Estimating Central Bank Reaction Functions Post 2008: USA and Switzerland

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for Economics 491

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Year 2018 Winner of the Douglas D. Purvis Prize in Economics

1. Introduction

The 2008 global financial crisis confronted central banks with unique challenges, many outside the scope of their past monetary policy experience. (Jordan, 2009; Federal Reserve, 2016) Specifically, as the effects of the housing market collapse in the United States spread across the world, widespread financial panic ensued. (De Haas, & Van Horen, 2012) Many banks faced negative shocks to their capital and found it very difficult to access long-term debt. This in turn lead to a negative feedback loop in which "balance-sheet constraints induced [banks] to deleverage abroad and thus transmit shocks across borders" (De Haas, & Van Horen, 2012) The ensuing liquidity crisis translated into adverse shocks to credit spreads throughout almost all advanced economies. Central banks all over the world were forced to quickly adapt; looking not only at theory but also at history, in an attempt to create policies to cope with these difficult circumstances.

In light of this discussion, this paper aims to test whether a simple rule can be created to describe the monetary policy reaction of two independent central banks: the Swiss National Bank (SNB) and the US Federal Reserve (the Fed). This paper focuses on these two banks as both have had unique experiences with monetary policy; furthermore, differences in their policy structure provide an interesting and informative starting point for analysis.

2. Background

Financial Conditions & Credit Spreads

"On Thursday, August 9, 2007 traders in New York, London, and other financial centers around the world suddenly faced a dramatic change in conditions in the money markets. The federal funds rate—the interest rate on overnight loans between banks jumped to unusually high levels compared with the Fed's target. Rates on longer term inter-bank loans, measured for example by the 3-month London Interbank Offered Rate (LIBOR), surged as well." (Taylor & Williams, 2008)

Alan Greenspan likened this spread between interbank rates and the overnight rate to "a barometer of fears of bank insolvency." (Thornton, 2009) During periods of "calm" in the financial sector, the spread usually remains small and relatively constant. In such cases, ignoring the spread when analyzing monetary policy is a reasonable simplifying assumption. However, during the 2008 financial crisis the spread became large and unpredictable, reflecting a severe shock to credit conditions compounded by persistent fear and uncertainty. (Federal Reserve, 2016; Thornton, 2009) The Federal Reserve reacted swiftly by cutting the overnight rate, but the significant introduction of liquidity was not enough to decrease the spread between the policy rate and the interbank rate. Instead, the interbank rate became disconnected from the overnight rate, rising far above and failing to return to lower levels (Thornton, 2009) (*Figure 2.1*).

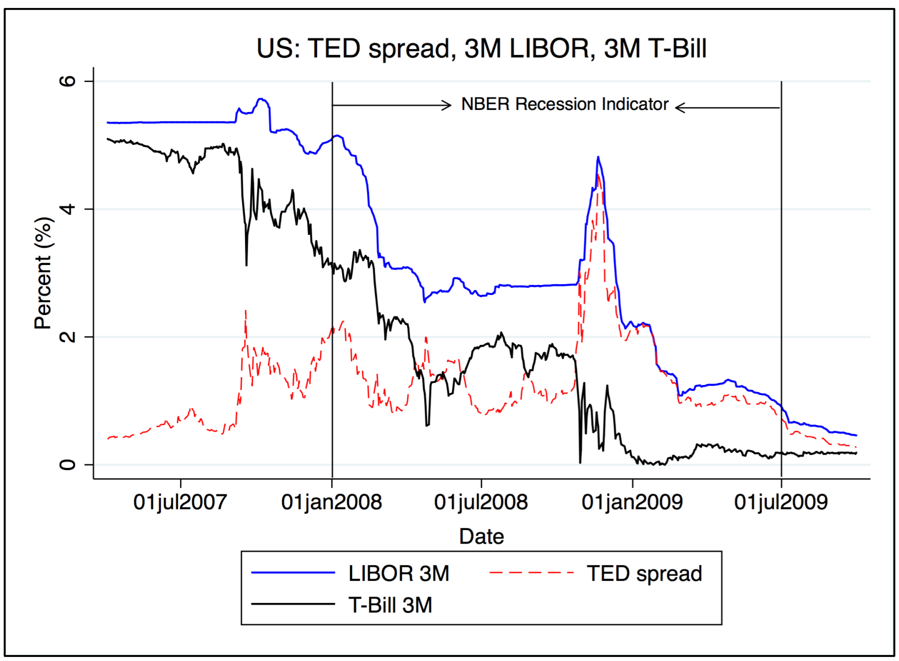


Figure 2.1: 3-Month London Interbank Offered Rate (LIBOR), based on U.S. Dollar, Percent, Daily (Retrieved from: FRED), Effective US Federal Funds Rate, Percent, Daily (Retrieved from: FRED), TED Spread, Percent, Daily (Retrieved from: FRED)

This disconnect represented a serious consideration for policymakers as a persistent increase in the spread between the overnight rate and interbank rates reflects an adverse dislocation of the transmission mechanism of monetary policy. In the event of such a disconnection between these rates, the ability of monetary policy to stimulate the economy and minimize cyclical downturns is weakened significantly. (Curdia & Woodford, 2010) It is the interbank rate, not the federal funds rate, that determines the cost of capital on trillions of dollars in assets in financial markets. Thus, if these two rates do not move together, the central bank may lose its power to stimulate real GDP activity in the short run. This type of policy dislocation calls into question the validity of the Taylor rule's limited set of parameters (which will be outlined in the next section) and represents the original motivation behind this research.

The Taylor rule

In 1993, John Taylor proposed a simple and straightforward rule which linked the policy rate to changes in inflation and real GDP. (Taylor, 1993) The rule describes the optimal monetary policy to minimize the social loss function in a particular New Keynesian model. In his original paper, Taylor posited that: "policy rules have a major advantage over discretion in improving economic performance." (Taylor, 1993) The Taylor rule gained traction because some economists argued that it lead to the "Great Moderation," a time period from the 1980s-1990s where a reduction in the volatility of the business cycle was associated with more a more systematic approach to monetary policy. (Taylor, 2008)

Regardless of its strengths and weaknesses (which will be outlined later), the Taylor rule has become a popular framework for modelling the response of central banks to changing macroeconomic conditions. It describes the policy rate reacting systematically to contemporaneous deviations from the inflation target and potential output, where $\bar{r}$ is the real natural rate, π_t is the current inflation rate, and h and b are coefficients determining the strength of the policy response:

$$i_t^p = \bar{r} + \pi_t + h(\pi_t - \pi^*) + b(y_t - \bar{y})$$

However, while the Taylor rule provides a tractable starting point for understanding and modelling central bank behavior, it is unlikely to represent the central bank's best policy response to all types of macroeconomic conditions.

