

Can Regulators Allow Banks To Set Their Own Capital Ratios?

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Abstract

Basel regulators have received widespread criticism for failing to prevent two credit crises that hit the U.S. over the last two decades. Nonetheless, banks were considerably overcapitalized prior to the onset of the 2007-2009 subprime crisis compared to those which had undergone the 1990-1991 recession. Therefore, if capital requirements were achieved prior to the subprime crisis, how could the Basel framework be blamed again for having accelerated if not caused another credit crunch? We find that the answer to this question lies in the relationship between the capital ratio and the leverage ratio which is governed by risk-weights categories determined by the Basel regulation. We show that changes to risk-weight categories which affect the correlation pattern between both ratios are not reflected in the subprime crisis. This minimizes the implication of the Basel II regulation in the crunch that succeeded its announcement, in stark contrast to Basel I. We demonstrate that these dynamics are governed by a formula linking the two ratios together which derives from the sensitivity of the risk-based capital ratio to a change in its risk-weight(s). One implication of our work regarding the Basel III regulation consists in validating the newly established capital increments in a mathematical rather than heuristical approach.

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1. Introduction

The Basel Committee on Banking Supervision (BCBS) has been widely criticized for failing to meet its bank safety objective after the U.S. witnessed two credit crunches in a span of less than twenty years. Indeed, after the introduction of Basel I (BCBS (1988)), banks struggled to meet the newly established risk-based capital requirements and hence shifted their portfolio composition towards safer assets to boost their capital ratios (CRs). This resulted in a lending contraction during the 1990-1991 recession, hereafter referred to as the first crunch.

In contrast, since the Basel II framework was released (BCBS (2004) and BCBS (2006)), it seems that banks willingly increased their CRs beyond the target thresholds. According to Chami and Cosimano (2010), in the early stages of the subprime crisis, the top 25 banks in the U.S. and Europe had a Tier 1 capital ratio of 8.3% and 8.1% while the Total capital ratio was 11.4%

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and 11.6%, respectively. Due to the distortionary incentives created by holding such high capital buffers (or moral hazard as indicated by Brinkmann and Horvitz (1995)), banks reached dangerous leverage ratios¹ (LR) judging by the standards set by the main U.S. regulators (OCC, FDIC and FED) for well-capitalized institutions. Indeed, Gilbert (2006) states that up until mid-2005 only the two largest U.S. banks had a LR higher than 5%. Once defaults began their domino effect which triggered the second credit crunch in 2007-2009, the blame was directed at the regulators for having incentivized banks to take on excessive risk prior to the crisis.

In sum, the effects of capital requirements have been investigated from two interconnected perspectives. The first is related to the impact on lending growth (Bernanke and Lown (1991); Peek and Rosengren (1992, 1994, 1995a,b); Barajas et al. (2004); Cathcart et al. (2013b)) whereas the second focuses on risk incentives (Koehn and Santomero (1980); Furlong and Keely (1987); Kim and Santomero (1988); Furlong and Keely (1989); Keely and Furlong (1990); Gennotte and Pyle (1991); Shrieves and Dahl (1992); Calem and Rob (1999); Blum (1999); Montgomery (2005); Berger and Bouwman (2013)). Still, opinions remain mixed as to the effect capital can have in each case, with different implications depending on the choice of variable used to measure capital adequacy: Tier 1 VS Total (Demirguc-Kunt et al. (2010)).

Note that under each perspective, all but the last citations in our literature survey relate to the first crunch. This underlines the greater attention attributed to the Basel regulation following this period. However, aside from minor changes to capital definitions, if the regulatory target thresholds were maintained throughout the two decades at the pre-established 4% and 8% levels for Tier 1 and Total CR, any changes to CRs on the bank side would have been endogenous while the LR remained outside the scope of the Basel regulation. In principal, this would cancel out the regulatory effect on the second crunch.

Still, the latter effect could result from a more tacit change in the regulation, the introduction of new risk-weight categories. While the authors in our survey alternate between the use of the CR or LR when exploring the impact of capital, in this paper, we complement the existing literature by showcasing that the two are not entirely independent. In fact, the two ratios are related through changes in the number of risk-weight categories which is exogenously determined by the regulators. This interaction between both ratios can lead to a new perspective on relating the abovementioned crunches to the effects of capital requirements.

Our perspective relies on a four-step procedure. First, we motivate our discussion on the basis that a shift in the banks' binding constraint as witnessed between crises can be related to changes in risk-weights. In order to showcase the shifts in banks' binding constraints between the two crunches, we conduct a bank failure analysis in relation to the CR and LR requirements. While one might consider bank failure as being the adverse consequence of excessive risk-taking, not all failures can be attributed to banks' risky behavior with regard to capital adequacy². Since the existing literature investigated the causal linkages to the subprime crisis outside the realm of risk-based capital requirements (leverage, liquidity, securitization), our study re-emphasizes the effects of these requirements on failures in an aim to fill the gap.

Second, we develop our theoretical framework which relies on a set of partial differential equa-

¹Leverage is not to be confused with the traditional corporate finance definition as the ratio of debt to equity. In the regulatory context it is defined as the ratio of equity to assets (see section 2). In that sense, the higher the ratio, the safer the bank.

²Operational risk, for instance, has been at the helm of many investigations: fraud (Daiwa, Sumitomo), rogue trading (Barings Bank).

tions (PDE) related to the sensitivity of the CR which combines the two capital requirements together. The closed-form solution of this equation can assist policy-makers in setting adequate rather than heuristic targets for the CR and LR. This can also shed light on the controversy highlighted by various authors (Hall (1993); Thakor (1996); Blum (2008); Buehler et al. (2010); Blundell-Wignall and Atkinson (2010); Kiema and Jokivuolle (2010)) regarding the effects of combining the two capital measures together under a single framework. In turn, this has implications on the Basel III regulation which seeks to incorporate the LR as a “backstop” measure alongside the CR.

Third, we investigate the changes to the correlation patterns of LR and CR in order to give preliminary evidence of the explanatory power of our framework. We show that these patterns are related to economic fundamentals such as lending and GDP which allows us to pinpoint the loan category mostly correlated with the crunches.

Fourth, building on the previous step we provide empirical evidence of our model by analyzing its behavior over the two crunches. Our conclusions give support to the role of Basel I during the first crunch but discharges Basel II from any implication in regard to the second crunch.

Hence, in order to validate our four-step procedure we proceed as follows. In section 2, we describe our dataset. In section 3, we replicate the work conducted by Avery and Berger (1991) for the first crunch to illustrate the impact of CR and LR requirements on bank failures during the second crunch. In section 4, we develop our theoretical model linking the CR to the LR. In section 5, we relate our theory to the correlation patterns which distinctively occurred during both crunches. In section 6, we validate our model from an empirical standpoint. We conclude with our main results and policy implications.

2. Data

Our dataset is based on FDIC Call Reports³ for the crunch periods 1990Q1-1991Q2 and 2007Q3-2009Q2. Ideally, in the case of exploring the regulatory impact following Basel I, we should have begun in 1988; however, risk-weight data is only available as of 1990 which coincides with the start of the recession. Therefore in order to limit any bias between the periods and for comparative purposes, we restrict the second period also to the subprime crunch period⁴.

Both CR and LR are proportional to Tier 1 capital by definition⁵. After discarding all negative CR⁶ values, we construct various sub-samples of the dataset based on the distribution of the CR. The latter range from the 90th to the 50th percentiles. Our choice of 90% cutoff value relates to removing the effect of outliers mostly located in the upper percentiles of the data, while the limit of 50% is used to maintain a reasonable amount of observations. Descriptive statistics for the upper and lower bounds of the sub-samples are shown in Table I.

The survivorship bias is apparent in our study as can be seen from the reduction in the number of banks between both periods. However, as the higher moments of the data are fairly similar

³Also known as Reports of Condition and Income taken from the Federal Financial Institutions Examination Council (FFIEC).

⁴We will show in section 6.2 that this restriction does not impact our result in relation to the actual implementation dates for the respective Basel regulations.

⁵With reasonable approximation based on the risk-based capital definitions for Prompt Corrective Action (PCA) as posted by the FDIC, $CR = K/RWA$; $LR = K/A$ where K is Tier 1 Capital. See Theory section for more details.

⁶The formulae in this study imply that the CR and LR should be positive.

between the two periods, our sample is not affected by the bias. Furthermore, we witness an order of magnitude increase in the value of (risk-weighted) assets due to balance-sheet expansions, mergers and acquisitions. In particular, mortgage lending, which played a key role in both crises, witnessed an important increase.

Table I:
Summary Statistics

The data in this table relates to the beginning of each designated crunch period, 1990Q1 and 2007Q3. Values are shown after winsorizing the data with respect to the CR at the 90th and 50th percentiles. Risk-weighted assets (RWA), Total Assets (TA) and Mortgage Assets (A) are in USD.

