Cat bonds and reinsurance: the competitive effect of information-insensitive triggers

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Abstract

We identify a novel benefit of catastrophe bonds with parametric triggers. Private information about insurers' risk affects competition in the reinsurance market. Outsiders are subject to adverse selection as only a high-risk insurer may find it optimal to change reinsurers. This results in high reinsurance premiums and cross-subsidization of high-risk insurers by low-risk insurers. An information-insensitive cat bond with a parametric trigger is not subject to adverse selection. The availability of cat bonds with a sufficiently low level of basis risk reduces the level of cross-subsidization as well as the insider's rent. However, absent other benefits of cat bonds, insurers will continue to choose reinsurance contracts with indemnity triggers.

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1 Introduction

Catastrophic events, such as hurricanes and earthquakes are one of the main risks that insurers and reinsurers face. These hazards can result in huge losses and financing problems. For a long time reinsurance contracts have been the only way to hedge against these risks; however, since the early 1990s, catastrophe (cat) bonds have evolved as a prominent alternative to standard reinsurance contracts. Cat bonds are similar to regular bonds, but they have an additional forgiveness provision: In the case of a catastrophic event, the bond holders lose the total or a fraction of the principal amount of the bond to the benefit of the cat bond's sponsor. For the purpose of our paper, the main difference between reinsurance contracts and cat bonds is the trigger that is underlying the contracts. A reinsurance contract's payoff is almost always based on the realized loss (indemnity payment). In contrast, cat bonds usually have an index or a parametric trigger. In the first case, the payoff after the catastrophic event is based on an index of industry-wide losses; in the second, the payoff is determined by certain parameters such as the actual magnitude and location of the earthquake or hurricane.[1] Thus, the payoff is largely, and in the case of a parametric trigger, completely, independent of the sponsor's realized loss. Upon their introduction, cat bonds were expected to grow quickly and become a significant alternative to reinsurance. Empirically, however, the absolute level of coverage obtained through cat bonds is rather small, and the growth rate has increased only recently.

A main advantage of parametric or index triggers, as discussed in the literature, is seen in their positive effect on moral hazard. We provide a novel argument in favour of parametric or index-based cat bonds: Reinsurers are better informed about the risk of their clients' insurance portfolios than other (external) reinsurers, leading to asymmetric information; information-insensitive triggers help to overcome the problems related to such asymmetry. Asymmetric information between inside and outside reinsurers locks insurers into their relationship with their current reinsurer, who is therefore able to extract an

[1]For example, the payoff might depend on a predetermined Richter scale value for an earthquake in a special geographic region.

information rent. This rent is limited by the competition from outside reinsurers. However, because outside reinsurers fear adverse selection, they bid less aggressively than they would without asymmetric information. Information-insensitive cat bonds are not subject to adverse selection and place an upper bound on the premium that an insurer is willing to pay for reinsurance. Thereby, the availability of cat bonds affects the competition between inside and outside reinsurers. However, absent other benefits, cat bonds are not used in equilibrium. Because of basis risk, an informed reinsurer can adjust the premium so that it is not optimal for an insurer to choose the cat bond.

We derive our results in the simplest setting possible. An insurer faces a large cost of financial distress after a catastrophic event. To reduce the expected costs of financial distress, the insurer hedges the risk. The insurer can obtain indemnity-based reinsurance from the current reinsurer (incumbent or insider) or from another reinsurer (outsider) or, it can issue a cat bond with a parametric trigger. The insurer and the insider know whether the expected loss is high or low, while the outsider does not have this information. Because of the information disadvantage, an outsider fears that low-risk types will be retained by insiders and that only high-risk types will go to a new reinsurer. If the outsider were certain to obtain only the high-risk types, it would set the premium equal to a high-risk type's expected loss. However, this would allow the insider to also increase the premium for a low-risk type up to the same level (or slightly below). Now it would be profitable for the outsider to choose a premium slightly below the insider's premium to sell reinsurance to both types. Therefore, the insider and the outsider compete by choosing a premium between the pooling premium and a high-risk type's expected loss in a mixed strategy equilibrium. Hence, the expected premium that a low-risk insurer has to pay exceeds the pooling premium, resulting in a rent to the insider and cross-subsidization of high-risk insurers by low-risk insurers. A cat bond with a parametric trigger is independent of the insurer's expected loss and type. Therefore, the adverse-selection problem does not arise. Instead, there will be basis risk as the cash flow from the cat bond is not perfectly correlated with the insurer's loss. The insurer will issue the cat bond if the reinsurance premium exceeds the expected loss by more than the expected costs of financial distress from basis risk. This places an upper bound on the reinsurance premium that an insurer will accept. Both the insider and the outsider take this condition into account when making their offers, which reduces the premiums aimed at attracting a low-risk type. At the same time, the expected premium for a high-risk type increases as the level of cross-subsidization decreases. Therefore, the availability of cat bonds can play an important role for the pricing of reinsurance contracts. The introduction of cat bonds helps to restore the competitive position of low-risk insurers, and the profitability of low-risk insurers increases while the profitability of high-risk insurers decreases.

There exists a large body of literature that discusses potential benefits of cat bonds. One strand of the literature focuses on benefits of using index and parametric triggers to reduce moral hazard (Doherty, 1997, and Doherty and Richter, 2002). Another strand argues that large catastrophic losses are costly to reinsure because of intermediaries' high cost of raising and holding capital (Jaffee and Russell, 1997, Froot, 1999, 2001, and Niehaus, 2002). Our main contribution is to provide a novel argument in favor of cat bonds with index or parametric triggers and to analyze their effect on competition in the market for traditional reinsurance.

Froot (2001) argues that cat bonds reduce barriers to entry and that therefore the reinsurance market has become more contested, thereby decreasing premiums for traditional reinsurance. In our model the source of reinsurers' market power is asymmetric information between reinsurers, which creates an adverse selection problem and therefore reduces competition. Cat bonds with index or parametric triggers can reduce the cost of entry because they are not subject to adverse selection. However, because of basis risk, the alternative does not restore perfect competition.

Basis risk is sometimes viewed as a major obstacle to using cat bonds with index or parametric triggers. While cat bonds are not used in equilibrium in our model, the benefit of being able to use them would greatly diminish in the presence of large basis risk. However, Cummins, Lalonde, and Phillips (2002, 2004) show that for cat losses from hurricanes in

Florida, basis risk is unlikely to deter insurers from potentially using cat bonds to hedge their exposure.