The most glaring issue with the Taylor Rule is that frictions in the financial system were not included in the model used to derive it, yet many central banks explicitly state that financial stability is an essential policy objective. (Crockett, 1997) The Taylor rule has no way of directly accounting for, or reacting to, disturbances in the financial sector. Consequently, excluding consideration of financial conditions from the central bank's decision-making framework is unlikely to lead to optimal policy in all circumstances. Indeed, Bernanke and Gertler (1999) demonstrate that explicitly adding a measure of financial conditions into the Taylor rule improves the estimated monetary policy response. For instance, during the Russian debt default in 1998 it was optimal for the Fed to ease the policy rate, and thereby minimize the risk of deflation caused by the rise in credit spreads. (Bernanke & Gertler, 1999; Greenspan, 2004)

This potential flaw in the Taylor rule has inspired many studies of optimal policy guidelines in dynamic stochastic general equilibrium (DSGE) models. One such framework which paved the way for analysis of financial systems and monetary policy during business cycles was the "Financial Accelerator" model developed by Bernanke, Gertler and Gilchrist (1998). Their model exhibits a mechanism which causes adverse developments in credit markets to amplify negative shocks elsewhere in the economy; a very relevant pattern in observed recessions. A study within this type of framework by Bauducco, Cihák, & Bulir, (2008) at the IMF demonstrated that: "If the central bank responds to a deterioration in the credit risk faced by the financial system by monetary easing, using an augmented rule, such a "preemptive strike" stabilizes inflation and output better in the short run than the simple Taylor rule." This type of central bank behaviour more accurately reflects historical developments seen in recent recessions and certainly warrants further investigation as a starting point to improve the original Taylor rule.

In fact, John Taylor himself acknowledged this flaw in his proposed rule and in 2008 he suggested that: "One possible approach to adjusting the systemic component of monetary policy would be to subtract a smoothed version of [the LIBOR-OIS] spread from the interest rate target that would otherwise be implied by developments with inflation and real GDP" (Taylor, 2007).

Using that idea as a starting point, this paper will use an SVAR to determine if adding a measure of financial conditions to the existing Taylor rule can significantly improve the ability of the rule to predict central bank behavior during recessions.

Historical Context: USA

The Federal Reserve was founded in 1913 in order to maintain a stable monetary and financial system in the United States of America. Explicitly, the Federal Reserve Act states that the Board of Governors and the FOMC should conduct policy "to promote effectively the goals of maximum employment, stable prices, and moderate long-term interest rates." (Federal Reserve, 2016) These policy objectives are inherently tied to the broader goal of promoting a stable and productive economy.

As mentioned before, the Taylor rule provides a succinct way of summarizing the optimal policy response to meet these goals. However, historical data indicates the Taylor rule does not work under all circumstances. For instance, at the onset of the financial crisis in the fall of 2007 the FOMC reduced the federal funds rate. However, as the risk of deflation grew much stronger in 2008, the Fed cut the overnight rate to the zero lower bound (ZLB), a reaction that the Taylor rule does not predict. Furthermore, faced with the binding ZLB constraint on the overnight rate, the Fed began purchasing longer-term securities, and creating lending facilities to provide even more monetary stimulus. (Federal Reserve, 2016) Prior to 2007, the bank had mostly held treasury assets of shorter maturity. However during the crisis it was necessary to conduct large scale asset purchases to lower long-term yield rates. (Federal Reserve, 2016) It was also crucial to the recovery that that the Fed acted as a direct lender, extending credit where it was needed through programs such as the Term Auction Facility (TAF). (Curdia & Woodford, 2010)

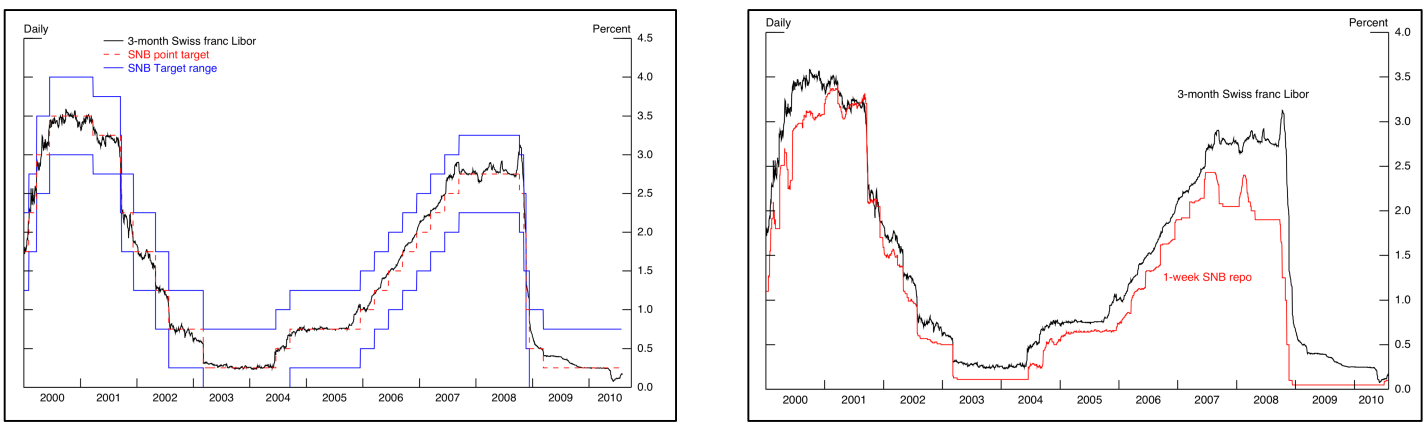
The sheer size and scope of these monetary easing policies during the crisis demonstrate that central banks closely monitor fear-based disruptions in financial markets which can lead to disastrous debt-deflation if they do not intervene. (Fisher, 1933)

Historical Context: Switzerland

The Swiss National Bank (SNB) is different from all other central banks in that it does not explicitly announce a monetary policy target for the overnight lending rate. Instead, the SNB announces a target range for the 3M Swiss franc LIBOR. (Jordan, 2009) The SNB implements its target by conducting fixed-rate repo operations, usually at a maturity of one week and it enforces the upper end of its target range by providing overnight financing at a penalty rate through a standing lending facility. (Jordan, 2009) The 3M LIBOR target was chosen over a target for the overnight rate as it "is the main reference rate to which the pricing of Swiss franc credit is linked, including many mortgages. Moreover, the Swiss domestic repo market was not (and is not) sufficiently developed and lacks the liquidity to support operations in very short maturities, such as overnight." (Schindler, 2010)

This allows the SNB to react to shocks in financial markets without explicitly changing the operational 3M LIBOR target. (Abbassi et al., 2009) Indeed, changes in SNB repo rates are often caused by fluctuations in money market rates rather than shifts in the bank's operational target. (Olivei, 2002) This is relevant to the purpose of this paper, which is to demonstrate how central banks behave when faced with widening spreads in the interbank money markets. Targeting the overnight rate (as the Fed does) and targeting the 3M LIBOR (as the SNB does) lead to very similar outcomes in times of stability. However, during times of crisis, targeting the 3M LIBOR directly implies that the central bank will actively control credit spreads and stabilize interbank lending in a predictable way. It may therefore be an option that other central banks should explore. (Abassi et al., 2009)

Note that prior to 2000, the SNB did not have an explicit goal for price stability nor did it target the 3M LIBOR. Instead, it used foreign exchange swaps to control the monetary base. (Abbassi, Nautz, & Offermanns, 2009) Starting in 2000, the SNB began using the 3M LIBOR to target an annual CPI inflation rate of less than 2%. (Olivei, 2002) This paper will study the behaviour of the SNB from 2000 to the present when the reaction function can be assumed to remain relatively consistent and predictable. *Figure 2.2* shows the behaviour of the SNB target range and the 3M Swiss franc LIBOR from 2000-2010.



