

## OPTIONS AND SWAPS ON MOTOR CLAIMS

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Résumé de l'article

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## OPTIONS AND SWAPS ON MOTOR CLAIMS

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Taehan Bae<sup>a\*</sup> and Changki Kim<sup>b</sup>

### ■ ABSTRACT

In this paper, we introduce new motor insurance linked securities: motor loss rate ratchet options and motor loss rate swaps which can be used effectively by insurers to manage their liability risks by transferring loss rate risks to capital markets. We discuss the valuation of these customized over-the-counter hybrid securities under the assumption that motor insurance aggregate claims follow a compound Poisson distribution. The Fourier inversion method is employed for the numerical calculation of the risk neutral prices of the motor loss rate derivatives, and some illustrative examples are given based on a set of assumptions on the severity distribution and the model parameters.

*Key words:* Securitization, Risk transfer, Ratchet option, Swaps, Motor insurance loss rates.

### 1. Introduction

It is often observed that the loss ratio of a motor insurance portfolio fluctuates considerably year by year. This may be caused by several reasons such as catastrophic events, systematic risks, failure of underwriting process, inadequate premium policy, etc. The mismatch between the actual claims and the anticipated claim amounts can lead to problems in the management of assets and liabilities. If the actual motor loss rates increase more than the expected one, motor insurers will have to make additional payments during the contract period. This will lead to losses on their motor insurance business. The insurers may

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need additional, low-cost tools to manage motor loss exposure. The insurer will profit if the realized losses from the motors insured decrease below the expected level. However, an appropriate portion of such profits needs to be set aside to cover the potential future losses. In many cases, the problem can be alleviated by increasing the size of the insurance pool. However, there exist unhedgeable risks such as catastrophic and systematic risks, and the transfer of such unfavorable risks may be an effective solution. Even though the traditional risk transfer methods of reinsurance and sidecars are still dominant in practice, for the past few years, several insurance linked securities including catastrophe bonds/derivatives and longevity/mortality bonds, have successfully been introduced to the markets. For references on catastrophe bonds, see Lakdawalla and Zanjani (2012), Härdle and Cabrera (2010), Barrieu and Loubergé (2009), and Lee and Yu (2002). Cummins and Weiss (2009) provide a survey on the recent developments of various types of insurance linked securities. Klein and Wang (2009) examine and compare regulatory and other government policies on the financing of catastrophe risks in the United States and the EU.

Regarding the motor insurance securitization, the very first motor insurance linked security (MILS) was introduced in 2005 by a French insurance company AXA based on their French motor insurance portfolio. The waterfall structure of the security resembles that of Collateralized Debt Obligation (CDO). Based on the success of the first issue, AXA launched the second motor insurance tranche notes in 2007 that combined motor insurance portfolios from four different countries (Germany, Belgium, Italy, and Spain) into a global portfolio, providing diversification of the motor insurance loss risks<sup>1</sup>. In 2010, the three year junior tranche notes have also been issued to securitize four quota share treaties on the global portfolio. This movement presents significant implications for the future of motor insurance-linked securities toward the creation of standardized markets, where risk concentration should be avoided. Readers may refer to Bae et al. (2009) for the development and valuation of the CDO type motor insurance loss rate securities.

There are several motivating factors for the securitization of motor insurance portfolio risks. These include the issuer gaining an alternative source of financing, a channel of risk transfer, and a method of capital management that helps improve the solvency of the company. Securitization also allows the insurer to reduce or eliminate counterparty default risks by accessing traditional asset-backed securities investors. Also, it allows the insurer to access those tools that are used by banks for risk management and anticipate the expected evolution of solvency rules. These transactions will also optimize the insurer's

business and balance sheet with respect to volume, pricing, and terms. By providing greater diversification of investment portfolios, insurance securitization also creates new investment opportunities for groups of investors including the insurer's policyholders, the government, the companies and organizations related to the motoring industry, and the general investors who seek high-yield securities. Insurance linked securities become more attractive to investors in bear markets. Recently multi-strategy hedge funds and pension funds have increased the weights of products to their broader investment portfolios due to the relatively strong performance of insurance linked products during the financial crisis.

In this paper, we introduce two new types of motor insurance linked securities: the motor insurance loss rate ratchet option and motor insurance loss rate swap. The characteristics of these securities are described in Section 2. Section 3 discusses the risk neutral probability measure change through Esscher transform and the pricing methods for the motor loss rate ratchet option and swap are provided in Sections 4 and 5, respectively. Section 6 provides numerical examples and discusses some issues on MILS. Finally Section 7 concludes the paper.

## 2. Characteristics of Motor Insurance Loss Rate Swap and Option

A motor loss rate swap is a contract to exchange cash flows in the future based on the outcome of at least one presumably random motor loss rates. The objective is for insurers to hedge motor loss rate risks by exchanging one or more future cash flows, at least one of which is random.

**Definition 1.** *A motor loss rate swap is an agreement between two parties to exchange payments involving at least one random motor loss rate dependent payment for a certain period of time.*

In a simple case, a motor loss rate swap involves the exchange of a single fixed payment for a single random motor loss rate-dependent payment. Suppose that at time 0, two parties enter into an agreement to exchange a pre-fixed value  $k_t$  for a random value  $S_t$  that is dependent on the realized motor loss rate at some future time  $t$ . The fixed amount  $k_t$  may depend on the past empirical history on loss experiences.  $S_t$  is the actual loss amount realized until time  $t$ . Therefore, it is a random variable at time 0. It can be related to the number of accidents from time 0 to time  $t$  and the realized loss amounts for each accident from a specified reference motor insurance pool. It is reasonable for the two parties to make an agreement that they would exchange only the net

difference between the two payment amounts. For example, party A pays party B a value of  $k_t - S_t$  if  $k_t > S_t$ , or party B pays party A a value of  $S_t - k_t$  if  $S_t > k_t$ . In this case, party A benefits when the realized loss amount  $S_t$  is higher than the pre-fixed amount  $k_t$ . It makes losses if  $S_t$  turns out to be lower than  $k_t$ . Therefore, Party A has a long position to  $S_t$  whereas party B has a short position to  $S_t$ .

Insurance companies may use motor loss rate swaps to exploit natural hedging across their motor insurance businesses.

When an insurer is particularly interested in managing extreme loss rate risks, a swap contract seems to be inappropriate. In this case, the insurer has a higher chance to make a payment rather than to be paid at each settlement point. Even though the corresponding swap rate may be determined based on the historical data, both parties would like to enter into a swap contract when they expect a fair chance of getting paid. Alternatively, a motor loss rate ratchet option can be used to protect the motor insurance providers against the risks of higher motor loss rates but without giving up the possible benefits of lower motor loss rates. In other words, a motor loss rate ratchet option “insures” the motor insurance providers. The cost of the motor loss rate option is the “insurance premium.”

