On the relative pricing of long maturity S&P 500 index options and CDX tranches

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Securitized Credit Markets Crisis

- Pre-crisis saw large growth in securitized credit markets (CDO).
- Pooling and tranching used to create ‘virtually risk-free’ AAA securities, in response to high demand for highly rated securities.
- During the crisis all AAA markets were hit hard:
  - Home equity loan CDO prices fell (ABX.HE AAA < 60%).
  - Super Senior (30-100) tranche spreads > 100bps.
  - CMBX.AAA (super duper) > 750bps.
- Raises several questions:
  Q? Were ratings incorrect (ex-ante default probability higher than expected)?
  Q? Are ratings sufficient statistics (risk ≠ expected loss)?
  Q? Were AAA tranches mis-priced (relative to option prices)?
- Many other surprises:
  - Corporate Credit spreads widened (CDX-IG > 200bps).
  - Cash-CDS basis negative (-200 bps for IG; -700bps for HY).
  - LIBOR-Treasury and LIBOR-OIS widened (> 400bps).
  - Long term Swap spreads became negative (30 year swap over Treasury < −50 bps).
  - Defaults on the rise (Bear Stearns, Lehman).
Evidence from ABX markets

- ABX.HE (subprime) AAA and BBB spreads widened dramatically (prices dropped)
Evidence from CMBX markets

- CMBX (commercial real estate) AAA spreads widened even more dramatically
Corporate IG CDX Tranche spreads

- The impact on tranche prices was dramatic

- Implied correlation on equity tranche hit > 40%
- Correlation on Super-Senior tranches > 100%! with standard recovery assumption
- Relative importance of expected loss in senior tranche versus in equity tranche indicates increased crash risk.
Evidence from S&P500 Option markets

- Implied volatility index widened dramatically: increased market and crash risk.
CDX Index & CDX Tranche Markets

- **Credit Default Swaps (CDS)**
  - Buyer of protection makes regular (quarterly) payments = CDS spread
  - Seller of protection makes buyer whole if underlying bond defaults
  - CDS spread $\approx$ corporate bond spread $(y - r_f)$

- **CDX Investment Grade (IG) Index**
  - Portfolio of 125 IG credits
  - Buyer of protection makes regular payments on **remaining portfolio notional**
  - Seller of protection makes buyer whole at time of each bond default
  - CDX index spread $\approx$ weighted average of CDS spreads

- **CDX (IG) Tranches written on same portfolio**
  - Associated with standard attachment/detachment points (subordination levels):
    - 0-3% (Equity tranche)
    - 3-7% (Mezzanine tranche)
    - 7-10%
    - 10-15%
    - 15-30% (Senior tranche)
    - 30-100% (Super-senior tranche)
  - Buyer of protection makes regular payments on **remaining tranche notional**
  - Seller of protection makes buyer whole for each bond default which reduces tranche notional

- CDS, CDX index spreads determined from **marginal** default probabilities.
- CDX tranche spreads need entire **joint** distribution (correlation market).
Relation Between SP500 Index Option Prices and CDX Tranche Spreads

- Given the Arrow-Debreu (or state) prices for every date and every state of nature, one can determine the arbitrage-free price of any (derivative) security

- Given option prices across all strikes (and dates) of SP500 index options, one can back out the A/D prices
  - Breeden and Litzenberger (1978)

- Due to diversification effects of 125 firms composing CDX index, CF’s associated with CDX tranche positions closely tied to overall market performance
  ⇒ Identifying state prices from option prices should be useful for estimating tranche spreads

- In practice, strikes typically limited to (70% - 130%) of current index levels

- Can we extrapolate state prices from SP500 option prices to price credit derivatives?
  - Payoffs of most senior tranches associated with losses well below 70% of current levels
  - Need to extrapolate well beyond observable prices
Structural/Copula Models of Default

- Specify market (S&P500) value dynamics as:
  \[
  \frac{dM}{M} = (r - \delta_M) \, dt + \sigma_M \, dz^Q_M
  \]

- Specify firm asset value dynamics via CAPM (market plus idiosyncratic risks):
  \[
  \frac{dA_i}{A_i} = (r - \delta_i) \, dt + \beta_i \sigma_M \, dz^Q_M + \sigma_i \, dz^Q_i
  \]

  Note: total variance is sum of market variance plus idiosyncratic variance
  \[
  \nu_i^2 = (\beta_i \sigma_M)^2 + \sigma_i^2
  \]

- Default occurs if \( A(t) \leq B \) for \( t < T \)

- From Black/Scholes/Merton, to determine CDS spread, only need to know \( \nu^2 \)
  - To determine CDX index spread on 2 (or 125) identical firms, only need to know \( \nu^2 \)