(a) SNB 3M LIBOR target range

(b) 3M LIBOR & 1-week SNB repo

Figure 2.2: Swiss Monetary Policy Variables. John Schindler FOMC Memo: *The Swiss National Bank's Three-month Libor Target,* Aug 5, 2010.

3. Methodology

This paper will use a structual vector autoregression (SVAR) with two distinct specifications to estimate monetary policy reaction functions for the SNB and the US Fed during the 2008 financial crisis. The methodology was inspired by an undergraduate paper titled: "*The Reaction Function of The Federal Reserve Post 2008 Financial Crisis.*" Cassard (2015). Cassard's paper expanded on Stock and Watson's "Vector Autoregressions" (2001) which provided an introduction to econometric analysis of monetary policy based on a simple three-variable VAR.

The three key variables Stock and Watson (2001) included were: inflation, unemployment, and the federal funds rate. The idea behind this specification comes from Taylor rule and is intended to capture the dual mandate of the Fed: ensuring price stability and maximum employment. (Federal Reserve, 2016; Taylor, 1993)

As stated in the literature review, both central banks reacted strongly to the sharp increase in spreads during the crisis. By comparing two specifications of an estimated reaction function; one based on a simple Taylor rule and the other based on the Taylor rule augmented with an indicator of financial conditions, this paper attempts to quantify the importance of financial sector disturbances to both bank's policy decisions. Analysis of the impulse response functions (IRFs) will demonstrate how the central banks in both countries reacted to observed shocks. Additionally, 24-Month forecasts starting from set periods during the crisis will be used to compare the forecasting power of the competing Taylor rule models. Finally, a Markov-switching model will be used to examine the presence of a time-varying relationship in the Fed's policy reaction.

An SVAR framework was chosen to compare these two rules as it efficiently captures detailed dynamics contained within multiple time series. Within this type of model, the evolution of each variable is explained by a collection of its own lagged terms as well as lagged terms of the other variables. (Sims, 1980) A simple reduced-form VAR would have adequately captured the aforementioned dynamic relationship within the data, however it was insufficient for two reasons. First, a reduced-form VAR does not allow for contemporaneous relationships among its variables. This contradicts economic theory as monetary policy decisions are determined by current values of macroeconomic indicators (rather than t-1 values). (Lütkepohl, 2005) Second, the error terms would likely be correlated, which would invalidate inference regarding shocks: if the error terms are correlated, then a shock to one variable is inherently associated with a shock to all other correlated variables. (Lütkepohl, 2005)

Therefore, in order to test the hypothesis that the central bank reacts to adverse financial conditions shocks in its own economy, an SVAR identified using the Cholesky decomposition was used. The Cholesky decomposition orthogonalizes the error terms, thereby making them uncorrelated and allowing for valid impulse-response analysis (provided that the identifying assumptions are accurate). The results of this test are sensitive to the identifying assumptions and different orderings of the variables reflecting alternative theories about the underlying structure of the model would change the IRFs.

The SVAR model is specified as follows; SVAR is identified by the Cholesky decomposition, A is the identity matrix, and B is a lower triangular matrix with zeroes on the upper triangle above the diagonal. y_t represents the vector of endogenous variables, u_t represents the vector of the error terms, and k represents the lag-order.

$$Ay_t = C_1 y_{t-1} + \cdots + C_k y_{t-k} + Bu_t$$

The vectors of endogenous variables for the two Taylor rule specifications are:

1) *A Simple Taylor Rule* (Simple TR): $y_{t(TR)} = [In_t \quad Un_t \quad OR_t]$
2) *A Financial Conditions Augmented Taylor Rule* (FC TR): $y_{t(FC\,TR)} = [In_t \quad Un_t \quad FC_t \quad OR_t]$

In_t Represents the inflation rate, Un_t represents the unemployment rate, FC_t represents an indicator of financial conditions, and OR_t represents the overnight rate. These variables are ordered according to how they contemporaneously affect each other. This ordering assumes that inflation is not affected by the current values of the other variables, perhaps reflecting price stickiness within the period (one month). On the other hand, the overnight policy rate is assumed to react to the observed values of all of the other variables within the period.

Data: Model (1) uses the three variables proposed by Stock and Watson (2001). Model (2) uses the same set of three variables plus a measure of financial conditions. Admittedly, there are multiple ways to measure financial conditions. And each measure would lead to slightly different results. For the purpose of simplicity, this paper will focus on one measure for each economy studied. However, the robustness of results was confirmed using alternative indicators such as the Chicago Fed's National Financial Conditions Index, and other similar metrics.

Switzerland

Variable	Source	Description
Unemployment Rate	SNB data portal	Jobless Rate, Seasonally Adjusted
Inflation rate	SNB data portal	*SFSO* - Inflation according to the national consumer price index
Financial Conditions indicator	SNB data portal	3M CHF LIBOR *minus* 3M SNB Repo, Percent
Overnight rate	SNB data portal	Swiss Average Overnight Rate (SARON), Percent

