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ABSTRACT

This article considers the problem of the optimal form of insurance contract when the indemnity can be made contingent only upon an imperfect signal of the final wealth of the insured person. This is the case, for example, when some risks affecting wealth cannot be insured by the market. The optimal contract is shown to contain a straight deductible when the distribution of the uninsurable risk is independent of the size of the loss of the insurable asset. Under a plausible condition on the utility function, the existence of an uninsurable risk reduces the optimal deductible. If the risk on the uninsurable asset increases with the size of the loss of the insurable asset, the optimal contract contains a "disappearing deductible" if the policyholder is prudent ($u''' > 0$). This model also is useful for analyzing the design of optimal insurance when losses are observed by the insurer with an error.

INTRODUCTION

Arrow (1965) and Raviv (1979) have shown that, under various conditions, socially efficient insurance contracts contain full insurance above a straight deductible. The deductible policy is the best compromise between the desire to cover large losses and the willingness to limit the cost of insurance. The optimality of the deductible clause in insurance relies on two basic assumptions. First, the insurer must be risk neutral, otherwise coinsurance above the deductible would be optimal. Second, transaction costs must be a function of the expected indemnity alone.[1] This is an important result since, under these conditions, the insurance decision simplifies to a one-dimensional choice problem, that is, the selection of the optimal deductible. This problem has been solved by Mossin (1968).

It is always assumed in this literature that the indemnity schedule can be made contingent on the actual aggregate loss of the insured person. There are

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[1] Raviv (1979), Huberman, Mayers, and Smith (1983), and Gollier (1987a, 1987b) examine optimal insurance when these assumptions are relaxed.

several reasons to believe that this can be at best a crude approximation of what happens in the real world. First, insurers prefer in general to cover different sources of risk by different contracts (Gollier and Schlesinger, 1995). Second, in many instances, some risks affecting the final wealth of the agent may not be insured. The existence of uninsurable risks is a well-known phenomenon that can be explained by the existence of an adverse selection or a moral hazard problem. In consequence, insurance contracts are not written for wealth losses but for losses on specific assets which may be thought of as imperfect measures of the wealth losses.

Suppose that the wealth loss $\tilde{x}$ has two components, $\tilde{\varepsilon}$ and $\tilde{y}$. This article takes as given that the indemnity cannot be made contingent on the uninsurable component $\tilde{\varepsilon}$ of the loss. Rather, I analyze how this uninsurability problem affects the optimal design of the insurance contract on the insurable component $\tilde{y}$. This problem has been examined by Doherty and Schlesinger (1983), who show in a simple example that Arrow's deductible result is not robust to the introduction of an uninsurable risk. The intuition is that the insurance policy can be used to cover part of the uninsurable risk if it is correlated to the insurable risk. To reinforce this intuition, I formally show in a more general model that the optimal insurance policy has a deductible clause in the case of independence. But the existence of an independent uninsurable risk can affect the optimal level of the deductible. In order to sign this effect, I use the concept of "risk vulnerability" introduced by Gollier and Pratt (1996).

Also considered is the dependent case. Under the plausible assumption that an increase in the insurable loss makes the conditional distribution of the uninsurable loss riskier, the optimal insurance contract entails a "disappearing deductible" clause if the insured person is prudent. The concept of prudence has been introduced and justified by Kimball (1990). Some of the above results have been found independently by Briys and Viala (1995).

The next section presents the model and relates it to the existing literature. Then, the optimal insurance contract is derived when $\tilde{\varepsilon}$ is an independent white noise. The fourth section is devoted to the case where $\tilde{y}$ and $\tilde{\varepsilon}$ are correlated, and the fifth section provides another illustration of the model.

THE MODEL

A risk-averse agent with wealth w faces a risk of loss $\tilde{x}$. The agent has the opportunity to purchase insurance, but the indemnity can be made contingent upon random variable $\tilde{y}$ which is potentially correlated to $\tilde{x}$. Following Arrow (1965) and Raviv (1979), the insurance contract is described by a couple (I, P), where P is the premium and I is the indemnity schedule; that is, a function I(y) determining the payment by the insurance company observing $\tilde{y} = y$. The insured person may select any contract (I, P) which is feasible. A feasible contract satisfies two conditions: (1) the indemnity must be nonnegative:[2] $I(y) \geq 0$ for all y; and (2) there is an insurance tariff that determines a premium P for any indemnity schedule $I(\cdot)$. As standard in this literature, it is assumed that the premium is based upon the expected indemnity:

$$P = f(EI(\tilde{y})), \tag{1}$$

with $f(0) = 0$ and $f'(e) \geq 1$ for all e. E is the expectation operator. If $f'(e)$ is larger than unity, a marginal increase in coverage is costly because the increase in premium would be larger than the increase in expected indemnity. If $f(e) = (1 + \lambda)e$, this tariff is sustained by a competitive insurance market with risk-neutral insurers and transaction costs that are proportional to claims.