Our setting is closely related to the literature on relationship lending and informational lock-in in banking as developed by Sharpe (1990), Rajan (1992), and von Thadden (2001). We apply this setting to the reinsurance market and extend the analysis by introducing an alternative that is information insensitive to the quality of insurers.

Informational lock-in in the insurance sector has been analyzed by Kunreuther and Pauly (1985), Cooper and Hayes (1987), and Nilssen (2000). Kunreuther and Pauly (1985) use a multi-period model with experience rating and myopic customer behavior and find informational lock-in for low-risk types. Nilssen (2000) shows that type-contingent contracts weaken, but do not always eliminate the informational lock-in. Ge and Cox (2004) find empirical evidence for informational lock-in in insurance markets.

The paper is structured as follows. We outline the model in the next section and derive the equilibrium competition between reinsurers without cat bonds in Section 3, where we focus on the problem of informational lock-in between insurers and reinsurers. In Section 4 we introduce cat bonds and analyze their effect on reinsurance premiums. The robustness of the model and possible extensions are discussed in Section 5. We discuss some empirical implications in Section 6 and conclude in Section 7.

2 The model

We consider a two-period model with risk-neutral agents. In each period, a (representative) insurer can incur a catastrophic loss that results in large costs of financial distress if borne by the insurer. The insurer can hedge the potential loss using reinsurance or a cat bond.

Catastrophic loss. A catastrophic event occurs with probability θ. The insurer's expected loss depends on its type, high risk or low risk. Conditional on the catastrophic event, the insurer realizes a loss X with probability $p_i \in \{p_l, p_h\}$, where p_l and p_h denote the loss probabilities of the low-risk and the high-risk type respectively, with $p_l < p_h$. The proportion of low-risk types in the economy is q and the proportion of high-risk types is $1-q$. If there is no catastrophic event, the insurer incurs no loss. Catastrophic events are independent over time, and the risk-free interest rate is zero.

Risk transfer: motive and alternatives. A large catastrophic loss, if borne by the insurer, can result in high costs above and beyond the direct loss X. These costs stem from problems of financial distress, the high cost of raising new capital after the catastrophic event, reduced underwriting capacity, and a downgraded credit rating, as well as distorted incentives of the insurer and adverse reactions of policyholders. We denote these costs as (indirect) bankruptcy costs B. Because of these bankruptcy costs the insurer wants to hedge a catastrophic loss.

The insurer can obtain either a reinsurance contract or a cat bond. Reinsurance contracts are short term in nature. In our two-period model we capture this by assuming that only one-period reinsurance contracts are available. While it seems rather natural to assume that reinsurance contracts do not cover the lifespan of an insurer, we want to point out that the need to renew reinsurance contracts is central to our analysis.

A reinsurance contract indemnifies the insurer's realized loss X. A cat bond pays X conditional on the realization of a parametric trigger. The mechanism of the cat bond is described in Section 4. If the insurer's loss X is covered by reinsurance or the cat bond's payoff, no bankruptcy costs B occur.

Without loss of generality, we assume that the insurer always finds it worthwhile to buy protection given the equilibrium conditions of the available contracts. Relaxing this assumption does not change our results about the role of cat bonds; a brief discussion is provided in Section 5.3.

Information. All parameters with the exception of the insurer's type are common knowledge. If reinsurance is used in the first period, the reinsurer who provides the reinsurance (insider or incumbent) learns the insurer's type after the first period.[2] Outside reinsurers in the second period do not have this information. For simplicity we assume that the insurer also learns its type only after the first period.

Competition between reinsurers. We focus on the effect that cat bonds have on the price of reinsurance contracts in the second period, when the insider has an information advantage over outside reinsurers about the insurer's type. Therefore, we assume that the insurer uses a reinsurance contract in the first period and show in Section 5.1 that this is indeed optimal for the insurer. Moreover, we assume that full reinsurance is obtained from one reinsurer; the possibility to use multiple reinsurers and retention are discussed in Sections 5.2 and 5.3.

In the first period, there is no asymmetric information and Bertrand competition between reinsurers. Reinsurers quote the premium K at which they are willing to indemnify the insurer's loss. The insurer randomly picks a contract from the group of reinsurers that demands the lowest premium. A loss is realized with probability θp_i, which is then indemnified by the reinsurer. At the end of the first period, the insurer and the incumbent reinsurer observe the insurer's type $i \in \{h, l\}$.

In the second period, the incumbent and outside reinsurers quote the premiums at which they are willing to indemnify the insurer's loss. For ease of exposition, we assume that there is one representative outsider who chooses the premium to be equal to the expected indemnity payment in equilibrium. K^{in} and K^{out} are the premiums demanded by the incumbent and the outsider respectively. The insurer chooses between a reinsurance contract and a cat bond with a parametric trigger, which it can obtain at a fair premium. The insurer maximizes the total expected net payoff and stays with the incumbent if it is indifferent. Losses are again realized with probability θp_i, and the contract makes the promised payment.

[2] Alternatively, asymmetric information may stem from different capabilities to evaluate an insurer's expected loss.

3 Reinsurance equilibrium

In this section we analyze the competition between asymmetrically informed reinsurers in the second period, if only traditional reinsurance contracts are available to indemnify the insurer's realized loss. The insider and the outsider simultaneously quote the premiums at which they are willing to offer full reinsurance. As the insider knows whether the expected loss is $\theta p_l X$ or $\theta p_h X$, the insider can offer different premiums to both types, $K^{in}(l)$ and $K^{in}(h)$. The outsider offers a type-independent premium K^{out}. We define $K_l \equiv \theta p_l X$, $K_h \equiv \theta p_h X$, and $K_{pool} \equiv (1 - q + qp_l)\theta X$ as the fair premiums for a low-risk type, a high-risk type, and the pooling premium, respectively. The outsider does not know the type and must fear that only a high-risk type changes the reinsurer. To carve out the problem of asymmetric information between reinsurers, suppose that the outsider demands the pooling premium, i.e., $K^{out} = K_{pool}$. At this premium a reinsurer expects to break even if both types accept the contract. In this case, it is optimal for the insider to choose $K^{in}(l) = K^{out}$ and $K^{in}(h) = K_h$. The high-risk type will then accept the outsider's offer while a low-risk type will remain with the insider. (Recall that we assume that the insurer chooses the insider if indifferent. Alternatively, the insider has to choose $K^{in}(l)$ slightly below K^{out}.) The outsider foresees that only a high-risk type will accept the contract. To break even, the outsider has to set $K^{out} = K_h$. Again, it is optimal for the incumbent to choose $K^{in}(l) = K^{out}$, which is now equal to K_h. But this cannot be an equilibrium either, because outsiders can now make a profit by offering reinsurance at a premium $K_{pool} < K^{out} < K_h$, which will be chosen by both types of insurers given $K^{in}(l) = K_h$. The following lemma directly follows from the discussion.

