicly provided improvements to road safety, this variable could also be used to reflect privately chosen precautionary devices as described above. The important point for our modeling exercise is that adoption of such items may have an impact on the marginal productivity of safer driving habits (p_i) according to the size and sign of $\frac{\partial^2 D}{\partial \theta \partial p_i}$.

- Individual self-insurance decisions reflecting the use of costly items such as airbags or larger vehicles. These items can be represented by the variable λ with its effect to reduce the severity or size of loss (i.e., through the function $L(\lambda)$, where $L_\lambda < 0$.)

Besides influencing such choices directly by making their adoption mandatory (direct regulation), as typified by the common practice of enforcing seat-belt use, government could also tax or subsidize such items. Of course, the general point that an important externality is at play when individuals choose the level of care when driving has been well-recognized. Moreover, the effects of a variety of government and non-government *intervention* have been studied. These factors include measures to regulate p_i, θ, and λ through speed limits and other traffic regulations of the Highway Code, liability systems in conjunction with an at fault insurance system, and rating systems for automobile insurance (i.e., bonus-malus systems).[4] We leave these considerations aside here and implicitly assume that individual decisions over p_i cannot be directly influenced due to inherent unobservability. We recognize that experience rating is a way to indirectly influence the

[4]See, for example, Boyer and Dionne (1987) and Gossner and Picard (2005).

level of p_i without having to observe it. We will not consider this possiblity here but instead focus on government influencing choices over θ, and λ through mandated use regulations or tax-subsidy policies.

So, first consider the individual's optimal choice of λ. This choice reflects the level of safety equipment that reduces severity of loss should an accident occur. The presence, number, and quality of airbags is a good example. For now we will assume θ is fixed,[5] and so the individual chooses $\{\lambda, p_i\}$ to minimize

$$\Omega(\lambda, p_i, \theta) = D(p_i, \overline{p}, \theta)L(\lambda) + c(p_i) + K(\lambda, \theta) \tag{19}$$

leading to first order conditions

$$\Omega_\lambda = D(p_i^*, \overline{p}, \theta)L_\lambda(\lambda^*) + K_\lambda(\lambda^*) = 0 \tag{20}$$

$$\Omega_{p_i} = D_1(p_i^*, \overline{p}, \theta)L(\lambda^*) + c'(p_i^*) = 0 \tag{21}$$

where $\{\lambda^*, p_i^*\}$ reflect privately optimal choices. We assyme $L_\lambda < 0$, $L_{\lambda\lambda} > 0$, $K_\lambda > 0$, $K_{\lambda\lambda}(\lambda^*) > 0$, and further that Ω is a convex function in the choice variables.

Equations (20) and (21) have simple interpretations. Letting MB^x and MC^x represent the private marginal benefit and cost functions for variables $x = p_i$, λ (and later θ), we have that

$$MB^\lambda = -D(p_i^*, \overline{p}, \theta)L_\lambda(\lambda^*) = K_\lambda(\lambda^*) = MC^\lambda \tag{22}$$

$$MB^{p_i} = -D_1(p_i^*, \overline{p}, \theta)L(\lambda^*) = c'(p_i^*) = MC^{p_i} \tag{23}$$

Note that the private benefits of course do not include any externality effects. Upon continuing the presumption that the social planner cannot influence p directly as discussed above, we want to determine whether social welfare is maximized (in a second-best sense) by the private decisions described above. In particular, will the individual choose too low or too high a level of λ. This is a useful question since λ reflects a market choice and so the government can influence this choice through a tax or subsidy.

