Does One Shock Affect All?

Abstract

This paper investigates under what circumstances would a loss shock affect the line-specific prices in competitive markets. Specifically, three major questions are discussed: (a) Does a loss shock have to be relevant to the lines written by an insurer to affect insurance prices? (b) Would every loss shock affect the line-specific prices if it is directly relevant to the lines of business or the firm? (c) Does and when would a loss shock affect all? A simple theoretical model in the presence of market competition is developed to analyze how the line-specific prices are affected by loss shocks from different sources. The predictions of the model show that the key factor for a loss shock to influence insurance prices is through the change in the insolvency risk of the insurers. That is, one shock does affect all as long as the shock threatens the financial quality of insurers. It could not only affect the prices from the same line, the prices of other lines under the same firm, but also the prices of other competing insurers in the market. More interestingly, empirical evidence is found that even if one insurer only writes liability lines, an industry-level property shock would increase their liability-line prices.

Key words: Line-Specific Prices, Loss Shock, Competitive Market, Financial Quality

1. Introduction

It is very common to read from the news that natural disasters drive up the insurance prices. As a matter of fact, the conventional wisdom is that the uncertainty caused by capital/loss shocks contributes to the fluctuation of insurance prices in equilibrium (Winter, 1994; Gron, 1994; Cagle and Harrington, 1995; Cummins and Danzon, 1997). The supply elasticity and demand elasticity determine how prices react to market conditions.

Collectively, the existing theories and arguments seem to imply that capital/loss shocks have to necessarily be related to the lines of business written by an insurer. Building on prior efforts, this paper aims at exploring how line-specific prices respond to different sources of loss shocks in competitive markets. Specifically, I mainly focus on discussing under what circumstances would a loss shock affect line-specific prices. More importantly, the goal is to offer new perspectives in explaining market dynamics of pricing behaviors following loss shocks from different sources.

The contribution of this paper can be displayed in two aspects. First, instead of regarding shocks as a general concept, I specify where a loss shock comes from explicitly. Second, by taking into account the competitive dynamics of insurance pricing behaviors in the market, we can shed light upon the main channel through which an unanticipated loss shock affects line-specific prices.

The remainder of this paper is structured as follows. The literature regarding insurance pricing is reviewed in section 2. In section 3, a simple model is described to illustrate the intuitions and to tease out the proposed hypotheses. The corresponding empirical methods, the selection of sample, and the empirical results are presented in section 4, 5, 6, respectively. At last, in section 7 the conclusion is provided and the associated implications are discussed.

2. Prior Literature

The literature that studies the fluctuation of insurance prices mostly concentrates on discussing the market response to a capital/loss shock. Particularly, it is long known that there exists an underwriting cycle. The relevant literature already develops well-established theories in providing frameworks to explain the observed pricing dynamics, including probability updating (Lai et al., 2000), capacity constraint hypothesis (Winter, 1994; Gron, 1994), and risky debt hypothesis (Cummins and Danzon, 1997).

The fundamental framework is the economic theory between demand and supply, where the change in expectation for anticipated loss distribution after a capital/loss shock is the key (Lai et al., 2000). With an increase in expected losses, the demand of insurance increases and become more price inelastic. As a result, policyholders are willing to pay more for their coverage. Additionally, provided that the extra component of risk charge is also incorporated in the price, the higher variance and covariance induced by the shock can also drive price up.

The capital constraint theory (Winter, 1994; Gron, 1994) predicts that hard market occurs when demand is high relative to capital, whereas soft market occurs when capital is high relative to demand. The key assumptions underlying capital constraint theory is that insurers need to hold sufficient capital to lower their insolvency risk close to zero but holding and raising capital is costly. Yet, this theory limits insurers to be constrained by zero insolvency risk. Cagle and Harrington (1995) relax the assumption and consider the scenario when insolvency risk is endogenous. They show that when demand is inelastic, insurance price can also increase after a loss shock, but the magnitude is small.

Further, Cummins and Danzon (1997) develop a risky debt theory, in which demand for insurance is modeled an inverse function of insolvency put option. In this case, the market might react differently to different capital shocks considering the fact that buyers are concerned with insurers' financial quality. Particularly, the response of price depends on three factors: price elasticity of demand ($\partial Q/\partial p$), quality elasticity of demand ($\partial Q/\partial b$), and price elasticity with respect to quality ($\partial^2 Q / \partial p \partial b$). The pricing response is likely to be negative after a loss shock if the increase in insolvency risk makes the demand more price elastic, that is, when $\partial^2 Q / \partial p \partial b < 0$.

In terms of empirical methodology, Winter (1994) and Gron (1994) focus on industry-level time-series variation of insurance premiums. They both find negative relation between insurance prices and capital, in support of capital constraint theory. In contrast, Doherty and Garven (1995), Cummins and Danzon (1997), and Weiss and Chung (2004) concentrate on the firm-level story of pricing fluctuation. Doherty and Garven (1995) explore the relationship between changes in the level of underwriting profit and changes in interest rate. They find that interest rate fluctuation can affect pricing through surplus duration. Cummins and Danzon (1997) use a two-equation model to present the joint relationship between insurance prices and capital. In the first equation, price level is regressed on lagged capital, while in the second equation newly issued equity is regressed on change in price. Weiss and Chung (2004) test both capital constraint theory and risky debt theory by using a pooled cross-sectional, time series model, in which reinsurance price is regressed on both firm-specific capital, loss shock, and industry/world capacity. In their model, the capacity-constraint theory can be tested through a time series relationship, while the risky-debt model could explain the cross-sectional price variation across insurers. Different from previous literature, this paper aims to explicitly specify the sources of loss shocks and explore whether and how a loss shock affects line-specific prices.

3. Model and Hypotheses

Similar to Cummins and Danzon (1997), a one-period model with two dates (time 1 and time 2), where capital is endogenously determined, is studied. Differently, I extend the setting into a competitive insurance market consisting of two competing insurers so that the response of prices to different sources of shocks can be discussed.

3.1. The Model

Consider two rival insurers, insurer *i* and insurer *j*, competing with each other in the market. At time 1, taken the point of view of insurer *i*, the firm initially has assets A_1^i, preexisting liabilities (maturing at time 2) with a face value of L_1^i, and equity $A_1^i - L_1^i$. It is worth noting that here L_1^i represents the promised loss payments to policyholders without taking into account any possibilities of insurer *i*'s failure. Given the chance to default, the part of promised payments that is unable to be paid is $Max\left(0, L_1^i - A_1^i\right)$. That is, whenever the assets A_1^i falls below the liabilities L_1^i, insurer *i* defaults and policyholders can only receive A_1^i instead of L_1^i. In this case, the default value per dollar of liabilities can be modeled as a put option (Merton, 1974; Cummins and Danzon, 1997) as $b^i\left(x^i\right)$, where x^i is the asset-to-liability ratio. Thus, the value of preexisting liabilities adjusted for default risk at the beginning of the period is simply the riskless present value of promised payments less the insolvency put option, that is, $L_1^i\left[e^{-r\tau} - b_1^i\left(x_1^i\right)\right]$.

Meanwhile at time 1, insurer *i* makes decisions on issuing new equities E_2^i and new policies Q^i (also maturing at time 2) with price p_2^i.[1] Accordingly, right after the issuance the assets of insurer *i* becomes $A_1^i + A_2^i = A_1^i + \left(E_2^i + p_2^i Q^i\right)$ and the value of liabilities adjusted for default risk $\left(L_1^i + Q^i\right)\left[e^{-r\tau} - b^i\left(x^i\right)\right]$.

By applying the put-call parity, the values of equity adjusted for default risk right before and after the issuance of new equity and policies at time 1 are, respectively,

$$C_1^i = A_1^i - L_1^i\left[e^{-r\tau} - b_1^i\left(x_1^i\right)\right] \tag{1}$$

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[1] Here, the lines of business are not specified for simplicity. Yet, the results still hold if the lines of business are specified in the model.

$$C_2^i = \left(A_1^i + A_2^i\right) - \left(L_1^i + Q^i\right)\left[e^{-r\tau} - b^i\left(x^i\right)\right]$$
$$= \left[A_1^i + \left(E_2^i + p_2^i Q^i\right)\right] - \left(L_1^i + Q^i\right)\left[e^{-r\tau} - b^i\left(x^i\right)\right] \quad (2)$$

where $x_1^i = A_1^i / L_1^i$,

$x^i = \left(A_1^i + A_2^i\right) / \left(L_1^i + Q^i\right) = \left(A_1^i + E_2^i + p_2^i Q^i\right) / \left(L_1^i + Q^i\right)$,

$r =$ risk-free rate,

$\tau =$ time until expiration of the policies; here, $\tau = 1$.

