Pricing extreme mortality risk in the wake of the COVID-19 pandemic

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L18: The Eighteenth International Longevity Risk and Capital Markets Solutions Conference

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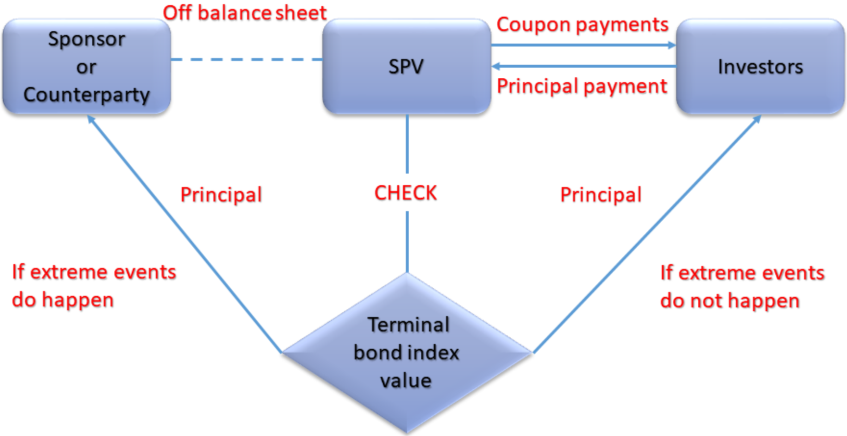
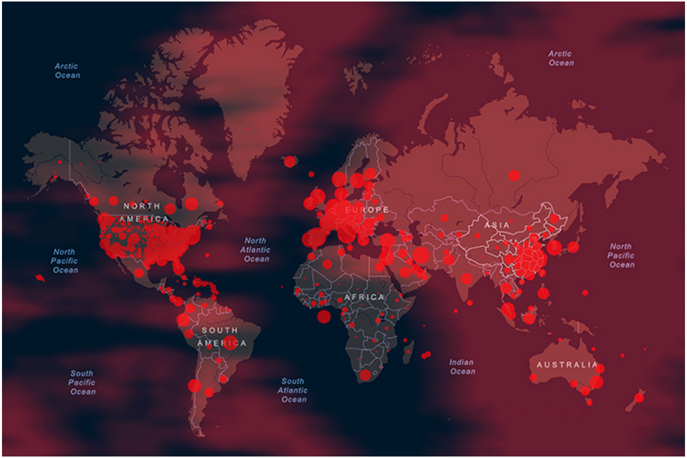
Catastrophe bond and extreme insurance risk