Lemma 1 *There exists no equilibrium in pure strategies.*

With asymmetric information, there only exists a mixed equilibrium in which the insider and the outsider randomize over the premiums that they will demand. The insider is chosen by the low-risk insurer whenever $K^{in}(l) \leq K^{out}$. In this case, the outsider is left with the high-risk type and makes a loss if $K^{out} < K_h$. If $K^{in}(l) > K^{out}$, both types of insurers choose the outsider's contract and the expected indemnity payment equals K_{pool}. Therefore, K_{pool} places a lower bound on K^{out}, while $K^{out} = K_h$ constitutes an upper bound at which the outsider's profit from selling to a high-risk type is zero.

Proposition 1 *The following mixed strategies constitute a Nash equilibrium:*
(i) The insurer chooses the contract with the lowest premium and stays with the insider if indifferent.
(ii) The insider chooses $K^{in}(h) = K_h$ for a high-risk type and $K^{in}(l) \in [K_{pool}, K_h]$ with density

$$\omega(K) = \frac{K_{pool} - K_l}{q(K - K_l)^2} \tag{1}$$

for a low-risk type.
(iii) The outsider chooses $K^{out} \in [K_{pool}, K_h]$ where $K^{out} = K_h$ has a point mass of $(1 - q)$ and $K^{out} \in [K_{pool}, K_h)$ has density

$$\phi(K) = q\omega(K). \tag{2}$$

The equilibrium is derived in the appendix.

The outsider's expected profit equals zero. When choosing $K^{out} = K_h$, the outsider will never sell to a low-risk insurer and the outsider's expected profit is zero. By reducing K^{out}, the outsider might also sell to a low-risk insurer at a profit but at the same time will make an expected loss if it does not succeed in underbidding the insider. The insider's mixed strategy has the property that the outsider is indifferent between any $K^{out} \in [K_{pool}, K_h]$.

The insider's information advantage allows the insider to earn a rent. If the insider chooses $K^{in}(l) = K_{pool}$, the low-risk insurer always stays with the insider and the rent is $K_{pool} - K_l$. Increasing $K^{in}(l)$ increases the expected profit from a low-risk type but reduces the probability of selling reinsurance to a low-risk type because now the outsider's premium may be lower. The outsider's mixed strategy has the property that the insider is indifferent between any $K^{in}(l) \in [K_{pool}, K_h]$. Thus, the expected rent from a low-risk insurer equals $K_{pool} - K_l$.

The insider's *ex ante* expected information rent is $q\left(K_{pool}-K_l\right)=q(1-q)\left(K_h-K_l\right).$ It has a maximum at $q=0.5$. Increasing q has a positive effect since it increases the probability of a low-risk type, but also a negative effect as it reduces the pooling premium. The rent also depends on the difference between the expected losses of a high-risk type and a low-risk type, K_h-K_l. This difference can be interpreted as a measure of the degree of adverse selection in the economy. The higher the degree of adverse selection or information asymmetry, the more valuable is the inside information and the higher is the rent that the insider can extract.

We now take a closer look at the insurer's cost of buying reinsurance in the described equilibrium. A low-risk insurer buys reinsurance either from the insider or from the outsider, and the expected premium is $E[\min\{K^{in}(l),K^{out}\}]$ whereas a high-risk insurer obtains insurance at an expected premium $E[K^{out}]$.

From the discussion above, it immediately follows that $E[\min\{K^{in}(l),K^{out}\}]>K_{pool}$ and $E[K^{out}]<K_h$. Thus, a low-risk type expects to pay a premium that exceeds the pooling premium. The reason is that with asymmetric information about the insurer's type, an uninformed outsider bids less aggressively because of the adverse selection problem. If all reinsurers are uninformed, reinsurers demand K_{pool}. The potential profit from insuring a low-risk insurer, $K_{pool}-K_l$, compensates for the potential loss from selling to a high-risk insurer, K_h-K_{pool}. This cross-subsidization of types is required for a reinsurer to expect to break even in a pooling equilibrium where both types choose the contract. With asymmetric information, the outsider also has to be compensated for situations where $K^{out}<K_h$ and only a high-risk type accepts the offer. The outsider's expected profit from a low-risk type is derived in the appendix and given by

$$\begin{aligned} E\left[\Pi^{out}|l\right] &= \int_{K_{pool}}^{K_h}(1-\Omega(K))(K-K_l)\phi(K)dK \\ &= (K_h-K_l)\frac{(1-q)^2}{q}\left[\frac{q}{1-q}+\ln(1-q)\right]. \end{aligned} \tag{3}$$

The expected profit compensates the outsider for the expected loss from a high-risk type, $E\left[\Pi^{out}|h\right]<0$. In equilibrium, the outsider's ex ante expected profit is zero and $qE\left[\Pi^{out}|l\right]+$

$(1-q)E\left[\Pi^{out}|h\right]=0$. Thus, $E\left[\Pi^{out}|h\right]=-[q/(1-q)]E\left[\Pi^{out}|l\right]$.

Therefore, the expected premium for a low-risk type consists of three components: the expected indemnity payment, K_l; the (expected) rent to the insider, $E\left[\Pi^{in}|l\right] = (K_{pool}-K_l)$; and the level of (expected) cross-subsidization, $E\left[\Pi^{out}|l\right]$:

$$E[\min\{K^{in}(l),K^{out}\}]=K_l+E\left[\Pi^{in}|l\right]+E\left[\Pi^{out}|l\right].$$

The expected premium for a high-risk type is

$$E[K^{out}]=K_h+E\left[\Pi^{out}|h\right]=K_h-\frac{q}{1-q}E\left[\Pi^{out}|l\right].$$

For future reference we can now state the following lemma:

Lemma 2 *The difference between the expected premiums of a low-risk insurer and a high-risk insurer is given by*

$$E[K^{out}]-E[\min\{K^{in}(l),K^{out}\}]=(K_h-K_l)\frac{1-q}{q}[\ln\frac{1}{1-q}-q].$$

The difference in expected premiums is negatively related to the insider's rent and the level of cross-subsidization.