So, social welfare is given by

$$\Psi(\lambda, \theta) = -D(p(\lambda, \theta), p(\lambda, \theta), \theta)L(\lambda) - c(p(\lambda, \theta)) - K(\lambda, \theta) \tag{24}$$

where again θ is assumed to be held fixed for now. The planner or government has no direct control over p but recognizes that the individuals' optimal choice for λ will influence p. Individuals ignore the external benefit of increasing p_i and the effect on welfare is reflected by the term $D_2 < 0$. Moreover, we have earlier shown that $\frac{\partial p_i}{\partial \lambda} < 0$. Thus, it

[5]Some safety features of automobiles could affect both the likelihood of sustaining an accident and the severity of the consequences. Improved brake systems may be an example. For ease of analysis we artificially maintain a distinct separation between these two types of safety features.

is not surprising that at the privately optimal choices $\{\lambda^*, p_i^*\}$ social welfare will rise if λ^* were to fall; that is, in this second-best environment individuals spend excessively on self-insurance. This result is shown formally below.

$$\Psi_\lambda = -D(\cdot,\cdot,\cdot)L_\lambda - (D_1 + D_2)p_\lambda \cdot L - c' \cdot p_\lambda - K_\lambda \tag{25}$$

Upon collecting terms and evaluating this derivative at the privately optimal choices $\{\lambda^*, p_i^*\}$, we can see from the first-order condition above (w.r.t. p_i), equation (21), that $(-D_1 - c')p_\lambda = 0$ and (w.r.t. λ), equation (20), that $-D(\cdot,\cdot,\cdot)L_\lambda - K_\lambda = 0$. This leaves us with

$$\Psi_\lambda = -D_2 \cdot p_\lambda \cdot L < 0 \tag{26}$$

Thus, a decrease in λ from the privately optimal value would increase social welfare.

To understand more clearly why this is so, note that in the absence of explicit control over choice of p_i it follows that the net benefit of a marginal change in λ can be expressed as the marginal social benefit (MSB^λ) less the marginal social cost (MSC^λ). Private and social benefits can be equated but marginal social cost of λ includes the external cost (MEC^λ) associated with the fact that an increase in λ leads to a reduction in care that has both a private cost and an external cost on "other" road users. Thus, we can write

$$MSC^\lambda = MC^\lambda + MEC^\lambda \text{ where } MEC^\lambda = D_2 \cdot p_\lambda \cdot L > 0 \tag{27}$$

From these results it is clear that a standard Pigouvian tax that reflects this external cost of λ would be an optimal second-best intervention. This is a second-best argument because it follows only because government can't directly control p_i. If government could ensure somehow that individuals followed the first-best level in choice of driving habits, then they should be allowed to choose their privately desired level of λ. In the second-best setting, however, the optimal tax can be seen to be higher the greater is the response of changes in λ on individuals choice of self-protection as measured by p_λ, the greater is the external effect as measured by D_2. Although it may seem somewhat perverse, the tax should be higher the worse the severity of loss L; that is, the bigger the loss to the individual, the more any effort to reduce this loss should be taxed - albeit in proportion to the loss.

The above analysis also questions the common practice of government implementation of mandatory safety requirements when the impact of these requirements has an offsetting behavioral effect and in our model this is exaggerated by the external effect of reduced level of safe driving habits. Our results here represent explicit treatment of concerns implicity treated by, for example, Peltzman (1975) and Boyer and Dionne (1987).[6]

[6] Boyer and Dionne (1987) point out that policies such as compulsory wearing of seatbelts may indeed

Now consider a similar exercise but involving an individual's optimal choice of θ. This choice reflects the level of some safety equipment or feature of an automobile that reduces the probability of an accident but has no effect on severity of loss. The quality of brakes or presence and quality of anti-skid or stability system are possible examples. Here we assume λ is fixed (and sometimes subsumed in notation) and the individual chooses $\{\theta, p_i\}$ to minimize $\Omega(\lambda, p_i, \theta)$ given in equation (19), leading to first-order conditons

$$\Omega_\theta = D_3(p_i^*, \overline{p}, \theta^*)L(\lambda) + K_\theta(\theta^*) = 0 \tag{28}$$

$$\Omega_{p_i} = D_1(p_i^*, \overline{p}, \theta^*)L(\lambda) + c'(p_i^*) = 0 \tag{29}$$

where $\{\theta^*, p_i^*\}$ reflect privately optimal choices. We assume $D_3 < 0$, $D_{33} > 0$, $K_\theta > 0$, $K_{\theta\theta}(\lambda^*) > 0$, and further that Ω is a convex function in the choice variables.