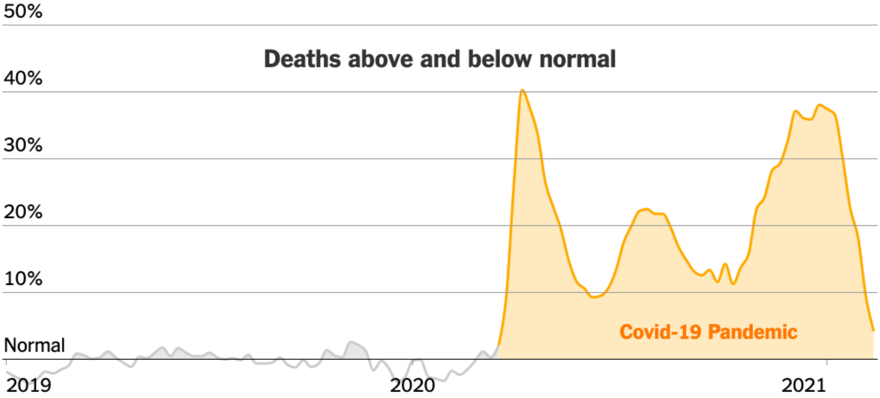


A 1 in 100 (?) year event



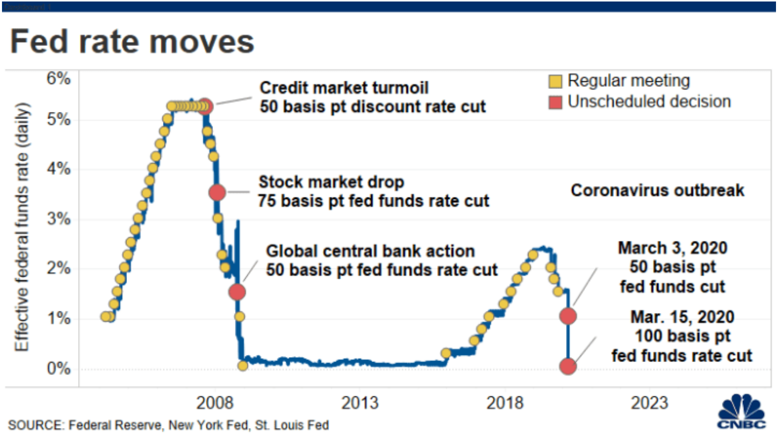
Source: `https://coronavirus.jhu.edu/map.html`

US: 574,000 more deaths than normal since March 2020



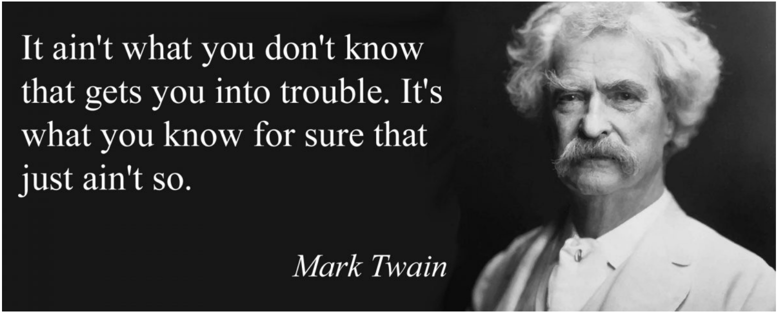
Source: `https://www.nytimes.com/interactive/2021/01/14/us/covid-19-death-toll.html`

Federal Reserve: emergency rate cut



It is a common practice, but ...

It is **commonly** **assumed**, but **rarely** **tested**, that the interest rate and the mortality rate are *mutually independent*.



Outline of the talk

1. Background and motivation
2. The affine jump-diffusion (AJD) model
   - Dynamics under P
   - The pricing measure Q
3. Modeling mortality-linked securities
   - Model calibration
   - Atlas IX Capital Ltd. bond 2013
4. Implied market prices of risk
   - Numerical analysis
   - Sensitivity test
5. Conclusion remarks

The affine jump-diffusion (AJD) model

Assume that the bivariate process $\{\mathbf{Y}_t = (r_t, \mu_t)^\intercal\}_{0\leq t\leq T}$ follows an affine jump-diffusion (AJD) process. Precisely, for $0 \leq t \leq T$,

$$d\mathbf{Y}_t = \mathbf{K}_t(\boldsymbol{\theta}_t - \mathbf{Y}_t)dt + \boldsymbol{\Sigma}_t\sqrt{\mathbf{S}_t}d\mathbf{W}_t + \sum_{i=1}^{m} d\mathbf{J}_{i,t}, \tag{1}$$

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- the elements of $\mathbf{K}_t$, $\boldsymbol{\Sigma}_t$, and $\boldsymbol{\theta}_t$ are all deterministic functions of t;

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where:

- the elements of $\mathbf{K}_t$, $\boldsymbol{\Sigma}_t$, and $\boldsymbol{\theta}_t$ are all deterministic functions of t;
- $\mathbf{W}_t = (W_{1,t}, W_{2,t})^\intercal$ is a standard **Brownian motion**;

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- the elements of $\mathbf{K}_t$, $\boldsymbol{\Sigma}_t$, and $\boldsymbol{\theta}_t$ are all deterministic functions of t;
- $\mathbf{W}_t = (W_{1,t}, W_{2,t})^\intercal$ is a standard **Brownian motion**;
- $\mathbf{S}_t$ is a diagonal matrix, where $[\mathbf{S}_t]_{ii} = \alpha_{i,t} + \boldsymbol{\beta}_{i,t}^\intercal \mathbf{Y}_t$ with $\alpha_{i,t}$ and $\boldsymbol{\beta}_{i,t}$ being deterministic functions of t;

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- $\mathbf{J}_{i,t} = \sum_{k=1}^{N_{i,t}} \mathbf{X}_{i,k}$ is a **compound Poisson process** with rate $\lambda_i > 0$ and jump size distribution G_i.