The problem of the decision-maker with concave utility function u is to determine the indemnity schedule and the premium that maximize expected utility under the above-mentioned constraints:

$$\max_{I(\cdot),\, P} \; Eu(w - \tilde{x} + I(\tilde{y}) - P) \tag{2}$$
$$\text{subject to conditions (1) and } I(\cdot) \geq 0.$$

One can solve this problem in two steps. First, take P as given. Then, problem (2) is a standard calculus of variation problem. Moreover, because $I'(y)$ does not appear in the objective or in the constraint, the Euler equation simplifies to a succession of (pointwise) first-order conditions for $I(\cdot)$. In short, problem (2) can be solved by using Kuhn-Tucker conditions for $I(y)$ for all y. It yields the following first-order conditions:

$$E[u'(w - \tilde{x} + I(y) - P) \mid \tilde{y} = y] = \mu f'(EI(\tilde{y})) - \phi(y) \quad \forall y, \tag{3}$$

where μ and $\phi(y)$ are the Lagrangian multipliers associated respectively to constraint (1) and constraint $I(y) \geq 0$, with

$$\phi(y) \begin{cases} = 0 & \text{if } I(y) > 0, \\ \geq 0 & \text{otherwise.} \end{cases} \tag{4}$$

The second step is to optimize with respect to P. The first-order condition associated to this problem is:

[2] It is also often required that the indemnity be less than the loss. Otherwise the occurrence of an accident would make the insured person wealthier, thereby creating a moral hazard problem. More generally, the incentive-compatibility constraint expresses the fact that the insured person may not be better off with an accident than with no accident. It can be shown that, as in the standard model, this condition is always satisfied in our setting.

$$E[u'(w - \tilde{x} + I(\tilde{y}) - P)] = \mu. \tag{5}$$

The remainder of this section reexamines the well-known case of optimal insurance with no uninsurable source of risk, that is, the special case with $y = x$ almost surely. If $\tilde{x}$ and $\tilde{y}$ are perfectly correlated, this model is equivalent to the one analyzed by Arrow (1965) and Raviv (1979). Then condition (3) can be rewritten as

$$u'(w - y + I(y) - P) = \mu f'(EI(\tilde{y})) \quad \forall y : I(y) > 0. \tag{6}$$

This means that, in every state of the world in which an indemnity is paid, the marginal utility of the insured person must be constant. This implies that $y - I(y)$ is constant in those states, that is, $I'(y) = 1$. This can be seen directly by fully differentiating condition (6) with respect to y. Thus, the optimal insurance schedule contains two segments in the (y, I) graph: a horizontal line ($I(y) = 0$) where the nonnegativity constraint is binding and an unconstrained 45-degree line ($I(y) = y - D$) for some D. Arrow (1965) concludes that there must exist a scalar D such that $I(y) = \max(0, y - D)$, that is, the optimal insurance contract contains full insurance above a straight deductible D. The optimal level of the deductible is obtained by combining conditions (3) and (5):

$$u'(w - D - P) = f'(EI)\, Eu'(w - \min(\tilde{x}, D) - P), \tag{7}$$

where $P = f(EI)$ and $EI = E(\max(0, \tilde{x} - D))$. Mossin (1968) proves that D is positive as long as insurance is costly ($f'(\cdot) > 1$). Notice that, contrary to the optimal *form* of the insurance contract, the *size* of the optimal deductible depends upon the degree of risk aversion of the insured person.