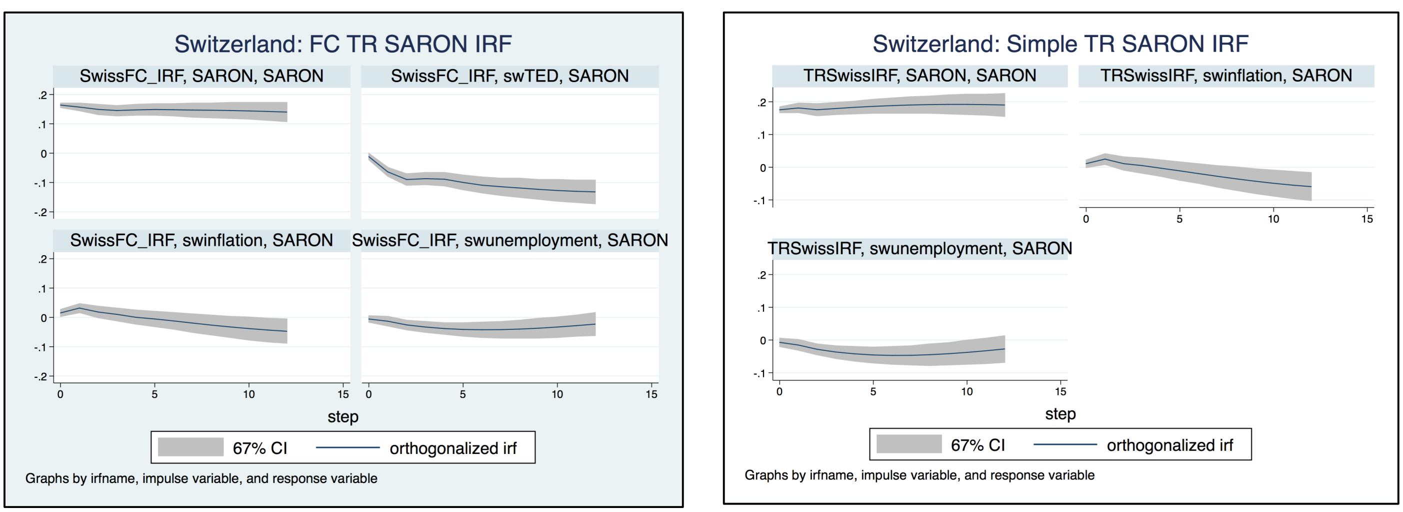
USA

Variable	Source	Description
Unemployment	BLS	Civilian Unemployment Rate, Percent, Monthly, Seasonally Adjusted
Inflation rate	BLS	Inflation rate according to Consumer Price Index for All Urban Consumers, Seasonally Adjusted
Financial Conditions Indicator	FRED	Moody's Seasoned Baa Corporate Bond Yield Relative to Yield on 10-Year Treasury Constant Maturity, Percent
Overnight rate	U.S. Fed	Effective Federal Funds Rate, Percent

4. SVAR Results: Switzerland

For the sample period (January 2000 to September 2017) the eigenvalues of both SVARs (FC TR and simple TR) have a modulus less than 1, implying that the stability condition is satisfied. (Lütkepohl, 2005) Although economic theory was used to identify the SVAR, it cannot be used to determine the optimal number of lags to include; this must be answered by the data. Accordingly, lag order selection criteria were computed for the FC TR model and the simple TR model. Three lags were included in both models, as suggested by the AIC, FPE, and HQIC.

In the FC TR model, all the variables are jointly significant in predicting each other at the 5% level. Furthermore, all the variables jointly predict the overnight rate at the 0.05% level. In the simple TR model, all variables are also jointly significant at the 5% level. However, the significance of all variables in predicting the overnight rate is lower than in the FC TR model (only significant at the 5% level). *Figure 4.1* shows the impulse response functions (IRFs) for the Swiss overnight rate (SARON).



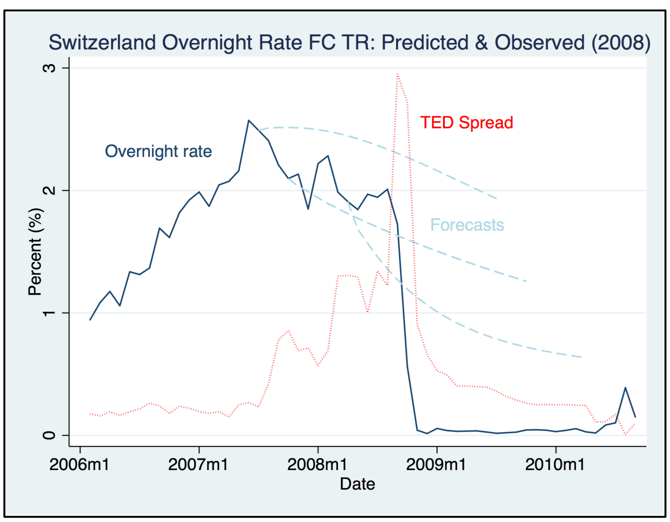
(a) Financial Conditions Augmented Taylor Rule

(b) Simple Taylor Rule

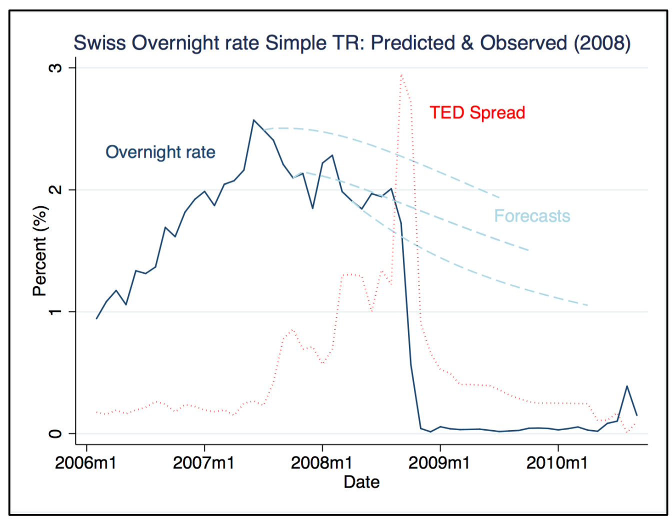
Figure 4.1: Orthogonalized impulse response functions under the two model specifications. Displays the reaction of the federal funds rate to a unit shock to the listed variables.

Impulse response functions describe the reaction of one variable to a unit shock in another. In other words, they trace the reaction of current and future values of each variable to a 1-unit increase in the current value of one of the VAR errors. (Stock & Watson, 2001) In both models, an increase in unemployment puts a small amount of downward pressure on the overnight rate, however even with a 67% confidence interval the effect is hard to distinguish from zero. An increase in inflation within both models causes the bank to react by raising the rate in the next period, however a slight decrease in the rate often follows by the end of the year.

The most notable finding from these IRFs is that in the FC TR model, an adverse unit shock to financial conditions (proxied by the Swiss TED spread) causes the SNB to react by cutting the overnight rate by 10 bps. This corresponds to the original hypothesis that including a measure of financial conditions in the Taylor rule would help in predicting central bank behavior during the crisis. The following graphs (*Figure 4.2 & 4.3*) expand on this idea by showing how the predictive power of the SVAR changes when financial conditions are included.