- Consider insurance contract (\( \sim \) CDX tranches) that pays iff exactly 1 firm defaults
  - If \( \nu^2 = (\beta \sigma_M)^2 \), returns perfectly correlated: either zero firms or all firms will default
    - value of insurance on exactly one default is zero
  - If \( \nu^2 > (\beta \sigma_M)^2 \), returns are imperfectly correlated: a single default is possible
    - value of insurance on exactly one default is positive
Coval, Jurek and Stafford (CJS, 2009)

- **Model Specification** (∼ standard copula with Option-implied market factor)
  - Estimate 5-year state prices using 5-year SP500 option prices (∼ local vol model)
  - Specify idiosyncratic risk as Gaussian diffusion
  - Calibrate model to match the 5-year CDX index spread
    - Have only 5-year state prices; estimating PV[ CF’s ] (0-5 years)

- **Findings**: Observed spreads on
  - equity tranche too high compared to model predictions
  - other tranches (except super-senior) too low compared to model predictions

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- **Interpretation**:
  - sellers of insurance on senior tranches naive:
    - focused on high credit ratings/low probability of payout
    - did not properly account for the level of systematic risk exposure
Our Approach

▶ Methodology:
  ▶ Specify several (jump-diffusion-SV) structural model for both market (S&P500) and individual (CDX) firm dynamics.
  ▶ Price options (closed-form) and tranches (Monte-carlo simulations).
  ▶ Calibrate market dynamics to match all maturities and strikes of SP500 options.
  ▶ Calibrate idiosyncratic dynamics to match all maturities of CDX index spreads.
  ▶ Calibrate to beta and total variance (estimated from CRSP/Compustat for constituents of CDX index).

▶ Main Findings:
  ▶ Spread on super-senior tranche too far out of the money to estimate using option prices
  ▶ Taking Super Senior spreads as input, other tranche spreads well estimated by any model

▶ Interpretation:
  ▶ sellers of insurance on senior tranches sophisticated:
    ▶ Required fair (relative) compensation for risks involved
    ▶ May have enjoyed the “window dressing” associated with highly rated securities (∼ rating ‘arbitrage’).
A structural model for pricing long-dated S&P500 options

- The market model is the Stochastic Volatility Common Jump (SVCJ) model of Broadie, Chernov, Johannes (2009):

\[
\frac{dM_t}{M_t} = (r - \delta) dt + \sqrt{V_t} dw_1^Q + (e^y - 1) dq - \bar{\mu}_y \lambda^Q dt + (e^{\gamma_c} - 1) (dq_c - \lambda^Q dt)
\]
\[
dV_t = \kappa_v (\bar{V} - V_t) dt + \sigma_v \sqrt{V_t} (\rho dw_1^Q + \sqrt{1 - \rho^2} dw_2^Q) + y_V \ dq
\]
\[
d\delta_t = \kappa_\delta (\bar{\delta} - \delta_t) dt + \sigma_\delta \sqrt{V_t} (\rho_1 \ dw_1^Q + \rho_2 \ dw_2^Q + \sqrt{1 - \rho_1^2 - \rho_2^2} \ dw_3^Q) + y_\delta \ dq.
\]

- We add stochastic dividend yield (SVDCJ) to help fit long-dated options as well.

- The parameters of the model are calibrated to 5-year index option prices obtained from CJS.

- State variables are extracted given parameters from time-series of short maturity options (obtained from OptionMetrics).

- Advantage of using structural model: Arbitrage-free extrapolation into lower strikes (needed for senior tranches).
A structural model of individual firm’s default

Given market dynamics, we assume individual firm $i$ dynamics:

$$\frac{dA_i(t)}{A_i(t)} + \delta_A \, dt - r \, dt = \beta_i \left( \sqrt{V_t} \, dw_i^Q + (e^y - 1) \, dq - \bar{\mu}_y \, \lambda Q \, dt \right) + \sigma_i \, dw_i$$

$$\quad + (e^{\gamma_C} - 1) (dq_C - \lambda_C^Q \, dt) + (e^{\gamma_i} - 1) (dq_i - \lambda_i^Q \, dt).$$

Note

- $\beta$: exposure to market excess return (i.e., systematic diffusion and jumps).
- $dq_C$: ‘catastrophic’ market wide jumps.
- $dq_i$: idiosyncratic firm specific jumps.
- $dw_i$: idiosyncratic diffusion risks.

Default occurs the first time firm value falls below a default barrier $B_i$ (Black (1976)):

$$\tau_i = \inf\{t : A_i(t) \leq B_i\}.$$  \hspace{1cm} (1)

Recovery upon default is a fraction $(1 - \ell)$ of the remaining asset value.
Pricing of the CDX index via Monte-Carlo

- The running spread on the CDX index is closely related to a weighted average of CDS spreads.