THE INDEPENDENT CASE

As a benchmark, this section assumes that risks $\tilde{y}$ and $\tilde{\varepsilon}$ are independent. Without loss of generality, it is assumed that the expectation of $\tilde{\varepsilon}$ is zero. Replacing $\tilde{x} \mid y$ by $y + \tilde{\varepsilon}$ in equation (3) yields the following first-order condition on the indemnity schedule:

$$E[u'(w - y + I(y) - P - \tilde{\varepsilon})] = \mu f'(EI(\tilde{y})) - \phi(y) \quad \forall y. \tag{8}$$

In order to analyze condition (8), let us define the indirect utility function v as

$$v(z) = Eu(z - \tilde{\varepsilon}). \tag{9}$$

One can thus rewrite condition (8) as follows:

$$v'(w - y + I(y) - P) = \mu f'(EI(\tilde{y})) - \phi(y) \quad \forall y. \tag{10}$$

Conditions (6) and (10) are basically equivalent with function u replaced by function v. Since the sign of the successive derivatives of the increasing and concave utility function u is passed on to indirect utility function v, the same arguments as those developed by Arrow (1965) can be used to derive the following result.

Proposition 1

Suppose that, in every state of the world, the actual loss x equals the estimated loss by the insurance company, y, plus an independent white noise. Then, the optimal insurance contract provides full insurance above a straight deductible D_ε : $I(y) = \max(0, y - D_\varepsilon)$.

Thus, an independent uninsurable risk does not modify the optimal design of the insurance contract. However, the independent background risk $\tilde{\varepsilon}$ will in general affect the optimal *level* of the deductible. How does $\tilde{\varepsilon}$ affect the optimal deductible on $\tilde{y}$? The interaction among independent risks has been analyzed by Samuelson (1963), Nachman (1982), Kihlstrom, Romer, and Williams (1981), Pratt and Zeckhauser (1987), Pratt (1988), Kimball (1993), and Gollier and Pratt (1996).

The intuition suggests that the presence of a zero-mean background risk should increase the demand of insurance—that is, reduce the optimal deductible—for any other independent risk. This is possible if and only if any zero-mean background risk makes the decision-maker more risk averse.[3] By construction, the attitude toward risk of a decision-maker with utility function u who faces the uninsurable background risk $\tilde{\varepsilon}$ is characterized by the degree of concavity of function v.

More specifically, background risk $\tilde{\varepsilon}$ raises the aversion toward another independent risk if v is more concave than u in the sense of Arrow-Pratt. As shown by Gollier and Pratt (1996), this is not true in general. Some restrictions on the original utility function must be satisfied to guarantee that adding a zero-mean risk to wealth raises risk aversion. The necessary and sufficient condition on u is refered to as "risk vulnerability," to stress the idea that the willingness to accept a risk is vulnerable to any independent background risk. Gollier and Pratt (1996) characterize this condition. A sufficient condition for risk vulnerability is that the Arrow-Pratt measure of absolute risk aversion $-u''(z)/u'(z)$ be decreasing and convex in wealth z. All familiar utility functions such as the exponential, the logarithm, and the power functions are vulnerable to risk. This discussion on the effect of the uninsurability of $\tilde{\varepsilon}$ on the optimal deductible is summarized in the following proposition.

[3] The fact that more risk aversion raises the demand for insurance is proven by Schlesinger (1981).

Proposition 2

Consider the same economic environment as in Proposition 1. Under risk vulnerability, the independent white noise $\tilde{\varepsilon}$ reduces the optimal deductible: $D_\varepsilon \leq D$.

Still, since v is concave, one can apply Mossin's result that full insurance is never optimal, except if insurance is costless ($f'(\cdot) = 1$). Since D_ε is the optimal deductible of a policyholder with concave utility v under the Mossin model with full information, Mossin's result can also be applied here: $0 < D_\varepsilon$.

THE DEPENDENT CASE

As in the previous section, we assume that $\tilde{x} \mid y = y + \tilde{\varepsilon}$, with $E[\tilde{\varepsilon} \mid \tilde{y} = y] = 0$. Consider now the possibility for $\tilde{\varepsilon}$ to be correlated with $\tilde{y}$. As shown by Doherty and Schlesinger (1983), the optimal insurance design is not necessarily of the deductible type. The indemnity schedule I must now satisfy condition (11):

$$E[u'(w - y + I(y) - P - \tilde{\varepsilon}) \mid \tilde{y} = y] = \mu f'(EI(\tilde{y})) - \phi(y) \quad \forall y. \tag{11}$$

Without additional restrictions to the model, the indemnity schedule can take basically any form. It can be decreasing in some intervals and it can intersect the horizontal line more than once. More structure may be placed on the model by assuming that an increase in y induces a riskier conditional distribution of $\tilde{\varepsilon}$. This assumption is expressed by condition (12):

$$\int_{-\infty}^{\varepsilon} G_y(t \mid \tilde{y} = y)\, dt \geq 0 \quad \text{for all } \varepsilon \quad \text{and} \quad \int_{-\infty}^{+\infty} G_y(t \mid \tilde{y} = y)\, dt = 0, \tag{12}$$

where $G(\cdot \mid \tilde{y} = y)$ is the cumulative distribution function of $\tilde{\varepsilon}$ conditional to $\tilde{y} =$ y.