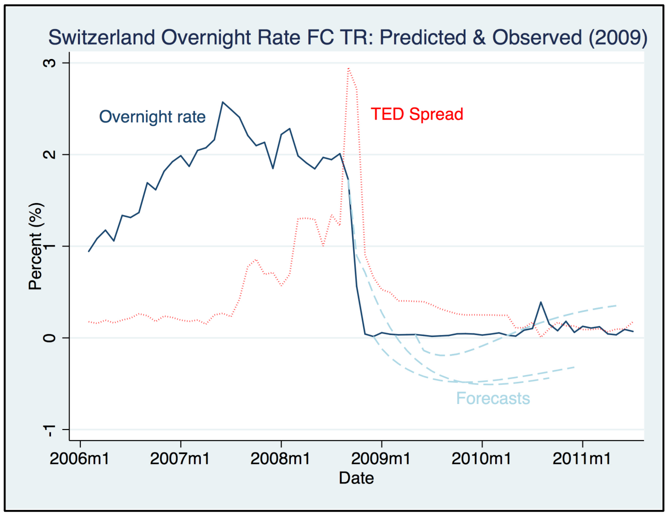


(a) Forecasts: Aug 2007 - FC TR

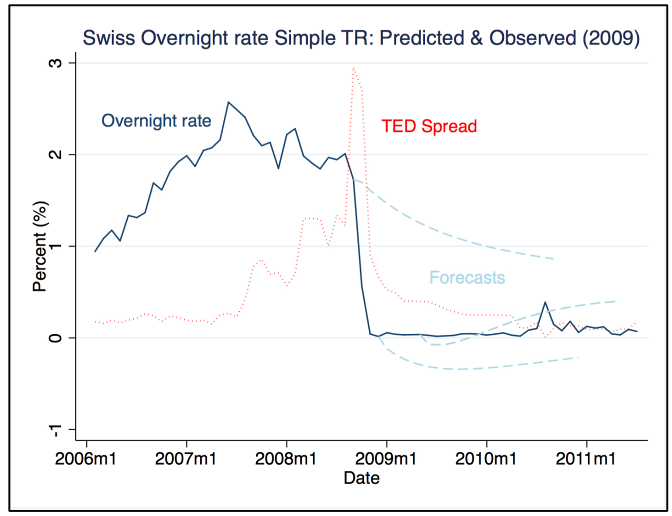


(b) Forecasts: Aug 2007 - Simple TR

Figure 4.2: 24-month pseudo out-of-sample forecasts under the two SVAR specifications. Forecasts beginning at August 2007, November 2007, and February 2008.



(c) Forecasts: Oct 2008 - FC TR



(d) Forecasts: Oct 2008 - Simple TR

Figure 4.3: 24-month pseudo out-of-sample forecasts under the two SVAR specifications. Forecasts beginning at October 2008, January 2009, and June 2009.

Figure 4.2 shows that before 2008, the forecasts provided by the FC TR and the simple TR follow a similar pattern. However, The FC TR forecasts are shifted down slightly compared to the simple TR forecasts. This indicates that when faced with growing uncertainty in global financial markets post-2007, the FC TR suggests more monetary easing was necessary to maintain the SNB's target for the interbank rate.

Figure 4.3 demonstrates a pronounced difference between the two policy rules later in the crisis. The forecast provided by the FC TR beginning in October 2008 (right after the collapse of Lehman Brothers on September 15, 2008) follows the policy rate with a striking amount of precision. (De Haas & Van Horen, 2012) The simple TR does not come close to predicting the severe rate cut implemented by the SNB.

As mentioned before, the SNB targets three-month interbank lending rates. And when the 3M LIBOR rises out of their target range, they react very swiftly to bring it back into line. By providing nearly unlimited short-term liquidity during the crisis they were able to effectively control the cost of capital throughout their economy. Furthermore, they implemented large-scale purchases of foreign currency which eased the upward pressure on the Swiss franc and helped avoid an unwanted tightening of monetary conditions. (Jordan, 2012) This reaction accounts for the observed behaviour of the Swiss TED spread shown on both graphs: while it spikes in latter half of 2008, it quickly shrinks in the following months returning to pre-crisis levels within a year.

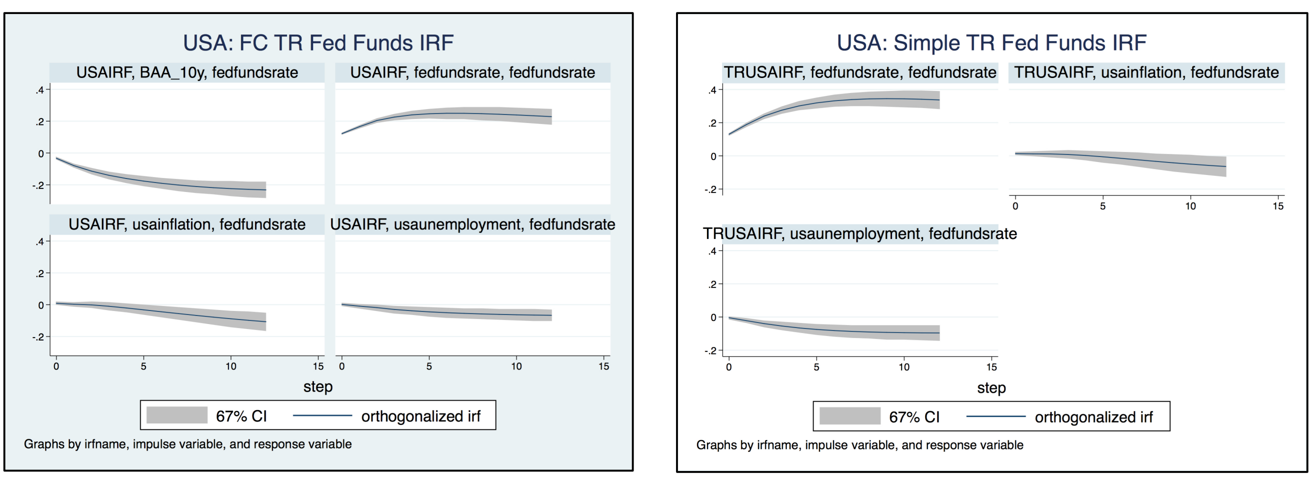
Under normal conditions, the reaction to a small spike in the TED spread would generally have been less severe. There is substantial evidence that the relationship between the overnight rate and the 3M LIBOR is not fixed over time, reflecting crisis-specific behaviour.

A regime-switching model in (Jordan, Ranaldo, & Söderlind, 2009) indicated that Swiss financial markets reacted differently to SNB policy during the crisis. By controlling for implied market volatility, market liquidity, and expectations of the policy rate, the study demonstrates that before the crisis "a change of 25 basis points in the 1-week repo rate translates, on average, into a change in the Libor of 5 basis points. This finding suggests that market participants scrutinize SNB repo operations to understand its monetary policy stance which, in turn, affords a smooth implementation of monetary policy." However, during the crisis, changes in the repo rate were much more effective at controlling the 3M LIBOR; an unanticipated 25bp drop in the repo rate caused a 30bp reduction in the 3M LIBOR. (Jordan et al., 2009)

A similar study by Abassi et al., 2009 uncovered similar time-varying dynamics by examining the relationship between the 3M LIBOR and the repo rate using an error-correction model. The error-correction model was estimated over a pre-crisis and crisis sample to account for observed structural shifts in the transmission mechanism of monetary policy. They found that during the crisis, the repo rate combined with expectations of accommodative monetary easing are effective at lowering interbank lending rates. "In particular, the transparency of the SNB's interest rate policy during the crisis might have contributed to keep the risk premia revealed by the Libor-OIS spreads relatively low." (Abassi et al., 2009) These two studies not only demonstrate that the SNB cares about credit spreads, they also show the SNB goes to great lengths to reduce them during times of crisis.