**Definition 2.** *A motor loss rate ratchet option is a series of call options on motor loss rates where strike thresholds are reset periodically.*

A motor loss rate ratchet option is a right, not an obligation, to exchange cash flows related to motor loss rates. On each exercise date, the option holder receives the excess amount of loss above the pre-specified strike threshold. It is important to reset strike thresholds periodically based on the realized loss rate of the previous period. By doing this, both counterparties are eager to remain in the contract even when they experience extreme loss events in some periods.

These hybrid derivatives have several advantages over motor loss rate bonds. They can be arranged at lower transaction costs than a bond issue. The proposed swap and option cover multiple time periods. Thus, it is more efficient than buying a series of stop loss reinsurance treaties. They are more flexible and can be tailor-made. Most of the arrangements are private placements. They do not need a liquid market. It involves willing counterparties who exploit their comparative advantages or trade views on the development of motor loss rate over time. Their flexibility and low costs provide motor insurers with advantages over the traditional reinsurance treaties.

### 3. Motor Insurance Loss Rate Models

The following section describes the derivation involved in the securities pricing via the pricing formulas for the stop loss premiums. As in Bae et al. (2009), we assume that the aggregate claims for motor insurance follow a marked point process<sup>2</sup>. Specifically, we denote the Poisson process with the parameter  $\lambda_t$  by  $N_t$ , for any time  $t \geq 0$ . On a probability space  $(\Omega, F, P)$ , we assume that the aggregate loss  $S_t$  is

$$S_t = \int_{(0,t]} \int_{R^+} g(u, x) N(du, dx) = \sum_{i=1}^{N_t} g(T_i, X_i), \quad (1)$$

where  $T_i$ 's are jump times of the Poisson process  $N_t$  and the magnitudes  $X_i$ 's of positive random shocks are independently and identically distributed with the distribution function  $F_X(x)$ . The random shock  $X_i$  arrived at time  $t$  results in a claim measured by a continuous function  $g(t, x)$  defined on  $(0, T] \times R_+$ , which is increasing in  $x$ . Here, we further assume that  $N_t$  and  $X_i$  are independent for model simplicity. Note that  $N(du, dx)$  is a Poisson random measure with the mean measure

$$m(du, dx) = du v_u(dx),$$

where  $v_u(dx) = \lambda_u dF_X(x)$  is the Lévy measure.

The following theorem can be shown by using standard machinery in the probability theory. See also Lemma 4.3 of Resnik (1986).

**Theorem 1.** *For any continuous bivariate function  $g \in C((0, T] \times R_+)$  such that  $\int_{(0,T]} \int_{R_+} g(u, x) N(du, dx) < \infty$ , the following holds:*

$$\begin{aligned} & E \left[ \exp \left( \int_{(0,T]} \int_{R_+} g(u, x) N(du, dx) \right) \right] \\ &= \exp \left[ \int_{(0,T]} \int_{R_+} \lambda_u \left( e^{g(u,x)} - 1 \right) dF_X(x) du \right]. \end{aligned} \quad (2)$$

Here we assume that the Poisson process  $N_t$  is a time homogeneous process characterized by the constant rate parameter  $\lambda$ , and the claim size distribution is a discounted random shock  $g(u, X) = e^{-ru} X$ . Then, the aggregate loss process (1) is also referred to as a discounted compound Poisson process. See Delbaen and Haezendonck (1987), Paulsen (1993), and Nilsen and Paulsen (1996) for more details on the distribution of a discounted compound Poisson process.

Mapping techniques, such as Fourier transform and its inverse transform, can be employed in calculating the market prices of stop loss premiums and other relevant securities.

**Corollary 2.** *Let us denote the distribution function of  $S_t$  by  $F_S(x, t)$ . The Fourier transform of the distribution of  $S_t$  for a given  $t$  is expressed as*

$$\hat{f}_S(u, t) = \int_{R^+} e^{iux} dF_S(x, t) = E[e^{iuS_t}] = \exp \left\{ \int_0^t \lambda_s \left( \hat{f}_X(ue^{-rs}) - 1 \right) ds \right\}, \quad (3)$$

where  $\hat{f}_X(u)$  is the Fourier transform of the distribution of a claim size random variable  $X$ .

Numerous risk neutral probability measures are present because the market is incomplete, and each probability measure does not result in any arbitrage price for insurance risks. The Esscher transform is suitable for such changes in probability measures due to some preferable characteristics. The Esscher transform is known as the minimal entropy martingale probability measure in a geometric Levy process model and it maximizes the expected power utility function<sup>3</sup>. The response of the market to insurance risks can be interpreted by the Esscher parameter  $b$  of the Esscher transform, which can be obtained under the martingale state. The zero real interest rate corresponds to the constant risk adjustment parameter  $b$  (as determined by a martingale condition). Otherwise, due to the effect of discounting, the risk adjustment parameter is a function of time. For each maturity  $t > 0$  and under a filtered probability space  $\{F_t \mid t > 0\}$ , we define a probability measure  $Q$  whose Radon-Nikodym derivative is

$$\left. \frac{dQ}{dP} \right|_{F_t} = \frac{e^{b_t S_t}}{E^P[e^{b_t S_t}]}. \quad (4)$$

Equivalently,

$$dF_S^Q(x, t) = \frac{e^{b_t x}}{E^P[e^{b_t S_t}]} dF_S^P(x, t),$$

when  $E^P[e^{b_t S_t}]$  exists. Note that  $b_t$  is non-negative deterministic function that satisfies the martingale condition described below in Eq. (\*).<sup>4</sup>

By corollary 2, we have,

$$\begin{aligned}\hat{f}_S^Q(u, t) &= \int_0^\infty e^{iux} \frac{e^{b^*x}}{E^P[e^{b^*S_t}]} f_S^P(x, t) dx = \frac{\hat{f}_S^P(u - ib^*, t)}{\hat{f}_S^P(-ib^*, t)} \\ &= \exp \left\{ \lambda \int_0^t \left\{ \hat{f}_X^P((u - ib^*)e^{-rs}) - \hat{f}_X^P(-ib^*e^{-rs}) \right\} ds \right\}. \quad (5)\end{aligned}$$

Equation (5) can be represented as follows. This enables us to identify the distribution of  $S_t$  under the changed measure  $Q$ .

$$\begin{aligned}\hat{f}_S^Q(u, t) &= \exp \left\{ \lambda \int_0^t \left\{ \hat{f}_X^P((u - ib^*)e^{-rs}) - \hat{f}_X^P(-ib^*e^{-rs}) \right\} ds \right\} \\ &= \exp \left\{ \int_0^t \lambda \hat{f}_X^P(-ib^*e^{-rs}) \left\{ \frac{\hat{f}_X^P((u - ib^*)e^{-rs})}{\hat{f}_X^P(-ib^*e^{-rs})} - 1 \right\} ds \right\}.\end{aligned}$$