The pricing measure Q

Under the measure Q, we look at two types of risk embedded in our model

- Systematic risk: $\{\mathbf{W}_t\}$, the main driving force inherent in the market

$$d\mathbf{W}_t^Q = d\mathbf{W}_t - \mathbf{\Gamma}_t dt, \qquad 0 \leq t \leq T,$$

- Jump risk: For each $i = 1, \ldots, m$, $\{\mathbf{J}_{i,t}\}_{0 \leq t \leq T}$ is a compound Poisson process with intensity λ_i^* and common jump size distribution G_i^*;

$\{\mathbf{W}_t^Q\}_{0 \leq t \leq T}$ and $\{\mathbf{J}_{i,t}\}_{0 \leq t \leq T}$, $i = 1, \ldots, m$, are mutually independent.

An important special case

The interest rate and mortality rate intensities are modeled by

$$
\begin{cases}
dr_t = (m_1 - d_1 r_t)dt + \sigma_1 dW_{1,t} + d\sum_{i=1}^{N_t} X_{1,i}, \\
d\mu_t = (m_2 - d_2 \mu_t)dt + \sigma_2 \left(\rho_1 dW_{1,t} + \sqrt{1-\rho_1^2} dW_{2,t}\right) + d\sum_{i=1}^{N_t} X_{2,i},
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where, under measure P,

- $m_i \in \mathbb{R}$, $d_i \neq 0$, $\sigma_i > 0$, for $i = 1, 2$, and $\rho_1 \in [-1, 1]$ are constants;

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- $\{\mathbf{X}_j = (X_{1,j}, X_{2,j})^\intercal\}_{j \in \mathbb{N}}$ and $\mathbf{X} \sim N(\nu_1, \nu_2; \phi_1, \phi_2; \rho_2)$;

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- $\{N_t\}_{0\le t\le T}$ and $\{\mathbf{X}_j\}_{j\in\mathbb{N}}$ are independent.

An important special case

Under the Q measure, we consider

- Market price of diffusion risk: $\mathbf{\Gamma}_t = (\gamma_1, \gamma_2)^\intercal \in \mathbb{R}^2$, where

$$dW_{i,t} = dW_{i,t}^Q + \gamma_i dt \text{ for } i = 1, 2$$

We can then rewrite the dynamics as

$$\begin{cases} dr_t = (m_1^* - d_1 r_t)dt + \sigma_1 dW_{1,t}^Q + d\sum_{i=1}^{N_t} X_{1,i}, \\ d\mu_t = (m_2^* - d_2\mu_t)\,dt + \sigma_2\left(\rho_1 dW_{1,t}^Q + \sqrt{1-\rho_1^2}dW_{2,t}^Q\right) + d\sum_{i=1}^{N_t} X_{2,i}, \end{cases}$$

with

$$m_1^* = m_1 + \gamma_1\sigma_1, \qquad m_2^* = m_2 + \gamma_1\sigma_2\rho_1 + \gamma_2\sigma_2\sqrt{1-\rho_1^2}.$$

An important special case

Under the Q measure, we also consider

- Market price of jump-frequency risk
  - $\{N_t\}_{0\leq t\leq T}$ is a Poisson process with intensity $\lambda^* > 0$;
  - $\chi = \frac{\lambda^*}{\lambda} > 0$ reflects the market price of jump-frequency risk.
- Market price of jump-size risk:
  - Normalized multivariate exponential tilting to construct the common distribution G^* of $\{\mathbf{X}_j\}_{j\in\mathbb{N}}$;
  - $\mathbf{X} \sim N\left(\nu_1^*, \nu_2^*; \phi_1, \phi_2; \rho_2\right)$ where $\nu_1^* = \nu_1 + \phi_1\kappa_1$ and $\nu_2^* = \nu_2 + \phi_2\kappa_2$.