5. SVAR Results: USA

The SVARs for the US sample period (February 1990 to September 2017) satisfy the stability condition of having all eigenvalues having a modulus less than 1. (Lütkepohl, 2005) Lag order selection statistics were computed for both TR models. The AIC and FPE suggest that the optimal lag-order is 4. However, the AIC and FPE are designed to minimize the forecast error variance, and are likely to suggest overspecification. (Lütkepohl, 2005) The SBIC and HQIC generally suggest a more parsimonious specification which is often more accurate, in this case 3 lags were determined to be optimal for both models. (Lütkepohl, 2005) Granger causality tests for the FC TR show that all variables with 3 lags are at least jointly significant at the 0.5% level. Furthermore, all variables are jointly significant in predicting the federal funds rate at the 0.05% level.



(b) Financial Conditions Augmented Taylor Rule

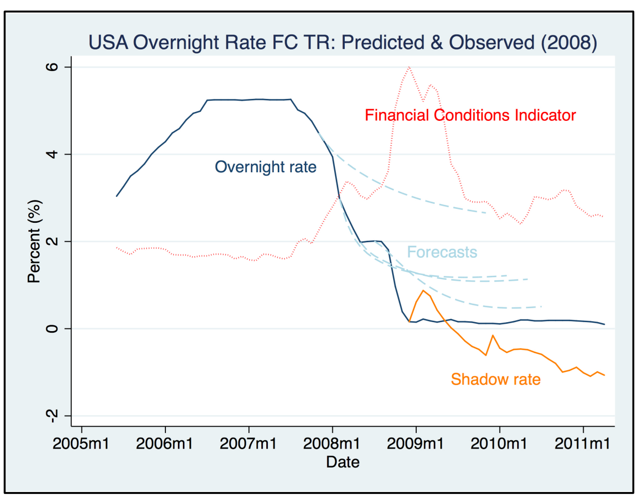
(b) Simple Taylor Rule

Figure 5.1: Orthogonalized impulse response functions under the two model specifications. Displays the reaction of the federal funds rate to a unit shock in the listed variables.

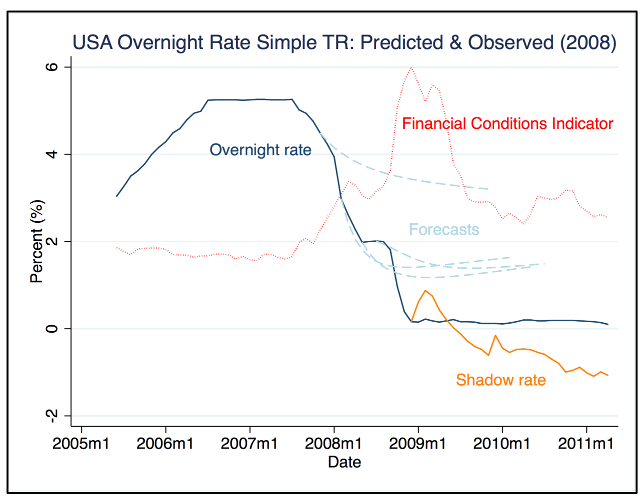
However, in the simple TR model. The Granger causality test shows that all variables only jointly predict the federal funds rate at the 10% level.

As stated before, the impulse response functions (*Figure 5.1*) show how the estimated reaction function behaves in response to different shocks. In the FC TR model, a unit shock to financial conditions (BAA_10y) causes the Fed to react by cutting rates by almost 25 basis points, which supports the idea that the Fed also reacts to credit spreads. Shocks to inflation and unemployment do not elicit nearly such a strong reaction. This may be due to misspecification, or incorrect identifying assumptions, but this is unlikely. The confusing behaviour of the federal funds rate and inflation (negative relationship) likely reflects the Fed's difficulty in meeting the target for a large part of the sample and the fact that the policy rate was constrained at the ZLB.

Figures 5.2 & 5.3 compare two pseudo out-of-sample forecasts to determine how the predictive power of the SVAR varies when financial conditions are included.

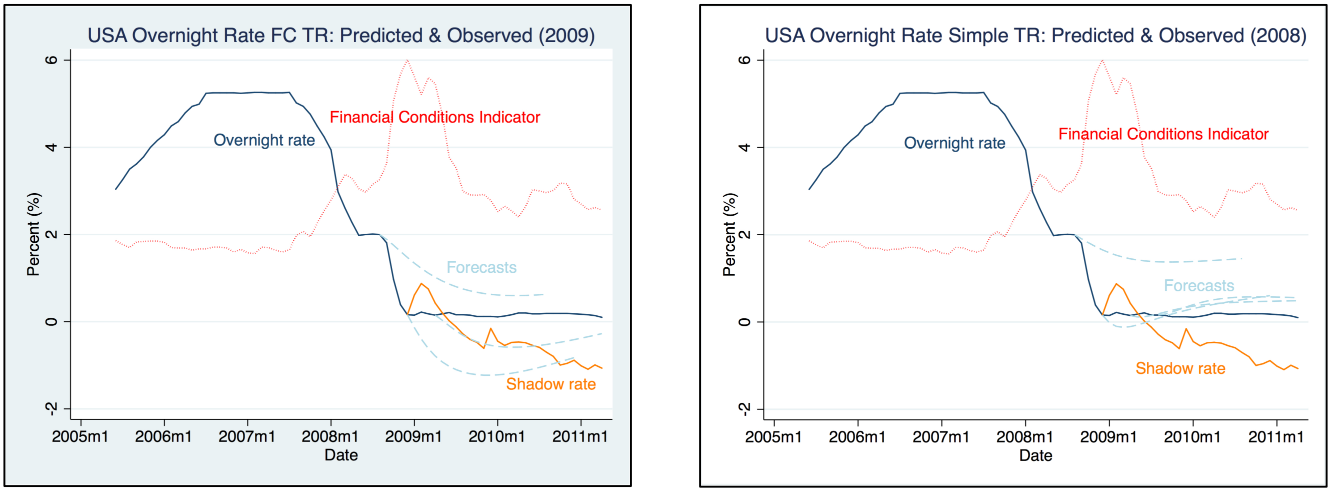


(a) Forecasts: Nov 2007 - FC TR



(b) Forecasts: Nov 2007 - Simple TR

Figure 5.2: 24-month pseudo out-of-sample forecasts under the two SVAR specifications. Forecasts beginning at November 2007, February 2008, May 2008, and July 2008.