**Remark 1.** By comparing the above with (3), for each fixed maturity  $t$ , we can conclude the following:

(i) The Poisson parameter  $\lambda$  has changed to  $\lambda_s^Q = \lambda \hat{f}_X^P(-ib^*e^{-rs})$ ,  $s \leq t$ ;

(ii) The distribution of the claim size,  $dF_X^P(x)$ , has changed to

$$dF_X^Q(x, s) = \frac{\exp\{b^*e^{-rs}x\}}{\hat{f}_X^P(-ib^*e^{-rs})} dF_X^P(x) \text{ and } \hat{f}_X^Q(ue^{-rs}) = \frac{\hat{f}_X^P((u - ib^*)e^{-rs})}{\hat{f}_X^P(-ib^*e^{-rs})}, s \leq t.$$

Note that the Lévy measure under  $Q$  is

$$v_s^Q(dx) = \lambda_s^Q dF_X^Q(x, s) = \lambda \exp\{b^*e^{-rs}x\} dF_X^P(x). \quad \blacksquare$$

For each  $t$ ,

$$E^Q[S_t] = \int_0^\infty \frac{xe^{b^*x}}{E^P[e^{b^*S_t}]} dF_S^P(x, t) = \frac{E^P[S_t e^{b^*S_t}]}{E^P[e^{b^*S_t}]} = \frac{\partial}{\partial b^*} \{\log E^P[e^{b^*S_t}]\}. \quad (6)$$

Because  $E^P[e^{b^*S_t}] = \hat{f}_S^P(-ib^*, t)$ , the latter can be reduced to

$$E^Q[S_t] = \lambda \int_0^t \frac{\partial}{\partial b^*} \hat{f}_X^P(-ib^*e^{-rs}) ds = \frac{\lambda}{rb^*} \left\{ E^P[e^{b^*X}] - E^P[e^{b^*e^{-r}X}] \right\}. \quad (7)$$

The second equality can be obtained via Corollary 2 by changing the order of integration and expectation.



The arbitrage free price of stop loss contract can be determined with a retention level of  $d$  for the motor loss rate option pricing. Mathematically this is represented as

$$E^Q[(S_t - d)_+] = \int_d^\infty (x - d) dF_s^Q(x, t). \tag{8}$$

The following equation is obtained by applying Theorem 3.4 in Dufresne et al. (2009):

$$E^Q[(S_t - d)_+] = \frac{E^Q[S_t]}{2} + \frac{1}{\pi} PV \int_0^\infty \operatorname{Re} \left[ \frac{e^{-iud} (\hat{f}_s^Q(u, t) - 1)}{(iu)^2} \right] du. \tag{9}$$

Here,  $PV \int$  refers to the Cauchy principle value integral.

Substitution of (5) and (7) into (9) results in an Esscher no-arbitrage price formula for stop loss contract.<sup>5</sup>

If there is no arbitrage between insurance market and capital market, the discounted surplus process should be a martingale under a risk neutral measure  $Q$ .<sup>6</sup> We define the accumulated surplus process as follows,

$$U_t = u_0 e^{rt} + e^{rt} C_t - e^{rt} S_t, \tag{10}$$

where  $u_0$  is the initial surplus,  $r$  is the risk free rate compounded continuously, and  $C_t$  is the time zero value of the risk-adjusted aggregated premiums collected on  $[0, t]$ . We define

$$C_t = (1 + \theta) E^P[S_t] = (1 + \theta) \lambda E^P[X] \bar{a}_{t|} = C \bar{a}_{t|},$$

with a risk adjustment parameter  $\theta > 0$ . We denote the continuous premium rate by  $C = (1 + \theta) \lambda E^P[X]$  and the present value of continuously paying annuities by  $\bar{a}_{t|} = (1 - e^{-rt}) / r$ .

We can find an equivalent martingale measure  $Q$  that satisfies the following:<sup>7</sup>

$$E^Q[e^{-rt}U_t | F_s] = e^{-rs}U_s, \quad Q\text{-a.s.} \quad (*)$$

for any  $0 \leq s \leq t$ . By (7), for the maturity  $t$ , we can show that  $h_t$  is the solution of the following equation. This also satisfies the existence of the Esscher transform (4).

$$E^Q[S_t] = \frac{\lambda}{rh_t} \left\{ E^P[e^{h_t X}] - E^P[e^{h_t e^{-rt} X}] \right\} = C \bar{a}_{t|}. \quad (11)$$

Using L'hospital's rule, it can be shown that

$$\lim_{h_t \rightarrow 0} E^Q[S_t] = \lambda E^P[X] \bar{a}_{t|}.$$

Eq. (11) and the above identity imply that if the risk adjusted parameter  $\theta = 0$  or  $C = \lambda E^P[X]$ , then  $h_t \equiv 0$ , which means that the market takes the risk fully.

It can be shown that the constant Esscher parameter is the solution to the equation below (similar to (11)) in the presence of zero real interest rate.

$$E^P[Xe^{hX}] = \frac{C}{\lambda}.$$

From Eqs. (5) and (11), the moment generating function of the claim size distribution plays a crucial role in determining mathematical tractability of the price formula. Setting aside empirical studies on the motor insurance claim size data, we illustrate a tractable example,<sup>8</sup> which is also practical.

### Example 1. Generalized Erlang(n) claim size distribution

Let us assume that  $X$  follows a generalized Erlang(n) distribution with parameters  $(n, \beta_1, \beta_2, \dots, \beta_n)$  such that  $E^P[X] = \sum_{k=1}^n \beta_k$ . The Fourier transform is then given by  $\hat{f}_X^P(u) = \prod_{k=1}^n (1 - i\beta_k u)^{-1}$ . The expectation of discounted claims under  $Q$  is

$$E^Q[S_t] = \frac{\lambda}{rh^*} \left\{ \prod_{k=1}^n (1 - \beta_k h^*)^{-1} - \prod_{k=1}^n (1 - \beta_k e^{-rt} h^*)^{-1} \right\}. \quad (12)$$

Note that the Esscher parameter, if any, must be smaller than  $1 / \max\{\beta_1, \dots, \beta_k\}$  in order to guarantee the existence of the moment generating function or the Esscher transform.