Data description

We consider the US weekly mortality and interest rate data for the period of 2017–2020, which are collected from three sources as follows:

- ***CDC COVID-19 Data***. We collect national-level weekly observed deaths and the expected deaths for the period Jan 2017–Dec 2020.
- ***U.S. Census Bureau***. We collect population data for 2017–2020.

We define excess mortality as

$$\mu_t = \frac{d_t - E(d_t)}{e_t},$$

where d_t is the observed number of deaths, and $E(d_t)$ and e_t are, respectively, the expected number of deaths and the population exposure.

Data description

- ***Federal Reserve Economic Data (FRED)***. The weekly interest rate data comes from the 3-month treasury bill rates, collected at the same frequency and for the same period as the mortality data.

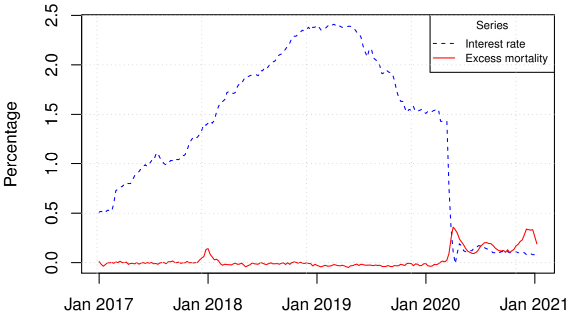

Figure: U.S. weekly interest rate and excess mortality

Model calibration: MCMC

- Likelihood based inference using MCMC.
- Evolution of the moment generating function is a Partial Differential Equation (PDE).
- This PDE is used to approximate the likelihood to a high degree of accuracy.
- Random Walk Metropolis Hastings used to explore the posterior.

Calibration including the pandemic experience

The interest rate and mortality rate intensities are modeled by

$$\begin{cases} dr_t = (0.005 - 0.126 r_t)dt + 0.002 dW_{1,t} + d\sum_{i=1}^{N_t} X_{1,i}, \\ d\mu_t = (0.002 - 2.301\mu_t)dt + 0.124\left(-0.038 dW_{1,t} + 0.99928 dW_{2,t}\right) + d\sum_{i=1}^{N_t} X_{2,i}, \end{cases}$$

where, under P,

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- $\{\mathbf{X}_j = (X_{1,j}, X_{2,j})^\intercal\}_{j \in \mathbb{N}}$ is a sequence of i.i.d. bivariate random vectors such that the generic vector $\mathbf{X} \sim N(-0.001, 0.035; 0.002, 0.074;$ **–0.479**$)$;

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Calibration excluding the pandemic experience

The interest rate and mortality rate intensities are modeled by

$$\begin{cases} dr_t = (0.016 - 0.727 r_t)dt + 0.002 dW_{1,t} + d\sum_{i=1}^{N_t} X_{1,i}, \\ d\mu_t = (-0.217 - 16.368\mu_t)dt + 0.095\left(0.017 dW_{1,t} + 0.99986 dW_{2,t}\right) + d\sum_{i=1}^{N_t} X_{2,i}, \end{cases}$$

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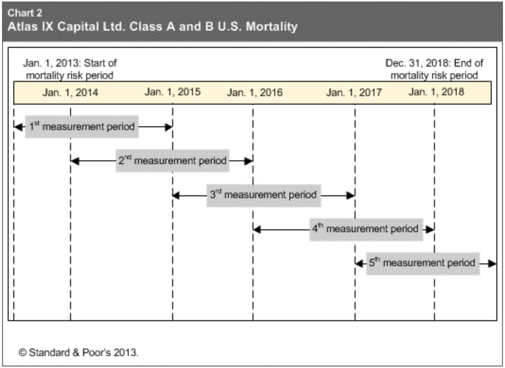
- $\{\mathbf{X}_j = (X_{1,j}, X_{2,j})^\intercal\}_{j\in\mathbb{N}}$ is a sequence of i.i.d. bivariate random vectors such that the generic vector $\mathbf{X} \sim N\left(0.000, 0.026; 0.001, 0.056; \mathbf{-0.479}\right)$;