As before, the first-order conditions have simple interpretations involving marginal benefit and cost of each variable p_i and θ.

$$MB^\theta = -D_3(p_i^*, \overline{p}, \theta^*)L(\lambda) = K_\theta(\theta^*) = MC^\theta \tag{30}$$

$$MB^{p_i} = -D_1(p_i^*, \overline{p}, \theta^*)L(\lambda^*) = c'(p_i^*) = MC^{p_i} \tag{31}$$

Note, of course, that the private benefits do not include any externality effects. Again, continuing the presumption that the social planner cannot influence p directly as discussed above, we want to determine whether social welfare is maximized (in a second-best sense) by the private decisions described above. In particular, will the individual choose too low or too high a level of θ.

Recall that social welfare is given by $\Psi(\lambda, \theta)$ in equation (24). The impact on social welfare of a change in θ evaluated at the privately optimal choices $\{\theta^*, p_i^*\}$ is shown formally below.

$$\Psi_\theta = -(D_1 + D_2) \cdot p_\theta \cdot L - D_3 \cdot L - c' \cdot p_\theta - K_\theta \tag{32}$$

This can be rewritten as

$$\Psi_\theta = -(D_1 \cdot L + c') \cdot p_\theta - (D_3 \cdot L + K_\theta) - p_\theta \cdot D_2 \cdot L \tag{33}$$

Upon collecting terms and evaluating this derivative at the privately optimal choices $\{\lambda^*, p_i^*\}$, we can see from the first-order conditions above (w.r.t. p_i and θ) that the first two terms (in brackets) are zero. This leaves us with

$$\Psi_\theta = -p_\theta \cdot D_2 \cdot L \tag{34}$$

lead to less careful driving. Although they hold the size or severity of loss constant, they do consider the effect of such a policy on p_i in a reduced form manner consistent with our equilibrium function $p(\lambda, \theta)$ with $p_\lambda < 0$. They consider a broader range of policies to influence the indivdiual's choice of p_i than do we.

It is not a clear-cut case whether individuals will over- or under-utilize the safety feature θ. The sign of Ψ_θ is the same as the sign of p_θ. Thus, use of θ should be taxed if it reduces marginal effectiveness of p (safe driving habits) but should be subsidized if it increases marginal effectiveness of p. Although this may seem intuitively obvious, one should remember that it is not the effect of θ on the marginal impact of safer driving habits per se that is important but only through its relationship with the external effect of p. That is, if $D_2 = 0$ then the privately optimal choice for θ would also be the socially optimal choice regardless of whether θ improves or worsens the marginal effectiveness of safe driving habits. In other words, in the absence of any externality from individuals' choices, the existence of some off-setting effect of improved automobile safety is of no relevance to social welfare. However, this is a crucial factor in the presence of an external effect.

As with the choice of λ the above relationships can be expressed in terms of the marginal social benefit (MSB^θ) and the marginal social cost (MSC^θ) of θ. Private and social benefits can be equated but marginal social cost of θ includes the external cost, or in this case possibly benefit, (MEC^θ) associated with the fact that an increase in θ may lead to either a reduction or increase in care that has both a private cost and an external cost on *other* road users. Thus, we can write

$$MSC^\theta = MC^\theta + MEC^\theta \text{ where } MEC^\theta = D_2 \cdot p_\theta \cdot L > 0 \tag{35}$$

To summarize, individual choices involving expenditure on automobile safety features that reduce the size of loss (self-insurance) are excessive when driving habits cannot be observed or otherwise controlled. Thus, a tax on the cost of any such feature should be applied. Individual choices involving expenditure of safety features that reduce the probability of getting into a traffic accident should be taxed only in the case where these features reduce the marginal productivity of unobserved self-protective activities (i.e., safer driving habits). If such a feature has a neutral effect on marginal productivity of safer driving habits, then an individual's optimal choice will also be socially optimal. If such a feature increases the marginal productivity of safer driving habits, then the individual will under-consume such a feature and it should be subsidized.