Panel A: 1990Q1

Pct	90%					50%				
Var	Obs	Mean	Std Dev	Skew	Kurt	Obs	Mean	Std Dev	Skew	Kurt
CR	12069	12.5	4.3	0.5	3.0	6714	9.5	2.1	-1.2	4.7
LR	12069	8.0	2.5	1.8	33.1	6714	6.7	2.0	5.2	155.2
RWA	12069	2.5 ⁸	2.6 ⁹	45.8	2903.8	6714	3.9 ⁸	3.4 ⁹	34.5	1636.1
TA	12069	3.1 ⁸	2.5 ⁹	34.9	1731.8	6714	4.8 ⁸	3.3 ⁹	26.6	997.0
A	12069	1.0 ⁸	7.7 ⁸	30.3	1198.2	6714	1.6 ⁸	1.0 ⁹	23.3	697.5

Panel B: 2007Q3

Pct	90%					50%				
Var	Obs	Mean	Std Dev	Skew	Kurt	Obs	Mean	Std Dev	Skew	Kurt
CR	7729	14.4	4.9	1.1	3.6	3838	10.7	1.3	-0.4	4.0
LR	7729	10.3	3.1	2.0	9.6	3838	8.6	1.3	0.6	8.3
RWA	7729	12.3 ⁸	20.4 ⁹	38.2	1630.3	3838	22.4 ⁸	28.8 ⁹	27.2	823.9
TA	7729	15.4 ⁸	26.0 ⁹	40.4	1804.4	3838	27.3 ⁸	36.8 ⁹	28.8	910.8
A	7729	6.0 ⁸	76.4 ⁸	33.2	1331.2	3838	10.3 ⁸	10.6 ⁹	24.4	709.9

Moreover, the CR and LR statistics which increased by around two percentage points allow us to re-assert the finding in Chami and Cosimano (2010) that banks were indeed better capitalized before the second crunch compared to the first. This could have happened either through a voluntary increase in capital by banks, or involuntarily through changes to risk-weights.

One conclusion that can be made from our data inspection is that had the regulators linked the CR and LR together by any linear association (for instance, $CR - LR > \text{Constant}$), we would expect similar distributions for each ratio. However, this is not the case as can be seen at the 90th percentile⁷ with the quasi-normal distribution of the CR (Skewness ≈ 0 , Kurtosis ≈ 33) versus a positively skewed and leptokurtotic distribution for the LR (Skewness ≈ 2 , Kurtosis varies according to the period) during the first crunch. This indicates the presence of a non-linear, if any, linkage between the two ratios.

3. Motivation

The CR and LR are the most popular measures of capital adequacy. In view of the common capital feature embedded in both ratios, any changes between the CR and LR can be attributed to changes in their denominators, risk-weighted versus unweighted assets. However, each of the two ratios can have very different effects on a bank's behavior depending on which of the two is

⁷The sample distribution is no longer normal at the 50th percentile.

the binding constraint (Berger and Udell (1994), Hancock and Wilcox (1994), Peek and Rosengren (1994), Chiuri et al. (2002), Barajas et al. (2004), Blundell-Wignall and Atkinson (2010)).

Two studies which investigated the impact of the CR and LR on bank failures during the first crunch are Avery and Berger (1991) and Estrella et al. (2000). Although the latter study came at a much later time than the former, it only pointed out the critical regions at which banks were affected by one ratio or the other. Hence, no consideration was given to the combined effect of the two ratios. However, one important observation we make from the authors' results is that at least one year prior to its failure, a bank can have the same LR in the critical region as one which eventually survived. This supports the fact that the LR has no predictive power regarding bank failures in contrast to the CR, in line with the authors' conclusion. However, it is important to make sure this statement remains valid during the second crunch.

Avery and Berger (1991) make a similar assessment by which they calculate the number of banks that went bankrupt just before the start of the first crunch given that these banks had earlier failed to meet one or more of the CR and/or LR regulations. For example, almost a third of the 6% of banks which could not meet the targets for Tier 1 capital, Total capital or leverage failed over the next 2 years⁸. More importantly, 50% of all banks failing the Tier 1 target eventually went bankrupt, putting this requirement at pole position in terms of forecasting power.

Following the same line of thought as the previous authors we analyze the relationship between these capital standards and bank failures for the second crunch. This complements findings such as those of Berger and Bouwman (2013) who observed that a one standard deviation decrease in capital more than doubles the probability of bankruptcy. However, their result shows this relation as being linear even though authors which differed on their assessment of risk and capital (Koehn and Santomero (1980); Furlong and Keely (1987); Kim and Santomero (1988); Furlong and Keely (1989); Keely and Furlong (1990)) still agreed that capital shortfalls weigh more on a bank's survival rate than surpluses.

Notwithstanding some components might have changed, the CR targets were not altered between the two Basel frameworks. This allows for a direct comparison with Avery and Berger (1991). Nonetheless, instead of exploring changes before and after the Basel II capital standards were brought in, our study uses three intervals (pre, mid and end of the crisis), in order to gauge the evolution in meeting these standards along with the leverage requirement as the crisis unfolded.

Unlike the fixed CR targets, the choice of which LR is chosen to compare between banks is at each author's discretion. This is because CAMEL ratings, which guide national regulators in their discretionary LR requirement for each bank, are not disclosed⁹. Both Avery and Berger (1991) and Hall (1993) chose the minimum leverage target of 3% for their analysis which could be the reason they amount to similar conclusions on the binding effect of capital rather than leverage ratios. In the latter author's own words, if the average LR were assumed at 3%, the CR becomes the more likely first crunch culprit since most banks are able to fulfill the LR requirement. However, if the LR were established at a level of 5% then at least 18% of these would fail the leverage target. In order to circumvent these issues, we look at a range of leverage targets 3%, 4% and 5% and maintain that our results are valid at each level. Finally, we look at how combinations of both

⁸Note that in the Basel framework, if a bank fails Tier 1 it automatically fails the Total requirement as the regulators impose that Tier 2 cannot exceed 50% of Tier 1.

⁹Under this rating scheme, the safest banks, attributed the best rating of 1, are given a leverage target of 3%. Depending on their condition, all other banks are set a target of either 1 to 2 percentage points higher. Even if it were known, the function underlying the "CAMEL-to-Leverage" specification is arguably not bijective.

standards impact on bankruptcies.

Table II shows a number of compelling findings. Bearing in mind that banks were transiting from the 1980's flat rate system to Basel I requirements, we recall that Avery and Berger (1991) had obtained a 94% estimate of the proportion of banks that passed all three requirements prior to the first crunch. In contrast, banks did not have to modify their capital thresholds after Basel II, which explains the higher proportion of compliant banks (99%) at the onset of the second crunch. This validates the similar estimates obtained by Greenspan et al. (2010). Another difference between these periods is that the non-compliant banks accounted for a quarter of total assets according to Avery and Berger (1991). Based on Berger and Udell (1994), this amounted to a 20% increase in banks not abiding by the regulation. In contrast, non-compliant banks were less than 1% in terms of total assets during the post-Basel II period which reinforces the idea that very few had actually failed the standards.

Nevertheless, failing any of the standards in the latter period had more serious repercussions since a much greater proportion of the pre-crunch bank pool ended up bankrupt. Ultimately, all banks failing either the Tier 1 CR or a 3% LR in the pre-crisis period went bankrupt. Moreover, we point out the increase in the failure to meet any of the requirements over time. This contrasts with a simultaneous decrease in bankruptcy rate, specifically between the start and end of the observation period. The first finding stresses the weakened capital position of banks eroded by losses throughout the crunch period. The second finding relates to corporate finance theory in that survival rates increase for banks which can endure more phases of a crunch (Klapper and Richmond (2011)).

A striking feature is that during all three phases of the crunch, all banks that failed Tier 1, and obviously Total, capital ratios also failed the LR requirement of 4%. As a matter of fact, from the same proportion of banks which ended up bankrupt prior to the crunch, more banks had failed because of the minimum 3% LR rather than the CR requirement. This has crucial implications on Basel III as it brings back into question the purpose of imposing dual requirements, suggesting that the BCBS' decision of imposing a backstop 3% requirement could be overly conservative. While the implications from failing the CR in terms of bankruptcy were higher for the CR compared to the LR requirement at the peak of the crisis (2008Q2), this is not sufficient to rule out leverage as the binding constraint on banks as increasing the target by 1% always resulted in an average doubling of the failure rate to meet the requirement across all periods (above 1% failure rate for the 5% target).

Moreover, when quantifying the magnitude of failing a specific standard one must relate it to surpluses, or alternatively shortfalls¹⁰. As a matter of fact, Brinkmann and Horvitz (1995) emphasize that regulators should not only look at how many banks are likely to fail a newly introduced standard but also by how much their (excess) capital cushion would vary¹¹. Hence, one motivation for performing the following study is to assess the adequacy of the new Basel III standards.