A low-risk insurer's expected premium is lower than a high-risk insurer's expected premium. However, the difference in premiums is lower than the difference in the expected loss, K_h-K_l, because of the insider's rent and cross-subsidization of types. The difference in premiums between high-risk and low-risk types is negatively related to the insider's rent and the level of cross-subsidization.

4 Cat bonds

Catastrophe (cat) bonds have emerged as a capital market-based alternative to reinsurance. From the perspective of our paper a main difference to an indemnity-based reinsurance contract is that the payment is usually not conditional on the actual loss of the insurer, but on the realization of a parametric trigger or an index. Cat bonds are similar to regular bonds with an additional forgiveness provision. If an insurer issues a cat bond, the investors pay the principal amount X to a "special-purpose vehicle" (SPV), which acts as a clearing institution. If the trigger is set off, the insurer gets the principal X and the investors loose their investment; otherwise, they get back the full amount X. In addition, investors receive a fixed premium that compensates them for the potential loss of the principal amount.

An important characteristic of the cat bond is the trigger's correlation with the insurer's loss. The higher the correlation, the lower the basis risk. We assume that, given a catastrophic event, the cat bond "pays" the amount X with probability p_T. Thus, the probability does not depend on the insurer's type. This assumption implies that a parametric trigger is used or that the insurer's portfolio is a negligible part of the index. The fair premium equals $\theta p_T X$, which is the expected loss for investors and the cat bond's expected payoff to the insurer. To determine the level of basis risk, we define the joint probability that the trigger is set off and that an insurer of type $i \in \{l, h\}$ incurs a loss as p_T^i, with $p_T^i \in [p_T p_i, \min\{p_i, p_T\}]$. Thus, $p_T^i = p_T p_i$ corresponds to the case of zero correlation, and an increasing p_T^i reflects an increasing correlation between the trigger and the insurer's loss. Unless the cat bond's payoff and the insurer's loss are perfectly correlated and $p_i = p_T^i$, the insurer has to bear basis risk $B_i^{risk} \equiv (p_i - p_T^i)\,\theta B$. (For ease of exposition, we assume that $p_i > p_T^i$.) It is important to note that we define basis risk as the expected bankruptcy costs that stem from the possibility that the cat bond's payoff does not perfectly match the insurer's loss.

With a cat bond, an insurer receives the coverage at a fair premium but has to bear basis risk. This has important implications for reinsurance. Reinsurance does not result in basis risk, but the premium exceeds the fair premium for a low-risk insurer. The low-risk insurer will only choose the reinsurance contract if the premium $K = \min\{K^{in}(l), K^{out}\}$ does not exceed the fair premium K_l by more than the basis risk B_l^{risk}, i.e., if $K - K_l \leq B_l^{risk}$. Hence, the availability of a cat bond places an upper bound on the reinsurance premium that a low-risk type will accept. It is the highest K for which the inequality is binding and

$K_{cat}^{max} \equiv K_l + B_l^{risk}$.

A high-risk insurer will never choose a cat bond over reinsurance because the maximum premium it has to pay is the fair premium K_h.

The insider makes zero profit if the low-risk insurer does not buy insurance from it. Hence, the insider will never demand a premium that exceeds K_{cat}^{max}. Without cat bonds, the maximum premium is K_h (Proposition 1). Thus, the constraint binds if K_h exceeds K_{cat}^{max}. That is, if

$$K_l + B_l^{risk} < K_h. \tag{4}$$

Condition (4) holds ceteris paribus for low bankruptcy costs, B, for a "high correlation" between the insurer's and the cat bond's payoff, p_T^l, and for a high level of asymmetric information, $K_h - K_l$. In this case, the availability of the cat bond affects the pricing of informed insiders in the reinsurance market.

We first consider the case where K_{cat}^{max} is so low that the insider is not able to demand a premium that exceeds the pooling premium, K_{pool}. This is the case if

$$K_l + B_l^{risk} \leq K_{pool}. \tag{5}$$

Proposition 2 *Assume that a cat bond, as described above, is available. For $K_l + B_l^{risk} \leq K_{pool}$, the following pure strategies constitute a Nash equilibrium:*
(i) A high-risk insurer always chooses the reinsurance contract with the lowest premium. A low-risk insurer chooses the contract with the lowest premium if the premium does not exceed K_{cat}^{max}; otherwise it chooses the cat bond. If the insurer is indifferent, it stays with the insider.
(ii) The insider chooses $K^{in}(h) = K_h$ and $K^{in}(l) = K_{cat}^{max}$.
(iii) The outsider chooses $K^{out} = K_h$.

The insurer always stays with the insider; the cat bond is never chosen.

If (5) holds, the insider chooses a premium for a low-risk type at or below the pooling premium. The outsider will never offer a premium below the pooling premium because this contract is chosen either by both insurers or only by the high-risk insurer, yielding an expected loss in both cases. The premium that the insider offers to a low-risk type is sufficiently low so that it is never optimal for the insider to choose the cat bond.

If (5) is violated, but (4) holds, we again obtain a mixed strategy equilibrium with K_{cat}^{max} as a new upper bound. The following proposition states the new equilibrium:

Proposition 3 *Assume that a cat bond as described above is available. For $K_{pool} < K_l + B_l^{risk} \leq K_h$ the following mixed strategies constitute a Nash equilibrium:*
(i) The insurer behaves as in Proposition 2.
(ii) The insider chooses $K^{in}(h) = K_h$ and $K^{in}(l) \in [K_{pool}, K_{cat}^{max}]$ where $K^{in}(l) = K_{pool}$ is chosen with probability

$$\frac{1-q}{q}\left[\frac{K_h - K_l}{B_l^{risk}} - 1\right]$$

and $K^{in}(l) \in (K_{pool}, K_{cat}^{max}]$ with density (1) in Proposition 1.
(iii) The outsider chooses $K^{out} \in \{[K_{pool}, K_{cat}^{max}], K_h\}$ where $K^{out} = K_h$ is chosen with probability

$$(1-q)\frac{K_h - K_l}{B_l^{risk}}$$

and $K^{out} \in [K_{pool}, K_{cat}^{max}]$ with density (2) in Proposition 1.

The cat bond is never chosen in equilibrium.

The equilibrium is derived in the appendix.