4.2 Communicable Diseases (HIV)

First we develop an interpretation of our model in the context of communicable or infectious diseases. In our model the (per capita expected) loss associated with a communicable disease, including the cost of precaution, is

$$D(p_i, \overline{p}, \theta)L(\lambda) + c(p_i) \tag{36}$$

where $D(p_i, \overline{p}, \theta)$ is the probability of becoming infected, $L(\lambda)$ is the loss created by infection, and $c(p_i)$ is the cost of taking precaution at level p_i. Recall that $\overline{p}$ is the impact on individual i's probability of becoming infected due to "others'" level of precaution. We will consider these as lifetime values. As noted by Philipison (2000, p. 1766), the orthodox, or epidemiological, approach to assessing the cost or burden of illness (COI) is the product of prevalence and severity. This ignores the term $c(p_i)$ in the above equation, which is the cost of adjusting behaviour that is induced by the existence of the disease. The standard epidemiological approach will thus underestimate the cost of disease relative to the behavioural or economic approach. Of more interest here is that the two approaches will also provide very different answers when addressing the impact of policies - θ - that alter the probability of disease (or prevalence), as reflected in $D(p_i, \overline{p}, \theta)$, and policies - λ - that can reduce the severity of disease, L. Existing results from economic, or behavioural, models demonstrate how public policies such as those mentioned above provide less benefit due to counteracting effects of individual behavior (see Philipson (2000) for a useful survey on this research).

Our contribution is to provide a more detailed anlaysis of the prevalence or probability function $D(p_i, \overline{p}, \theta)$, and in particular the role of the sign of the cross partial $\frac{\partial^2 D}{\partial p_i \partial \theta}$.[7] However, the modeling of infectious diseases is more complex than that of jointly determined safety precautions for such problems as traffic or workplace safety. The source of the added complexity is that when coming into contact with an individual, whether in an intimate way when considering HIV or other sexually transmitted diseases, or in a more casual way when considering SARS or influenza, the probability of a person who is currently uninfected becoming infected depends on whether the person he/she has come into contact with has in fact already become infected. That in turn depends on the contact intensity of the person in previous time preiods, thus estabilishing potentially complex dynamic phenomena.[8] Even if one assumes one is in a steady state equilibrium, it is still important to recognize the role of the infection (prevalence) rate in society as well as contact intensity and precautionary behaviour when proposing reasonable functional form assumptions about the function $D(p_i, \overline{p}, \theta)$.

For now we simply assume that a steady state equilibrium exists and that it is locally stable, thus allowing us to consider the impact of marginal changes in policies to reduce D and L. The per capita expected loss (welfare loss) in the steady state (symmetric)

[7]Gersovitz and Hammer (2004, p. 2) note that this literature "'formulates prevention as an entirely discrete choice"', whereas in many circumstances a continuum of choices for self-prevention or loss mitigation exist. Although Gersovitz and Hammer's model does take this same perspective as does ours, they model choices of indivduals that are observable. Thus, our emphasis is quite different.

[8]Modeling the phenomena of safety in traffic, for example, doesn't require this sort of dynamic consideration.

eqilibrium is

$$\Lambda = D(p(\lambda,\theta),\overline{p}(\lambda,\theta),\theta)L(\lambda) + c(p(\lambda,\theta)) \tag{37}$$

where $p(\lambda,\theta)$ and $\overline{p}(\lambda,\theta)$ are identical functions with $\overline{p}$ representing the external effect of others' behaviour on any given individual's probability of infection and p representing an individual's optimal choice of precaution. To explore reasonable assumptions for the functional form of $D(p(\lambda,\theta),\overline{p}(\lambda,\theta),\theta)$ we first consider the model described in Philipson (2000) for studying the HIV infection. Appropriate alterations in notation are made in order to avoid confusion. I will refer to that model as the "HIV model", but recognizing of course that other models incorporating behavioural choices have been proposed to study HIV (e.g., Kremer, 1996) and other communicable diseases.