¹⁰Focusing on shortfall is arguably a better choice than surplus. Firstly because, the fact that banks were overly capitalized prior to the crunch did not fare well for some of them during the crunch. In other words, while the capital buffer size does matter for the regulators, it does not reflect quality of capital. This means that surplus could be a biased signal for the health of the banking sector. Secondly, shortfall is more amenable to the idea of setting minimum capital requirements.

¹¹Regulators classify institutions into four main capital surplus/shortfall categories: Adequately/Under capitalized and Significantly/Critically undercapitalized.

Hence, in the same spirit as Hancock and Wilcox (1994), we calculate the average shortfall as the sum of differences between the target ratio and the actual ratio divided by the number of non-compliant banks. Shortfall turned out to be equal to 1.5% for Tier 1 capital which is actually in line with the current steps taken by the BCBS to increase the Tier 1 requirement by 2%. However, the BCBS decision to abide by the 3% leverage requirement could end up short of expectations as our analysis reveals that the shortfall of 0.5% could double if the target was increased to 4%. This suggest a review of the CAMEL ratings system to reflect the median bank’s behavior during crises periods.

While it is difficult to ascertain which of the two ratios was the binding constraint on banks purely on the basis of failure and shortfall analysis, one definite conclusion is that compared to the statistics in Avery and Berger (1991), the LR played a much more important role for this crunch. This is in contrast with the first crunch where banks were mostly struggling to meet their CR requirements. Hence, our conclusion statistically corroborates the statements in Gilbert (2006)¹² and Blundell-Wignall and Atkinson (2010).

On reflexion, Furfine (2000) claims that the same magnitude change in either ratios can lead to drastically opposite effects in terms of portfolio risk. In fact, Gilbert (2006) suggests that changing the risk-weights in the CR would impact the number of banks bound by the LR despite the fact that the latter is insensitive to risk-weights by definition. More specifically, using the exact scenario that occurred prior to the subprime crunch, in other words a reduction in the risk-weight attributed to first-lien residential mortgages¹³, the author shows that a risk-weight lowering lead to an increase in the number of banks bound by the LR. The latter is achieved by moving banks further from the CR constraint without changing the distance to the LR constraint. As a result, when capital is reduced due to loan losses, the first constraint that banks would hit is the LR requirement. This hypothesis has fueled our incentive to explore the interaction between the CR and LR from the perspective of risk-weight changes.

Table II:
Bankruptcy Predictions from Banks Failing to Meet Various Capital Standards

Our results for the period 2004Q3-2009Q2 are broken down into three consecutive dates (pre, mid, end of crisis). With regard to the overall sample, we account for the bank percentage in terms of number (%B) and assets (%A). Each row consists of a different regulatory target. Numbers in brackets are for use in the last rows as combinations of the previous single standards where || denotes the logical OR and & is the logical AND. The last row is for banks which passed all standards (with a 3% LR). In that case, the following identity can be applied: $\text{Prob}[\text{Pass}] = 1 - \text{Prob}[(1)\|(2)\|(3)]$.

Standard	Pre-crisis (2007Q2)			Mid-crisis (2008Q2)			End-crisis (2009Q2)		
	%B	%A	%Bkrpt	%B	%A	%Bkrpt	%B	%A	%Bkrpt
Tier1-CR(1)	0.02	0.00	100.00	0.10	0.25	88.89	0.49	0.37	30.23
Total-CR(2)	0.10	0.12	55.56	0.25	0.11	63.64	0.94	0.37	12.20
3%-LR(3)	0.03	0.02	100.00	0.09	0.01	62.50	0.47	0.31	31.71
4%-LR(4)	0.07	0.05	66.67	0.15	0.25	46.92	0.89	0.45	27.27
5%-LR(5)	0.14	0.15	69.23	0.39	0.34	42.86	1.42	0.85	17.89
(1)\ (2)\ (3)	0.12	0.12	63.64	0.37	0.35	66.67	1.44	0.74	18.40
(1)\&(2)\&(3)	0.02	0.00	100.00	0.07	0.00	83.33	0.43	0.30	32.43
Pass	99.86	99.85	7.02	99.63	99.65	3.38	98.55	99.26	0.49

¹²Though the author uses a different definition for the binding capital requirement based on surpluses rather than the actual number of banks that achieved the given target.

¹³Although the author’s specification changes the original value of 50% to half its value, rather than the one chosen by Basel of 35%.

4. Theory

In this section, we undertake a mathematical approach in order to assess whether the two ratios, LR and CR, are inter-related. The equations presented here will be important for the derivations we conduct at a later stage.

According to the Basel framework, risk-weighted assets are defined as the weighted sum of assets on a bank's balance sheet, where the weights are attributed according to the asset's credit risk. Hence, denoting K as Tier 1 capital, the ratio of Risk-Weighted Assets (RWA) to Total Unweighted Assets (TA) in equation (1) is commonly used as a measure of risk as it is bound between 0 and 1 in increasing order of credit risk. This is because RWA tends towards TA as the proportion of risky assets (high risk-weight) increases. Therefore, what is not noted in most of the recent literature which uses this credit risk proxy (Van-Roy (2005), Hassan and Hussain (2006), Berger and Bouwman (2013)) is that it is equivalent to an interaction between the CR and LR, irrespective of capital K ¹⁴.

$$\frac{RWA}{TA} = \frac{\frac{K}{CR}}{\frac{K}{LR}} = \frac{LR}{CR} \quad (1)$$

Moreover, it is apparent from equations (2) and (3), that the more a bank invests in the assets (A_i), in the limit where all assets belong to the lowest risk-weight category ($w_i = 0$) the CR converges to infinity. In other words, the CR is not affected by changes to assets unlike the LR which always moves with the level of assets. The two ratios are expected not to be correlated in this case. In contrast, in the limit where all assets belong to high risk-weight categories ($w_i = 1$), the CR will decrease until it coincides with the LR. In sum, the two ratios are correlated depending on the overall level of risk-weights.

$$\lim_{w_i \rightarrow 0} CR = \lim_{w_i \rightarrow 0} \frac{K}{\sum_{i=1}^N w_i A_i} = \infty = Cte \quad (2)$$

$$\lim_{w_i \rightarrow 1} CR = \lim_{w_i \rightarrow 1} \frac{K}{\sum_{i=1}^N w_i A_i} = \frac{K}{\sum_{i=1}^N A_i} = LR \quad (3)$$

4.1. Deriving the relationship between CR and LR

In similar spirit to Van-Roy (2005) and Hassan and Hussain (2006)¹⁵, the change in CR is derived with respect to a change in risk-weight, w_i , affecting a certain asset category i out of a pool of N categories¹⁶.

First, as can be seen from Equation (5), this change is negatively related to the product of the CR and a second term which is dubbed "asset proportion" (AP_i). This term refers to the "proportion" of asset whose risk-weight is being changed towards the total amount of risk-weighted assets.

¹⁴Kamada and Nasu (2000) are the closest to reach this result as they use Total capital in the definition of the CR versus Tier 1 capital for the LR. This leads to a different but related concept: the asset quality index.

¹⁵These authors derive changes with respect to CR itself, i.e. CR growth rather than with respect to a change in risk-weight.

¹⁶Prior to Basel II, $N=4$ for $i \in [0, 20, 50, 100]$.

$$\begin{aligned}
\frac{\delta CR}{\delta w_i} &= \frac{\delta}{\delta w_i} \left(\frac{K}{\sum_{j=1}^N w_j A_j} \right) = K \times \frac{\delta}{\delta w_i} \left(\frac{1}{\sum_{j=1}^N w_j A_j} \right) \\
&= -K \times \left(\frac{A_i}{(\sum_{j=1}^N w_j A_j)^2} \right) = -\frac{K}{\sum_{j=1}^N A_j} \times \frac{\sum_{j=1}^N A_j}{\sum_{j=1}^N w_j A_j} \times \frac{A_i}{\sum_{j=1}^N w_j A_j} \\
&= -LR \times \frac{1}{\frac{RWA}{TA}} \times \frac{A_i}{RWA} \\
&= -LR \times \frac{1}{\frac{LR}{CR}} \times AP_i = -CR \times AP_i
\end{aligned} \tag{4}$$

Since the product of terms is always positive, the change in CR resulting from a positive change in w_i is always negative. The intuition lies in the fact that an increase in risk-weight means more risky assets which implies a negative (positive) shock to the CR numerator (denominator) resulting in an overall decrease. This statement has policy implications with regard to one prominent example which occurred during the transition from Basel I to Basel II as the risk-weight on residential mortgages fell from 50% to 35%, respectively (Blasko and Sinkey (2006) and Cathcart et al. (2013b)). Seemingly without anticipating the artificial increase this change would have on CRs, regulators maintained the same CR targets despite lowering the risk-weight¹⁷. In fact, they should have increased the CR targets even further to maintain adequate capital buffers. While some might argue that this strategy could have exacerbated the crunch by increasing the contraction in lending, it might have proven worthwhile in weathering it by having forced banks to hold higher loss-absorption layers. Arguably, this has been taken into consideration under Basel III in the setting of the new CRs.