Modeling mortality-linked securities

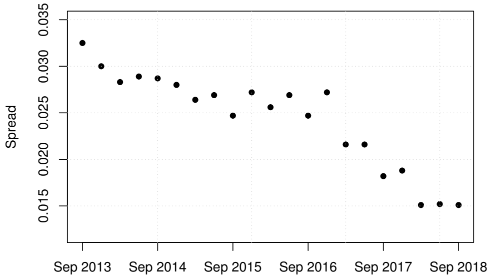
Launched by Atlas IX Capital Ltd in September 2013, the Atlas bond is the first catastrophe bond from SCOR which covers extreme mortality risk.



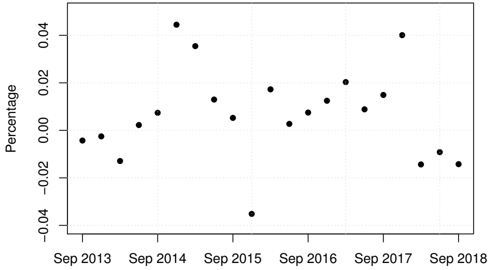
- Risk period: Jan 2013 – Dec 2018
- Coupon payment: 3.25% above the three-month LIBOR rate
- Underlying mortality: U.S. total population

Market prices of risk

Baseline price: the Atlas bond market price throughout 2013–2018.



Quarterly market-indicated spreads of the Atlas bond, published by Lane Financial L.L.C.



Estimated quarterly excess mortality.

Three scenarios

Idea: Minimizing the difference between theoretical price and observed price.
Method: Limited-memory Broyden–Fletcher–Goldfarb–Shanno method.

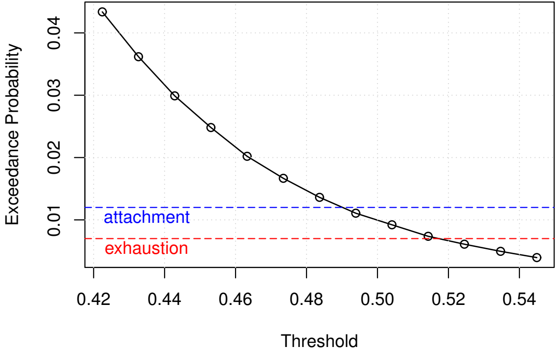
We compute the MPRs for three different scenarios:

S1. Underlying risks ⇒ post-pandemic model
Bond trigger levels ⇒ post-pandemic model;

S2. Underlying risks ⇒ pre-pandemic model;
Bond trigger levels ⇒ pre-pandemic model;

S3. Underlying risks ⇒ post-pandemic model
Bond trigger levels ⇒ pre-pandemic model.

Scenario one

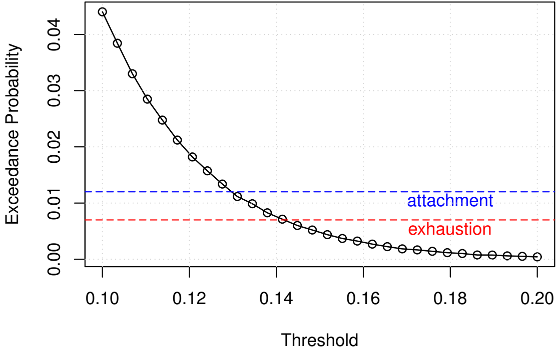


The MPR vector is obtained as

$$\zeta_1 = (\gamma_1, \gamma_2; \kappa_1, \kappa_2; \chi) = (0.4161,\ 0.1897;\ 0.1119,\ 0.3889;\ 1.0918)\,.$$

Investors' perceived parameter values under Q are all riskier than their P measure counterparts.