By (11) and after some simple algebra, it can be shown that the Esscher parameter  $b^*$  is a solution of the following equation.<sup>9</sup>

$$\sum_{k=1}^n \left\{ \frac{\beta_k}{\prod_{j \neq k} (\beta_k - \beta_j)} \right\} \left\{ \frac{1}{(1 - \beta_k b)(1 - \beta_k e^{-rt} b)} \right\} = (1 + \theta) \sum_{k=1}^n \beta_k, \quad b < \frac{1}{\max\{\beta_1, \dots, \beta_k\}}. \tag{13}$$

Note that the exponential distribution is a special case when  $n = 1$ . The Esscher parameter in this case is

$$b^* = \frac{1}{2\beta} \left\{ 1 + e^{rt} - \sqrt{(1 + e^{rt})^2 - 4e^{rt}\theta / (1 + \theta)} \right\}. \tag{14}$$

It follows that

$$\begin{aligned} k(u, \eta, b^*, l, t) &:= \lambda \int_{(l,t)} \hat{f}_X^P((u(1-\eta) - ib^*)e^{-rs}) ds \\ &= \frac{\lambda}{2r} \sum_{k=1}^n \left[ \frac{2\beta_k^{n-1} \left\{ \arctan\left(\frac{u(1-\eta)\beta_k}{\beta_k b^* - e^{rt}}\right) - \arctan\left(\frac{u(1-\eta)\beta_k}{\beta_k b^* - e^{rt}}\right) \right\} i + \beta_k \log \left\{ \frac{u^2(1-\eta)^2 \beta_k^2 + (e^{rt} - \beta_k b^*)^2}{u^2(1-\eta)^2 \beta_k^2 + (e^{rt} - \beta_k b^*)^2} \right\}}{\prod_{j \neq k} (\beta_k - \beta_j)} \right] \end{aligned} \tag{15}$$

For notational simplicity, we denote

$$A(u, \eta, l, t) = \prod_{k=1}^n \left\{ \frac{u^2(1-\eta)^2 \beta_k^2 + (e^{rt} - \beta_k b^*)^2}{u^2(1-\eta)^2 \beta_k^2 + (e^{rt} - \beta_k b^*)^2} \right\}^{\frac{\lambda \beta_k}{j \neq k}},$$

and

$$B(u, \eta, l, t) = \frac{\lambda}{r} \sum_{k=1}^n \left[ \frac{\beta_k^{n-1} \left\{ \arctan\left(\frac{u(1-\eta)\beta_k}{\beta_k b^* - e^{rt}}\right) - \arctan\left(\frac{u(1-\eta)\beta_k}{\beta_k b^* - e^{rt}}\right) \right\}}{\prod_{j \neq k} (\beta_k - \beta_j)} \right].$$

Then, the Fourier transform of the distribution of  $S_t$  can be written as

$$\hat{f}_S^Q(u, t) = \exp\{k(u, 0, b^*, 0, t) - k(0, 0, b^*, 0, t)\} = \frac{A(u, 0, 0, t)}{A(0, 0, 0, t)} e^{iB(u, 0, 0, t)} \quad (16)$$

Substituting the above into (9) gives the market price of the stop loss contract. ■

#### 4. Risk Neutral Distribution of Increment of Loss Processes and a Ratchet Option Price

We now derive the Fourier transform of the risk neutral distribution of the increment of the loss process. The price formula of a ratchet option is shown.

For a fixed  $\eta \geq 0$  and  $0 \leq l \leq t \leq T$ , let us consider a general increment of the loss process,

$$\begin{aligned} Z_{l,t}(\eta) &:= S_t - \eta S_l = \int_{(0,t] R^+} e^{-ru} x N(du, dx) - \eta \int_{(0,l] R^+} e^{-ru} x N(du, dx) \\ &= \int_{(0,l] R^+} (1 - \eta) e^{-ru} x N(du, dx) + \int_{(l,t] R^+} e^{-ru} x N(du, dx) \quad (17) \end{aligned}$$

As noted in the Remark 1, under  $Q$ , the jump process follows an inhomogeneous Poisson process with the intensity function  $\lambda_s^Q = \lambda \hat{f}_X^P(-ib^* e^{-rs})$ , which depends on time. The claim size distribution

$dF_X^Q(x, s) = \frac{\exp\{b^* e^{-rs} x\}}{\hat{f}_X^P(-ib^* e^{-rs})} dF_X^P(x)$  is also a function of time. Fortunately,

the distribution still has an independent increments property. The first and the second terms in (17) are non-overlapping and thus independent under both measures  $P$  and  $Q$ . Based on Theorem 1, the property provides the following expression for the Fourier transform of  $Z_{l,t}(\eta)$  under  $Q$ .

**Corollary 3.** For a fixed  $\eta \geq 0$  and  $0 \leq l \leq t \leq T$ , the Fourier transform of risk neutral distribution of the general increment process  $Z_{l,t}(\eta)$  is expressed as

$$\begin{aligned}
 \hat{f}_{Z_{l,t}}^Q(u, \eta) &= E^Q \left[ e^{iu(S_t - \eta S_l)} \right] \\
 &= E^Q \left[ \exp \left\{ iu \left( \int_{(0,l)} \int_{R^+} (1-\eta) e^{-rs} x N(ds, dx) + \int_{(l,t)} \int_{R^+} e^{-rs} x N(ds, dx) \right) \right\} \right] \\
 &= E^Q \left[ \exp \left\{ \int_{(0,l)} \int_{R^+} iu(1-\eta) e^{-rs} x N(ds, dx) \right\} \right] E^Q \left[ \exp \left\{ \int_{(l,t)} \int_{R^+} iue^{-rs} x N(ds, dx) \right\} \right] \\
 &= \exp \left\{ \lambda \left( \int_{(0,l)} \hat{f}_X^P((u(1-\eta) - ib^*) e^{-rs}) ds + \int_{(l,t)} \hat{f}_X^P((u - ib^*) e^{-rs}) ds - \int_{(0,l)} \hat{f}_X^P(-ib^* e^{-rs}) ds \right) \right\}
 \end{aligned} \tag{18}$$

The expectation of  $Z_{l,t}(\eta)$  is

$$E^Q[Z_{l,t}(\eta)] = \frac{\lambda}{rb^*} \left\{ (1-\eta)E^P[e^{b^*X}] - E^P[e^{b^*e^{-r}X}] + \eta E^P[e^{b^*e^{-r}X}] \right\}. \tag{19}$$

By substituting the Fourier transform (18) and the expectation (19) into the stop-loss price formula (9), we can obtain

$$E^Q[(S_t - \eta S_l)_+] = E^Q[(Z_{l,t}(\eta))_+] = \frac{E^Q[Z_{l,t}(\eta)]}{2} + \frac{1}{\pi} PV \int_0^\infty \text{Re} \left[ \frac{(\hat{f}_{Z_{l,t}}^Q(u, \eta) - 1)}{(iu)^2} \right] du. \tag{20}$$