More importantly, by taking into account the competitive dynamics between two insurers, I specify the demand function of insurer *i*'s newly issued policies, Q^i, with a set of assumptions. First, Q^i is a decreasing and concave function of insurer *i*'s own price p_2^i and own insolvency put option $b^i\left(x^i\right)$. Intuitively, as the price offered by insurer *i* increases, its own demand is reduced. The more the price increases, the more the demand is weakened. The same applies to the insolvency put option of insurer *i*. Second, Q^i is an increasing and convex function of competitor *j*'s price p_2^j and its insolvency put option $b^j\left(x^j\right)$. That is, a higher price offered by competitor *j* helps increase insurer *i*'s demand. The greater competitor *j* increases its price, the more insurer *i*'s demand is strengthened. The same relationship holds between Q^i and the insolvency put option of competitor *j*. Third, Q^i is more sensitive to the price change and insolvency risk change of insurer *i* itself than to those of competitor *j* in absolutely values at any points. Fourth, an increase in competitor *j*'s insolvency risk would make insurer *i*'s demand less sensitive to the change in its own insolvency risk. Similarly, an increase in insurer *i*'s insolvency risk would also lower the sensitivity of its own demand to competitor *j*'s insolvency risk. The last but not the least, a positive competitor reaction sensitivity is expected. Simply put, after observing a decrease in insurer *i*'s price, competitor *j* has an incentive to defend its market share by responding with lowering price as well. Putting together,

(a) $Q_p^i < 0,\ Q_{pp}^i < 0;\ Q_b^i < 0,\ Q_{bb}^i < 0$;

(b) $Q_{p^j}^i > 0,\ Q_{p^j p^j}^i > 0;\ Q_{b^j}^i > 0,\ Q_{b^j b^j}^i > 0$;

(c) $\left|Q_p^i\right| > \left|Q_{p^j}^i\right|,\ \left|Q_b^i\right| > \left|Q_{b^j}^i\right|,\ \left|Q_{pp}^i\right| > \left|Q_{p^j p^j}^i\right|,\ \left|Q_{bb}^i\right| > \left|Q_{b^j b^j}^i\right|$;

(d) $Q_{bb^j}^i > 0,\ Q_{b^j b}^i < 0$;

(e) $\dfrac{\partial p_2^j}{\partial p_2^i} > 0$;

where $Q_p^i,\ Q_b^i,\ Q_{p^j}^i,\ Q_{b^j}^i = \partial Q^i / \partial p_2^i, \partial Q^i / \partial b^i, \partial Q^i / \partial p_2^j, \partial Q^i / \partial b^j$, respectively,

$Q_{pp}^i,\ Q_{bb}^i,\ Q_{p^j p^j}^i,\ Q_{b^j b^j}^i = \dfrac{\partial^2 Q^i}{\partial \left(p_2^i\right)^2}, \dfrac{\partial^2 Q^i}{\partial \left(b^i\right)^2}, \dfrac{\partial^2 Q^i}{\partial \left(p_2^j\right)^2}, \dfrac{\partial^2 Q^i}{\partial \left(b^j\right)^2}$, respectively,

$Q_{bb^j}^i,\ Q_{b^j b}^i = \partial Q_b^i / \partial b^j, \partial Q_{b^j}^i / \partial b$, respectively.

Following Cummins and Danzon (1997), the objective of insurers is to maximize the value added to equity such that the issuance of new equity and policies at time 1 is for the best interest of both old and new stockholders as well as old and new policyholders. That is,

$$\underset{p_2^i,\ E_2^i}{Max}\ C_2^i - \left(E_2^i + C_1^i\right) = Q^i \cdot \left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + L_1^i\left[b^i\left(x^i\right) - b_1^i\left(x_1^i\right)\right] \tag{3}$$

The first order conditions with respect to the price of new policies p_2^i and the newly issued equity E_2^i for this maximization problem are, respectively,

$$\begin{aligned}&\left\{Q^i + \left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\right\} \\ &\qquad + \left\{Q_b^i\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + Q^i + L_1^i\right\} b_x^i x_p^i = 0\end{aligned} \tag{4}$$

$$\left\{Q_b^i\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + Q^i + L_1^i\right\} b_x^i x_e^i = 0 \tag{5}$$

where $b_x^i,\ x_p^i,\ x_e^i = \partial b^i / \partial x^i, \partial x^i / \partial p_2^i, \partial x^i / \partial E_2^i$, respectively,

$b_x^j,\ x_p^j,\ x_e^j = \partial b^j / \partial x^j, \partial x^j / \partial p_2^j, \partial x^j / \partial E_2^j$, respectively.

Equation (4) explicitly shows how competitor *j*'s reaction and its effect on insurer *i*'s demand are simultaneously considered in determining the optimal price of insurer *i*. More specifically, I can define the overall effect of insurer *i*'s price change on its demand after taking into account the competitive factors as:

$$\frac{dQ^i}{dp_2^i} = Q_p^i + \left(Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} \right) = \frac{-Q^i}{p_2^i - e^{-r\tau} + b^i\left(x^i\right)} < 0 \tag{6}$$

The two terms in parentheses from equation (6) represent the competitive effects from competitor *j*'s reaction in response to insurer *i*'s initial action in price change. The intuition is after observing a decrease in insurer *i*'s price, competitor *j* would also tend to lower its price to keep some of its customers. However, in this way competitor *j* also sacrifices the opportunity to further strengthen its solvency level through charging high price from newly issued policies. It is worth noting that the only difference between a monopolistic market and a competitive market lies exactly in the two terms.[2] Nevertheless, it is easy to find that the sign of the overall effect from equation (6) is negative, consistent with the sign of Q_p^i.[3] It makes sense that the competitive effect from competitor *j* only moderates the main effect from own price sensitivity of demand Q_p^i.

Based on the optimal solutions from equation (4) and (5), next three major questions are analyzed: (a) How does the optimal price of insurer *i* respond to competitor *j*'s retroactive loss shocks? (b) How does the optimal price of insurer *i* respond to its own retroactive loss shocks? (c)

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[2] Since Cummins and Danzon (1997) do not consider any competitive elements, in their paper $dQ^i / dp_2^i = Q_p^i$.

[3] By rearranging equation (4) and equation (5), it is easily seen that

$$Q_p^i + \left(Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} \right) = \frac{-Q^i}{p_2^i - e^{-r\tau} + b^i\left(x^i\right)} < 0 .$$

How does the response of price differ for idiosyncratic shocks that only affects one insurer and industry-level shocks that are correlated between two insurers?

3.2. Response of Price to Competitor's Loss Shocks

Assuming a retroactive loss shock increases the face value of competitor *j*'s preexisting liabilities L_1^j, insurer *i*'s optimal price change in response to the loss shock is:

$$\frac{\partial p_2^i}{\partial L_1^j} = \frac{Q_{b^j}^i + \left[Q_{pb^j}^i + \frac{\partial p_2^j}{\partial p_2^i} \left(Q_{p^j b^j}^i + Q_{b^j b^j}^i b_x^j x_p^j \right) \right] \left[p_2^i - e^{-r\tau} + b^i \left(x^i \right) \right]}{-D \big/ b_x^j x_{L_1}^j} \tag{7}$$

where $D =$ the second derivatives of the objective function with respect to insurer *i*'s price p_2^i; to ensure there exists a local maximum, it is required that $D < 0$.

The expression suggests that competitor *j*'s loss shocks could possibly influence insurer *i*'s price. Also, the direction of the response depends on how an increase in competitor *j*'s insolvency risk following the shock affects insurer *i*'s own price sensitivity and cross price sensitivity from competitor *j*.[4] Suppose the loss shock only threatens the financial quality of competitor *j*, it is more likely that insurer *i*'s demand would become less sensitive to its own price change, but more sensitive to competitor *j*'s price change (that is, $Q_{pb^j}^i > 0$ and $Q_{p^j b^j}^i > 0$). In this case, a positive relationship between insurer *i*'s price and competitor *j*'s loss shock is expected, or $\partial p_2^i / \partial L_1^j > 0$. Intuitively, concerned about the credibility of insurer *j* to payoff the promised loss payments following the shock, insurer *j*'s policyholders would prefer to reenter the market and buy the same policies from insurer *i* for its better financial quality. Given the advantage, insurer *i* could easily increase its prices without being worried about losing customers.

Interestingly, this prediction implies that even if a loss shock is irrelevant to an insurer at

[4] In equation (7), the only terms whose signs are uncertain are $Q_{pb^j}^i$ and $Q_{p^j b^j}^i$.

all, its insurance prices of any lines would increase as long as the shock only dampens the financial strength of its competitors. Inspired by the same idea, the following hypothesis is proposed and empirically tested:

Hypothesis 1: For an insurer who *only* write liability lines, the liability-line prices would increase following an industry-wide property-line shock.

3.3. Response of Price to Own Loss Shocks

Assuming a retroactive loss shock increases the face value of insurer *i*'s preexisting liabilities L_1^i, the optimal price change in response to its own loss shock is:

$$\frac{\partial p_2^i}{\partial L_1^i} = \frac{\frac{dQ^i}{dp_2^i} + Q_b^i + \left[Q_{pb}^i + \frac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b}^i + Q_{b^i b}^i b_x^j x_p^j \right) \right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i \right) \right]}{-D / b_x^i x_{L_1}^i} \tag{8}$$

Similar to the discussion in subsection 3.2, the response of insurer *i*'s price to its own loss shock depends on how an increase in its own insolvency risk affects insurer *i*'s own price sensitivity and cross price sensitivity from competitor *j*, according to equation (8).[5] Specifically, if the loss shock only threatens the financial quality of insurer *i*, it is more likely that insurer *i*'s demand would become more sensitive to its own price change, but less sensitive to competitor *j*'s price change. That is, $Q_{pb}^i < 0$ and $Q_{p^j b}^i < 0$. Consequently, a negative relationship between insurer *i*'s price and its own loss shock is expected, or $\partial p_2^i / \partial L_1^i < 0$, which is consistent with the prediction in Cummins and Danzon (1997). The intuition corresponds to the competitive disadvantage from being financially weakened following the loss shock. As a result, a lower price can only be offered.

Noticeably, the key here is how a loss shock changes an insurer's insolvency risk.

[5] In equation (8), the only terms whose signs are uncertain are Q_{pb}^i and $Q_{p^j b}^i$.