Scenario two



The MPR vector is obtained as

$$\zeta_2 = (\gamma_1, \gamma_2; \kappa_1, \kappa_2; \chi) = (0.1099,\ 0.0924;\ 0.1068,\ 0.0961;\ 1.3144)\,.$$

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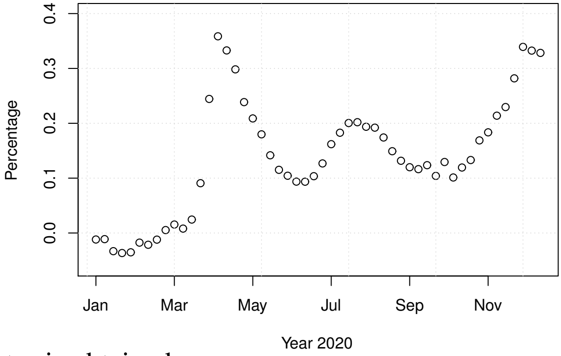
Scenario three



The MPR vector is obtained as

$$\zeta_3 = (\gamma_1, \gamma_2; \kappa_1, \kappa_2; \chi) = (1.0944,\ -1.6196;\ 1.0743,\ -4.0847;\ 1.6419)\,.$$

Investors are receiving negative mortality risk premia although the interest rate risk premia they receive are positive.

Three scenarios

	Scenario 1		Scenario 2		Scenario 3	
Parameter	Under P	Under Q	Under P	Under Q	Under P	Under Q
$m_1 \leftrightarrow m_1^*$	0.005	0.0058	0.016	0.0162	0.005	0.0072
$m_2 \leftrightarrow m_2^*$	0.002	0.0235	−0.217	−0.2080	0.002	−0.2038
$\nu_1 \leftrightarrow \nu_1^*$	−0.001	−0.0008	0.000	0.0001	−0.001	0.0011
$\nu_2 \leftrightarrow \nu_2^*$	0.035	0.0638	0.026	0.0314	0.035	−0.2673
$\lambda \leftrightarrow \lambda^*$	4.865	5.3118	1.909	2.5091	4.865	7.9877