- Determined such that the present value of the protection leg ($V_{idx,prot}$) equals the PV of the premium leg ($V_{idx, prem}$):

  \begin{align*}
  V_{idx, prem} (S) &= SE \left[ \sum_{m=1}^{M} e^{-rt_m} (1 - n(t_m)) \Delta + \int_{t_{m-1}}^{t_m} du e^{-ru} (u - t_{m-1}) dn_u \right] \\
  V_{idx, prot} &= E \left[ \int_{0}^{T} e^{-rt} dL_t \right].
  \end{align*}

- We have defined:
  - The (percentage) defaulted notional in the portfolio: $n(t) = \frac{1}{N} \sum_i 1_{\{\tau_i \leq t\}}$,
  - The cumulative (percentage) loss in the portfolio: $L(t) = \frac{1}{N} \sum_i 1_{\{\tau_i \leq t\}} (1 - R_i(\tau_i))$
Pricing of the CDX Tranches via Monte-Carlo

- The tranche loss as a function of portfolio loss is
  \[ T_j(L(t)) = \max \left[ L(t) - K_{j-1}, 0 \right] - \max \left[ L(t) - K_j, 0 \right]. \]

- The initial value of the protection leg on tranche-\( j \) is
  \[ \text{Prot}_j(0, T) = \mathbb{E}^Q \left[ \int_0^T e^{-rt} dT_j(L(t)) \right] \]

- For a tranche spread \( S_j \), the initial value of the premium leg on tranche-\( j \) is
  \[ \text{Prem}_j(0, T) = S_j \mathbb{E}^Q \left[ \sum_{m=1}^{M} e^{-r_t} \int_{t_{m-1}}^{t_m} du \left( K_j - K_{j-1} - T_j(L(u)) \right) \right]. \]

- Appropriate modifications to the cash-flows
  - Equity tranche (upfront payment),
  - Super-senior tranche (recovery accounting).
Calibration of firms’ asset value processes

- Calibrate 7 (unlevered) asset value parameters \((\beta, \sigma, B, \lambda_1, \lambda_2, \lambda_3, \lambda_4)\) to match median CDX-series firm’s:
  - Market beta
  - Idiosyncratic risk (estimated from rolling regressions for CDX series constituents using CRSP-Compustat)
  - Term structure of CDX spreads (1 to 5 year)

- Set jump size to \(-2\) (\(\sim\) jump to default).

- When present, calibrate catastrophic jump intensity to match super-senior \((\lambda_C < 1\) event per 1000 years).

- Set loss given default \(1 - \ell\) to 40% (\(\sim\) match historical average) in normal times.

- Set \(1 - \ell = 20\%\) if catastrophe jump occurs (\(\sim\) Altman et al.).

Average tranche spreads predicted for pre-crisis period

- We report six tranche spreads averaged over the pre-crisis period Sep 04 - Sep 07:
  - The historical values;
  - Benchmark model: Catastrophic jumps calibrated to match the super-senior tranche; Idiosyncratic jumps and default boundary calibrated to match the 1 to 5 year CDX index.
  - $\lambda_Q^C = 0$: No catastrophic jumps; Idiosyncratic jumps and default boundary calibrated to match 1 to 5 year CDX index;
  - $\lambda_Q^i = 0$: Catastrophic jumps calibrated to match the super-senior tranche; No idiosyncratic jumps; Default boundary calibrated to match only the 5Y CDX index.
  - $\lambda_Q^C = 0, \lambda_Q^i = 0$: No catastrophic jumps; No idiosyncratic jumps; Default boundary calibrated to match only the 5Y CDX index;
  - The results reported by CJS

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$|CJS−Data|$
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Interpretation

- Errors are an order of magnitude smaller than those reported by CJS.
- However, model without jumps ($\lambda^Q_C = 0, \lambda^Q_i = 0$) generates similar predictions to CJS.

- Why? Problem is two-fold:
  - **Backloading** of defaults in standard diffusion model:

    | Average CDX index spreads for different models |
    |-----------------------------------------------|
    | Data                          | 1 year | 2 year | 3 year | 4 year | 5 year |
    |-----------------------------------------------|
    | Benchmark                       | 13     | 20     | 28     | 36     | 45     |
    | $\lambda^Q_C = 0$              | 13     | 20     | 28     | 36     | 45     |
    | $\lambda^Q_i = 0$              | 6      | 7      | 16     | 29     | 45     |
    | ($\lambda^Q_C = 0, \lambda^Q_i = 0$) | 0      | 3      | 13     | 28     | 45     |

- Idiosyncratic jumps generates a five-year loss distribution that is more peaked around the risk-neutral expected losses of 2.4%.
  (loss distribution with $\lambda^Q_C = 0, \lambda^Q_i = 0$ has std dev of 2.9%, whereas loss distribution with ($\lambda^Q_C > 0, \lambda^Q_i = 0$) has std dev of 1.7%).
More Generally....