In any model of infectious diseases one needs to recognize that individuals can be in a number of states. Let s represent the state of being susceptible (person as yet doesn't have the disease) and i the state of being infected. For some diseases, such as flu, being infected is a temporary state from which one passes into a state of being immune through recovery, denoted state r. However, for HIV we use only states s and i. Philipson adopts a discrete choice set for precaution, denoted by $d \in \{0, 1\}$. The value $d = 0$ refers to an individual using no protection (or choosing to remain exposed) while $d = 1$ refers to "full protection" or nonparticipation in contact. Only those who choose $d = 0$ are at risk and their loss from contracting the disease is the difference in utility associated with changing from state s into state i. This value is written

$$L = u(s, 0) - u(i, 0) \tag{38}$$

The decision to take precaution ($d = 1$) depends on the severity of loss L and the risk of infection. Let I denote the prevalence rate and β, a parameter, denote the transmission rate that describes the probability that a susceptible (i.e. uninfected) individual will become infected upon contact with another infected person. Therefore, in equilibrium a given value of L induces individual precaution decisions which in turn generate an equilibrium value of prevalence. Of course, there is a feedback (circular) effect in that prevalence also affects individuals' precaution decisions that in turn affect the prevalence of the disease. This is summarized in the function $I(L)$, where $I_L < 0$. Although not included in this model, one could also add an intensity parameter/decision that represents the number of individuals a person comes in contact with (i.e., number of sexual partners).[9]

Given the explicit dynamic characteristic of HIV, a discount rate α is used in conjunction with future utility. Thus, an individual decides to remain exposed (or be a participant in the risky activity) provided current utility from doing so exceeds the net present value

[9] See Kremer (1996) for a model that focuses on this decision.

of the expected future cost due to risk of infection. This is given by the rule

$$d = 0 \iff C \equiv u(s, 0) - u(s, 1) \geq \alpha\beta I_t[V(s) - V(i)] \tag{39}$$

where C is the cost of prevention (i.e., the excess burden of the disease due to the avoidance of exposure. $V(s)$ and $V(i)$ are the state dependent continuation levels of future expected utility. In the case of HIV, $V(i)$ represents the expected utility for someone who has contracted HIV and this would include one's expectations about the effectiveness of possible future treatments. An increase in $V(i)$ (or a reduction in β) would reduce the size of the RHS of the inequality, thus generating conditions more favourable for the decision $d = 0$. $V(s)$ is as defined below:

$$V(s) = \max\{u(s, 1) + \alpha V(s), u(s, 0) + \alpha[\beta I_t V(i) + (1 - \beta I_t)V(s)] \tag{40}$$

In our model the function $D(p(\lambda, \theta), \overline{p}(\lambda, \theta), \theta)$ plays the role of βI_t in that it reflects the probability that someone will become infected should one choose to be exposed (i.e., participate in contact with others). The role of self-protection in our model is explictly recognized by choice of p having an effect on this probability while self-protection in the HIV model is determined by whether one engages in, or avoids, sexual contact. The externality of the level of precaution by others (or the general level of precaution in the population) is explicitly noted in our probability function by the term $\overline{p}(\lambda, \theta)$. External effects from the decision about level of precaution is implicitly incorporated in the HIV model through the effect that the participation decision ($d = 0, 1$) has on the equilibrium rate of infection I_t. Neither model uses an intensity of contact decision (e.g., decision about number of sexual partners given this is at least one) as does Kremer (1996). This would obviously be an interesting extension to either of these models.