Therefore, even if a shock is directly relevant to the business line written by an insurer, as long as the financial quality of the firm is unaffected by the shock, the insurance prices from that line would not change. Accordingly, the following two hypotheses are proposed:

Hypothesis 2: The response of the liability-line prices to a firm-level liability shock is stronger for insurers who *only* write liability lines.

Hypothesis 3: For insurers who write both liability and other lines, a liability-line shock that does not threaten the financial quality would not affect their liability-line prices.

It is worth noting that hypothesis 3 can potentially be used to test for the difference with the theory of expectation changes by Lai et al. (2000), under which as long as the expected losses and risk premiums increase following a loss shock, the insurance prices are expected to rise, no matter the firm's financial quality is affected or not.

3.4. Response of Price to Industry-Wide Shocks

Now let's assume a retroactive loss shock is correlated between insurer *i* and insurer *j*. The financial qualities of both insurers are threatened simultaneously by the same shock. Again, the response of price depends on how it affects insurer *i*'s own price sensitivity and cross price sensitivity from competitor *j*. In this case, the sign of the response is ambiguous as it is difficult to predict how sensitive the demand becomes to both insurers' price change. As in equation (7), if insurer *i*'s demand becomes less sensitive to competitor *j*'s price change (that is, $Q^i_{p^j b^j} < 0$) and the change is strong enough, a different and negative relationship is also possible from equation (7). Similarly, in equation (8) if Q^i becomes less sensitive to its own price change (that is, $Q^i_{pb^j} > 0$), a different and positive relation is also possible in an extreme case. Taken together, I propose the following hypothesis:

Hypothesis 4: Insurance prices decrease following any type of firm-level idiosyncratic shocks, as long as the shock threatens the financial quality of the firm. Differently, the response of the prices to an industry-wide shock is ambiguous.

4. Empirical Analysis

To test for the response of line-specific prices to loss shocks from different sources, I need to empirically distinguish (a) the shocks from different business lines; and (b) idiosyncratic loss shocks and industry-wide shocks. Accordingly, I estimate a bootstrapped regression model in a firm-year level as the following:

$$\begin{aligned} P_{i,t} = {} & I^{Liability-only}\begin{pmatrix} \theta_1 Ind.\ Property\ Shock_{t-1} + \theta_2 Ind.\ Liability\ Shock_{t-1} \\ +\beta_1 Res.\ Firm\ Shock_{i,t-1} + \phi_1 X_{t-1} + \phi_2 Y_{i,t-1} \end{pmatrix} \\ & + I^{Liability\&other}\begin{pmatrix} \tilde{\theta}_1 Ind.\ Property\ Shock_{t-1} + \tilde{\theta}_2 Ind.\ Liability\ Shock_{t-1} \\ +\tilde{\beta}_1 Res.\ Firm\ Shock_{i,t-1} + \tilde{\beta}_2 Res.\ Liability\ Shock_{i,t-1} \\ +\tilde{\phi}_1 X_{t-1} + \tilde{\phi}_2 Y_{i,t-1} \end{pmatrix} + \varepsilon \end{aligned} \quad (9)$$

where $P_{i,t}$ = the liability-line prices of insurer *i* at time *t*, defined as the ratio of premium written to present value of incurred losses (inverse loss ratio);[6]

$Ind.\ Property\ Shock_{t-1}, Ind.\ Liability\ Shock_{t-1}$ = industry-level property-line shock and liability-line shock, respectively, defined as the industry-level one-year loss reserve development for losses incurred in years prior to time *t*-1;

$Res.\ Firm\ Shock_{i,t-1}$ = the idiosyncratic shock that is not induced by any industry-level shocks, which is estimated as the residual from regressing firm-level loss reserve adjustment on industry-level loss reserve adjustment;

$Res.\ Liability\ Shock_{i,t-1}$ = the firm-level liability-line-specific shock that does not affect the financial quality of insurer *i* at time *t*-1, which is estimated as the residual from regressing firm-

[6] The incurred losses here also include defense and cost containment expense incurred.

level liability-line loss reserve adjustment on firm-level loss reserve adjustment;[7]

$I^{Liability-only}$ = a dummy variable equal to 1 for an insurer who only write liability lines, and 0 otherwise;

$I^{Liability\&other}$ = a dummy variable equal to 1 for an insurer who write both liability lines and other lines, and 0 otherwise;

X_{t-1} = industry-level variables at time *t*-1;

$Y_{i,t-1}$ = insurer-specific variables of insurer *i* at time *t*-1;

Also, firm fixed effects are included to control for unobserved firm characteristics. As there exist industry-level variables in the regression (9) that only vary by time, year fixed effects are not included for the concern of multicollinearity.

There are two major advantages to use this regression model. First, by interacting all variables with both $I^{Liability-only}$ and $I^{Liability\&other}$ in the same regression, I can easily compare the coefficients of interest from the two different samples directly using Wald tests. Second, I do not need to worry about the small sample problem from having comparatively small observations for insurers who only write liability lines.

As a major variable, the retroactive loss shock is a continuous measure defined as the one-year loss reserve development for losses incurred in years prior to time *t*-1, following Cummins and Danzon (1997) and Weiss and Chung (2004). More specifically, this shock variable can be decomposed from the surplus variable as:

$$Surplus_{t-1} = Surplus_{t-2} + New\ External\ Capital_{t-1} + New\ Internal\ Capital_{t-1} - Retroactive\ Loss\ Shock_{t-1} \quad (10)$$

[7] In the liability-only sample, no firm-level line-specific shock is included as every liability shock is firm-level shock.

where *New External Capital* is estimated as the capital paid in minus dividends.[8] *New Internal Capital* is the sum of underwriting income (net of company retroactive loss shock), investment income, other income, and other changes in surplus. All variables in equation (10) are all scaled by prior year liability. The use of loss reserve adjustments as the measure of loss shocks can be justified in the sense that any adjustments in reserves do affect the risk level of insurers. Therefore, from the perspective of signifying the financial quality of insurers, loss reserve adjustments are indeed usable.

Except for industry-level loss shocks, there are two other variables that only vary by time in the regression model, including relative capacity (Winter, 1994; Gron, 1994) and the change in interest rate (Doherty and Garven, 1995). More specifically, $\textit{Relative Capacity}_{t-1}$ is measured as total surplus in year *t*-1 divided by the 5-year average value of surplus from *t*-6 to *t*-2 (Winter, 1994).[9] Moreover, the firm-specific variables included in regression (9) are surplus scaled by prior-year total liability, size, and a financial rating indicator equal to one if the insurer has an A.M. best rating of A or higher. Additionally, a reinsurance usage variable is included, defined as the ratio of reinsurance premiums cede relative to the sum of direct premiums written and reinsurance premiums assumed.

To further verify the prediction of the model, I exploit a policy change – the enactment of tort reforms at state level – as a natural experiment. Tort reforms involves a change in U.S. legal system that either lowers the damages that can be received by the victim or reduces the ability for them to bring tort litigation into courts. This results in an exogeneous decrease in the insurance costs of liability lines.

In this case, under hypothesis 1, insurers who only write property lines in states that adopt

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[8] Specifically, capital paid in is measured by capital changes and surplus adjustments in the statement of income page of *NAIC* annual statement.

[9] Surplus is inflation adjusted using CPI in each year to make them comparable.

tort reforms would expect their competitors who also write liability lines to be less affected by an industry-wide liability loss shock. Thus, their property-lines prices are expected to increase less. Also, if a firm-level liability-line-specific shock that does not dampen the financial quality of the firm is expected not to affect liability-line prices, as in hypothesis 3, we do not expect any significant differences in price change following the shock for insurers in states that enact tort reforms and in states that do not. Given hypothesis 4, it is expected that tort reforms help insurers become less prone to insolvency risk after an idiosyncratic loss shock. Therefore, when observing the same level of default probability, policyholders in states with tort reform may view it as a worse signal, which consequently becomes more sensitive to price change. That is, the demand becomes even more price elastic in states with tort reform in response to the same level of increase in insolvency risk. Thus, price may decrease more in states that enact tort reform following the same level of idiosyncratic loss shock.

Accordingly, I estimate a firm-state-year level regression as:

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\begin{aligned}
P_{i,s,t} = {} & I^{Liability-only}\begin{pmatrix} \theta_1 Ind.\ Property\ Shock_{t-1} + \theta_2 Ind.\ Liability\ Shock_{t-1} \\ +\beta_1 Res.\ Firm\ Shock_{i,t-1} + \beta_1' Res.\ Firm\ Shock_{i,t-1} \times TortReform_{s,t-1} \\ +\phi_1 X_{t-1} + \phi_2 Y_{i,t-1} + \phi_3 Z_{s,t-1} \end{pmatrix} \\
& + I^{Liability\&other}\begin{pmatrix} \tilde{\theta}_1 Ind.\ Property\ Shock_{t-1} + \tilde{\theta}_2 Ind.\ Liability\ Shock_{t-1} \\ +\tilde{\beta}_1 Res.\ Firm\ Shock_{i,t-1} + \tilde{\beta}_1' Res.\ Firm\ Shock_{i,t-1} \times TortReform_{s,t-1} \\ +\tilde{\beta}_2 Res.\ Liability\ Shock_{i,t-1} + \tilde{\beta}_2' Res.\ Liability\ Shock_{i,t-1} \times TortReform_{s,t-1} \\ +\tilde{\phi}_1 X_{t-1} + \tilde{\phi}_2 Y_{i,t-1} + \tilde{\phi}_3 Z_{s,t-1} \end{pmatrix} + \varepsilon
\end{aligned} \quad (11)
$$

where $TortReform_{s,t-1}$ = an index equal to 0, 1, 2, 3, 4, indicating the number of 4 major types of tort reforms enacted in state *s* at time *t*-1; the 4 major types of tort reforms are reforms to joint and several liability, the collateral source rule, punitive damage caps, and non-economic damage caps;

X_{t-1} = industry-level variables at time *t*-1;

$Y_{i,t-1}$ = insurer-specific variables of insurer *i* at time *t*-1;

$Z_{s,t-1}$ = state-level variables in state *s* at time *t*-1.