Sensitivity analysis

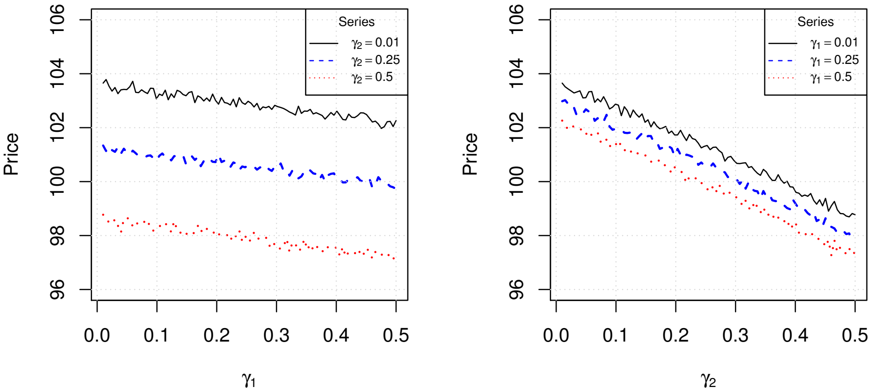


Figure: Sensitivity analysis with respect to γ_1 and γ_2

Sensitivity analysis

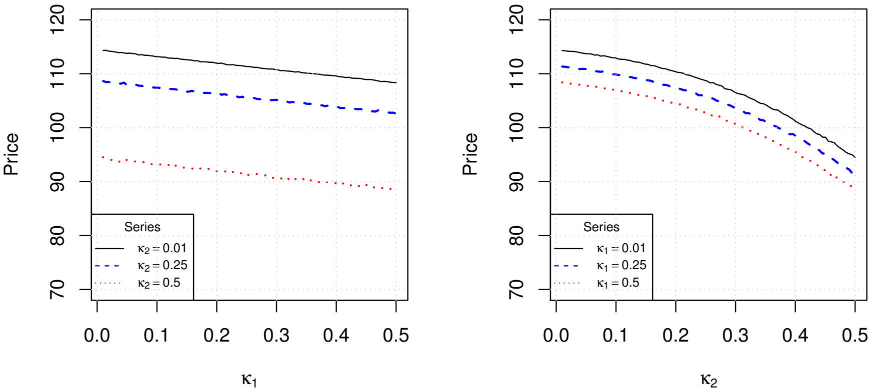


Figure: Sensitivity analysis with respect to κ_1 and κ_2

Sensitivity analysis

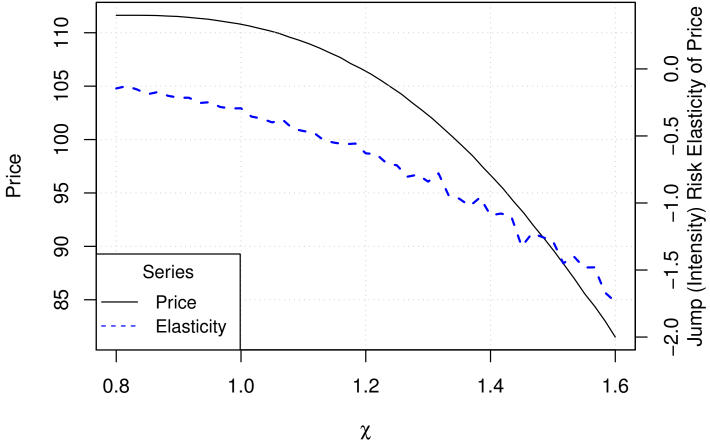


Figure: Sensitivity analysis with respect to χ

Concluding remarks

In this research, we ...

- Propose a bivariate AJD structure to jointly model the interest rate and excess mortality.
- Show that the COVID-19 pandemic experience greatly intensifies the negative instantaneous correlations.
- Develop a risk-neutral pricing measure that accounts for both a diffusion risk premium and a jump risk premium.
- Solve for the market prices of risk based on mortality CAT bond prices.

End of presentation

Thank you!

Any questions/ comments/ suggestions?

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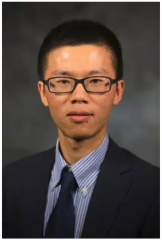
(a) Han Li


(b) Haibo Liu


(c) Qihe Tang


(d) Zhongyi Yuan

Appendix

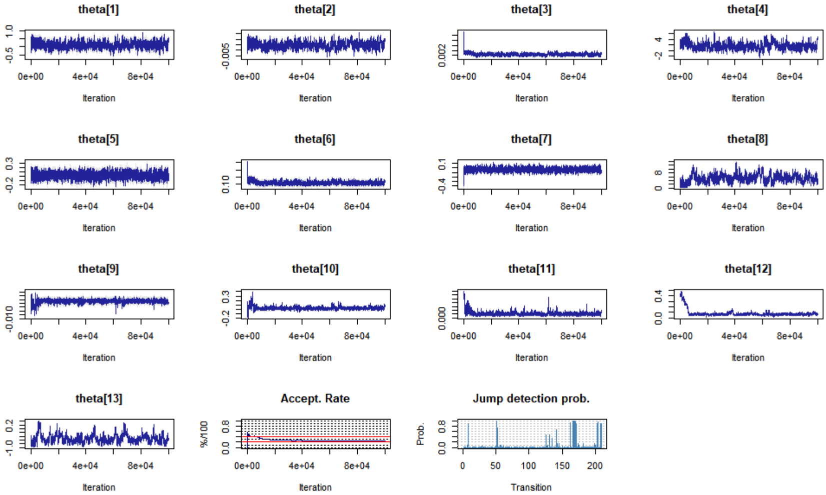


Figure: Convergence diagnostics for the MCMC sampler (including pandemic experience).