As observed in the previous section, $I'(y)$ equals unity if $\tilde{\varepsilon}$ is independent of $\tilde{y}$. The specific effect of the statistical relationship between these two random variables can be analyzed by considering condition (11), which states that the expected marginal utility of the policyholder must be constant when an indemnity is paid ($\phi = 0$). Consider a marginal increase in the insurable loss y. If the marginal utility is a convex function of wealth, then the induced increase in risk on $\tilde{\varepsilon}$ increases expected marginal utility. In order to compensate this effect, $w - y + I(y) - P$ must be increased in accordance, since u' is decreasing. It follows that $I'(y)$ must be larger than unity. The fact that the indemnity increases more than the increase of the insurable loss means that the deductible to be retained by the policyholder tends to disappear for large losses. This kind of insurance clause is often called the "disappearing deductible" clause. It is standard in marine insurance, for example. An example of an indemnity schedule with such a clause is drawn in Figure 1. The convexity of marginal utility—that is, $u''' > 0$—has long been recognized as a realistic behavioral assumption. It is a necessary condition for decreasing absolute risk aversion. Also, it is necessary and sufficient for an increase in future income risk to induce consumers to save more, a condition called prudence by Kimball (1990).

Proposition 3

Suppose that any increase in the insurable loss y received by the insurer induces the background risk $\tilde{\varepsilon}$ to be riskier. Under prudence ($u''' > 0$), the optimal indemnity schedule takes the form of a disappearing deductible: $\exists D_\varepsilon \in R$:

$$I(y) \begin{cases} = 0 \text{ if } y \leq D_\varepsilon, \\ = J(y) \text{ otherwise,} \end{cases}$$

with $J(D_\varepsilon) = 0$ and $J' > 1$.

Proof

Consider any y such that $I(y) > 0$. For all these y, define function J such that

$$\int u'(w - y + J(y) - \varepsilon) dG(\varepsilon | \tilde{y} = y) = k, \tag{13}$$

where $k = \mu f(EI)$ is independent of y. It implies that $I(y) = J(y)$ for these y and

$$(-1 + J'(y)) \int u''(w - y + J(y) - \varepsilon) dG(\varepsilon | \tilde{y} = y)$$

$$+ \int u'(w - y + J(y) - \varepsilon)\, dG_y (\varepsilon | \tilde{y} = y) = 0,$$