Firm-state fixed effects are also included to control for unobserved characteristics.

Here, the variables used to capture state time-varying characteristics are the logarithm of gross state capita (GSP) per capita, the logarithm of income per capita, the proportion of insurance GSP to total GSP, and the proportion of insurance employment to total state population. To control for the market competition, the market-share (direct premiums written) Herfindahl index in each state is estimated and included as a state-specific variable.

More importantly, I also include a variable indicating state rate regulation stringency. Mello (2006) provides a case study of California where both prior-approval rate regulation and caps on non-economic damages were adopted and shows that it could be difficult to separate their effects on premiums. Meanwhile, it is mentioned that the effect of rate regulation also depends on how stringently the insurance commissioners exercise the regulation to disapprove rate changes. Since I look at the overall price level of insurers who write liability lines in equation (1), following Grace and Leverty (2012) I create a variable (*%Reg*), defined as the proportion of premiums written in business lines under stringent rate regulation, to capture the overall rate stringency level in a certain state. That is,

$$\%Reg_{st} = \frac{\sum_{il} PremiumsWritten_{istl} * StringentRegLaw_{stl}}{\sum_{il} PremiumsWritten_{istl}} \tag{5}$$

where $PremiumsWritten_{istl}$ = direct premiums written for firm *i*, at time *t*, in line *l*, operating in states *s*;

$StringentRegLaw_{stl}$ = a dummy variable equal to 1 if state *s* has a stringent rate regulation law that is applied to line *l* at time *t*, and 0 otherwise.

Based on Harrington (2002), a stringent rate regulation is defined as state-made rates, a prior approval law, or a file-to-use law that required prior approval of deviations. A non-stringent rate regulation law is defined as file-and-use, use-and-file, filing only, or flex rating with a large flex band.

5. Data and Sample

Data for the insurers' sample is obtained from *NAIC* over the period of 1997 to 2016. Specifically, I only focus on active insurers who write liability lines.[10] The Insurance Expense Exhibit is used to collect data on premiums earned and incurred losses at the firm level, and the Exhibit of Premiums and Losses (State Page) at the firm-state-level. The firm retroactive loss shock is estimated using the loss reserve data from Schedule P – Part 2 Summary, and liability-line retroactive loss shock estimated from Part 2B, 2C, 2D, 2F-Section 1, 2F-Section2, 2H-Section 1, 2H-Section2, 2R-Section 1 and 2R-Section2. The aggregated data is used for the measurement of industry retroactive loss shock. *A.M. Best Aggregate & Average* Schedule P – Part 3 is applied to estimate payout tails using chain-ladder method. The associated estimated future payments are discounted with U.S. Treasury yields from the *Federal Reserve Bank of St. Louis* (FRED). The A.M. best ratings and insurer's market type information is obtained from *A.M. Best Key Rating Guide*.

More importantly, the tort reform information is collected from *Database of State Tort Law Reforms* (Avraham, 2014; DSTLR 5th), which covers the period of 1980 to 2012. To match my sample period from 1997 to 2016, I update the tort reform database using the *Tort Reform Record* published by *American Tort Reform Association* (*ATRA*). Additionally, the state-level data is

[10] The liability lines include private passenger auto liability, commercial auto liability, workers' compensation, medical professional liability, other liability, and products liability. According to *NAIC*, active insurers include (1) conservatorship, (2) no regulatory action in process, (3) rehabilitation, permanent or temporary receivership, (4) being liquidated or has been liquidated; inactive insurers are those (1) merged or combined into another company, (2) voluntarily out of business, (3) estate has closed, (4) charter is inactive, (5) combined statement filer.

collected from *Bureau of Economic Analysis*. The rate regulation details are obtained and checked through *WestLaw*, where has a category of insurance regulation classified by states.

To ensure some of the variables to be estimated, insurers are required to operate for at least three-year consecutive years.[11] In each state, insurers with non-positive total admitted asset, liability, surplus, direct premium written, premium earned, and losses incurred are eliminated. Insurers that ceded all premiums to reinsurers are also excluded. In order to make sure the insurers to play a non-trivial role in the market, only the firms with at least 0.1 percent market share of premium written in liability lines are included.[12] After the data screening, the final sample consists of 3,525 firm-year observations and 77,232 firm-state-year observations.

Table 1 reports the summary statistics of all variables. At the firm level, the mean liability-line price is \$1.61 for each dollar expected to be paid to policyholders with a standard deviation of \$1.57. Comparatively, the mean liability-line price at the firm-state level, \$2.18, is slightly higher, and relatively more volatile with a standard deviation of \$1.63. The total surplus in each year is on average slightly higher than the average prior-five-year surplus after deflation by CPI. The mean industry retroactive loss shock is shown to be negative, indicating that insurers generally adjust loss reserve for losses from prior years downward. Comparing liability-line retroactive loss shock and property-line retroactive loss shock, the former is on average smaller although much more volatile. The high volatility is consistent with the documented greater reserving errors in liability lines due to their longer payout periods.

In terms of state-level insurance market, the rate regulation stringency is about 33%, while for liability lines the rate regulation seems to be more stringent at 37%. Also, the state market is

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[11] For example, liability at time *t*-3 is needed to normalize $Surpus_{t-2}$ in equation (6).

[12] Both Cummins and Danzon (1997) and Weiss and Chung (2004) require firms to have at least 0.5 percent market share. The 0.1 percent market share screening requirement is conducted instead of the 0.5 percent market share because there are only two firms covered in the insurer sample who only writes liability lines. Nevertheless, the results still hold for at least 0.5 percent market share requirement.

highly competitive with an average market share HHI index smaller than 0.1.

6. Results

Table 3 presents the response of liability-line price to loss shocks from different sources. Consistent with hypothesis 1, for insurers who only write liability lines, their liability-line prices do increase significantly following an industry-wide property-line loss shock. It appears that they do indeed benefit from being financially sound and are able to charge higher prices for being unaffected by the shock. Consistent with hypothesis 2, the response to firm-level liability shocks are stronger for those who only write liability lines. However, different from the prediction in hypothesis 3, the liability-line-specific shock that does not affect the financial quality of the firm seems to still influence the liability-line prices negatively, although the significance level is weak. It is possible that despite the fact that the line-specific shock does not change the insolvency risk of the firm, the adjustments in loss reserve still imposes doubts to policyholders on the credibility for the insurer to pay off the promised payments in the future, thus leads to a negative effect. Consistent with hypothesis 4, following any type of idiosyncratic loss shocks the liability-lines prices decrease significantly, while the response to industry-level loss shocks is uncertain, either positive or statistically insignificant.

Now let's turn to Table 4 and Table 5, in which the states that adopt tort reforms are used as a treatment group. Following an industry-wide liability loss shock, expecting their competitors to be less affected in states that enact tort reforms, the insurers who only write property lines increase their property-line prices less as predicted. Also, it is shown that there is no significant difference in the price change in states that adopt tort reforms and in those that do not, following a firm-level line-specific liability shock that does not increase the insolvency risk of the firm. Further, tort reforms are shown to significantly strengthens the negative effect of an idiosyncratic retroactive loss shock. This is consistent with the prediction that as the insolvency risk increases by the same level, policyholders in states with tort reform become more sensitive to price change after an idiosyncratic loss shock. Taken together, I find evidence in support of all four hypotheses proposed in the paper. As long as a loss shock threatens the financial quality of the insurers, it could possibly affect not only the insurance prices under the same line, but also the prices of other lines as well as the prices of other insurers competing in the markets.

7. Conclusion

This paper investigates under what circumstances would a loss shock affect the line-specific prices in competitive markets. Specifically, three major questions are discussed: (a) Does a loss shock have to be relevant to the lines written by an insurer to affect insurance prices? (b) Would every loss shock affect the line-specific prices if it is directly relevant to the lines or the firm? (c) Does and when would a loss shock affect all? Aiming at answering these questions, a simple theoretical model in the presence of market competition is built to analyze how the line-specific prices are affected by loss shocks from different sources. The prediction of the model shows that the key factor for a loss shock to influence insurance prices is through the change in the insolvency risk of the insurers. That is, one shock does affect all as long as a retroactive loss shock threatens the financial quality of insurers. It could not only affect the prices from the same line, but also the prices of other lines under the same firm as well as the prices of other competing insurers in the market. More interestingly, even if one insurer only writes liability lines, an industry-level property shock would increase their liability-line prices.

This paper differs from relevant literature by trying to specify the impact of different shocks on insurance prices. The underlying message is that the financial quality of insurers is the main factor in explaining the pricing dynamics following loss shocks from different sources.