Appendix

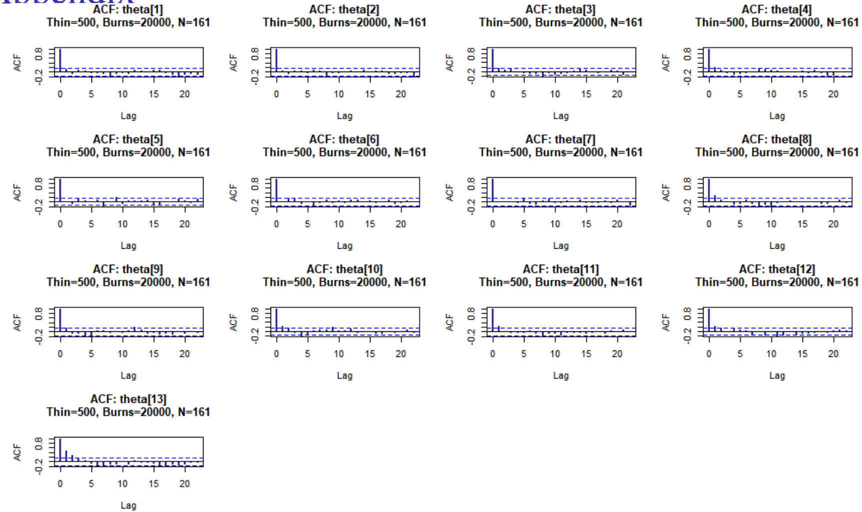


Figure: ACF of MCMC draws for each parameter in model (including pandemic experience).

Appendix

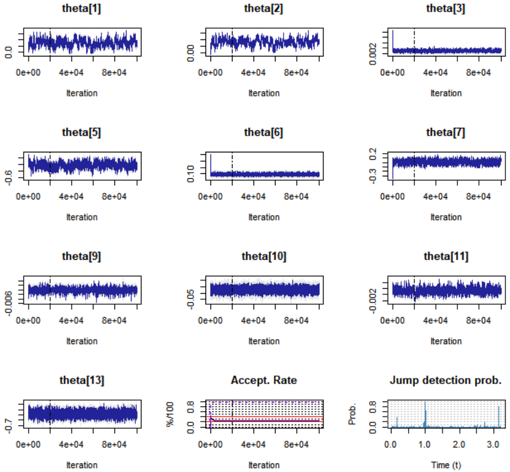


Figure: Convergence diagnostics for the MCMC sampler (excluding pandemic experience).

Appendix

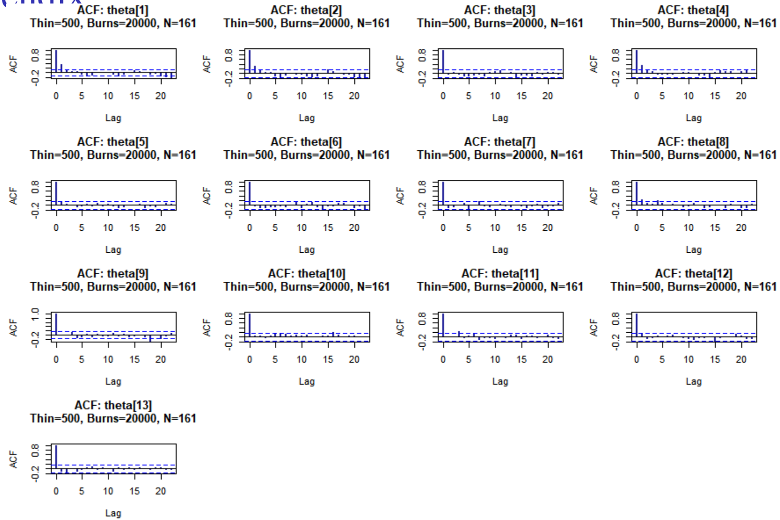


Figure: ACF of MCMC draws for each parameter in model (excluding pandemic experience).