For $K_{cat}^{max} \geq K_h$, the equilibrium strategies are equivalent to those in Proposition 1. As B_l^{risk} and therefore K_{cat}^{max} decrease, the insider no longer chooses $K^{in}(l) \in (K_{cat}^{max}, K_h]$ because a low-risk insurer would then choose the cat bond. The probability mass over this region is shifted to $K^{in}(l) = K_{pool}$. As a consequence, the outsider will also no longer offer contracts in this region because these contracts will only be accepted by a high-risk type. The probability mass is shifted to $K^{out} = K_h$. We note that for $K_{cat}^{max} = K_{pool}$, we obtain a pure strategy equilibrium with $K^{in}(l) = K_{pool}$ and $K^{out} = K_h$, which coincides with the one in Proposition 2.

The reinsurers' equilibrium strategies depend on the basis risk of the cat bond for the low-risk type. The case where $K_h - K_l \leq B_l^{risk}$ is equivalent to the case without a cat bond. For lower levels of basis risk, the expected premium that the insider demands from a low-risk type is reduced. For $K_{pool} - K_l < B_l^{risk} \leq K_h - K_l$, the insider can still guarantee itself an expected rent of $K_{pool} - K_l$ from a low-risk type. To understand why the insider is still able to capture the same rent as without the cat bond, it is important to recall that a higher premium does not result in a higher profit because the likelihood that the outsider underbids the offer increases as well, and in equilibrium the insider's expected profit does not change.

The constraint that the cat bond puts on the premiums that the insider can demand has an interesting effect on the bidding strategy of the outside reinsurer. The cat bond replaces competition from outside bids in the region $K_{cat}^{max} - K_h$. As the cat bond is not prone to adverse selection, the level of cross-subsidization decreases. Formally, the outsider puts less probability mass on premiums with which it tries to attract a low-risk insurer. This reduces the probability that a high-risk insurer benefits from premiums below its expected loss, and the expected amount of cross-subsidization is smaller than in the pure reinsurance case. The difference between the expected cross-subsidization in the pure reinsurance case and in the case with the cat bond is

$$\Delta = \frac{(1-q)^2}{q} (K_h - K_l) \left[\frac{K_h - K_l}{B_l^{risk}} - \ln \left[\frac{K_h - K_l}{B_l^{risk}} \right] - 1 \right] > 0 \tag{6}$$

for $K_{pool} - K_l < B_l^{risk} \leq K_h - K_l$, and is derived in the appendix. The difference is zero for $B_l^{risk} = K_h - K_l$ and increasing when B_l^{risk} decreases. Moreover, Δ is increasing in the degree of adverse selection or information asymmetry, $K_h - K_l$. The effect of $K_h - K_l$ on the level of cross-subsidization increases in the probability that a high-risk type receives a premium below its expected loss, which is higher without the cat bond.

If $B_l^{risk} \leq K_{pool} - K_l$, the cross-subsidization is zero. The insider's information rent now equals B_l^{risk}. Clearly, the rent decreases when the basis risk decreases.

Proposition 4 *For $K_l + B_l^{risk} \leq K_{pool}$, the availability of a cat bond reduces the hold-up and adverse selection problem inherent in the reinsurance relationship. The difference between the expected premiums that a high-risk type and a low-risk type have to pay is* *negatively related to the basis risk B_l^{risk} and positively related to the degree of information asymmetry $K_h - K_l$.*

The proposition follows directly from the discussion above. Reducing $B_l^{risk} \in (K_{pool} - K_l, K_h - K_l)$ reduces the level of cross-subsidization so that the high-risk type's premium increases and the low-risk types premium decreases. Reducing $B_l^{risk} \in (0, K_{pool} - K_l)$ reduces the insider's rent and the low-risk type's premium.

5 Robustness and extensions

5.1 First period

In the first period, all reinsurers have the same information and will therefore place identical bids. Since all reinsurers can become insiders when winning the bid in the first period, Bertrand competition will drive down the first-period premium, which then internalizes the insider's second-period rent. Bertrand competition implies perfect competition, no financing constraints for the reinsurers, and full internalization of insider profits. The first-period premium K_1 is then

$$K_1 = \begin{cases} K_{pool} - q(K_{pool} - K_l) & K_l + B_l^{risk} \geq K_{pool} \\ K_{pool} - qB_l^{risk} & K_l + B_l^{risk} < K_{pool}. \end{cases} \tag{7}$$

The level of expected cross-subsidization plays no role because this is a redistribution between types and in the first period insurers do not know their types either. The expected value of cross-subsidization is zero.

These costs have to be compared to the costs of the alternative of issuing a cat bond in the first period and then either issuing a cat bond in the second period or buying reinsurance at the pooling premium.

Lemma 3 *Given the premiums in (7), it is never optimal to issue a cat bond in the first period; the availability of a cat bond reduces the discount in the premium in the first period if $K_l + B_l^{risk} < K_{pool}$.*

The first part of the lemma follows directly from the observation that insurers receive a fair premium in the first period that takes into account the rent that is extracted in the second period. In contrast, the cat bond involves basis risk. The second part follows directly from the observation that the insider's second-period rent is reduced when a cat bond is available and $K_l + B_l^{risk} < K_{pool}$.

The analysis of the first period seems to suggest that cat bonds are irrelevant since insurers are compensated for the future extraction of information rents by lower premiums in the first period. However, this is not true. First, the benefit of using cat bonds in the second period remains: Low-risk insurers benefit from the availability of cat bonds in the second period, no matter how large the discount was in the first period. Second, reinsurers must be willing to pay for expected future rents. In a more general setting, they may be reluctant to do so because of potential intertemporal incentive and hold-up problems.

5.2 Multiple insiders

We now consider the case where the insurer can obtain reinsurance from multiple reinsurers in the first period. In the absence of monitoring costs and with symmetric information by insiders, Bertrand competition between the insiders will drive down the premiums demanded from a low-risk type to the fair premium K_l. The cat bond will then have no effect on the premiums as competition between insiders eliminates the lock-in from asymmetric information. However, this argument critically hinges on the assumption that both insiders will have the same information. If they end up with asymmetric information, the situation is similar to the one with an informed insider and an uninformed outsider. Rajan (1991, 1992) shows that in the presence of even a low monitoring cost and unequal access to information, insiders are again able to extract information rents, reestablishing the impact that the cat bond exerts on the reinsurers' strategies.