A few implications are worth mentioning. First, by extending the lines of business to different geographies, it is easy to generalize the results to the effects of reginal shocks. That is, a reginal shock that threatens the financial quality of insurers could also possibly influence the insurance prices in other regions. Second, as liability-line loss shocks are likely to affect the prices in property lines, the enactment of tort reforms could also possibly affect the insurance prices in property lines as tort reforms moderates the magnitude of liability costs brought by a liability-line shock. Third, although only loss shocks are discussed in this paper, those shocks from asset sides seem to be a more exogenous channel to test for this financial quality story. A further discussion on this aspect will become the development of this paper in the next step.

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Table 1
Summary Statistics: 1997-2016

Variable	Mean	Median	Std. Dev.	Min	Max
Firm-State-Level Variables					
Liability-Line Price	2.1777	1.6334	2.2437	0.3506	17.4898
Industry-Level Variables					
Relative Capacity$_{t-1}$	1.1253	1.1083	0.1435	0.8554	1.3996
Industry Shock$_{t-1}$/Total Liability$_{t-2}$	-0.0037	-0.0075	0.0139	-0.0194	0.0343
Industry Liability Shock$_{t-1}$/Total Liability$_{t-2}$	-0.0010	-0.0039	0.0097	-0.0164	0.0208
Industry Property Shock$_{t-1}$/Total Liability$_{t-2}$	-0.0028	-0.0024	0.0008	-0.0039	-0.0008
ΔInterest Rate$_{t-1}$	-0.0028	-0.0009	0.0113	-0.0270	0.0173
Firm-Level Variables					
Liability-Line Price	1.6123	1.5730	0.4002	0.6997	3.5720
Surplus$_{t-1}$/Liability$_{t-2}$	0.8953	0.6080	1.0971	0.1416	8.7852
Surplus$_{t-2}$/Liability$_{t-3}$	1.3557	0.6137	4.1139	0.1454	37.5593
New External Capital$_{t-1}$/Liability$_{t-2}$	0.0047	0	0.1203	-0.3334	0.7962
New Internal Capital$_{t-1}$/Liability$_{t-2}$	0.0374	0.0353	0.1228	-0.4311	0.6134
Company RL Shock$_{t-1}$/Liability$_{t-2}$	-0.0136	-0.0120	0.0587	-0.1997	0.2119
Company LRL Shock$_{t-1}$/Liability$_{t-2}$	-0.0093	-0.0068	0.0532	-0.1892	0.1987
Size$_{t-1}$	19.0931	19.0255	1.7246	15.4993	23.7946
Reinsurance$_{t-1}$	0.4089	0.3723	0.3007	0	0.9884
A.M. Best Rating$_{t-1}$	0.5381	1	0.4986	0	1
Line-HHI$_{t-1}$	0.4615	0.3776485	0.2763	0	1
State-Level Variables					
Liability-Line %Reg	0.3767	0.2340	0.3631	0	1
All-Line %Reg	0.3289	0.1108	0.3673	0	0.9862
Liability-Line Competition	0.0241	0.0212	0.0125	0.0091	0.1859
All-Line Competition	0.0217	0.0206	0.0079	0.0084	0.0836
GSP Per Capita	4.6791	4.3658	1.7927	2.5363	17.0723
Income Per Capita	3.8182	3.6920	0.7547	2.2667	6.8838
Insurance GSP	2.6224	2.0660	1.8812	0.5469	15.3172
Insurance Employment	0.9752	0.9009	0.3225	0.3548	2.2182

Notes: The final sample has 18,193 firm-year observations and 120,790 firm-state-year observations. All variables are winsorized at 1th and 99th percentiles. *Liability-Line Price* is the price of liability lines, defined as premium earned divided by the present value of losses incurred; liability lines defined in this paper include private passenger auto liability, commercial auto liability, workers' compensation, medical professional liability, other liability, and products liability; *Liability-Line Market Share* is the proportion of direct premiums written in one state-level market; *Relative Capacity* is total surplus of insurers in each year divided by the 5-year prior average value of surplus; *New External Capital* is the capital paid in minus dividends; *New Internal Capital* is the sum of underwriting income (net of company retroactive loss shock), investment income, other income, and other changes in surplus; *Company RL* (*Retroactive Loss*) $Shock_{t-1}$ is the increase (between time *t*-2 and *t*-1) in reserves for losses incurred in years < *t*-1; *Company LRL* (*Liability-line Retroactive Loss*) $Shock_{t-1}$ is the increase (between time *t*-2 and *t*-1) in reserves of liability lines for losses incurred in years < *t*-1; *Company ORL* (*Other-line Retroactive Loss*) $Shock_{t-1}$ is the difference between *Company RL* $Shock_{t-1}$ and *Company LRL* $Shock_{t-1}$; *Size* is the natural logarithm of total admitted assets; *Reinsurance* is defined as the ratio of reinsurance premiums cede relative to the sum of direct premiums written and reinsurance premiums assumed; *A.M. Best Rating* is a dummy variable equal to one if the insurer has an A.M. best rating of A or higher, and zero otherwise; *Liability-Line %Reg* is the proportion of direct premiums written in liability lines under stringent rate regulation (state-made rates, a prior approval law, or a file-to-use law that required prior approval of deviations) in each state; *All-Line %Reg* is the proportion of premiums written in all lines under stringent rate regulation (state-made rates, a prior approval law, or a file-to-use law that required prior approval of deviations) in each state; *Liability-Line Competition* is liability-lines market share (direct premiums written) Herfindahl index in each state; *All-Line Competition* is all-line-market-share Herfindahl index in each state; *GSP Per Capita* is annual gross domestic product divided by state population in each state, scaled by 10,000; *Income Per Capita* is the annual total personal income divided by state population in each state, scaled by 10,000; *Insurance GSP* is annual insurance gross domestic product divided by total gross domestic product in each state, multiplied by 100; *Insurance Employment* is the number of employment in insurance carriers, agents, brokers, and services in each state divided by total state population, multiplied by 100.

Table 2
Summary of Tort Reforms: 1997-2016

	Caps on Punitive Damages				Caps on Noneconomic Damages			
Year	Enacted		Newly Enacted	Repealed	Enacted		Newly Enacted	Repealed
1997	22	CO, FL, GA, IL, KS, LA, MI, NE, NV, NH, ND, OR, TX, VA, WA, WI, IN, NJ, NC, OK, OH, PA			19	AK, CA, CO, HI, ID, KS, MD, MA, MI, MO, OR, UT, WV, IL, WI, MT, ND, SD, OH		
1998	22		AK	OH	17			IL, OH
1999	22				17			
2000	23		AL		17			
2001	23				16			OR
2002	23				16			
2003	25		AR, MS		20		FL, MS, NV, OH	
2004	27		ID, MT		22		OK, TX	
2005	28		OH		23		GA	
2006	29		MO		25		IL, SC	
2007	29				25			
2008	29				25			
2009	29				25			
2010	29				24			IL
2011	29				24			
2012	31		SC, TN		26		NC, TN	
2013	31				26			
2014	31				26			
2015	32		WV		26			
2016	32				26			

	Modifications to Joint and Several Liability				Reforms to the Collateral Source Rule			
Year	Enacted		Newly Enacted	Repealed	Enacted		Newly Enacted	Repealed
1997	37	AK, AZ, CA, CO, CT, FL, GA, HI, ID, IA, KS, KY, LA, MI, MN, MS, MO, MT, NE, NH, NJ, NM, NY, ND, OK, OR, SD, TN, TX, UT, VT, WA, WV, WY, WI, IL, OH			30	AK, AZ, CA, CO, CT, DE, FL, HI, ID, IL, IN, IA, ME, MA, MI, MN, MT, NE, NV, NJ, NY, ND, OH, OR, RI, SD, TN, UT, WA, WI		
1998	35			IL, OH	29			OH
1999	35				29			
2000	35				29			
2001	35				30		AL	
2002	36		PA		32		OH, PA	
2003	38		AR, NV		33		WV	
2004	38				34		OK	
2005	38				34			
2006	38		SC	PA	34			
2007	38				34			
2008	38				34			
2009	38				34			
2010	38				34			
2011	39		PA		34			
2012	39				34			
2013	39				34			
2014	39				34			
2015	39				34			
2016	39				34			

Table 3
Response of Liability-Line Prices to Loss Shocks: 1997-2016

	Dependent Variable: Liability-Line Prices					
	Insurers Who *Only* Write Liability Lines			Insurers Who Write Liability & Other Lines		
	(1)	(2)	(3)	(1)	(2)	(3)
Industry Property Shock$_{t-1}$	668.77***	659.23***	682.45***	52.25	59.73**	54.25**
Industry Liability Shock$_{t-1}$	5.31	4.94	2.68	6.31***	6.45***	4.43***
Firm Shock$_{i,t-1}$		-5.19***			-2.62***	
Firm Liability Shock$_{i,t-1}$	-5.30***			-2.96***		
Res. Firm Shock$_{i,t-1}$			-3.53**			-1.91***
Res. Liability Shock$_{i,t-1}$					-1.36**	-1.17*
Observations	247	247	247	3,278	3,278	3,278
R^2	0.5586	0.5385	0.5047	0.5586	0.5385	0.5047
Adj. R^2	0.5564	0.4809	0.4429	0.5564	0.4809	0.4429
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table reports the results of estimating regression model (9). More detailed results including every variable is presented in *Appendix I*. *, **, *** indicate statistical significance at 10%, 5%, 1% confidence level, respectively.