**Example (continued): Generalized Erlang(n) claim size distribution**

The expectation of  $Z_{l,t}(\eta)$  is

$$E^Q[Z_{l,t}(\eta)] = \frac{\lambda}{rb^*} \left\{ (1-\eta) \prod_{k=1}^n (1 - \beta_k b^*)^{-1} - \prod_{k=1}^n (1 - \beta_k e^{-r} b^*)^{-1} + \eta \prod_{k=1}^n (1 - \beta_k e^{-r} b^*)^{-1} \right\}.$$

Recalling Eq. (15), the Fourier transform (18) can be written as

$$\begin{aligned}\hat{f}_{Z,t}^Q(u, \eta) &= \exp\{k(u, \eta, b^*, 0, t) + k(u, 0, b^*, l, t) - k(0, \eta, b^*, 0, t)\} \\ &= \frac{A(u, \eta, 0, l) \cdot A(u, 0, l, t)}{A(0, \eta, 0, t)} \exp\left[\{B(u, \eta, 0, l) + B(u, 0, l, t)\}i\right].\end{aligned}$$

By substituting these formulae into the price formula (20), we can obtain an integral expression of stop loss contract where the threshold depends on the loss history. ■

### Ratchet option on motor loss rate

The actual loss ratio is defined as the actual aggregate loss divided by the total gross premium over a period of time  $[0, t]$ . In practice, the fixed loss rate is essentially determined by the historical claims data and is usually accomplished by simulating the future loss that can be assumed to be retained by the insurance companies.

We denote gross aggregate premium collected on  $[0, t]$  by

$$G_t = (1 + \theta^*)E^P[S_t] = (1 + \alpha)C_t = (1 + \alpha)(1 + \theta)\lambda E^P[X]\bar{a}_{\bar{t}} = G\bar{a}_{\bar{t}}, \quad (21)$$

where  $\theta$  is a risk adjustment parameter, and  $\alpha$  is a security loading factor (expense rate).

Let us denote the actual cumulative loss rate by  $q_t$ ,

$$q_t = \frac{S_t}{G\bar{a}_{\bar{t}}} = \frac{L_t}{G\bar{s}_{\bar{t}}}, \quad (22)$$

where  $L_t = S_t e^{rt}$  is the cumulative loss until the time  $t$ ; and  $\bar{a}_{\bar{t}}$  and  $\bar{s}_{\bar{t}} = e^{rt}\bar{a}_{\bar{t}}$  are the present value and the accumulated value, respectively, of continuously paying annuities with unit of annual payment.

For each settlement point, the threshold of the ratchet option is defined as

$$\hat{q}_t(\pi) = \begin{cases} (1 + \pi)E^Q[q_t] = (1 + \pi)\frac{E^Q[S_t]}{G\bar{a}_{\bar{t}}}, & i = 1, \\ (1 + \pi)q_{t-1} = (1 + \pi)\frac{S_{t-1}}{G\bar{a}_{\bar{t}-1}}, & i > 1. \end{cases} \quad (23)$$

Note that the threshold evolves over time and depends on the actual loss of the previous settlement point. The parameter  $\pi$  ( $> -1$ ) determines the level of the subsequent strike thresholds and must be specified upfront. If an insurer would like to hedge the extreme losses above the previous period realized loss, a large  $\pi$  is preferred.

At each settlement date, the protection seller (issuer) will pay the premium collected multiplied by the excess loss rate beyond the prefixed threshold. Thus, a no-arbitrage price of the  $n$ -year ratchet option is given as

$$\begin{aligned}
 V(\pi; 0) &= E^Q \left[ \sum_{i=1}^n G\bar{a}_{\overline{t_i}|} (q_{t_i} - \hat{q}_{t_i}(\pi))_+ \right] \\
 &= E^Q \left[ G\bar{a}_{\overline{t_1}|} (q_{t_1} - (1 + \pi)E^Q[q_{t_1}])_+ \right] + E^Q \left[ \sum_{i=2}^n G\bar{a}_{\overline{t_i}|} (q_{t_i} - (1 + \pi)q_{t_{i-1}})_+ \right] \\
 &= E^Q \left[ (S_{t_1} - (1 + \pi)E^Q[S_{t_1}])_+ \right] + \sum_{i=2}^n E^Q \left[ (S_{t_i} - (1 + \pi)\delta(t_{i-1}, t_i)S_{t_{i-1}})_+ \right],
 \end{aligned} \tag{24}$$

where  $\delta(t_{i-1}, t_i) = \frac{1 - e^{-\eta t_i}}{1 - e^{-\eta t_{i-1}}}$ .

If we assume  $\eta = (1 + \pi)\delta(t_{i-1}, t_i)$ , then from (20) we obtain an integral expression of each summand in the ratchet option price formula (24).

## 5. Pricing Motor Loss Rate Swaps

### Plain Vanilla Motor Loss Rate Swaps

First, we consider a fixed-for-floating plain vanilla motor loss rate swap settled in arrears. Even though we have a continuous time loss rate model, we consider only the finite collection of discrete future dates  $\{T_j, j = 0, 1, \dots, n\}$  with  $T_0 = 0$ . The dates  $T_0, \dots, T_{n-1}$  are known as reset dates, and the dates  $T_1, \dots, T_n$  are known as settlement dates. The payments are made on the settlement dates and the number of payments  $n$  is called the length of a swap. The first date  $T_0$  is referred to as the start date of a swap, and we assume it is today for the sake of simplicity. The period  $[T_{j-1}, T_j]$  is called the  $j$ -th accrual period. We assume that Party A agrees to pay Party B a fixed amount of losses derived from a pre-agreed fixed loss ratio denoted by  $\hat{q}_{T_j}$  at each settlement date  $T_j, j = 1, \dots, n$ . In return, Party B agrees to pay Party A a floating amount of losses realized until each settlement date  $T_j, j = 1, \dots, n$ . The

two parties usually need to pay the net amount, that is, the difference between the two mutual obligations. Therefore, Party B should pay when the actual loss ratio exceeds the predetermined fixed loss ratio  $q_{T_j} > (1+s) \hat{q}_{T_j}$ , where  $s$  is a real number to be determined. That is,  $q_{T_j} > (1+s) \hat{q}_{T_j}$  implies that  $L_{T_j} > (1+s) \hat{q}_{T_j} G \bar{s}_{T_j|}$ , and Party B should pay  $L_{T_j} - (1+s) \hat{q}_{T_j} G \bar{s}_{T_j|}$ . If  $q_{T_j} \leq (1+s) \hat{q}_{T_j}$ , then Party A should pay  $(1+s) \hat{q}_{T_j} G \bar{s}_{T_j|} - L_{T_j}$  at time  $T_j$ .