To complete our desciption of the HIV model, it is assumed that, for a given level of L, each individual has a critical or reservation value for prevalence, K, above which he/she will choose not to be exposed. Upon solving for the value function $V(.)$, this implies that

$$d = 1 \iff I_t \geq K \equiv \frac{\alpha}{\beta} \frac{[u(s, 0) - u(s, 1)]}{[u(s, 1) - u(i, 0)]} \tag{41}$$

To gain more intution, this inequality can be expressed as

$$d = 1 \iff \beta[u(s, 1) - u(i, 0)]I_t \geq \alpha C \tag{42}$$

That is, a person chooses self protection if and only if the expected cost of becoming infected exceeds the discounted expected cost of avoiding contact. Given a population distribution on K represented by cdf $F(K)$, one can determine the rate of new infections for any given existing prevalence level. Using the above one can then generate a function that models the hazard hazard rate, $h(I_t)$, of the susceptible population into the infection state. This will depend on the level of severity of the disease L since there is a different $F(K)$ function for evey L (i.e., since an increase in L will, ceteris paribus, induce more people to chose protection/nonparticipation). Then by incorporating the mortality rate and birth rate into an explicity dynamic model one finds the steady state equilibrium for the prevalence rate.[10]

Based on the above, there is a function $N(I(L), L)$ that represents the equilibrium fraction of the population that does not participate (i.e., who choose $d = 1$), given the prevalence rate $I(.)$ and the severity of the disease L. In equilibrium the prevalence rate will depend on the severity level L, as indicated by writing $I(L)$. Thus, one can write $N(L)$ where the derivative $N_L > 0$. So, if C represents the cost of avoiding exposure (i.e., not participating in contact), it follows that the steady-state equilibrium welfare loss due to the disease is

$$\widetilde{\Lambda} = N(L)C + [1 - N(L)]I(L)L \tag{43}$$

Thus, the reduciton in welfare loss due to a marginal improvement in severity of the disease (i.e., a reduction in L) is

$$-\frac{d\widetilde{\Lambda}}{dL} = \underset{(+)}{N_L}[I(L)L - C] - (1 - N)[\underset{(-)}{I_L} \cdot L + I] \tag{44}$$

The first term in square brackets, $[I(L)L - C]$ represents the reduction in welfare loss due to the increase in utility from people who switch from nonparticipation into participation (exposure). The second term in square brackets, $[I_L \cdot L + I]$ is the reduction in welfare loss due to the lowered average cost on those who choose to participate in the risky activity.

It is useful to compare (43) with the effect of a reduction in L for the standard epidemiological (COI) model that ignores behavioural effects. So, assuming that demand for the risky activity is exogenous at level $(1 - \overline{N})$ and prevalence is exogenous at level $\overline{I}$, we get a revised welfare loss function of

$$\Lambda^0 = (1 - \overline{N})\overline{I}L \tag{45}$$

and so the impact of a marginal improvement in severity of the disease in this case is

$$-\frac{d\Lambda^0}{dL} = -(1 - \overline{N})\overline{I} \tag{46}$$

Recall that expected loss from disease for our model is given in (37). To compare the above results to our model we simply differentiate with respect to L (ignoring the previous

[10]See Geoffard and Philipson (1996) and Philipson (2000) for details, including sufficient conditions for existence of a steady-state equilibrium that is locally stable.

interpretation of changes in λ being the channel by which L is affected. [11]

$$-\frac{d\Lambda}{dL} = -D(p(\lambda,\theta),\overline{p}(\lambda,\theta),\theta) - \underset{(-)}{\frac{\partial D}{\partial \overline{p}}}\underset{(+)}{\frac{\partial \overline{p}}{\partial L}} \tag{47}$$

where the first term is negative and respresents the reduced welfare loss due to reduced loss for those who become infected (i.e., the same effect that is the total effect for the COI model). The second term being positive offsets this reduction. It represents the negative externality associated with the fact that decreasing the severity of the disease leads individuals to reduce their precaution in a way that takes account only on their own well–being while ignoring the impact on others.