Table 4
Response of Property-Line Prices to Loss Shocks: Interaction with Tort Reform

	Dependent Variable: Property-Line Prices	
	Insurers Who *Only* Write Property Lines	
	(1)	(2)
Industry Liability Shock$_{t-1}$	27.20**	49.20***
Industry Liability Shock$_{t-1}$ × TortReform$_{s,t-1}$		-8.86*

Table 5
Response of Liability-Line Prices to Loss Shocks: Interaction with Tort Reform

	Dependent Variable: Liability-Line Prices					
	Insurers Who *Only* Write Liability Lines			Insurers Who Write Liability & Other Lines		
	(1)	(2)	(3)	(1)	(2)	(3)
Industry Liability Shock$_{t-1}$	6.50	6.14	4.35	-2.30	-2.16	-4.76*
Industry Property Shock$_{t-1}$	795.18***	789.31***	804.76***	187.37**	193.67**	189.57**
Firm Shock$_{t-1}$		1.10			-1.48***	
Firm Shock$_{t-1}$ × TortReform$_{t-1}$		-2.19***			-0.38**	
Res. Firm Shock$_{t-1}$			-2.21			0.98
Res. Firm Shock$_{t-1}$ × TortReform$_{t-1}$			-1.68			-0.46**
Firm Liability Shock$_{t-1}$	1.14			-1.92**		
Firm Liability Shock$_{t-1}$ × TortReform$_{t-1}$	-2.10**			-0.32		
Res. Liability Shock$_{t-1}$					-2.21	-1.94
Res. Liability Shock$_{t-1}$ × TortReform$_{t-1}$					0.38	0.47

Notes: This table reports the results of estimating regression (11). More detailed results including every variable is presented in *Appendix II*.
*, **, *** indicate statistical significance at 10%, 5%, 1% confidence level, respectively.

Appendix I
Response of Liability-Line Prices to Loss Shocks: 1997-2016

	Dependent Variable: Liability-Line Prices					
	Insurers Who *Only* Write Liability Lines			Insurers Who Write Liability & Other Lines		
	(1)	(2)	(3)	(1)	(2)	(3)
Relative Capacity$_{t-1}$	0.09	0.06	0.12	0.79***	0.80***	0.85***
	(0.25)	(0.39)	(0.47)	(0.08)	(0.07)	(0.08)
Industry Liability Shock$_{t-1}$	5.31	4.94	2.68	6.31***	6.45***	4.43***
	(4.59)	(7.50)	(8.99)	(1.09)	(1.03)	(1.11)
Industry Property Shock$_{t-1}$	668.77***	659.23***	682.45***	52.25	59.73**	54.25**
	(104.09)	(231.89)	(260.20)	(33.82)	(24.40)	(26.01)
Industry Other Shock$_{t-1}$	10.82**	10.67*	10.78*	4.95**	5.30***	3.76***
	(4.35)	(5.58)	(6.52)	(2.33)	(1.17)	(1.19)
ΔInterest Rate$_{t-1}$	17.42***	17.55***	17.24***	-0.72	-0.65	-0.94
	(4.02)	(5.20)	(5.23)	(1.54)	(0.72)	(0.74)
Firm Shock$_{t-1}$		-5.19***			-2.62***	
		(1.34)			(0.33)	
Firm Liability Shock$_{t-1}$	-5.30***			-2.96***		
	(0.68)			(0.32)		
Res. Firm Shock$_{t-1}$			-3.53**			-1.91***
			(1.58)			(0.21)
Res. Liability Shock$_{t-1}$					-1.36**	-1.17*
					(0.61)	(0.61)
Surplus$_{t-2}$	-0.26***	-0.26	-0.27	-0.02	-0.02	-0.02
	(0.09)	(0.20)	(0.20)	(0.01)	(0.02)	(0.02)
New External Capital$_{t-1}$	-1.29***	-1.16	-1.74	0.06	0.08	0.02
	(0.42)	(1.06)	(1.18)	(0.07)	(0.07)	(0.08)
New Internal Capital$_{t-1}$	0.73	0.72	0.21	0.10*	0.12	-0.01
	(0.71)	(0.67)	(0.54)	(0.06)	(0.09)	(0.09)

$Reinsurance_{t-1}$	0.02	-0.01	0.05	-0.17**	-0.16**	-0.17**
	(0.21)	(0.26)	(0.29)	(0.07)	(0.08)	(0.08)
$Size_{t-1}$	0.08***	0.07	0.09	-0.03	-0.03	-0.03
	(0.02)	(0.06)	(0.07)	(0.02)	(0.02)	(0.03)
$Rating_{t-1}$	-0.22***	-0.22	-0.17	0.02	0.02	0.03
	(0.07)	(0.15)	(0.18)	(0.05)	(0.04)	(0.05)
$Line\text{-}HHI_{t-1}$	0.26	0.27	0.01	0.33***	0.31	0.33
	(0.42)	(1.20)	(1.33)	(0.07)	(0.20)	(0.23)
$Geography\text{-}HHI_{t-1}$	0.16	0.16	0.19	0.13**	0.12	0.16
	(0.16)	(0.39)	(0.47)	(0.05)	(0.13)	(0.15)
Observations	247	247	247	3,278	3,278	3,278
R^2	0.5586	0.5385	0.5047	0.5586	0.5385	0.5047
Adj. R^2	0.5564	0.4809	0.4429	0.5564	0.4809	0.4429
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table presents the detailed results of *Table 3* column (1) to (3). Here, $Surplus_{t-2}$ is scaled by $Liability_{t-3}$. *New External Capital*$_{t-1}$ and *New Internal Capital*$_{t-1}$ are scaled by $Liability_{t-2}$.
*, **, *** indicate statistical significance at 10%, 5%, 1% confidence level, respectively.

Appendix II
Response of Liability-Line Prices to Loss Shocks: Interaction with Tort Reform

	Dependent Variable: Liability-Line Prices					
	Insurers Who *Only* Write Liability Lines			Insurers Who Write Liability & Other Lines		
	(1)	(2)	(3)	(1)	(2)	(3)
Relative Capacity$_{t-1}$	-1.04	-1.06	-1.08*	0.34	0.35	0.41
	(0.65)	(0.66)	(0.58)	(0.25)	(0.25)	(0.25)
Industry Liability Shock$_{t-1}$	6.50	6.14	4.35	-2.30	-2.16	-4.76*
	(7.84)	(7.68)	(7.22)	(2.26)	(2.22)	(2.44)
Industry Property Shock$_{t-1}$	795.18***	789.31***	804.76***	187.37**	193.67**	189.57**
	(245.44)	789.31***	(219.86)	(82.46)	(83.61)	(85.49)
Industry Other Shock$_{t-1}$	-21.34*	(240.98)	-22.53*	2.26	2.67	1.99
	(11.80)	-21.27*	(11.79)	(3.60)	(3.66)	(3.78)
ΔInterest Rate$_{t-1}$	17.38*	(11.73)	18.14**	3.16	3.29	2.68
	(9.64)	17.53*	(8.34)	(2.97)	(2.97)	(3.08)
Firm Shock$_{t-1}$		(9.68)			-1.48***	
		1.10			(0.50)	
Firm Shock$_{t-1}$ × TortReform$_{t-1}$		(4.24)			-0.38**	
					(0.18)	
Firm Liability Shock$_{t-1}$	1.14			-1.92**		
	(4.43)			(0.75)		
Firm Liability Shock$_{t-1}$ × TortReform$_{t-1}$	-2.10**			-0.32		
	(0.90)			(0.27)		
Res. Firm Shock$_{t-1}$			-2.21			0.98
			(7.59)			(0.64)
Res. Firm Shock$_{t-1}$ × TortReform$_{t-1}$			-1.68			-0.46**
			(2.59)			(0.20)
Res. Liability Shock$_{t-1}$					-2.21	-1.94
					(2.12)	(2.16)

Res. Liability Shock$_{t-1}$ × TortReform$_{t-1}$					0.38	0.47
					(0.80)	(0.75)
Surplus$_{t-2}$	-0.78***	-0.78***	-0.79***	-0.15***	-0.15***	-0.15***
	(0.20)	(0.20)	(0.23)	(0.04)	(0.04)	(0.04)
New External Capital$_{t-1}$	-2.72***	-2.57***	-3.27***	-0.30**	-0.28*	-0.38***
	(0.72)	(0.71)	(1.16)	(0.15)	(0.15)	(0.14)
New Internal Capital$_{t-1}$	1.05	1.20	-0.19	-0.12	-0.10	-0.34**
	(1.80)	(1.92)	(1.12)	(0.15)	(0.15)	(0.16)
Reinsurance$_{t-1}$	-0.46	-0.50	-0.23	-0.19	-0.18	-0.18
	(0.43)	(0.44)	(0.38)	(0.14)	(0.14)	(0.13)
Size$_{t-1}$	0.13	0.13	0.14	-0.12***	-0.12***	-0.12***
	(0.10)	(0.10)	(0.10)	(0.04)	(0.04)	(0.03)
Rating$_{t-1}$	-0.02	-0.02	0.06	0.05	0.06	0.07
	(0.28)	(0.28)	(0.30)	(0.10)	(0.10)	(0.11)
Line-HHI$_{t-1}$	-2.70***	-2.68***	-2.88***	-0.05	-0.06	-0.06
	(0.98)	(0.99)	(1.02)	(0.23)	(0.23)	(0.23)
Geography-HHI$_{t-1}$	-0.16	-0.18	0.10	0.23	0.17	0.30
	(0.44)	(0.43)	(0.47)	(0.32)	(0.30)	(0.31)
Liability-Line %Reg	-0.24	-0.23	-0.25	-0.62*	-0.62*	-0.62*
	(0.67)	(0.67)	(0.67)	(0.34)	(0.34)	(0.33)
Liability-Line Competition	-2.97	-2.94	-2.14	-1.00	-0.97	-1.01
	(9.04)	(9.04)	(8.83)	(1.20)	(1.20)	(1.22)
Insurance GSP	-0.17***	-0.16***	-0.16***	-0.03	-0.03	-0.03
	(0.06)	(0.06)	(0.06)	(0.03)	(0.03)	(0.03)
Insurance Employment	0.12	0.13	0.12	0.21	0.21	0.19
	(0.62)	(0.62)	(0.62)	(0.17)	(0.17)	(0.16)
Income Per Capita	0.33	0.33	0.34*	0.05	0.05	0.04
	(0.21)	(0.21)	(0.21)	(0.07)	(0.07)	(0.07)
GSP Per Capita	1.61**	1.61**	1.57**	-0.29***	-0.29***	-0.29***
	(0.71)	(0.71)	(0.67)	(0.07)	(0.07)	(0.07)
Observations	2,041	2,041	2,041	75,191	75,191	75,191