5.3 Retention

We have assumed that it is always optimal for the insurer to buy reinsurance. This assumption is particularly relevant for a low-risk type in the second period. If the premium exceeds the sum of the expected loss and bankruptcy costs, i.e., $K > K_l + \theta p_l B$, it is not optimal for the insurer to buy reinsurance. Therefore, the possibility not to buy reinsurance and to bear the expected bankruptcy costs also places an upper bound on the possible price if $K_l + \theta p_l B < K_h$. The new equilibrium is equivalent to the equilibrium described in Proposition 3 for $K_{pool} < K_l + \theta p_l B$ and the equilibrium described in Proposition 2 for $K_{pool} \geq K_l + \theta p_l B$, where $K_{cat}^{max} = K_l + B_l^{risk}$ is replaced by $K_l + \theta p_l B$. The constraint imposed by the cat bond is always stricter than "no insurance" since the basis risk, $B_l^{risk} = (p_l - p_T^l)\theta B$, is strictly lower than the expected bankruptcy costs, $\theta p_l B$.

If Rothschild-Stiglitz type "price-quantity policies" are possible, outsiders may offer two types of contracts: one with full insurance and a premium K_h for a high-risk type (h-contract) and one with partial insurance and a fair premium for a low-risk type (l-contract). The retention is chosen so that a high-risk type will not choose this contract. Without loss of generality, we assume that the retention is implemented through a probability $p_R > 0$ with which, conditional on a loss, the insurer is not reimbursed for this loss, while it receives X with probability $1 - p_R$. Incentive compatibility implies that the cost saving for a high-risk type net of the increase in expected bankruptcy costs must not be positive, when choosing the l-contract instead of the h-contract, i.e., $(1 - p_R)(K_h - K_l) - p_R \theta p_h B \leq 0$. The lowest p_R that satisfies this condition is $p_R = (K_h - K_l)/(\theta p_h B + K_h - K_l)$. Again, this contract places an upper bound on the maximum price that a low-risk insurer is willing to pay for full reinsurance coverage. The argument is analogous to the previous discussion for the alternative to buy no reinsurance, which is akin to choosing $p_R = 1$. Given the availability of reinsurance with a retention p_R and a fair premium, the maximum premium that a low-risk type is willing to pay for full insurance is $K_l + p_R \theta p_l B$. The cat bond is useful even in this case if the basis risk is lower than the expected bankruptcy costs with the incentive-compatible retention, i.e., if $B_l^{risk} < p_R \theta p_l B$.

5.4 Counterparty risk

We have assumed that the reinsurer does not default on its obligation. However, counterparty risk can be quite important for catastrophe reinsurance. Indemnity-based reinsurance contracts are usually not funded, and the reinsurer may default after a catastrophic event. In contrast, because of the initial provision of the principal amount, default risk can be eliminated for a catastrophe bond. We discuss the implications of this difference between the two instruments in this subsection. To simplify the exposition, we assume that the reinsurer's default probability p_C is independent of the insurer's type, that no payment is made in the case of default, and that default involves no cost for the reinsurer. Thus, with probability p_C the insurer is not reimbursed for its loss, while it receives X with probability $1 - p_C$. Default risk by the reinsurer has a similar effect for an insurer as a retention, with the notable difference that default affects both types of insurers. The possibility of nonperformance by the reinsurance contract results in expected bankruptcy costs of $p_C \theta p_i B$ for a type-i insurer. We can now analyze how the possibility of default affects our main analysis.

Introducing credit risk does not change the qualitative results in the case where no catastrophe bond is available. Proposition 1 still holds, where the fair premiums with default are now given by $(1 - p_C)K_l$, $(1 - p_C)K_h$, and $(1 - p_C)K_{pool}$. However, if cat bonds are available, they may now be chosen in equilibrium if the credit risk is sufficiently high. This is straightforward for the case of a type-l insurer. If the expected cost of default due to nonperformance of the reinsurance contract exceeds the basis risk of the cat bond, it is optimal to use the cat bond even if the reinsurance contract is offered by the insider at the fair premium. If $p_C \theta p_l B < B_l^{risk}$, the counterparty risk is sufficiently low so that the cat bond is inefficient for a type-l insurer. Nevertheless, the availability of a cat bond can still have an effect on the pricing of reinsurance contracts. In the simplest setting the cat bond is also inefficient for a high-risk insurer, i.e., $p_C \theta p_h B < B_h^{risk}$. As in the case without credit risk, the possibility to use a catastrophe bond places an upper bound on the maximum price that the insider can demand for reinsurance from a low-risk insurer. The maximum premium is given by $K_l + B_l^{risk} - p_C \theta p_l B > 0$ since $p_C \theta p_l B < B_l^{risk}$.

5.5 Frictional cost of capital and transaction cost

Capital market frictions are a major reason for a positive probability of default (and, indeed, for the use of reinsurance in the first place). The cost of raising and holding capital can differ substantially for a reinsurer and an SPV that issues the cat bond. The SPV can be interpreted as a focused insurer whose only purpose it is to write one insurance contract. In contrast, a general insurer engages in many different activities and has many different risks on the balance sheet. An SPV helps to segregate the claims of different policyholders, and the risk that funds may be diverted to other uses is minimized. This can considerably reduce the cost of raising and holding capital and increases the insurer's confidence that the funds will be available when needed. These benefits are particularly pronounced when low-frequency and high-severity risks are involved and there is a high correlation of losses between policyholders, as in the case of catastrophe risk.

Explicitly taking into account the frictional cost of capital changes the equilibrium boundary conditions, but not the qualitative results. Frictional cost of capital are akin to transaction cost. We now introduce transaction cost of c_{re} for the reinsurance contract and c_{cat} for the cat bond. The transaction cost may differ because of differences in the frictional cost of capital, but this does not imply that c_{re} is always higher than c_{cat}. For example, the transaction cost of selling a cat bond may be higher because of the high cost of setting up an SPV. Given c_{re}, the breakeven premium for reinsurance is $(K_i + c_{re})$ for an insurer of type i. The randomization range in the pure reinsurance setting is given by $[K_{pool} + c_{re}, K_h + c_{re}]$. The insider's profit and the cross-subsidization remain unchanged compared to the case without transaction cost as the higher premium just covers the transaction cost.

Given c_{cat}, the maximum premium that a low-risk type will pay for reinsurance in the presence of cat bonds is $K_{cat}^{max} = K_l + B_l^{risk} + c_{cat}$. For $K_{pool} + c_{re} < K_l + B_l^{risk} + c_{cat} < K_h + c_{re}$, the insider's profit remains unchanged. The level of cross-subsidization again decreases, by more (less) than in the case without transaction cost if $c_{cat} > c_{re}$ $(c_{cat} < c_{re})$.