Second, another interesting feature which is apparent from equation (4) is that the sensitivity of the CR to a change in risk-weight is higher in absolute terms the higher the LR, the safer the bank in terms of credit risk (low RWA/TA), and the larger the affected asset proportion (AP_i). Hence, equation (4) provides the mathematical framework to highlight the importance of the credit risk ratio and asset proportion in dampening or intensifying the sensitivity of the CR. Note that the reason why the safest banks are the most sensitive to changes in CR can be understood in the context of an extreme scenario where the risk-weights are at zero. In that case, the CR is immune to changes in any amount of assets. However, any deviation in risk-weight away from zero is likely to perturb it significantly.

So far, our derivations have highlighted the dependence of the CR on the LR, affected by a negative sign for the case of a change with respect to a single risk-weight category, w_i . It is easy to show that the relationship between the CR and LR can be extended to all N categories which yields the following formulae in equations (6) and (7). We notice that most terms were adapted from the previous single risk-weight case, with the last factor being the product of asset proportions. Our focus, however, is on the preceding negative sign, which now changes to a sinusoidal pattern of positive/negative signs depending on the number of risk-weight categories. This captures, along

¹⁷Unless other risk-weight changes had, in their view offsetting effects.

with the factorial term¹⁸, the interactions between different changes in risk-weights.

$$\frac{\delta CR}{\delta w_1 \dots \delta w_N} = (-1)^N \times N! \times LR \times \frac{1}{\frac{RWA}{TA}} \times \prod_{i=1}^N AP_i \quad (6)$$

$$= (-1)^N \times N! \times CR \times \prod_{i=1}^N AP_i \quad (7)$$

Note that the behavior of the function in the CR sensitivity equations is undetermined as N tends to infinity. However, this is not an issue for a few number of risk-weight categories as is normally the case. Moreover, while the correlation between LR and CR is always positive, the sensitivity of the CR, as captured by its derivative(s) could vary depending on the total number and sign (positive/negative) of all possible changes affecting the risk-weight categories. This should always be taken into account by regulators when changing any of the constituents of the CR sensitivity. More importantly, for given change(s) in risk-weight(s), these formulae allow us to infer the necessary change in CR holding constant the changes in these constituents.

Finally, based on these formulae, we conjecture that the introduction of the risk-weight scheme under Basel I took N from one to four, triggering a change in the sign of the sensitivity of the CR. As such, the average risk-weight would have fallen from 1 to an arbitrary \bar{W} . This makes the change in w_i negative, resulting in a fall in CR for a positive change in LR. Thus the two ratios would vary in opposite ways, bringing down the correlation between them. In contrast, the four new risk-weights introduced under Basel II¹⁹ which would have taken N to eight would not have altered the sign on the sensitivity of the CR even if they had been fully implemented. An implication of this would be to minimize the role of the Basel regulation in relation to the crisis.

5. The Change in CR and LR Correlation Patterns

Before moving to the empirical validation of our theoretical findings, we elaborate further on the correlation patterns for the CR and LR during the distinctive periods of post-Basel regulations.

5.1. Pattern Reversals and Economic Fundamentals

In this section, we illustrate the changes in LR and CR co-movement patterns in each crunch period. Our correlation estimates are calculated on the basis of the 90th percentile sample in Table I and plotted in Figures 1 and 2 for each period, respectively.

Note that various authors have measured this correlation over a single period without mentioning if the resulting pattern is likely to be persistent over time. For instance, Estrella et al. (2000) perform their calculations for the first crunch only. Their yearly values coincide to a large extent with the ones we obtain for the first quarter of each year in Figure 1. To our knowledge, they were the first to have observed an imperfect time-varying correlation pattern between the two capital measures which hints to the fact that each ratio can provide independent information on capital adequacy for a given bank.

As such, the key point of our analysis is with regard to changes in the correlation patterns for each of the crises. During the first crunch (Figure 1), it would seem as though the correlation

¹⁸This term arises from the successive derivations with respect to the risk-weights.

¹⁹Those were 35%, 75%, 150% and 300%.