R^2	0.2206	0.2127	0.1993	0.2206	0.2127	0.1993
Adj. R^2	0.2197	0.1899	0.1749	0.2197	0.1899	0.1749
Firm-state FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table presents the detailed results of *Table 5* column (1) to (3). Here, $\textit{Surplus}_{t-2}$ is scaled by $\textit{Liability}_{t-3}$. $\textit{New External Capital}_{t-1}$ and $\textit{New Internal Capital}_{t-1}$ are scaled by $\textit{Liability}_{t-2}$.

*, **, *** indicate statistical significance at 10%, 5%, 1% confidence level, respectively.

Appendix III
Proofs of Equation (4), (5), (7), and (8)

The objective function of insurer *i* is to maximize the value added to equity as:

$$\underset{p_2^i,\, E_2^i}{Max}\ C_2^i - \left(E_2^i + C_1^i\right) = Q^i \cdot \left[\, p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + L_1^i\left[b^i\left(x^i\right) - b_1^i\left(x_1^i\right)\right] \tag{A1.1}$$

The First-order conditions with respect to p_2^i and E_2^i can be written as

$$\left(Q_p^i + Q_b^i b_x^i x_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)\left[\, p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + Q^i\left(1 + b_x^i x_p^i\right) + L_1^i b_x^i x_p^i = 0 \tag{A1.2}$$

$$Q_b^i b_x^i x_e^i \cdot \left[\, p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + Q^i b_x^i x_e^i + L_1^i b_x^i x_e^i = 0 \tag{A1.3}$$

Rearrange equation (A1.2) and (A1.3), we obtain:

$$\left\{Q^i + \left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)\left[\, p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\right\} + \left\{Q_b^i\left[\, p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + Q^i + L_1^i\right\} b_x^i x_p^i = 0 \tag{A1.4}$$

$$\left\{Q_b^i\left[\, p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + Q^i + L_1^i\right\} b_x^i x_e^i = 0 \tag{A1.5}$$

That is, the optimal solutions of p_2^i and E_2^i are given by:

$$Q^i + \left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)\left[\, p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] = 0 \tag{A1.6}$$

$$Q_b^i\left[\, p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] + Q^i + L_1^i = 0 \tag{A1.7}$$

Rearrange equation (A1.2) and (A1.3), we obtain:

$$Q_p^i + \left(Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right) = \frac{-Q^i}{p_2^i - e^{-r\tau} + b^i\left(x^i\right)} < 0 \tag{A1.8}$$

$$Q_b^i = \frac{-\left(Q^i + L_1^i\right)}{p_2^i - e^{-r\tau} + b^i\left(x^i\right)} < 0 \tag{A1.9}$$

Take the derivative with respect to L_1^j on both sides of equation (A1.6), we have:

$$\begin{aligned}
&\left(Q_p^i \frac{\partial p_2^i}{\partial L_1^j} + Q_b^i b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^j} + Q_{p^j}^i \frac{\partial p_2^j}{\partial L_1^j} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial L_1^j} + Q_{b^j}^i b_x^j x_{L_1}^j\right) + \left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)\left(\frac{\partial p_2^i}{\partial L_1^j} + b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^j}\right) \\
&+\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\begin{pmatrix} Q_{pp}^i \frac{\partial p_2^i}{\partial L_1^j} + Q_{pb}^i b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^j} + Q_{pp^j}^i \frac{\partial p_2^j}{\partial L_1^j} + Q_{pb^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial L_1^j} + Q_{pb^j}^i b_x^j x_{L_1}^j \\
+Q_{p^j p}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^j} + Q_{p^j b}^i b_x^i x_p^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^j} + Q_{p^j p^j}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^j}{\partial L_1^j} + Q_{p^j b^j}^i \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_p^j \frac{\partial p_2^j}{\partial L_1^j} + Q_{p^j b^j}^i \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_{L_1}^j \\
+Q_{b^j p}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^j} + Q_{b^j b}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^j} + Q_{b^j p^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^j}{\partial L_1^j} + Q_{b^j b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_p^j \frac{\partial p_2^j}{\partial L_1^j} + Q_{b^j b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_{L_1}^j \end{pmatrix} = 0
\end{aligned}$$

Rearrange the above equation, we have:

$$\frac{\partial p_2^i}{\partial L_1^j} \cdot D + \left\{ Q_{b^j}^i + \left[Q_{pb^j}^i + \frac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b^j}^i + Q_{b^j b^j}^i b_x^j x_p^j\right)\right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\right\} \cdot b_x^j x_{L_1}^j = 0 \tag{A1.10}$$

where $D = 2Q_p^i + \left(Q_b^i + Q_p^i\right) b_x^i x_p^i + \left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] \cdot \left(Q_{pp}^i + Q_{pb}^i b_x x_p\right)$

$$+\frac{\partial p_2^j}{\partial p_2^i}\begin{bmatrix} \left(Q_{p^j}^i + Q_{b^j}^i b_x^j x_p^j\right)\left(2 + b_x^i x_p^i\right) \\ +\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] \cdot \begin{pmatrix} 2Q_{pp^j}^i + 2Q_{pb^j}^i b_x^j x_p^j + Q_{p^j b}^i b_x^i x_p^i \\ +Q_{p^j p^j}^i \frac{\partial p^j}{\partial p} + 2Q_{p^j b^j}^i b_x^j x_p^j \frac{\partial p^j}{\partial p} \\ +Q_{b^j b}^i b_x^j x_p^j b_x^i x_p^i + Q_{b^j b^j}^i b_x^j x_p^j \frac{\partial p^j}{\partial p} b_x^j x_p^j \end{pmatrix} \end{bmatrix}$$

, which is exactly the second derivatives of the objective function (A1.1) with respect to p_2^i. Therefore,

$$\frac{\partial p_2^i}{\partial L_1^j} = \frac{Q_{b^j}^i + \left[Q_{pb^j}^i + \frac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b^j}^i + Q_{b^j b^j}^i b_x^j x_p^j\right)\right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]}{-D / b_x^j x_{L_1}^j} \tag{A1.11}$$

Take the derivative with respect to L_1^i on both sides of equation (A1.6), we have:

$$\left(Q_p^i \frac{\partial p_2^i}{\partial L_1^i} + Q_b^i b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^i} + Q_b^i b_x^i x_{L_1}^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i}\right) + \left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)\left[\frac{\partial p_2^i}{\partial L_1^i} + b_x^i x_{L_1}^i + b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^i}\right]$$
$$+\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\begin{pmatrix} Q_{pp}^i \frac{\partial p_2^i}{\partial L_1^i} + Q_{pb}^i b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^i} + Q_{pb}^i b_x^i x_{L_1}^i + Q_{pp^j}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{pb^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} \\ + Q_{p^j p}^i \frac{\partial p^j}{\partial p}\frac{\partial p_2^i}{\partial L_1^i} + Q_{p^j b}^i b_x^i x_p^i \frac{\partial p^j}{\partial p}\frac{\partial p_2^i}{\partial L_1^i} + Q_{p^j b}^i \frac{\partial p_2^j}{\partial p_2^i} b_x^i x_{L_1}^i + Q_{p^j p^j}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{p^j b^j}^i \frac{\partial p^j}{\partial p} b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} \\ + Q_{b^j p}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{b^j b}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^i} + Q_{b^j b}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^i x_{L_1}^i + Q_{b^j p^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{b^j b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} \end{pmatrix} = 0$$

Rearrange the above equation, we have:

$$\frac{\partial p_2^i}{\partial L_1^i}\cdot D + \begin{bmatrix} \left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right) + Q_b^i \\ + \left[Q_{pb}^i + \frac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b}^i + Q_{b^j b}^i b_x^j x_p^j\right)\right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] \end{bmatrix} b_x^i x_{L_1}^i = 0 \qquad \text{(A1.12)}$$

That is,

$$\frac{\partial p_2^i}{\partial L_1^i} = \frac{\frac{dQ^i}{dp_2^i} + Q_b^i + \left[Q_{pb}^i + \frac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b}^i + Q_{b^j b}^i b_x^j x_p^j\right)\right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]}{-D \big/ b_x^i x_{L_1}^i} \qquad \text{(A1.13)}$$

where $\frac{dQ^i}{dp_2^i} = Q_p^i + \left(Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)$.