We consider the value of a motor loss rate swap as a function of a real number  $s$  at time  $0 = T_0$ ,

$$\begin{aligned} MS(s) &= E^Q \left[ \sum_{j=1}^n e^{-rT_j} (L_{T_j} - (1+s) \hat{q}_{T_j} G \bar{s}_{T_j|}) \right] \\ &= E^Q \left[ \sum_{j=1}^n (S_{T_j} - (1+s) \hat{q}_{T_j} G \bar{a}_{T_j|}) \right]. \end{aligned} \quad (25)$$

We know that a swap value is zero at initiation; therefore, we naturally define the spread of a motor loss rate swap.

**Definition 3.** *The spread of a motor loss rate swap is the value of  $s$  that makes the value of a motor loss rate swap zero, i.e., the value of  $s$  for which  $MS(s) = 0$ .*

Using definition 3, we obtain an explicit formula for a motor loss rate swap spread,

$$s = \frac{\sum_{j=1}^n E^Q[S_{T_j}]}{\sum_{j=1}^n \hat{q}_{T_j} G \bar{a}_{T_j|}} - 1 = \frac{1}{1 + \alpha} \frac{\sum_{j=1}^n \bar{a}_{T_j|}}{\sum_{j=1}^n \hat{q}_{T_j} \bar{a}_{T_j|}} - 1. \quad (26)$$

When we consider only a one-period swap, that is,  $n = 1$ , the price is

$$s = \frac{1}{1 + \alpha} \frac{1}{\hat{q}_{T_1}} - 1.$$

If the expected loss rate  $\hat{q}_{T_1}$  is produced well enough to predict the real loss rate for the next period, then the swap prices should be zero and the expense rate should be

$$\alpha = \frac{1}{\hat{q}_{T_1}} - 1.$$



Given the value of  $s$  determined above, we can calculate the market price of the swap at any time  $t \geq T_0$ . The following Corollary 4 of Theorem 1 can be shown based on the fact that the loss distribution  $S_t$  still has the property of independent increments after the change in measure. This can also be seen in remark 1 in the previous section.

**Corollary 4.** Under the Esscher transformed measure  $Q$ , the Fourier transform of the conditional distribution  $S_t$  given by  $S_t = y$  has the following expression:

$$\begin{aligned} \hat{f}_s^Q(u, t; y, l) &= E^Q \left[ e^{i u S_t} \mid S_t = y \right] = E^Q \left[ \exp \left\{ i u y + \int_{(l, t)} \int_{R^+} i u x e^{-rs} N(ds, dx) \right\} \mid S_t = y \right] \\ &= \exp \left\{ i u y + \lambda \int_l^t \left\{ \hat{f}_X^P((u - i b_t) e^{-rs}) - \hat{f}_X^P(-i b_t e^{-rs}) \right\} ds \right\}. \end{aligned} \quad (27)$$

Then, the conditional expectation can be written as

$$\begin{aligned} E^Q[S_t \mid S_t = y] &= \frac{1}{i} \frac{d}{du} \hat{f}_s^Q(u, t; y, l) \Big|_{u=0} \\ &= y + \frac{\lambda}{r b_t} \left\{ E^P[e^{b_t e^{-rt} X}] - E^P[e^{b_t e^{-rt} X}] \right\}. \end{aligned} \quad (28)$$

By using the above conditional expectation under the measure  $Q$ , the market price of the swap at a time in the  $j$ -th accrual period,  $t \in (T_{j-1}, T_j)$ , can be expressed as

$$\begin{aligned} V(t) &= E^Q \left[ e^{rt} \sum_{i=j}^n (S_{T_i} - (1+s) \hat{q}_{T_i} G \bar{a}_{\bar{T}_i}) \mid S_t \right] \\ &= e^{rt} \left( \sum_{i=j}^n E^Q[S_{T_i} \mid S_t] - \frac{\sum_{i=j}^n \hat{q}_{T_i} \bar{a}_{\bar{T}_i}}{\sum_{i=1}^n \hat{q}_{T_i} \bar{a}_{\bar{T}_i}} \sum_{i=1}^n E^Q[S_{T_i}] \right) \\ &= e^{rt} \left( (n-j+1) S_t + \sum_{i=j}^n \frac{\lambda}{r b^*} \left\{ E^P[e^{b^* e^{-rt} X}] - E^P[e^{b^* e^{-rt} X}] \right\} - C \sum_{i=1}^n \bar{a}_{\bar{T}_i} \frac{\sum_{i=j}^n \hat{q}_{T_i} \bar{a}_{\bar{T}_i}}{\sum_{i=1}^n \hat{q}_{T_i} \bar{a}_{\bar{T}_i}} \right). \end{aligned} \quad (29)$$

## 6. Numerical Examples and Problems

Here, we consider some numerical examples under certain specific assumptions on the distribution of the discounted losses and the parameters.<sup>10</sup> At the end of the section, we also discuss a few issues on the development of motor insurance-linked securities.

As an illustration, we assume that the losses follow a discounted compound Poisson process with generalized Erlang(2) claim size distribution. We postulate the Poisson parameter  $\lambda = 12$ ,  $\beta_1 = 5$ ,  $\beta_2 = 15$ ,<sup>11</sup> and maturity  $T = 5$ .