(c) Forecasts: Aug 2008 - FC TR

(d) Forecasts: Aug 2008 - Simple TR

Figure 5.3: 24-month pseudo out-of-sample forecasts under the two SVAR specifications. Forecasts beginning at August 2008, December 2008, and April 2009.

The Wu and Xia shadow rate (orange line) was included on these graphs to provide a more accurate measure of the FED's monetary policy stance when the federal funds rate was constrained at the ZLB. In other words, the shadow rate summarizes the "macroeconomic effects of unconventional monetary policy" allowing monetary stimulus from large-scale asset purchases and forward guidance to be quantified. (Wu & Xia, 2016)

Graphs (a) and (b) (*Figure 5.2*) show forecasts beginning from the exact same time periods. During the beginning of the financial crisis, when the first set of large rate cuts were implemented, the FC TR predicts the interest rate path slightly better. The rise in credit spreads in the model can be thought of as pushing the rate down. This is especially noticeable later in the sample when the projected interest rate path follows a similar trajectory to the shadow rate. On the other hand, the simple TR forecasts do not follow the same downward trajectory, instead they begin to diverge from the shadow rate.

Graphs (c) and (d) (*Figure 5.3*) display similarly interesting dynamics, with the FC TR providing very good forecasts of the shadow rate. In fact, the FC TR forecast beginning in April 2009 follows the shadow rate almost perfectly for the first 16 months. Likewise, the forecast beginning in December 2009 suggests that the Fed should have reacted more severely and quickly provided additional monetary stimulus immediately once the policy rate was constrained at the ZLB.

The simple TR performs poorly in comparison. While it does suggest a brief drop in interest rates below zero at the onset of the crisis, it quickly predicts the Fed following up by tightening monetary policy. This implies that the policy rate would then diverge from the shadow rate and begin to increase. If the shadow rate reflects the optimal policy reaction, then it is clear that the Taylor rule augmented with financial conditions provides a better approximation of the monetary policy reaction during the 2008 crisis.

6. Markov-Switching Model

The SVAR results presented in Sections 4 & 5 demonstrated that adding financial conditions into a Taylor rule framework improved the predictive power of an estimated reaction function during the financial crisis. Specifically, during periods of financial panic, credit spreads become a powerful predictor of changes in the overnight rate. However, during periods of stability, when the spread was small, the central bank's reaction was better described by the original Taylor rule. In fact, the reaction function with financial conditions begins to harm the predictive power of the model in the periods before and after the crisis.

Given this observed disconnect, a two-state model seems more appropriate: one state reflecting the policy reaction during a financial crisis and the other reflecting the reaction during periods of relative stability. As mentioned in Section 3, regime-switching error-correction models estimated for Switzerland confirmed the observation that a different reaction function is likely to exist during times of crisis. This paper extends it analysis to the study of the US Federal Reserve.

It is of significant interest to economists that certain macroeconomic variables appear to behave quite differently during downturns. Many time series show dramatic structural breaks, introducing the need for an econometric tool to describe complicated time-varying relationships. James Hamilton's 1989 paper: *"A New Approach to the Economics Analysis of Time Series and the Business Cycle"* provides an excellent and "tractable approach to modeling changes in regime." (Hamilton, 1989) This work was influenced by Goldfeld & Quandt (1973) who originally introduced Markov processes to the field of econometrics.

This methodology has already been used to study changes in interest rate regimes. (Sims & Zha, 2004; Davig, 2004) The focus of the listed papers was to detect a regime shift caused by changes in Fed leadership and changes in fiscal policy, respectively. However, this section of the paper aims to approach the idea of regime-switching differently. Instead of looking at long-term trends over the course of many business cycles, this paper aims to detect structural shifts in monetary policy reactions within the business cycle.

Specifically, it introduces a comparison between a Markov-switching dynamic regression (MSDR) and a state-invariant multiple linear regression containing the exact same set of explanatory variables. Stata's *mswitch dr* command was used for the estimation of the MSDR model. It allows researchers to: "[fit] dynamic regression models that exhibit different dynamics across unobserved states using state-dependent parameters to accommodate structural breaks or other multiple-state phenomena." (StataCorp, 2015). MSDR models allow for quick adjustment in between states compared to MSAR models which describe more gradual adjustments between states in lowfrequency data. The MSDR model is therefore more suited to monthly data as rapid adjustments in policy decisions are expected in response to economic shocks.

The MSDR model has two hypothesized states *state1* and *state2* for any time *t*.

1. *state1* reflects a crisis state where the Fed reacts strongly to adverse financial conditions which impair the transmission of monetary policy.
2. *state2* reflects a non-crisis state where the Fed roughly follows a simple Taylor rule

The structure of the model is specified as follows:

$$i_t = u_s + \alpha_s i_{t-1} + \mathbf{B}_s \boldsymbol{z_t} + \varepsilon_{st}$$

$$\boldsymbol{z_t} = vector\ of\ exogenous\ variables\ [In_t \quad Un_t \quad BAA\_10y_t]\ with\ state\ dependent\ coefficients,\ \boldsymbol{B_s}$$

$$u_s = state\ dependent\ intercept$$

$$\varepsilon_s = an\ independent\ and\ i.i.d.normal\ error\ and\ state\ dependent\ variance\ \sigma_s^2$$

$$i_t \ = the\ Wu\ and\ Xia\ shadow\ rate\ with\ state\ dependent\ coefficient\ \alpha_s$$

It is not possible to know which state the process is in with absolute certainty. However, the probabilities of being in a certain state and the expected duration of that state can be estimated (Hamilton, 1989). The unobserved state variable changes according to a Markov process. The results of the model are given below. (Note: the option *vce(robust)* was used to minimize inaccurate standard errors caused by misspecification. (StataCorp, 2015))

State transition probability:

Transition Probabilities	*Estimate*	*Std. Err.*	*[95% Conf. Interval] - LB*	*[95% Conf. Interval]- UB*
p11	.9305654	.0318174	.8362062	.9723623
p12	.0694346	.0318174	.0276377	.1637938
p21	.0331263	.0135991	.0146882	.0729953
p22	.9668737	.0135991	.9270047	.9853118

Expected state duration:

Expected Duration	Estimate	Std. Err.	[95% Conf. Interval] - LB	[95% Conf. Interval] - UB
state1	14.40203	6.599525	6.105239	36.1824
state2	30.18746	12.39262	13.69952	68.08191

p11 represents the probability of staying in *state1* in the next period given that the process is in *state1*. p22 represents the probability of staying in *state2* given that the process is currently in *state2*. p12 and p21 represent state transition probabilities.

p11 and p22 are both quite close to 1.00, indicating that each state is quite persistent. This finding is corroborated by the state duration table which shows that the Fed stays in the crisis reaction state (*state1*) for approximately 1.15 years. The non-crisis state (*state2*) generally lasts around twice as long, or 2.5 years.