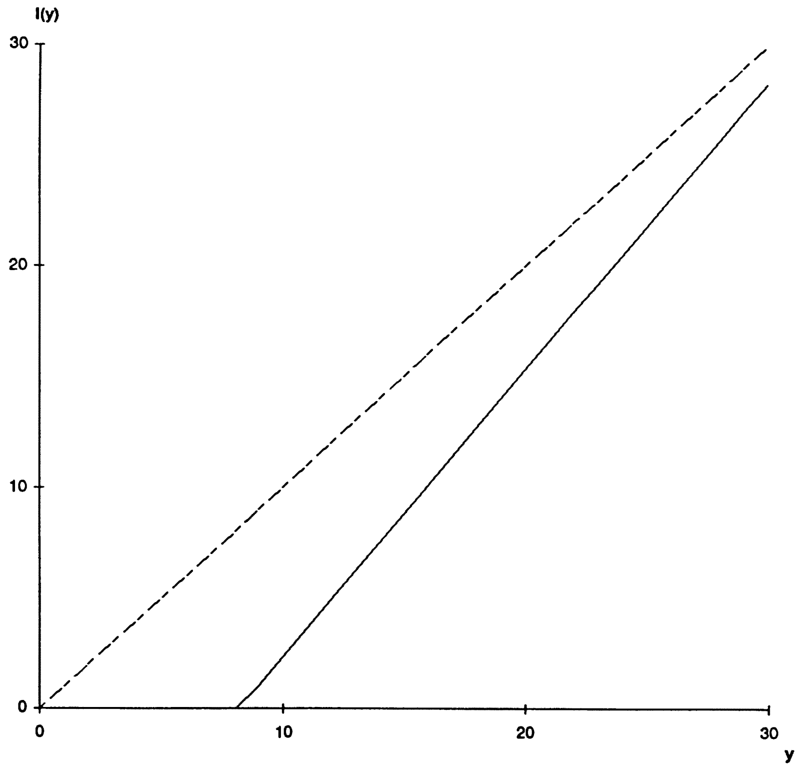
or, equivalently,

$$J'(y) = 1 - \frac{\int u'(w - y + J(y) - \varepsilon) dG_y (\varepsilon | \tilde{y} = y)}{\int u''(w - y + J(y) - \varepsilon) dG(\varepsilon | \tilde{y} = y)}.$$

The denominator in the right-hand side of the above equation is negative, whereas the numerator is positive under $u''' > 0$. This is a direct application of Rothschild and Stiglitz (1970).[4] Thus, $J'(y)$ is larger than one when $J(y)$ is positive. It can be easily verified that $I(y) = 0$ is a solution of condition (3) when $J(y)$ defined by (13) is negative.■

[4] This can be checked by integrating the numerator by parts twice. Condition (12) yields the result.

Figure 1
Optimal Insurance Schedule with A = 1, r = 0.3, and d = 10



Huberman, Mayers, and Smith (1983) prove that a disappearing deductible may be optimal without background risk, but with claim litigation costs that are concave with respect to the size of the claim. The disappearing deductible alternatively can be due to the fact that markets are incomplete. The intuition is that more wealth is desirable for the policyholder when the insurable loss y is larger because it indicates that the uninsurable loss $\tilde{\varepsilon}$ is riskier. This is because, under prudence, an increase in risk raises the willingness to increase wealth in order to forearm oneself against risk $\tilde{\varepsilon}$. The insurance contract on $\tilde{y}$ provides some form of coverage against the uninsurable noise. Notice that I' is less than unity if the policyholder is imprudent ($u''' < 0$). This is because an increase in background risk $\tilde{\varepsilon}$ *reduces* the willingness to increase wealth to forearm against that risk.[5]

[5] Briys and Viala (1995) show that the same result holds under risk aversion alone when an increase in y generates a first-order stochastic dominance shift in $\tilde{\varepsilon}$. This is a trivial consequence of condition (11).

Of course, the disappearing deductible clause suffers from an adverse incentives problem. As the loss is occurring, the insured has a positive incentive to make it larger, since it reduces the retained loss. In some types of insurance—such as marine insurance—these incentives may be unimportant, because the owner of the insured asset is not in charge of mitigating the loss as it occurs. Accordingly, this article assumes that the insured person has no control on losses, thereby eliminating this kind of *ex post* adverse selection problem.

The following example illustrates this result. Suppose that the uninsurable risk $\tilde{\varepsilon}$ is proportional to the insurable loss, with a two-point distribution: $\tilde{\varepsilon} \mid y \equiv (-ry, 0.5; ry, 0.5)$. In the estimation error story, this means that the insurance company always overestimates or underestimates the actual loss by r percent. If we assume that $u(z) = -A^{-1}e^{-Az}$, then the optimal insurance design takes the form presented in Proposition 3 with $J(y) = y + A^{-1} \ln(\cosh(Ary)) - d$, with $J'(y) = 1 + r \tanh(Ary) > 1$ and $J'' > 0$. Such an indemnity schedule is depicted in Figure 1.

The following corollary shows that partial insurance is still optimal if insurance is costly, under the assumption of Proposition 3. This result extends Proposition 2.

Corollary 1

Suppose that any increase in the insurable loss y received by the insurer induces the uninsurable risk to be riskier and that the policyholder is prudent. The disappearing deductible D_ε equals zero if insurance is costless ($f'(e) = 1$ for all e), whereas it is positive if insurance is costly ($f'(e) > 1$ for all e).