For $K_l + B_l^{risk} + c_{cat} < K_{pool} + c_{re}$ we again obtain an equilibrium in pure strategies where the insider offers reinsurance to the high-risk insurer at $K_h + c_{re}$ and to the low-risk insurer at $K = \max\{K_l + B_l^{risk} + c_{cat}, K_l + c_{re}\}$. If the transaction cost of reinsurance exceeds the transaction cost and basis risk of the cat bond, i.e., if $c_{re} > c_{cat} + B_i^{risk}$, it is optimal for a type-i insurer to choose the cat bond. Of course, a lower transaction cost may be a reason for using the cat bond despite basis risk.

6 Empirical implications

We have shown that cat bonds can play an important role for the pricing of reinsurance contracts. Practitioners and academics have argued that cat bonds reduce barriers to entry and that therefore the reinsurance market has become more contested (e.g., Froot, 2001). We formalize this idea in a setting with asymmetric information between reinsurers. Asymmetric information is an important source of market power because the fear of adverse selection has an anti-competitive effect on the pricing of reinsurance contracts. Tracing back the origin of market power to asymmetric information has several interesting implications.

Most notably, the effect of introducing cat bonds differs substantially for different types of insurers. While the availability of cat bonds with parametric triggers reduces the reinsurance premium for low-risk types, it increases the reinsurance premium to be paid by high-risk types.

The reinsurance premium is a cost to insurers that affects their underwriting business. Cross-subsidization and the insider's rent alleviate a low-risk insurer's competitive advantage when competing with a high-risk insurer for underwriting business. Thus, the introduction of cat bonds helps to restore the competitive position of low-risk insurers, as the pricing of reinsurance becomes more sensitive to an insurer's risk. As a consequence, the profitability of low-risk insurers increases while the profitability of high-risk insurers decreases. The price effect allows low-risk insurers to bid more aggressively in the primary market. Therefore, low-risk insurers are likely to grow faster than high-risk insurers. The increased sensitivity of reinsurance premiums to an insurer's risk also increases insurers' incentives to maintain low risk, which will reduce the average risk of insurers.

The effect of cat bonds on individual insurers cannot be measured directly. "High risk" and "low risk" in our model are defined relative to an insurer's expected type given any publicly available information. Therefore, high-risk and low-risk insurers cannot be distinguished based on publicly available information. Alternatively, empirical studies may focus on the heterogeneity of insurers' profitability and growth: Upon the introduction of cat bonds, the difference (heterogeneity) in profitability and growth between insurers increases. The magnitude of the effect depends on the level of basis risk and the degree of asymmetric information. The responsiveness of reinsurance contracts to the insurer's risk is more pronounced as the asymmetric information increases and the basis risk decreases.

Asymmetric information is likely to be higher for insurers that are incorporated in countries where accounting information is less informative about an insurer's risk. Moreover, mutual insurers are more opaque than stock insurers, for which more public information is available. Asymmetric information is therefore likely to be a greater problem for mutual insurers than for stock insurers.

The level of basis risk is lower for insurers that have a high concentration of exposure in regions with high risk of catastrophic events, so that the correlation between the individual insurers' losses and the parametric trigger is high. Examples for well-specified and regionally concentrated perils include Californian and Japanese earthquakes, as well as eastcoast hurricanes and Japanese typhoons.

We can therefore derive the following empirical predictions:

- Upon the introduction of cat bonds, the heterogeneity of insurers' profitability and growth increases.
- The effect is higher for mutual insurers than for stock insurers.
- The effect is particularly strong for insurers with a high concentration of their risk in California and on the eastcoast in the United States as well as in Japan.
- The effect increases with the introduction of cat bonds with more concentrated and specific triggers.

- To the extent that U.S. accounting information is more informative than Japanese accounting information, the effect is more pronounced for Japanese insurers than for U.S. insurers.

In our basic model cat bonds are not used. Of course, this is no longer true if one introduces credit risk, transaction cost, monitoring cost, or moral-hazard problems. However, the result is interesting as it shows that a potential benefit of cat bonds arises from their availability – not from their use. Therefore, cat bonds may be very important even when they are rarely used.

7 Conclusion

We have shown that cat bonds can play an important role in the pricing of reinsurance contracts when there is asymmetric information between inside and outside reinsurers about an insurer's risk. Thereby, we carve out a novel benefit of cat bonds that arises even in the absence of credit risk, transaction cost, monitoring cost, or moral-hazard problems. An interesting observation is that the benefit arises solely because of the potential availability of cat bonds, which has a disciplining effect on the premiums in the reinsurance market.

The existence of information-insensitive cat bonds can reduce the asymmetric-information and lock-in problems in a reinsurance relationship and discipline the rent extraction from insider information. The availability of information-insensitive cat bonds reduces the maximum demandable reinsurance premium for sufficiently small basis risk. As a consequence, the reinsurers place less probability mass on their mixed equilibrium strategies, which decreases the degree of cross-subsidization from the low-risk types to the high-risk types. If the basis risk is sufficiently low, the level of cross-subsidization is zero and the insider's information rent is reduced. Our primary findings on the competitive effect of cat bonds are robust to a number of extensions.

8 Appendix

Proof of Proposition 1. The proof is closely related to von Thadden (2001).

First, we show that the interval $K \in [K_{pool}, K_h]$ is the optimal support for the randomization strategies. For any bid below the pooling premium, the outsider's participation constraint is violated, so the minimum premium will be K_{pool}. Therefore, it also cannot be optimal for the insider to offer a lower premium to the low-risk type because raising the premium to the pooling premium increases profits. The upper bound K_h follows from the zero-profit constraint for offering a contract to a high-risk type.[3]

Second, we derive the optimal strategies. Let $\Phi(K)$ denote the cumulative density function (CDF) of the mixed equilibrium strategy by the outsider for the choice of K^{out} and $\Omega(K)$ denote the insider's CDF for the choice of $K^{in}(l)$. Given the offer K^{out}, the outsider's expected net payoff is $\Pi^{out}(K^{out}) = (1-\Omega(K^{out}))(K^{out}-K_{pool})+\Omega(K^{out})(1-q)(K^{out}-K_h)$, where $(1-\Omega(K^{out}))$ is the probability that $K^{out} < K^{in}(l)$. The expected profit in this case is the premium minus the expected average loss. If $K^{out} \geq K^{in}(l)$, a low-risk type stays with the insider and the outsider will only sell the reinsurance contract if the insurer has high risk, which occurs with probability $(1-q)$ and results in an expected loss of $K^{out} - K_h$. In equilibrium, the outsider makes an expected profits of zero. Moreover, in the mixed strategy equilibrium the outsider must be indifferent between different premiums. Hence, $\Pi^{out}(K^{out}) = 0$ for all $K^{out} \in [K_{pool}, K_h]$. From $(1-\Omega(K^{out}))(K^{out} - K_{pool}) = -\Omega(K^{out})(1-q)(K^{out} - K_h)$ and $K_{pool} = qK_l + (1-q)K_h$ it follows that the insider's CDF is $\Omega(K) = [K - K_{pool}] \,/\, [q(K - K_l)]$ for $K \in [K_{pool}, K_h]$.