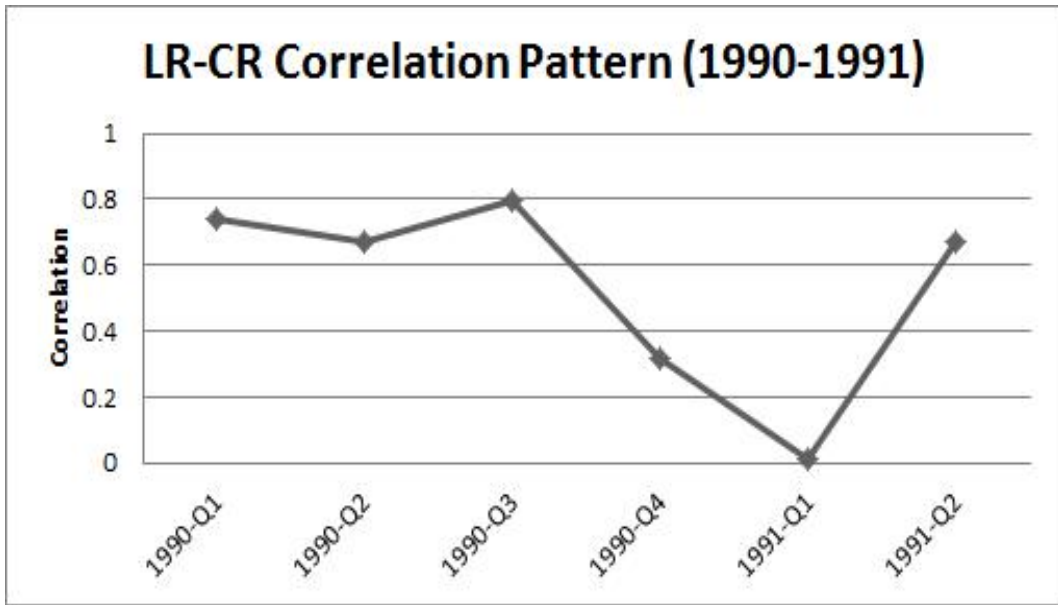


Figure 1: Correlation Pattern between LR and CR during the 1990-1991 crunch

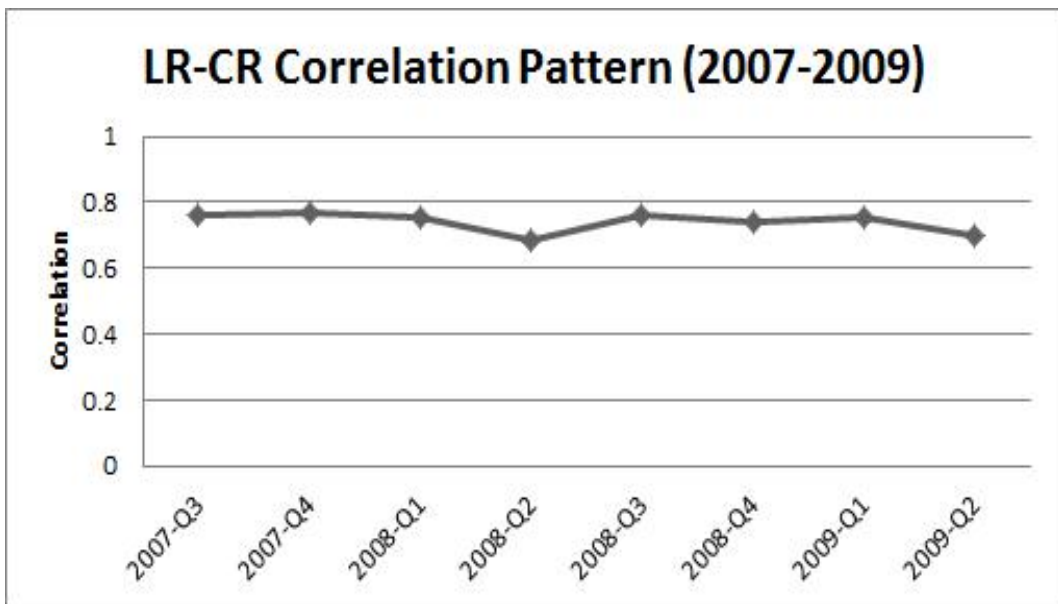


Figure 2: Correlation Pattern between LR and CR during the 2007-2009 crunch

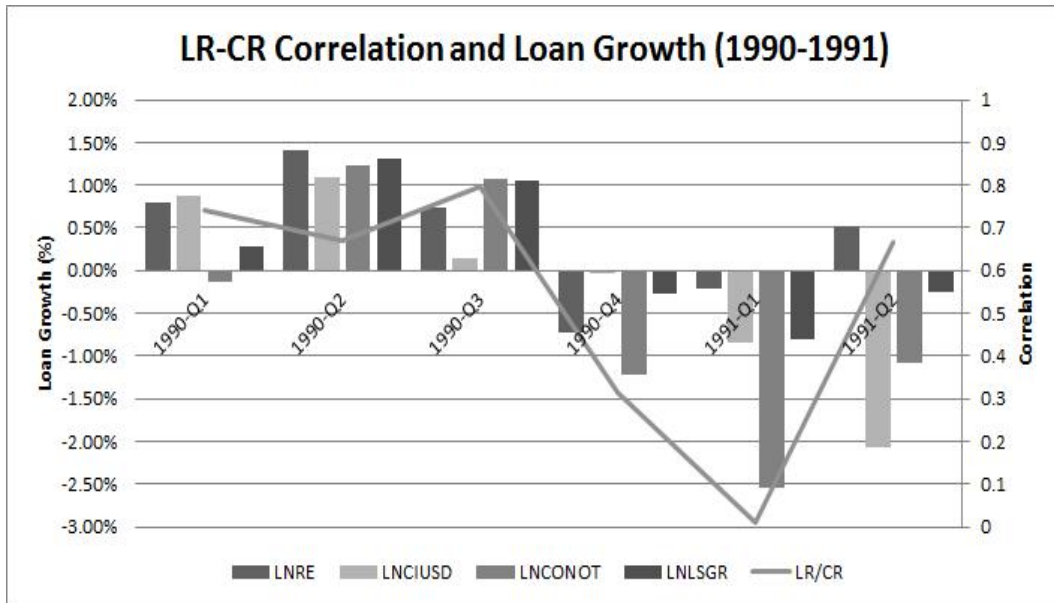


Figure 3: Relation between LR-CR Correlation Pattern and Loan Growth for different loan categories during the 1990-1991 crunch

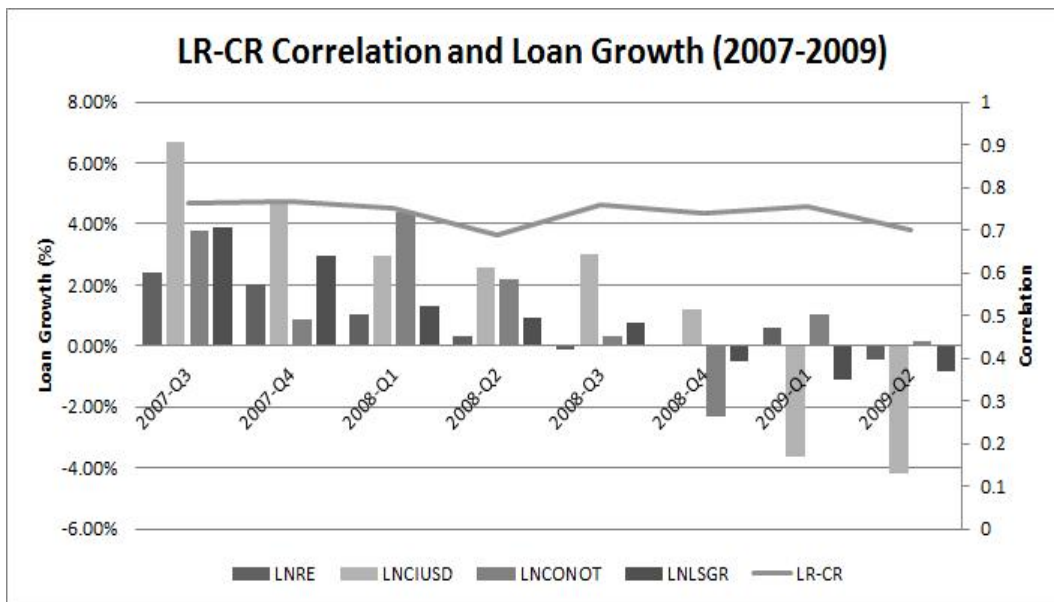


Figure 4: Relation between LR-CR Correlation Pattern and Loan Growth for different loan categories during the 2007-2009 crunch

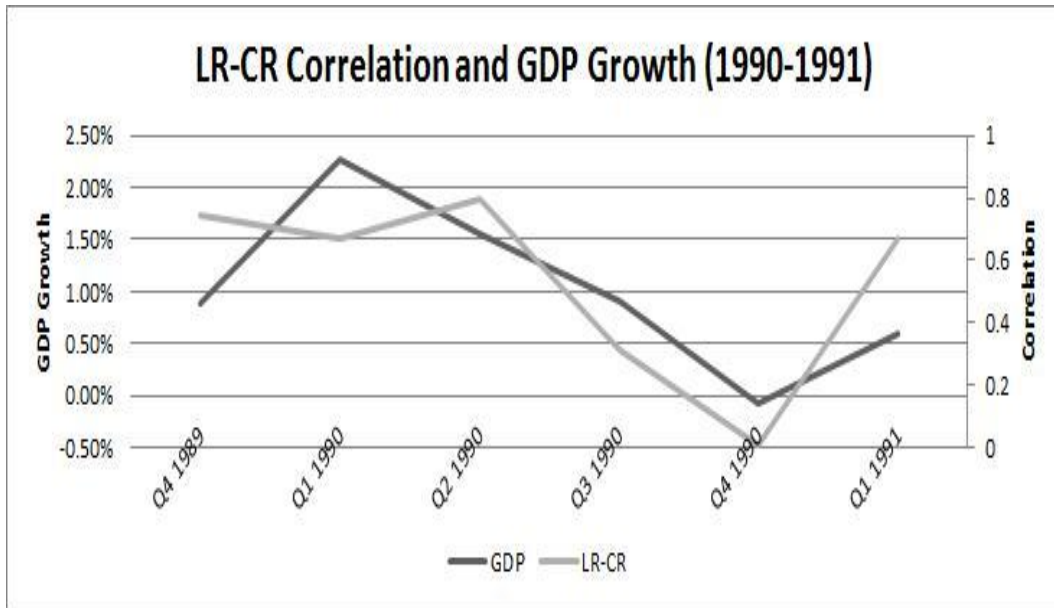


Figure 5: Relation between LR-CR Correlation Pattern and GDP during the 1990-1991 crunch

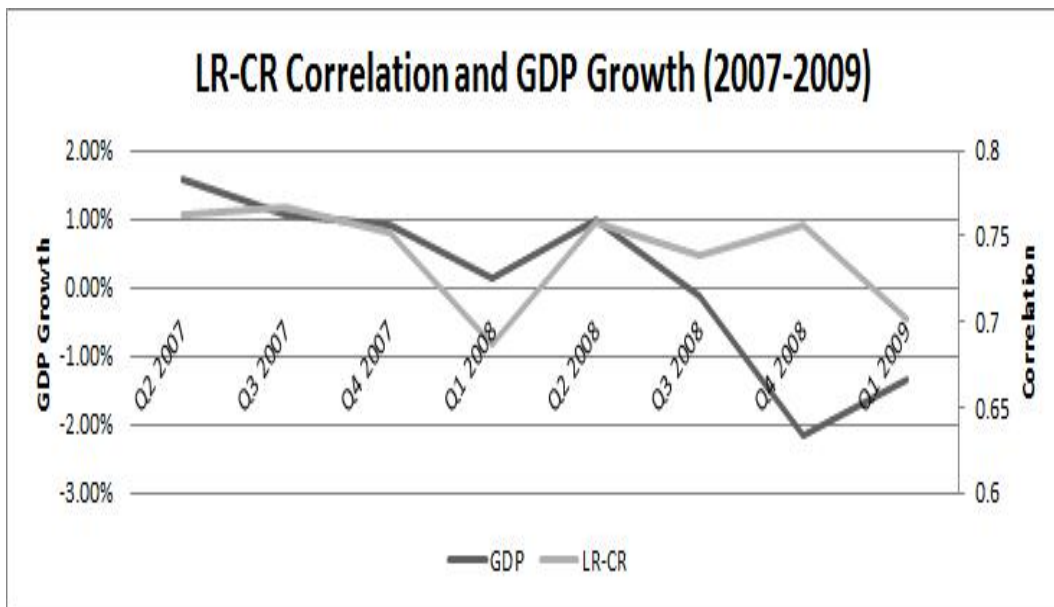


Figure 6: Relation between LR-CR Correlation Pattern and GDP during the 2007-2009 crunch

fluctuates around 0.75 in the first few quarters of the crunch. It then falls sharply between 1990Q4-1991-Q1 before reverting to its previous level. In contrast, during the second crunch, the pattern remains at 0.75 with no noticeable changes (Figure 2). Note that the presence of a fall during the first (and shorter) crunch is hinted to by the fact that the change in correlation between peak and trough is around ten times that in the second crunch.