Proof

Combining conditions (3) and (5) yields

$$\phi(y) = f'(EI(\tilde{y}))E[u'(w - \tilde{x} + I(\tilde{y}) - P)] - E[u'(w - \tilde{x} + I(y) - P) \mid \tilde{y} = y] \quad \forall y.$$

Taking the expectation of this equality with respect to $\tilde{y}$ yields in turn that

$$E\phi(\tilde{y}) = (f'(EI(\tilde{y})) - 1)E[u'(w - \tilde{x} + I(\tilde{y}) - P)].$$

Suppose first that $f' = 1$. Then $E\phi(\tilde{y})$ equals zero, and, by definition of ϕ, $I(\tilde{y})$ must be positive almost surely. Given Proposition 3, this is possible only if $D_\varepsilon = 0$. Alternatively, if $f' > 1$, $E\phi(\tilde{y})$ must be positive. It implies that the nonnegativity constraint $I(y) \geq 0$ must be binding for some y with a positive probability. Since J is increasing, that can be possible only if D_ε is positive.■

ANOTHER APPLICATION OF THE MODEL

This article is a first step in a long-term research project on the analysis of insurance markets when insurers can observe losses only with an error. Indeed, the specification $\tilde{x} = \tilde{y} + \tilde{\varepsilon}$ can be seen as a model in which the actual loss of the agent is $\tilde{x}$, but the insurer observes only $\tilde{y}$. In this case, random variable $\tilde{\varepsilon}$ is the error of observation. Because it is not observable by the insurer, the indemnity only depends upon the signal y. The signal observed by the insurer is an unbiased estimator of the actual loss; that is, $E[\tilde{\varepsilon} \mid \tilde{y} = y]$ is zero for all y.

The difficulty of observing the level of loss perfectly is a standard problem in insurance because of the possibility of fraud. Insurers commonly estimate the cost of fraud in non–life insurance lines to be around 10 percent of premiums collected. Because of the risk of fraud, this article assumes that insurers do not rely at all on insureds' annoucement on the size of their loss. This yields problem (2) for the agent.[6]

One can restate the main results of the model as follows. Proposition 1 states that the design of optimal insurance when the risk of error is independent of the signal is a deductible insurance contract. Proposition 2 shows that the existence of an independent unbiased error of observation of losses *raises* the demand for insurance under risk vulnerability. This result is surprising in the sense that the random error in estimating the loss can be seen as an insurance lottery. This is a loss in the quality of the "good"—the insurance contract—for all risk-averse consumers. Paradoxically, it induces consumers to increase their demand for the good. In fact, the insured person compensates the loss in quality by increasing the expected indemnity in each state. The consequence of this observation is that insurers do not necessarily have good incentives to fight against loss-adjustment errors *ex ante.*

It is reasonable to believe that the variability of the error is increasing with the observed size of the loss. Proposition 3 states that, in this case, the optimal insurance contract contains a disappearing deductible.

Notice that if $\tilde{x}$ and $\tilde{y}$ are independent, the signal $\tilde{y}$ is noninformative for the insurer. In such circumstances, conditions (3) and (4) yield

$$E[u'(w - \tilde{x} + I(y) - P)] = \mu f'(EI(\tilde{y})) \quad \forall y : I(y) > 0. \tag{14}$$

Differentiating the above condition with respect to y implies that $I'(y) = 0$: the indemnity must be a constant independent of the signal. If $f'(0) > 1$—that is, if insurance is costly—it is obvious that this constant is zero. The optimal contract entails no indemnity. In short, when the insurance company has no opportunity to get information about the size of potential losses, the underlying risk is uninsurable in the sense that there is no demand for insurance at the break-even premium rate for insurers.

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[6] A more realistic analysis would use a game theoretic approach in which the indemnity would depend upon the (potentially fraudulent) declaration of accident by the insured and the estimation of the loss by the insurer. This work is currently in progress. The results presented here are instrumental for this more general analysis.

CONCLUSION

This article shows how the existence of an uninsurable risk affects the optimal contract for another insurable risk. If the two risks are independent, Arrow's Theorem stating that the optimal insurance contract contains a straight deductible still holds. However, under risk vulnerability, the optimal deductible is reduced by the presence of this other independent risk. When the risk on the uninsurable asset increases with the size of the loss on the insurable asset, the optimal contract contains a disappearing deductible.

The model is also useful for analyzing the effect of an imperfect claim adjustment technology. When the error in estimating the loss is independent of the estimation of the loss, the optimal contract contains a straight deductible, which is less than with a perfect (error-free) claim adjustment technology. Thus, the risk of error increases the demand for insurance. Under prudence, if the variability of the error increases with the estimation of the loss, then a disppearing deductible policy is optimal.

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