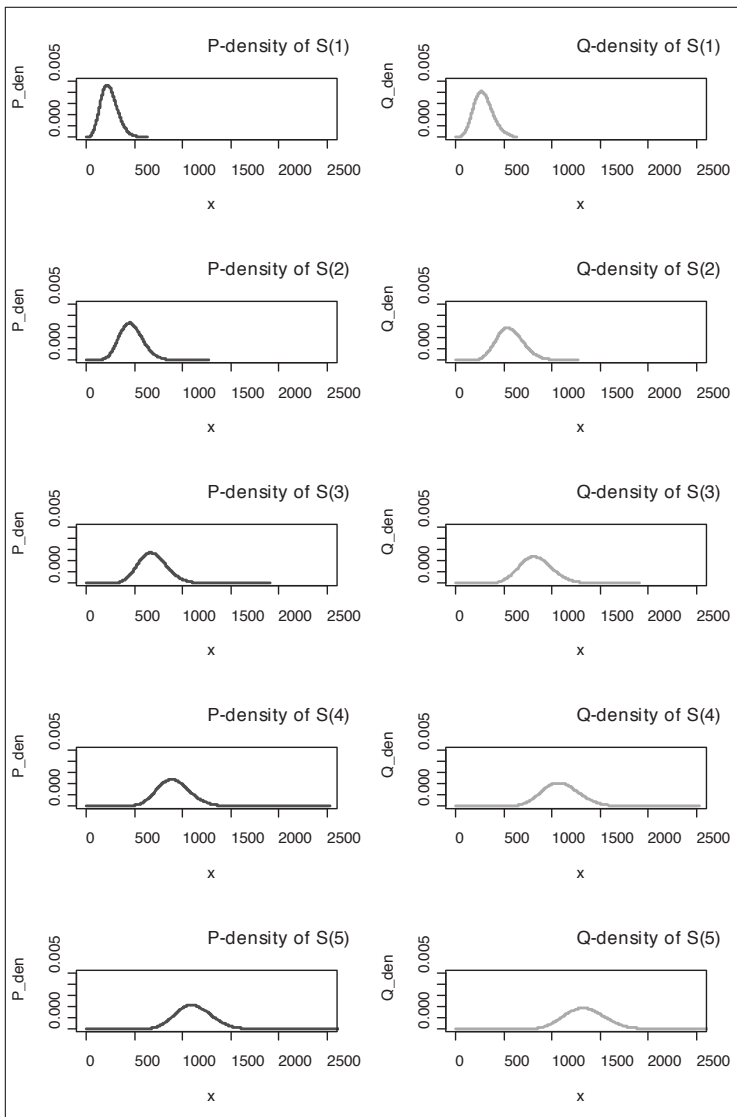
Table 1 summarizes the risk adjusted premium rate  $C = (1 + \theta)\lambda E^P[X]$  and the Esscher parameter  $b^* = b_5$  for several different choices of the risk adjustment parameter  $\theta$  and the interest rate  $r$ . It is evident from Table 1 that the Esscher parameter increases in both the loading factor and the interest rate. The risk adjustment parameter and the interest rate are the two main input components that determine the riskiness of the underlying loss process. The higher value of the Esscher parameter results in a shift of loss distribution to the right.

■ TABLE 1 *Premium rate and Esscher parameters*

$\theta$	$r$	$C$	$b^*$
0.1	0.01	264	0.002967
	0.03		0.003108
	0.05		0.003248
	0.07		0.003386
0.2	0.01	288	0.005534
	0.03		0.005802
	0.05		0.006066
	0.07		0.006326
0.3	0.01	312	0.007828
	0.03		0.008207
	0.05		0.008581
	0.07		0.008946

Figure 1 shows the evolution of the discounted loss distribution  $S_t$  over time and compares the two densities  $f_S^P(x,t)$  and  $f_S^Q(x,t)$  when  $\theta = 0.2$  and  $r = 0.03$  based on 100,000 simulations. For the simulation under the risk neutral measure, the arrival times of the inhomogeneous Poisson process with rate function  $\lambda_t$  are simulated by a thinning algorithm. For each simulated arrival time, a risk neutral claim amount is generated by the density  $f_X^Q(x,t)$  using rejection algorithm. See Ross (2002) for details on these algorithms.

■ FIGURE 1 Evolution of loss process



We can see from the figure that the distributions of the discounted losses under the Esscher transform are translated to the right, which reflects the risk aversion of capital market participants.

Table 2 gives the time zero prices of five-year ratchet options for different choices of  $\theta$  corresponding to different coverage levels  $\pi$ . Here we assume that the interest rate  $r$  is  $0.03$ . It shows that high risk adjustment parameters make the option price large for moderate coverage levels ( $\pi = 0, 0.1, \text{ or } 0.2$ ). The prices become smaller for extreme coverage cases. This is because the left tail of the Esscher transformed distribution becomes heavier as the risk adjustment parameter gets larger. One can also see from the table that the option prices decrease rapidly as the coverage rate  $\pi$  increases for each  $\theta$ .

■ TABLE 2 *Time zero price of five-year ratchet options*

$\theta$	$\pi$	$V(\pi; \theta)$	$\theta$	$\pi$	$V(\pi; \theta)$
0.1	0.0	183.65	0.3	0.0	201.59
	0.1	80.27		0.1	83.81
	0.2	40.29		0.2	40.62
	0.3	22.84		0.3	22.36
	0.4	14.02		0.4	13.34
	0.5	9.11		0.5	8.42
	0.6	6.18		0.6	5.56
	0.7	4.35		0.7	3.81
	0.8	3.15		0.8	2.70
0.2	0.0	192.85	0.4	0.0	209.84
	0.1	82.14		0.1	85.27
	0.2	40.49		0.2	40.69
	0.3	22.61		0.3	22.09
	0.4	13.68		0.4	13.00
	0.5	8.76		0.5	8.10
	0.6	5.86		0.6	5.28
	0.7	4.07		0.7	3.57
	0.8	2.91		0.8	2.49

Recall that swap spread depends on the trigger  $\hat{q}_t$ , which determines the level of insurance coverage of the swap contract. For the purpose of illustration only, we use percentile values of the loss ratio process  $q_t$  under the physical measure  $P$ . Table 3 provides the percentiles of the loss ratio process at the end of each year. We can see that the lower percentiles increase and upper percentiles decrease in time, which is due to the effect of discounting.

■ TABLE 3 Evolution of percentiles of loss ratio under  $P$   
 (  $\theta = 0.2, r = 0.03, \alpha = 0.1$  )

PERCENTILES	YR1	YR2	YR3	YR4	YR5
10%	0.42	0.51	0.56	0.58	0.6
20%	0.52	0.59	0.62	0.64	0.65
30%	0.59	0.65	0.67	0.68	0.69
40%	0.67	0.7	0.71	0.72	0.72
50%	0.73	0.75	0.75	0.75	0.75
60%	0.81	0.8	0.79	0.79	0.78
70%	0.88	0.85	0.84	0.83	0.82
80%	0.98	0.92	0.89	0.87	0.86

■ TABLE 4 Swap spreads for  $\theta = 0.2, r = 0.03, \alpha = 0.1$

$\hat{q}$	10%tile	20%tile	30%tile	40%tile	50%tile	60%tile	70%tile	80%tile
s	0.616	0.458	0.358	0.280	0.213	0.152	0.090	0.025

For given parameters, Table 4 gives the five-year swap spread for each percentile-based threshold  $\hat{q}_t$ . Let us choose the 80<sup>th</sup> percentile for the trigger  $\hat{q}_1 = 0.98$ . Then, the protection seller should pay  $1.025 \cdot 0.98 \cdot G \bar{s}_{\bar{1}|}$  to the protection buyer if the actual loss ratio is greater than  $1.025 \cdot 0.98$ . The protection buyer has to pay the same amount when the actual loss ratio is less than  $1.025 \cdot 0.98$ .