In addition, it seems as though the LR-CR correlation pattern during the first crunch is more correlated with microeconomic and macroeconomic fundamentals, such as loan growth (0.75 versus 0.43) and GDP (0.66 versus 0.37), than during the second crunch. As in Berger and Udell (1994) and Shrieves and Dahl (1995), we categorize lending growth into three major groups belonging to high-weighted risk categories (50%-100%): real estate (LNRE), commercial and industrial (LNCIUSD) and consumer (LNCONOTH) loans. We also include the aggregate (LNSGR). As is apparent during the first crunch, the correlation pattern is strongly associated with the overall²⁰ lending pattern (Figure 3). That is not the case during the second crunch (Figure 4). Hence, this favors a change in the dynamics between the two ratios and lending only during the first crunch. Such a change could be a result of changes in the high-risk weight categories which affect the correlation between the LR and CR as seen in equation (3).

Similarly, with regard to GDP, in line with the positive relationship between lending and GDP as established in Gambacorta and Mistrulli (2004), one could argue that in a financial crisis, macro effects take longer to appear in the economy than at the micro-banking level. For this reason, we use a one-quarter lagged LR-CR pattern instead of the concurrent one and plot it alongside GDP in Figures 5 and 6. The results are similar in comparison to loan growth. In sum, this highlights a new finding that the correlation between CR and LR can be considered as an economic signal as it reflects the lending and economic cycles.

Finally, we capture the loan category mostly linked to each of the crises by computing the correlation of each category with the LR-CR correlation pattern. The results for each category are shown in Table III. The correlation of the LR-CR pattern with real estate lending is perfectly in line with the overall loan portfolio (LNSGR) during the first crisis when this category received a lower risk-weight than the rest (50%). During the second crunch, it even surpasses the rest of the three categories at a time when it received a second round lowering to 35%. This illustrates the differential role this asset class played during each crunch. We refer to this in our empirical section.

Table III:
Correlation between ρ and Loan Asset Growth

The results in this table refer to the correlation between various loan asset classes and the observed LR/CR pattern for each designated crunch period.

Loan Asset Class	Crunch 1 (1990Q1-1991Q2)	Crunch 2 (2007Q3-2009Q2)
LNRE	0.75	0.59
LNCIUSD	0.30	0.41
LNCONOTH	0.84	0.14
LNSGR	0.75	0.43

²⁰Although one cannot infer from observing these figures which of the loan growth categories is mostly correlated with the LR-CR pattern, the lending contraction is obvious in both figures. We look at the individual categories next.

6. Model Verification and Policy Implications

6.1. The CR 3-Factor Model

In this section, we set out to test whether the 3-factor relation in equation (4) can empirically explain the sensitivity of the CR to a change in a single risk-weight. Using the derivative decomposition rule we can write:

$$\frac{\delta CR}{\delta w_i} = \frac{\delta CR}{\delta t} \times \frac{\delta t}{\delta w_i} \Rightarrow \frac{\delta CR}{\delta t} = -\frac{\delta w_i}{\delta t} \times LR \times \frac{1}{\frac{RWA}{TA}} \times \frac{A_i}{RWA} \quad (8)$$

To disentangle the effect of each factor in the equation we take logarithms at both ends. This translates into the following empirical model where the intercept α should equal the logarithm of the change in risk-weight which is constant for all banks in a given period:

$$\ln(\Delta CR)_j = \alpha + \beta_1 \ln(LR)_j + \beta_2 \ln(InvCrRatio)_j + \beta_3 \ln(AP)_j + \epsilon_j \quad (9)$$

Using Newey-White robust estimators, we verify the findings of this model by comparing the cross-sectional estimates from the two periods in Table I which differ by the timing of one crucial event. The 1990Q1-1992Q2 period was marked by the phasing-in of Basel I with the shifting of the risk-weight on residential real estate mortgages from 100% to 50%. However, although the Basel II change from 50% down to 35% began to be factored in by U.S. banks between 2004Q3-2009Q2, the actual deadline for enforcing it would come later on²¹. For our empirical setup to function properly, any change in risk-weight would have to occur on a specific date and enforced by all banks simultaneously. If this assumption is verified, the first crunch should exhibit a noticeable difference at phase-in date compared to the second.

Running the model at various sample percentiles as per Table I shows remarkably no difference for any periods. We therefore suffice with the results from the 90th percentile which are displayed in Figures 7 and 8 below²². These figures show the ability of the theoretical model to explain on average around 12% of the changes in CR. This suggests that in practice these changes are also governed by other exogenous factors or frictions which can arise from the fact that the LR and CR do not move in total freedom due to the constraint imposed by regulators on minimum thresholds.

Moreover, both crises show persistent coefficients for the inverse of the credit ratio while asset proportion barely has any effect in both periods. Despite the fact that both variables are a function of RWA, we base our finding on the fact that this component might have been factored in only by the credit ratio as a well-known determinant of the CR, while the importance of asset proportion, highlighted by equation (4), has so far not been recognized.

In contrast, the β_1 coefficient adjusts to around its expected value of 1 at the phase-in point at exactly the point in time where the regulation was phased-in during the first crisis: after the end of 1990 (or beginning 1991) according to Woo (2003) and Gambacorta and Mistrulli (2004). In fact, the coefficients on LR (β_1), Alpha_UC (α) and R^2 all rise in the same way at the phasing-in point. While this increase almost perfectly matches the fall in correlation witnessed in Figure 1,

²¹The worldwide full implementation of Basel II was scheduled for 2011 (Berger et al. (1995)) which came a year after Basel III was endorsed.

²²Note that since the regulatory variables were introduced in 1990Q1 and we are looking at changes in capital ratios, this implies that we would lose one observation in this designated period.

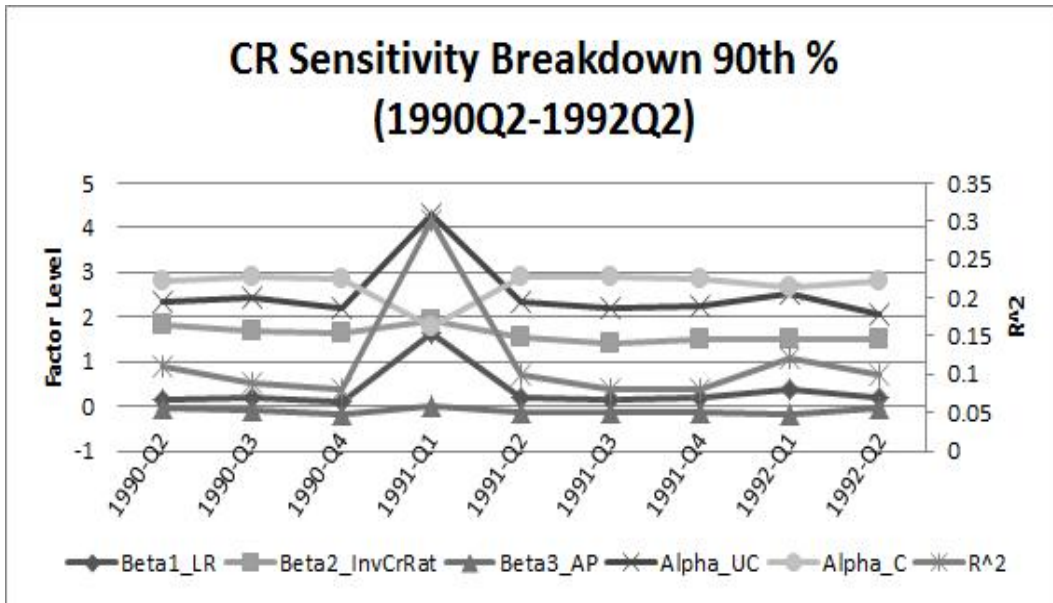


Figure 7: Three Factor Model for the CR sensitivity to a change in Risk-Weight during 1990Q2-1992Q2