Given the outsider's mixed strategy $\Phi(K)$, the insider's expected net payoff is $\Pi^{in}(K^{in}(l)) = q[(1-\Phi(K^{in}(l)))(K^{in}(l) - K_l)]$ for $K^{in}(l) \in [K_{pool}, K_h)$ and $\Pi^{in}(K^{in}(l)) = q[\Pr(K^{out} = \theta X)(K_h - K_l)]$ for $K^{in}(l) = K_h$. For $K^{in}(l) = K_{pool}$, the low-risk type will always stay with the insider who makes an expected profit of $\Pi^{in}(K_{pool}) = K_{pool} - K_l$. In a mixed-strategy equilibrium the insider must be indifferent between different $K^{in}(l)$ given the

[3] With Bertrand competition between outside insurers, the upper bound converges to K_h. See von Thadden (2001) or Engelbrecht-Wiggans, Milgrom, and Weber (1983).

outsider's strategy. Therefore, it must be the case that $\Pi^{in}(K^{in}(l)) = \Pi^{in}(K_{pool})$ for all $K^{in} \in [K_{pool}, K_h]$. From this we can derive the outsider's equilibrium strategy, which is $\Phi(K) = [K - K_{pool}] \,/\, [K - K_l] = q\Omega(K)$ for $K \in [K_{pool}, K_h)$ and $\Phi(K) = 1$ for $K = K_h$. The densities of the players' strategies can now be derived by differentiating the CDFs with respect to K, which yields (1) and (2). $\square$

Equation (3). Assume that the insurer is a low-risk type. Given the premium K, the outsider's expected profit is $\Pi^{out}(K) = (1-\Omega(K))(K-K_l) = [(1-q)/q]\,(K_h - K)$. Taking the expectation over the choice of K yields $E\,[\Pi^{out}|l] = \int_{K_{pool}}^{K_h}(1-\Omega(K))(K-K_l)\phi(K)dK = [(1-q)/q]\int_{K_{pool}}^{K_h}(K_h - K)\phi(K)dK = [(1-q)/q]\,(K_{pool} - K_l)\int_{K_{pool}}^{K_h}(K_h - K)\frac{1}{(K-K_l)^2}dK$.

Integration by part yields

$$E\left[\Pi^{out}|l\right] = \frac{1-q}{q}(K_{pool} - K_l)\left[\left[-\frac{K_h - K}{K - K_l}\right]_{K_{pool}}^{K_h} - \int_{K_{pool}}^{K_h}\frac{1}{K - K_l}dK\right]$$

Using $K_{pool} = qK_l + (1-q)K_h$, we obtain equation (3).

Proof of Proposition 3. We show that the mixed strategies in Proposition 3 constitute a Nash equilibrium. First, we consider the insider's strategy, taking the outsider's and insurer's strategies as given. $K^{in}(h) = K_h$ is optimal since $K^{in}(h) < K_h$ results in an expected loss and $K^{in}(h) > K_h$ yields the same expected payoff as $K^{in}(h) = K_h$. $K^{in}(l) > K_{cat}^{max}$ is never optimal since a low risk-type will then buy the cat bond; $K^{in}(l) < K_{pool}$ is also never optimal since the rent can be increased by increasing $K^{in}(l)$. Hence, $K^{in}(l) \in (K_{pool}, K_{cat}^{max})$. Given the outsider's strategy $\Phi(K) = [K - K_{pool}] \,/\, [K - K_l]$ for $K \in (K_{pool}, K_{cat}^{max})$,the insider's expected profit is $\Pi^{in}(K^{in}(l)) = q[(1 - \Phi(K^{in}(l)))(K^{in}(l) - K_l)] = q\,(K_{pool} - K_l)$ and thus independent of the own offer for any $K^{in}(l) \in (K_{pool}, K_{cat}^{max})$. Therefore, the insider's mixed strategy in the proposition is a best response. We now consider the outsider's strategy. It is never optimal for the outsider to choose $K \neq K^{out} \in \{(K_{pool}, K_{cat}^{max}), K_h\}$: For $K < K_{pool}$ both types accept the contract and their expected loss exceeds the premium; for $K_{cat}^{max} < K^{out} < K_h$ only the high-risk type accepts the contract at a premium below the expected loss. For $K^{out} = K_h$, $\Pi^{out}(K^{out}) = 0$, and for $K^{out} \in (K_{pool}, K_{cat}^{max})$,

$\Pi^{out}(K^{out}) = (1-\Omega(K^{out}))(K^{out} - K_{pool}) + \Omega(K^{out})(1-q)(K^{out} - K_h) = 0$ given the mixed strategy $\Omega(K) = [K - K_{pool}] / [q(K - K_l)]$, which we derived in Proposition 1. Therefore, the outsider's mixed strategy is weakly optimal. $\square$

Equation (6). Let $\Delta = E[\Pi^{out}|l] - E[\Pi^{out}|l, cat]$, where $E[\Pi^{out}|l]$ is given by equation (3). $E[\Pi^{out}|l, cat]$ is the expected cross-subsidization when the cat bond is available. It is derived in the same way as equation (3) with the only difference that K_h is replaced by K_{cat}^{max} in the integral. We obtain

$$E\left[\Pi^{out}|l, cat\right] = \frac{(1-q)^2}{q}(K_h - K_l)\left[\frac{1}{1-q} - \frac{K_h - K_l}{B_l^{risk}} - \ln \frac{B_l^{risk}}{(1-q)(K_h - K_l)}\right],$$

using $K_{pool} = qK_h + (1-q)K_l$ and $K_{cat}^{max} = K_l + B_l^{risk}$. Taking differences yields

$$\Delta = \frac{(1-q)^2}{q}(K_h - K_l)\left[\frac{K_h - K_l}{B_l^{risk}} - \ln\left[\frac{K_h - K_l}{B_l^{risk}}\right] - 1\right],$$

which is positive since $B_{crit_2} < B < B_{crit_1}$ implies $(K_h - K_l)/B_l^{risk} > 1$.

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