Appendix IV
Correlation

The objective function of insurer i is to maximize the value added to equity as:

$$\underset{p_2^i,\,E_2^i}{Max}\; C_2^i-\left(E_2^i+C_1^i\right)=Q^i\cdot\left[p_2^i-e^{-r\tau}+b^i\left(x^i\right)\right]+L_1^i\left[b^i\left(x^i\right)-b_1^i\left(x_1^i\right)\right] \tag{A1.1}$$

The First-order conditions with respect to p_2^i and E_2^i can be written as

$$\left(Q_p^i+Q_b^ib_x^ix_p^i+Q_{p^j}^i\frac{\partial p_2^j}{\partial p_2^i}+Q_{b^j}^ib_x^jx_p^j\frac{\partial p_2^j}{\partial p_2^i}\right)\left[p_2^i-e^{-r\tau}+b^i\left(x^i\right)\right]$$
$$+Q^i\left(1+b_x^ix_p^i\right)+L_1^ib_x^ix_p^i=0 \tag{A1.2}$$

$$Q_b^ib_x^ix_e^i\cdot\left[p_2^i-e^{-r\tau}+b^i\left(x^i\right)\right]+Q^ib_x^ix_e^i+L_1^ib_x^ix_e^i=0 \tag{A1.3}$$

Rearrange equation (A1.2) and (A1.3), we obtain:

$$\left\{Q^i+\left(Q_p^i+Q_{p^j}^i\frac{\partial p_2^j}{\partial p_2^i}+Q_{b^j}^ib_x^jx_p^j\frac{\partial p_2^j}{\partial p_2^i}\right)\left[p_2^i-e^{-r\tau}+b^i\left(x^i\right)\right]\right\}$$
$$+\left\{Q_b^i\left[p_2^i-e^{-r\tau}+b^i\left(x^i\right)\right]+Q^i+L_1^i\right\}b_x^ix_p^i=0 \tag{A1.4}$$

$$\left\{Q_b^i\left[p_2^i-e^{-r\tau}+b^i\left(x^i\right)\right]+Q^i+L_1^i\right\}b_x^ix_e^i=0 \tag{A1.5}$$

That is, the optimal solutions of p_2^i and E_2^i are given by:

$$Q^i+\left(Q_p^i+Q_{p^j}^i\frac{\partial p_2^j}{\partial p_2^i}+Q_{b^j}^ib_x^jx_p^j\frac{\partial p_2^j}{\partial p_2^i}\right)\left[p_2^i-e^{-r\tau}+b^i\left(x^i\right)\right]=0 \tag{A1.6}$$

$$Q_b^i\left[p_2^i-e^{-r\tau}+b^i\left(x^i\right)\right]+Q^i+L_1^i=0 \tag{A1.7}$$

Rearrange equation (A1.2) and (A1.3), we obtain:

$$Q_p^i+\left(Q_{p^j}^i\frac{\partial p_2^j}{\partial p_2^i}+Q_{b^j}^ib_x^jx_p^j\frac{\partial p_2^j}{\partial p_2^i}\right)=\frac{-Q^i}{p_2^i-e^{-r\tau}+b^i\left(x^i\right)}<0 \tag{A1.8}$$

$$Q_b^i = \frac{-\left(Q^i + L_1^i\right)}{p_2^i - e^{-r\tau} + b^i\left(x^i\right)} < 0 \tag{A1.9}$$

Take the derivative with respect to L_1^j on both sides of equation (A1.6), we have:

$$\begin{aligned}
&\left(Q_p^i \frac{\partial p_2^i}{\partial L_1^j} + Q_b^i b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^j} + Q_{p^j}^i \frac{\partial p_2^j}{\partial L_1^j} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial L_1^j} + Q_{b^j}^i b_x^j x_{L_1}^j\right) + \left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)\left(\frac{\partial p_2^i}{\partial L_1^j} + b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^j}\right) \\
&+\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\left(\begin{array}{l}
Q_{pp}^i \frac{\partial p_2^i}{\partial L_1^j} + Q_{pb}^i b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^j} + Q_{pp^j}^i \frac{\partial p_2^j}{\partial L_1^j} + Q_{pb^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial L_1^j} + Q_{pb^j}^i b_x^j x_{L_1}^j \\
+Q_{p^j p}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^j} + Q_{p^j b}^i b_x^i x_p^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^j} + Q_{p^j p^j}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^j}{\partial L_1^j} + Q_{p^j b^j}^i \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_p^j \frac{\partial p_2^j}{\partial L_1^j} + Q_{p^j b^j}^i \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_{L_1}^j \\
+Q_{b^j p}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^j} + Q_{b^j b}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^j} + Q_{b^j p^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^j}{\partial L_1^j} + Q_{b^j b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_p^j \frac{\partial p_2^j}{\partial L_1^j} + Q_{b^j b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_{L_1}^j
\end{array}\right) = 0
\end{aligned}$$

Rearrange the above equation, we have:

$$\frac{\partial p_2^i}{\partial L_1^j} \cdot D + \left\{Q_{b^j}^i + \left[Q_{pb^j}^i + \frac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b^j}^i + Q_{b^j b^j}^i b_x^j x_p^j\right)\right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\right\} \cdot b_x^j x_{L_1}^j = 0 \tag{A1.10}$$

where $D = 2Q_p^i + \left(Q_b^i + Q_p^i\right) b_x^i x_p^i + \left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] \cdot \left(Q_{pp}^i + Q_{pb}^i b_x x_p\right)$

$$+\frac{\partial p_2^j}{\partial p_2^i}\left[\begin{array}{l}
\left(Q_{p^j}^i + Q_{b^j}^i b_x^j x_p^j\right)\left(2 + b_x^i x_p^i\right) \\
+\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right] \cdot \left(\begin{array}{l}
2Q_{pp^j}^i + 2Q_{pb^j}^i b_x^j x_p^j + Q_{p^j b}^i b_x^i x_p^i \\
+Q_{p^j p^j}^i \frac{\partial p^j}{\partial p} + 2Q_{p^j b^j}^i b_x^j x_p^j \frac{\partial p^j}{\partial p} \\
+Q_{b^j b}^i b_x^j x_p^j b_x^i x_p^i + Q_{b^j b^j}^i b_x^j x_p^j \frac{\partial p^j}{\partial p} b_x^j x_p^j
\end{array}\right)
\end{array}\right]$$

, which is exactly the second derivatives of the objective function (A1.1) with respect to p_2^i. Therefore,

$$\frac{\partial p_2^i}{\partial L_1^j} = \frac{Q_{b^j}^i + \left[Q_{pb^j}^i + \frac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b^j}^i + Q_{b^j b^j}^i b_x^j x_p^j\right)\right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]}{-D / b_x^j x_{L_1}^j} \tag{A1.11}$$

Take the derivative with respect to L_1^i on both sides of equation (A1.6), we have:

$$
\begin{aligned}
&\left(Q_p^i \frac{\partial p_2^i}{\partial L_1^i} + Q_b^i b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^i} + Q_b^i b_x^i x_{L_1}^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i}\right) + \left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right)\left[\frac{\partial p_2^i}{\partial L_1^i} + b_x^i x_{L_1}^i + b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^i}\right] \\
&+\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\left(\begin{aligned}
&Q_{pp}^i \frac{\partial p_2^i}{\partial L_1^i} + Q_{pb}^i b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^i} + Q_{pb}^i b_x^i x_{L_1}^i + Q_{pp^j}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{pb^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} \\
&+Q_{p^j p}^i \frac{\partial p^j}{\partial p}\frac{\partial p_2^i}{\partial L_1^i} + Q_{p^j b}^i b_x^i x_p^i \frac{\partial p^j}{\partial p}\frac{\partial p_2^i}{\partial L_1^i} + Q_{p^j b}^i \frac{\partial p_2^j}{\partial p_2^i} b_x^i x_{L_1}^i + Q_{p^j p^j}^i \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{p^j b^j}^i \frac{\partial p^j}{\partial p} b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} \\
&+Q_{b^j p}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{b^j b}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^i x_p^i \frac{\partial p_2^i}{\partial L_1^i} + Q_{b^j b}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^i x_{L_1}^i + Q_{b^j p^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i} + Q_{b^j b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i} b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\frac{\partial p_2^i}{\partial L_1^i}
\end{aligned}\right) = 0
\end{aligned}
$$

Rearrange the above equation, we have:

$$
\frac{\partial p_2^i}{\partial L_1^i} \cdot D + \left[\begin{aligned}&\left(Q_p^i + Q_{p^j}^i \frac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \frac{\partial p_2^j}{\partial p_2^i}\right) + Q_b^i \\ &+\left[Q_{pb}^i + \frac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b}^i + Q_{b^j b}^i b_x^j x_p^j\right)\right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]\end{aligned}\right] b_x^i x_{L_1}^i = 0 \qquad \text{(A1.12)}
$$

That is,

$$
\frac{\partial p_2^i}{\partial L_1^i} = \frac{\dfrac{dQ^i}{dp_2^i} + Q_b^i + \left[Q_{pb}^i + \dfrac{\partial p_2^j}{\partial p_2^i}\left(Q_{p^j b}^i + Q_{b^j b}^i b_x^j x_p^j\right)\right]\left[p_2^i - e^{-r\tau} + b^i\left(x^i\right)\right]}{-D \big/ b_x^i x_{L_1}^i} \qquad \text{(A1.13)}
$$

where $\dfrac{dQ^i}{dp_2^i} = Q_p^i + \left(Q_{p^j}^i \dfrac{\partial p_2^j}{\partial p_2^i} + Q_{b^j}^i b_x^j x_p^j \dfrac{\partial p_2^j}{\partial p_2^i}\right)$.