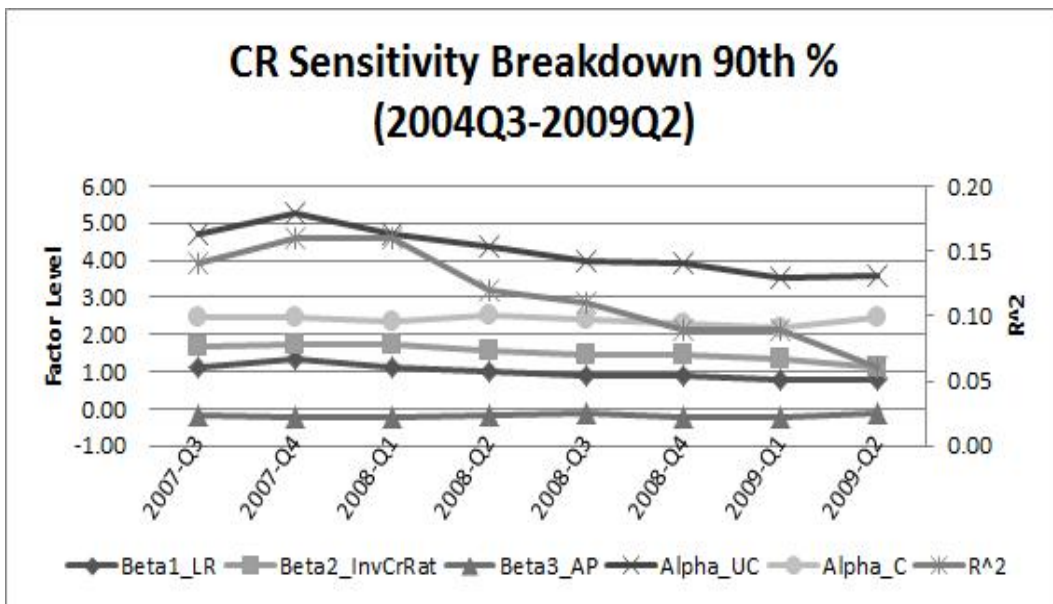


Figure 8: Three Factor Model for the CR sensitivity to a change in Risk-Weight during 2004Q3-2009Q2

there is no such perceivable change for the second crunch as seen from Figure 2. This almost certainly suggests that the Basel regulation was implicated in the first crunch but not the second through the changes in risk-weights which accompanied the new CR. In other words, the trough in Figure 1 which is almost 0, refers to the lowest possible correlation between LR and CR. According to equation (2), this relates to a period in which banks accumulated safe assets, in the form of Treasury Bills ($w_i = 0$), and as a result cut-down on lending which lead to the crunch.

In addition, we observe a significant value of 4.3 at 1% for the unconstrained α (Alpha_UC) in 1991Q1 which is almost twice as high as the ones obtained throughout the corresponding period. However, despite also being significant, our value of 4.6 changes relatively little during the second period and does not exhibit the same noticeable change as in the first period. Assuming the only risk-weight change that took place in both periods was related to residential mortgage assets, the model derivation in equation (9) implies that we should detect an α of 3.9 (2.7) for the first (second) period²³. Clearly, the expected value corresponding to the first crunch is much closer to the model-implied value which re-asserts the changes in risk-weights which happened at that time. In any case, the exact values could not have prevail owing to the fact that our formula is not enforced by the banking industry. Nonetheless, the comparison between both periods confirms that banks ratios still account for instantaneous changes in risk-weight which our model is sensitive to.

Note that our empirical findings are only valid for changes in a single risk-weight which could not always be the case. Our results could have therefore been affected by disturbances from unaccounted changes. Hence, we force the theoretical constraint that all coefficients be equal to 1 in equation (9). On one hand, the constrained α (Alpha_C) in the first period still undergoes a perceivable change in 1991Q1. This indicates that our constrained model remains sensitive to changes that occurred during this period. On the other hand, while the constrained α in the second period is almost the same as its expected value at around 2.4, the fact that it remains almost constant over time suggests again that banks did not undertake a specified change in risk-weight during the second crunch.

6.2. Linking the CR to the LR: Policy Implications

In this section, we derive a framework for explicitly setting the CR with respect to the LR. Our starting point is equation (7) which is a simple homogeneous partial differential equation (PDE) that can be solved in closed form. The derivations are stated in the Appendix. In the case of a single risk-weight change, the relationship becomes:

$$CR = LR \times e^{\sum_i^N [AP_i(1-w_i)]} \quad (10)$$

As the exponential power term is always positive, the CR should always be greater than the LR. Indeed, the formula implies that banks should at least meet a lower threshold of CR equal to LR; afterwards, they should increment their respective risk-based capital positions by a weighted average of their asset proportions as captured by the exponential term in equation (10). For example, with a 3% LR, the old Tier 1 CR of 4% is reasonable but for the less conservative LR of 5% it is not. Indeed, such distortions to the above identity could induce wrongful behavior on the part of banks as was reported in Gilbert (2006). Hence, as the CR is set to increase to 6% under Basel III, this is in line with both LR targets between 3-5%.

²³These values are equivalent to $\ln(-(50-100)/1)$ and $\ln(-(35 - 50)/1)$.

In the following, we test to what extent equation (10) holds empirically using the following panel regression. Our results are shown in Table IV.

$$\ln\left(\frac{CR}{LR}\right)_{jt} = \alpha + \beta \sum_i^N [AP_i(1 - w_i)]_{jt} + \epsilon_{jt} \quad (11)$$

We report that across the two sample periods all estimates are significant at the 1% level. As can be seen from panels A and B, at the 90th (95th) percentile, the R^2 increases to 93% (77%) for the first (second) crunch. The relationship then weakens the smaller our sample becomes as this makes it more specific to a particular type of banks. This confirms that the above relationship holds for the banking sector taken as a whole. Moreover, we notice that the α converges to 0 (1 in anti-logarithmic terms) as suggested by our theoretical model. This confirms the lower threshold of CR being at least equal to LR^{24} before any increments linked to asset proportions take effect.

Furthermore, we run a Chow test on the period stemming from the Basel II introduction to the end of the crisis to verify that the coefficients are stable between pre-crisis and crisis periods with the delimiter date set to 2007Q3²⁵. The results shown in Panel C illustrate that between the 99.9th and 80th percentiles, the hypothesis of stability cannot be rejected which means that our model is valid independently of the period under consideration²⁶. Nevertheless, even at its peak of around 0.4, the value of β is noticeably below 1. In other words, a good proportion of banks are operating below the theoretical CR requirement. This leaves policy-makers with the task of driving them upwards to ensure the compatibility between the two ratios is maintained.

Note that according to equation (1), CR/LR is equivalent to TA/RWA; hence our results should hold whether we use either ratio as the LHS variable in equation (11). Indeed, we rerun our robustness test version of our model in Table V and find that we reproduce to a large extent the results in Table IV.

Table IV:
Testing the CR formula stability (CR/LR)

The results in this table are obtained after running the original version of the regression model in Equation 11: $\ln\left(\frac{CR}{LR}\right)_{jt} = \alpha + \beta \sum_i^N [AP_i(1 - w_i)]_{jt} + \epsilon_{jt}$. Pct denotes the percentage remaining from the original sample after removal of outliers. Chow tests use the delimiter date of 2007Q3.

Panel A: 1990Q1-1992Q2									
Pct	100%	99.9%	99%	95%	90%	80%	70%	60%	50%
α	0.445	0.445	0.195	0.136	0.119	0.109	0.100	0.095	0.086
β	0.108	0.108	0.420	0.497	0.521	0.533	0.543	0.547	0.557
R^2	0.458	0.458	0.898	0.924	0.928	0.917	0.906	0.893	0.885
Panel B: 2007Q3-2009Q2									
Sample	100%	99.9%	99%	95%	90%	80%	70%	60%	50%
α	0.341	0.338	0.306	0.137	0.139	0.145	0.148	0.150	0.151
β	0.041	0.045	0.090	0.409	0.395	0.359	0.322	0.282	0.246
R^2	0.165	0.119	0.086	0.769	0.730	0.647	0.559	0.457	0.381
Panel C: Chow Tests									
Sample	100%	99.9%	99%	95%	90%	80%	70%	60%	50%

²⁴This can be seen by taking the Taylor series approximation for small numbers. For example, using the 50th percentile in Panel A: $\exp(0.086) \approx 1 + 0.086 = 1.086 \approx 1$.

²⁵Choosing a different date such as 2006Q3 in relation to the Basel II implementation does not change our results.

²⁶In all cases the coefficients are equal up to one decimal place.

β_1	0.038	0.038	0.048	0.360	0.361	0.357	0.371	0.366	0.361
β_2	0.042	0.043	0.057	0.356	0.356	0.349	0.362	0.356	0.351
p-val	0.417	0.183	0.040	0.077	0.082	0.077	0.165	0.203	0.353
χ^2	0.66	1.77	4.19	3.11	3.02	3.12	1.93	1.62	0.860

Table V:
Testing the CR formula stability (TA/RWA)

The results in this table are obtained after running a parallel version of the regression model in Equation 11: $\ln\left(\frac{TA}{RWA}\right)_{jt} = \alpha + \beta \sum_i^N [AP_i(1 - w_i)]_{jt} + \epsilon_{jt}$. Pct denotes the percentage remaining from the original sample after removal of outliers. Chow tests use the delimiter date of 2007Q3.