- We claim that if:
  - Take any “reasonable” dynamic model of market returns to match SP500 option prices
  - Specify idiosyncratic dynamics as a diffusion process
  - Calibrate the model to match the 5-year CDX index

- Then model will generate:
  - Short term credit spreads that are well below observed levels
  - Tranche spreads similar to those found by CJS

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Intuition for Findings

- Diffusion-based structural models can’t explain short maturity spreads for IG debt
  - Some level of jumps captured in market dynamics implied from options
  - However, most risk at individual firm level is idiosyncratic
    - Need to specify idiosyncratic dynamics with jumps to capture short term spreads

- By calibrating model to 5Y CDX index, all models agree on 5Y expected loss

- By calibrating model to observed term structure of spreads, defaults occur earlier
  - eliminate “backloading” of defaults
  - crucial for pricing equity tranche spreads
    - first default associated with $\approx 16\%$ drop in insurance premium payments
    - timing of defaults so crucial that equity tranche typically priced with an up-front premium
  - Agents willing to pay more initially if future payments expected to drop more quickly
  - “Backloading” biases equity tranche spreads downward
  - Downward bias on equity tranche generates an upward bias on senior tranches

- In addition, calibrating model to short maturity spreads increases proportion of idiosyncratic risk to systematic risk
  - Tends to make loss distribution more peaked
  - Also tends to increase spreads on equity tranche/decrease spreads on senior tranches
Calibrating Model to Term Structure of CDX Index Spreads

- When models are calibrated to match short term credit spreads, the results of CJS disappear, and sometimes are even reversed!!

- Predicted super-senior tranche spreads \( \approx 0 \)

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Calibrating Model to Term Structure of CDX Index Spreads and SS Spread

- However, can add a “catastrophic jump” to market dynamics
  - has negligible impact on observed option prices
  - has large impact on SS spreads.

![Fitted five-year option–implied volatility function](chart1)

![Five-year option–implied risk–neutral distribution](chart2)
Calibrating Model to Term Structure of CDX Index Spreads and SS Spread

- However, can add a “catastrophic jump” to market dynamics
  - has negligible impact on observed option prices
  - has large impact on SS spreads.
  - Can improve fit further by taking tranche spreads in-sample

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Time Series Performance

- Model fits data well, both pre-crisis and crisis periods
Conclusion

- CF’s associated with CDX tranche spreads occur throughout 5 year horizon
  - need dynamic model of market and idiosyncratic dynamics to price consistently

- Market dynamics (mostly) extracted from option prices

- Idiosyncratic dynamics extracted from term structure of credit spreads
  - need idiosyncratic jumps to explain short maturity spreads

- Without these jumps:
  - default events are “backloaded”
  - ratio of idiosyncratic to market risk is off
    - CDX equity tranche spreads biased downward
    - CDX senior tranche spreads biased upward

- Super senior tranche spreads cannot be estimated via extrapolation
  - Instead, need to take them as input
  - Other tranche spreads well-predicted by any model that also matches option prices, CDS spreads

- Calibrating model to term structure of credit spreads imposes more structure/less freedom
  - We used “HJM approach”
    - More consistently, can add state variables driving idiosyncratic jump processes
Are senior tranches priced inefficiently by naive investors?

- Investors care only about expected losses (∼ ratings) and not about covariance (ironic since they trade in correlation markets!).

⇒ Spreads across AAA assets should be equalized. Are they?

![AAA spreads by asset](source: Chart)

⇒ All spreads should converge to **Physical** measure expected loss.
  - We observe large risk-premium across the board ($\lambda_Q / \lambda_P > 6$.)
  - Large time-variation in that risk-premium.

⇒ Time-variation in spreads should be similar to that of rating changes (smoother?).

- Evidence seems inconsistent with marginal price setters caring only about expected loss (∼ ratings).
What drives differences between structured AAA spreads?

➤ 'Reaching for yield' by rating constrained investors who want to take more risk because their incentives (limited liability) and can because ratings simply do not reflect risk and/or expected loss.

➤ Taking more risk by loading on systematic risk was the name of the game (agency conflicts).

➤ Possible that excess 'liquidity'/leverage lead to spreads being 'too' narrow in all markets, but little evidence that markets were ex-ante mis-priced on a relative basis.

➤ Ex-post (during the crisis) other issues, such as availability of collateral and funding costs, seem more relevant to explain cross-section of spreads across markets.

➤ Indeed, how to explain negative and persistent:
  ➤ swap spreads?
  ➤ cds basis?