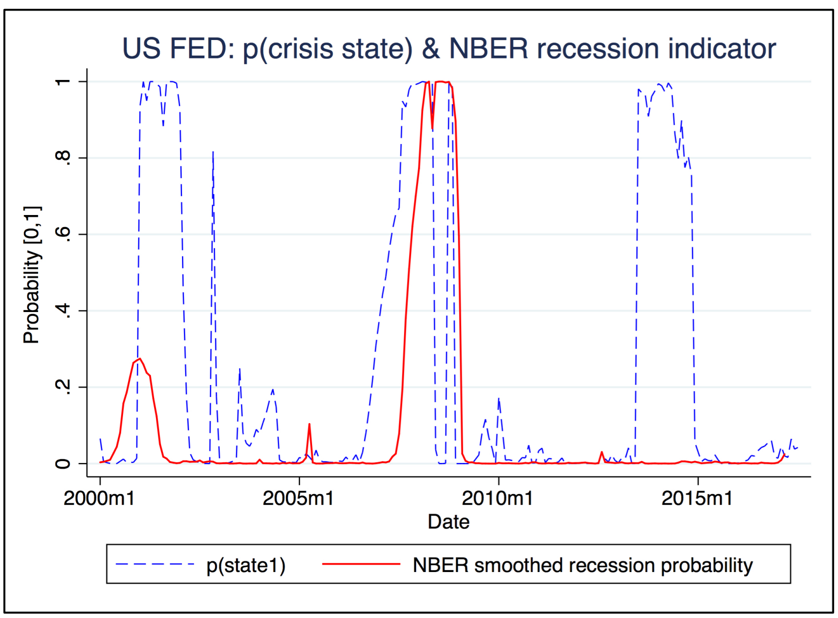


Figure 6.1: The probability of being in *state1*(crisis state) is plotted with smoothed U.S. recession probabilities retrieved from FRED (Piger & Chauvet, 2017)

Figure 6.1 demonstrates what was originally expected. A negative shock to financial conditions causes an impairment of the transmission channel of monetary policy which forces the

Fed to react in accordance with *state1*. The recession probability indicator can approximately predict when the state will transition, as the theoretical justification would suggest. The estimated coefficients for both states are given below:

VARIABLES	(1) State1	(2) State2
L.shadowrate	**0.985*** **	**0.986*** **
	(0.0148)	(0.00699)
usaunemployment	**-0.0202**	**-0.0330*** **
	(0.0289)	(0.00706)
usainflation	**-0.0432**	**-0.00653**
	(0.0313)	(0.00963)
BAA_10y	**-0.242*** **	**-0.0592**
	(0.0596)	(0.0377)
Constant	**0.655*** **	**0.444*** **
	(0.234)	(0.108)
Observations	330	330

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

All variables enter with the expected sign, except for the inflation rate (*usainflation*) which is not found to be statistically significant at the 10% level. In both cases, the lagged policy rate is highly significant (p<0.01) reflecting the consistency of interest rate smoothing. However, the predictive power of the other variables in describing the reaction function changes significantly between *state1* and *state2*

In *state2*, the non-crisis state, unemployment is the only other statistically significant explanatory variable in addition to the lagged policy rate. This reflects the fact that unemployment proxies inflationary pressure in the future, causing the Fed to react to this measure in order to reach the 2% CPI inflation target in the future. This mirrors the dynamics of the original Taylor rule, which does not react to financial conditions directly. Note that the coefficient on the *BAA-10y* spread variable is not statistically significant at the 10% level (p-value = .116) and the coefficient is quite small relative to *state1*.

In *state1*, the crisis state, the Fed reacts very strongly to the financial conditions indicator. The high negative coefficient on *BAA_10Y* compared to *state2* shows precisely how important reducing interbank lending rates is to the Fed during a financial crisis. In an effort to reduce the cost of capital to banks, the Fed cuts the overnight rate very quickly.

However, in testing the robustness of this finding it is important to compare the MDSR model to a static time-invariant reaction function. Therefore, a simple Multiple Linear Regression (MLR) was estimated as a comparison. The MLR model uses the exact same explanatory variables, except it does not allow for time-varying state changes

In the simple MLR, all the coefficients are highly significant (p<0.01) and all enter with the expected sign, except for inflation. Furthermore, the R-squared is very high (0.996) However, comparing the residuals between the two models shows that the Markov-switching model fits the data significantly better than the MLR model:

Residual	*Std. Error*	*Min*	*max*
MLR	.1737012	-.8028324	.7778676
Markov	.1245333	-.5313755	.5991471

Unfortunately, although the Markov-switching model fits the data better it does not directly provide economic intuition for the non-linear policy reaction. It assumes that the regime switches are exogenous, driven by an unobserved process. (Hamilton, 1989; Petersen, 2007) The same type of results could likely be replicated simply by using the NBER recession indicator as a dummy variable to account for state-varying central bank reaction coefficients. It is therefore unlikely to lead to any meaningful policy inference. Nonetheless, it does provide an accurate way of measuring the Fed's reaction function which was the purpose of this exercise.

Conclusion

This analysis is not intended to inform normative conclusions regarding optimal policy when distortions in the transmission mechanism of monetary policy are present. In reality, the optimal policy adjustment to adverse financial system shocks is likely to be determined by wide range of complicated factors outside of this paper's simple model. And furthermore, the optimal policy tool for such adjustment should not be independent of the nature of the financial disturbance. Studies of similar estimated policy rules within DSGE models show that: "even in the case of "purely financial" disturbances…the optimal degree of response to changes in the credit spread depends on the degree of anticipated persistence of the disturbance." (Curdia & Woodford, 2010)

Furthermore, the Taylor rule examined within this paper is strictly backward-looking, it does not explicitly take into account the expected path of inflation and real activity. Although the SVAR may indirectly be proxying for future changes to some degree through its dynamic structure, it ignores the crucial role that expectations and long-term projections play in the decision-making processes of central banks. Two studies have shown (Orphanides & Wieland, 2007; Curdia & Woodford, 2010) that a large fraction of the perceived deviations in the federal funds rate from the Taylor rule can be attributed to forward-looking projections created by the FOMC. It may be incorrect to discount the Taylor rule's predictive power without first extending the model to include expectations.

Ultimately, this paper adds to the discussion of central bank reaction functions in a simple and concise way. It clearly demonstrates that monetary policy must react to financial system shocks (indicated by large credit spreads) and it quantifies the strength of this response. Additionally, the two econometric models used are sufficiently simple to allow these findings to be replicated and extended to other countries.

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