Philipson's model indirectly includes the sort of externality effect of others behaviour through the fact that the self-protection decision (all all or nothing participation decision) has an effect on the overall incidence or prevalence rate of the disease through $I_L < 0$. So a reduction in L induces more participation which in turn leads to an increase in prevalence. In our case by setting $\frac{dL}{d\lambda} = -1$ (or $dL = -d\lambda$), our negative externality becomes $\underset{(-)}{\frac{\partial D}{\partial \overline{p}}}\underset{(+)}{\frac{\partial \overline{p}}{\partial L}}$ (i.e., $\frac{dD}{d\overline{p}}$). Thus, we have effectively the same effect but through a different channel - i.e., a self-protection decision which is not an all or nothing choice such as reflected by $d = \{0, 1\}$. Thus, there is a broader range of applications in our model. For example, our model accomodates choices such as using a condom only some of the time when having sex, say especially with new partners or when one thinks one might have a sore or abrasion that could increase the likelihood of transmission.

One problem in models like Philipson's is that the participation decision, which is the only method of self-protection, is in a sense "'behind the scenes"' as described above. However, in the steady state equilibrium, with heterogeneous individuals holding different reservation prevalence levels for a given set of parameters (L, I), the marginal participant's cost of avoidance (protection or $d = 1$) - C - equals the expected loss from participation (no protection or $d = 0$) - $I(L)L$. So with $I(L)L = C$ the first term of (44) should be zero. The reason is just hidden in the build-up of the model (i.e., there is an application of the envelope theorem effect in that model but it is just "once removed" so to speak). Our model takes this directly into account.

Gersovitz and Hammer (2004) model choices over λ and θ, which they refer to as therapy and prevention, in a manner more similar to ours. However, their focus is on how government provision of such inputs can be optimally provided in the context of a wide range of disease type that vary in their dynamic effects. We consider activities of loss mitigation and self-protection that are not observable to government. Moreover,

[11] In this formulation we simply think of $\overline{p}$ as being a function of L rather than λ with $\frac{\partial \overline{p}}{\partial L} > 0$. Note that we could also have differentiated Λ (rather than $-\Lambda$) with respect to λ and set $L_\lambda = -1$.

an important advantage of our model is that we explicitly take into account the effect of changes in θ and the importance of the effect of θ on marginal productivity of self protection through the term $\frac{\partial^2 D}{\partial p_i \partial \theta}$ as well as consider the possiblity of enhancements to these unobservable decisions that arise from individual market-oriented choices.

5 Conclusions

There has been a long-standing and active interest in determining whether publicly provided safety enhancements or loss mitigation measures have off-setting behavioral effects which reduce or possibly eliminate the observed impact of such measures on the accident rates or consequences of accidents.[12] Besides road safety, similar phenomena apply to workplace safety and the rate of infectious diseases including HIV/AIDS. We have provided a very simple model to sythesize some of the results from the literature across these areas of concern and to provide additional welfare analysis.

In the absence of insurance market effects, we see that inclusion of off-setting behavior in itself does not necessarily lead to different answers to questions such as how to evaluate government investments designed to improve health and safety. Nor do off-setting behavioral effects imply that individuals will take socially inefficient decisions regarding self-protection or loss-mitigation activities. However, when individuals' unobserved self-protection levels do affect the probability of adverse outcomes for others, then not surprisingly such external effects imply social inefficiency. Our analysis helps to identify the impact of such inefficient choices. This depends critically on how public policies affect the marginal benefit of unobserved self-protection activity as well as the size of the externality (i.e., sensitivity of individuals' behavior on others probability of loss). Thus, meauring either the size of the direct impact of government policy and/or the size of off-setting effects is of no help to guiding policy. One also needs to know the size of the external effect.

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[12] A recent newspaper article in the Toronto Star (March 14, 2006) even points out that good weather leads to drivers increasing their speeds with the outcome that, although there are fewer accidents, the severity of accidents is much greater.

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