Panel A: 1990Q1-1992Q2

Pct	100%	99.9%	99%	95%	90%	80%	70%	60%	50%
α	0.442	0.442	0.192	0.133	0.116	0.106	0.097	0.092	0.083
β	0.105	0.105	0.416	0.494	0.517	0.529	0.538	0.542	0.553
R^2	0.457	0.457	0.897	0.924	0.928	0.917	0.906	0.894	0.8866

Panel B: 2007Q3-2009Q2

Sample	100%	99.9%	99%	95%	90%	80%	70%	60%	50%
α	0.349	0.325	0.304	0.136	0.138	0.144	0.146	0.148	0.150
β	0.041	0.045	0.090	0.408	0.393	0.357	0.320	0.279	0.243
R^2	0.165	0.118	0.085	0.771	0.731	0.649	0.561	0.460	0.382

Panel C: Chow Tests

Sample	100%	99.9%	99%	95%	90%	80%	70%	60%	50%
β_1	0.038	0.039	0.048	0.360	0.361	0.356	0.370	0.365	0.359
β_2	0.042	0.045	0.057	0.355	0.354	0.348	0.360	0.354	0.348
p-val	0.417	0.183	0.040	0.069	0.070	0.060	0.130	0.155	0.272
χ^2	0.66	1.79	4.21	3.21	3.27	3.55	2.29	2.02	1.21

Finally, our results showed that the Basel III guidelines with respect to CR increments are in line with the theoretical implications of our model. They also highlight that there is room to improve on the choice of capital targets by making them more adequate using a dataset of representative banks to calibrate a generalized model for the banking sector. Alternatively, this could create the possibility for having endogenous bank-specific requirements rather than a one-size fits-all guideline; a change called for by some critics since the birth of the Basel regulation. Notably, this would help European regulators especially in the context of establishing homogeneous capital requirements for all EU countries (Cathcart et al. (2013a)).

7. Conclusion

In this paper, we investigate the impact changes in risk-weight(s) can have on the behavior of banks towards adjusting their CRs and LRs. We first assess which of these latter two ratios was the binding constraint on banks during the 2007-2009 credit crunches. Our results indicate that unlike the first crunch, the LR was more to blame for triggering the subprime crisis. Our work complements the analysis of Avery and Berger (1991) and reveals the impact of crises on bank capital cushions, and vice versa. More specifically, we illustrate the erosion in capital ratios caused by the subprime crisis while establishing the beneficial impact of capital on survival rates.

Furthermore, we study the changes in correlation patterns between the two ratios over the two crunch periods. These patterns are found to be economic signals as they are related to both loan growth (microeconomy) and GDP (macroeconomy with appropriate lag). We then show that this

reversal has its roots set in a mathematical relation emerging from the sensitivity of the CR to a change in its risk-weight(s). While the correlation patterns may have changed during different crises, we show that the impact on the binding constraints could not have been caused by changes in risk-weights attributed to Basel II. That is not the case; however, for Basel I.

Finally, we provide a formula that relates the sensitivity of the CR to the LR, the inverse of the credit risk ratio, and a new factor conveniently dubbed “asset proportion”. As the formula was not applicable as part of the Basel framework, its empirical testing reveals limited explanatory power and explains the multiplicity of other factors provided by the literature to study the behavior of capital ratios. While we welcome these additions, we emphasize that any model which does not account for the factors in our formula would inherently suffer from omitted variable bias. In addition, an extension of our formula gives way to a first-order homogeneous partial differential equation (PDE) governing the behavior of the CR. We solve for single and multiple changes in risk-weights which fit into a generic closed form solution. This allows for setting adequate CRs which reflect changes in risk-weights while taking into consideration its counterpart capital measure, the LR. In fact, this can be done in a straightforward and rigorous manner with not much added complexity compared to enforcing arbitrary Basel ratios. Hence, this allows us to move away from the use of heuristics with regard to capital target selection.

While our study does not consider other factors that might have impacted the crises, our results are helpful in assessing the improvements brought by the new Basel III regulation with respect to capital requirements. Considering the ongoing efforts of improving the granularity of the risk-weight scheme by introducing new risk-weight buckets, our framework will facilitate the setting of adequate CRs. Hence, doing so in a mechanical rather than heuristic way could eliminate some of the criticism linked to the impact of the Basel capital ratio on banks. It would be interesting to explore any changes unrelated to the Basel regulation in between the periods defined in our study. This would allow us to pinpoint non-structural drivers of banks’ capital ratios as suggested by our empirical section. In addition, given that changes to risk-weights did not take place during the second crunch, further research is required on how the LR effectively became a more binding constraint.

Appendix A. Solution to the CR equation

Assuming the CR is a function defined on $]0, 1]^N$ with N possible risk-weights (w_i), the solution to the partial differential equation (PDE) in equation (7) is solved in the exponential form $Ae^{\sum_{i=1}^N c_i w_i}$ where c_i are arbitrary constants to be found. Let $g(w_1, \dots, w_N)$ be another function defined on the same support as CR and representing the product term in the equation ($\prod_{i=1}^N AP_i$). Substituting into (7) we get:

$$\prod_{i=1}^N c_i = (-1)^N \times N! \times g(w_1 \dots w_N) \quad (\text{A.1})$$

As stated earlier, the only boundary condition we have is regarding the sensible approximation that $\text{CR}(1, \dots, 1) = Ae^{\sum_{i=1}^N c_i} = \text{LR}$. Denoting by n the subset of N asset categories with respect to which we are calculating the sensitivity of the CR, this yields a system of two equations with $n+1$ unknowns. We solve for the cases of $n=1$, $n=2$ and $n=N$.

Appendix A.1. Solution with n=1

The system of equations for the case of a single risk-weight change becomes:

$$\begin{cases} c_i = -g(w_i) & \text{(A.2)} \\ LR = Ae^{\sum_{i=1}^N c_i} & \text{(A.3)} \end{cases}$$

By substitution:

$$LR = Ae^{\sum_{i=1}^N c_i} \rightarrow A = LR \times e^{-\sum_{i=1}^N c_i} \quad \text{(A.4)}$$

$$CR = LR \times e^{-\sum_{i=1}^N c_i} \times e^{\sum_{i=1}^N c_i w_i} = LR \times e^{-\sum_{k \neq i}^N c_k + AP_i} \times e^{\sum_{k \neq i}^N c_k w_k - AP_i w_i} \quad \text{(A.5)}$$

$$= LR \times e^{-\sum_{k \neq i}^N [c_k(1-w_k)] + AP_i(1-w_i)} \quad \text{(A.6)}$$

By symmetry, the same form applies for a change in asset j which gives:

$$CR = LR \times e^{-\sum_{k \neq j}^N [c_k(1-w_k)] + AP_j(1-w_j)} \quad \text{(A.7)}$$

By the ratio of the two changes in assets we get the following identity:

$$1 = e^{-\sum_{k \neq i}^N [c_k(1-w_k)] + AP_i(1-w_i) + \sum_{k \neq j}^N [c_k(1-w_k)] - AP_j(1-w_j)} \quad \text{(A.8)}$$

Taking logarithms at both ends and applying the principle of linearity we get: $c_k = -AP_k$ for all asset classes. This gives the final version of the CR equation given below. Note how the riskiest risk-weight class has no bearing on the differential between CR and LR in the same way that the safest risk-weight category has no impact on total RWA.

$$CR = LR \times e^{\sum_{i=1}^N [AP_i(1-w_i)]} \quad \text{(A.9)}$$

Appendix A.2. Solution with n=2

The boundary condition remains the same. Hence, using symmetry to overcome the under-specification in the case of 3 risk-weight categories, the system of equations for the case of any two risk-weight changes becomes:

$$\begin{cases} c_i c_j = 2 \times g(w_i, w_j) = 2 \times AP_i AP_j & \text{(A.10)} \\ c_j c_k = 2 \times g(w_j, w_k) = 2 \times AP_j AP_k & \text{(A.11)} \\ c_k c_i = 2 \times g(w_k, w_i) = 2 \times AP_k AP_i & \text{(A.12)} \end{cases}$$

Combining these equations together we get: $c_i^2 = 2AP_i^2, c_j^2 = 2AP_j^2, c_k^2 = 2AP_k^2$. This gives two possible solutions; however the first solution (A.13), is discarded as the CR is increasing in w_i which is counter-intuitive.

$$CR = LR \times e^{-\sum_{i=1}^N [\sqrt{2}AP_i(1-w_i)]} \quad \text{(A.13)}$$

$$CR = LR \times e^{\sum_{i=1}^N [\sqrt{2}AP_i(1-w_i)]} \quad \text{(A.14)}$$

Appendix A.3. Solution with $n=N$

Similarly, using symmetry and discarding the erroneous cases for n even, we obtain the general solution as below.

$$CR = LR \times e^{-\sum_{i=1}^N [\sqrt[N]{AP_i(1-w_i)}]} \quad (\text{A.15})$$

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