As one can see from the spread formula (26), a fair spread has an inverse relationship with the expense rate  $\alpha$  and the trigger  $\hat{q}_t$ . In general, counterparties can agree to use arbitrary thresholds. For some

cases, the spread can even be negative when the expense rate is chosen to be much higher than the ideal level. The spread can be equal to zero when the expense rate  $\alpha = \frac{\sum_{j=1}^n \bar{a}_{T_j}}{\sum_{j=1}^n \hat{q}_t \bar{a}_{T_j}} - 1$ . When the  $P$ -percentile-based thresholds are used (as in this example), the effect of the increase in expense rate is cancelled out due to the decrease in the threshold at the same rate. Thus, the swap spread remains unchanged regardless of the choice of expense rates. This suggests that  $P$ -percentile is a sensible choice for the trigger  $\hat{q}_t$ .

Now, let us discuss a few issues on the MILS.<sup>12</sup> Bae et al. (2009) derived the theoretical framework and methodology and showed the usefulness of motor loss rate securitization. There are certain benefits of using options and swaps over the existing market instruments for motor insurance securitization. The main advantages of the hybrid derivatives over tranche notes are their easiness and flexibility. They can design the derivatives according to their needs. The swaps and options are over-the-counter contracts; they would require smaller transaction costs. However, over-the-counter contracts may have counterparty risks, and this can be a disadvantage.

For tranche notes with fixed loss rate trigger, there would be possibility of moral hazard by insurers. As maturity approaches, insurers may mark up their insurance loss ratios to obtain reimbursement from the protection sellers (investors). Also, it is possible that motor insurers may put less effort in underwriting and loss assessment to minimize insurance losses. These moral hazards can be reduced by establishing independent special purpose vehicles (SPVs) responsible for auditing the determination of loss ratios as well as issuing and pricing the securities. The motor insurance loss rate ratchet option proposed in this paper dissuades insurers from inflating their insurance losses in the middle of the security tenure. The multi-term ratchet option resets the loss trigger periodically according to the realized loss ratios of the previous years. The insurer may obtain benefits by manipulating the loss ratio of one period. However, the benefit will be cancelled in the following period due to a high loss rate trigger. Also, there can be legal issues in almost all aspects of the MILS operation. They can resolve the legal issues using regulations or laws. In particular, regulators should focus on the financial soundness of issuers and market participants.

Motor insurance-linked securities can be an effective alternative to the reinsurance markets, which have a strong development potential for high-risk groups that may not be (re)insured under the current

insurance/reinsurance practices. Capital market investors are likely to welcome the risks expecting high returns as compensation for taking risks. Insurance companies benefit from the securitization because they can expand the risk pool by accepting high-risk groups that are otherwise uninsurable. In addition, the ability to insure the high-risk groups makes the insurance industry competitive and gives it a level playing field with other financial institutions such as banks.

## 7. Conclusions

When an insurer decides to sell motor insurance contracts covering the losses from motor accidents, it should consider appropriate models to estimate the expected amount of annual claims. However, the insurer can be exposed to the risk of the actual loss rate being higher than expected. As a hedging method, we suggest the use of hybrid derivatives for motor insurance loss rate risk transfer. We consider a few motor insurance-linked derivatives such as motor insurance loss rate options and swaps, which can be traded over the counter in a capital market. They are designed not only to provide the insurer with innovative hedging methods for its loss rate risks but also to give more investment choices to the potential investors in the financial market.

The insurer may want to exchange random cash flows in the future based on the outcome of motor loss rates with prefixed values. In this case, the insurance company would use motor loss rate swaps. When an insurer is particularly interested in managing extreme loss rate risks, a swap contract would be inappropriate. Alternative methods considered is a motor loss rate ratchet option that can be used to protect the motor insurance providers against the risks of higher motor loss rates without giving up the possible benefits of lower motor loss rates. The pricing formulas of a ratchet option and swaps on motor insurance loss rates are given under a few assumptions made on the aggregate loss process. We choose the Esscher transform to link between the insurance market and capital market. The risk neutral pricing formulas for the ratchet option and swaps are obtained by using Fourier inversion and are expressed in integral forms.

We show numerical examples using numerical integration and simulation methods to illustrate the derivative prices and their characteristics when the claim amount distribution follows a generalized Erlang distribution.

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## NOTES

1. For more detailed information and discussion see Deringer (2006), De Mey (2007), AXA Financial Protection (2005), and Towers Perrin, Tillinghast (2006).

2. For modelling the aggregate losses, losses will be accumulated from the date of issue to maturity.

3. See Gerber and Shiu (1994) or Miyahara and Fujiwara (2003) for details.

4. Once maturity  $t$  is fixed,  $h_t$  is determined and assumed to be constant over the period  $(0, t]$ . For notational convenience, it is denoted by  $h^*$ .

5. Price of a stop loss contract under the compound Poisson distribution can be calculated by using the numerical method or recursion such as the Panjer recursion formula. See Covens et al. (1979), Bühlmann (1984), Gerber (1982), and Panjer (1981) for reference. The Esscher change of measure, the general form of the Laplace transforms, and the expectations of these processes are well studied in the literature such as Jacod and Shiryaev (2003) and Dufresne et al. (2009).

6. Same idea is used in Jang and Krvavych (2004).

7. We can find a martingale measure  $Q$  or the Esscher parameter  $h_t$  directly from the market when the market becomes active and mature. This approach can be an alternative when the market is new and young.

8. Exponential (or Gamma) distribution is often used in generalized linear models on aggregated insurance data. See Smyth and Jorgensen (2002) for examples.

9. We assume that the Esscher parameter is constant once the maturity  $t$  is fixed. Thus, we drop  $t$  in the expression.

Numerical integrations are implemented using the R-function *integrate*. A 100,000 simulations of  $S_t$  are conducted under  $Q$  based on Remark 1. For each simulation, the risk neutral arrival times of the inhomogeneous Poisson process with rate function  $\lambda_t$  are simulated by a thinning algorithm. For each arrival time, a risk neutral claim amount is generated by the density  $f_x^Q(x, t)$  using rejection algorithm. See Ross (2002) for details on these algorithms.

10. The choice of loss frequency and claim size parameters is more or less arbitrary. We roughly use the 2007 US private passenger insurance losses data given by Insurance Information Institute, in Auto Insurance (2009), available at <http://www.iii.org/media/facts/statsbyissue/auto/>. Statistics indicate that the frequency of liability claims is about 5 per 100 vehicles, and the average claim severity is about \$15,000 when we add bodily injury and property damage. For collision and comprehensive coverage, the frequency is about 7 per 100 vehicles and the average per claim severity is roughly \$5,000. We use the Poisson parameter  $\lambda = 12$  ( $= 5+7$ ),  $\beta_1 = 5$  and  $\beta_2 = 15$  for illustrative purposes. The results may vary when the assumptions are changed.

11. More detailed discussions regarding MILS can be found in Bae and Kim (2010).