Sweden's Riksbank Encounters the Lower Bound

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Abstract

In 2009, in the midst of a global recession, Sweden's Riksbank approached a lower bound on nominal interest rates. This encounter with the lower bound provides a natural experiment for investigating the causes of monetary policy inertia. To exploit this experiment, we estimate Taylor rules with dynamic Tobit specifications in which unobserved lagged dependent variables are included as explanatory variables. Results indicate that interest rate smoothing was a more important reason for policy inertia than slow adjustment of underlying policy preferences.

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1. Introduction

Taylor (1993) proposed his famous rule as the Great Moderation began in the United States and much of the world. A consensus emerged that the Taylor rule was not only an appealing prescription but also a useful description of the behavior of the Federal Reserve and other central banks during the Great Moderation and even over longer horizons (e.g., Berg et al. 2006; Clarida et al. 1999, 2000; Jansson and Vredin 2003; Judd and Rudebusch 1998; Jung 2013; Orphanides 2001, 2003, 2004; Taylor 1999). It became the default empirical specification for the estimation of central bank reaction functions.[1] An important stylized fact to emerge from the literature on empirical Taylor rules is that monetary policymaking is highly inertial, although explanations for observed policy inertia have remained controversial.

One explanation for inertia is that policymakers consciously smooth interest rates; i.e., they adjust target rates so that they approach perceived optimal rates slowly and incrementally. Bernanke (2004) and Goodfriend (1991) describe some of the benefits of this type of gradualism, and Coibion and Gorodnichenko (2012) and Söderström et al. (2005) provide supporting evidence. In contrast, Rudebusch (2002) has argued that the appearance of inertia is a consequence of misspecification. If empirical Taylor rules omit serially correlated variables to which central banks respond, then estimations will spuriously display persistence. In the Rudebusch view, policymakers are constantly adjusting target rates to equal perceived optimal rates, but optimal rates are themselves responding to persistent economic shocks. Assessing these competing explanations for observed inertia is of practical importance in macroeconomics—any model that forecasts

[1] There have been dissenting voices. Chari, Kehoe, and McGrattan (2009) argue that the Taylor rule may not be the best empirical specification for the central bank interest rate policy rule because it implies a behavioral pattern in long-term interest rates that is inconsistent with the data.

the macroeconomic consequences of non-monetary shocks must implicitly make assumptions about the nature of endogenous monetary policy responses.

By 2008, the Great Moderation had ended and much of the world was in recession. Central banks responded actively and, in some cases, in unconventional ways. In the United States, the federal funds rate has remained near zero since 2008. The Taylor rule, and interest rate targeting generally, have been irrelevant for describing monetary policy in the United States since then. However, the experience for Sweden's Riksbank was different—Sweden experienced a severe downturn, the Riksbank eased aggressively, and a strong recovery followed. The Riksbank's target interest rate flirted with a lower bound during the recession and then returned to higher levels.

We will argue that Sweden's encounter with the zero lower bound provides a natural experiment that can shed light on the sources of inertia in monetary policymaking. The essence of the argument is that the interest rate smoothing hypothesis applies to actual interest rates, while the persistent shocks hypothesis applies to underlying determinants of optimal interest rates. Our method involves the use of a dynamic Tobit specification to estimate Taylor rules in the presence of a lower bound. In the Tobit model the observed interest rate is subject to a lower bound, but an underlying (and unobserved) "desired" interest rate is unconstrained. Thus, when the lower bound is encountered, actual and desired interest rates diverge. The interest rate smoothing argument suggests that policy inertia should be captured by the inclusion of lagged actual interest rates as explanatory variables in the Taylor rule specification. In contrast, the persistent shocks hypothesis suggests that lags of the unobserved desired rate should be included.

To compare these distinct hypotheses, it is essential that we be able to estimate a Tobit model in which unobserved variables appear on the right-hand side. While previous researchers have used Tobit models to estimate Taylor rules, none has estimated a model with this feature.[2] Our estimation of such a model is an independent contribution of this paper, but one that is intrinsically connected to our substantive purpose.

Our analysis also has a second purpose. Taylor rules have frequently been estimated using data samples that covered the years of the Great Moderation. Given the lack of macroeconomic volatility in these samples, it was difficult to assess how monetary policy might have responded to large business cycle fluctuations. Since 2008, the experience has, of course, been different. Evidence of a more aggressive response in the face of large business cycle fluctuations would lend some support to the argument that policymakers promptly adjust target rates to approach optimal rates. Because Sweden experienced both a severe downturn and relatively rapid recovery, it provides a uniquely appropriate setting for examining how monetary policy responds to changing macroeconomic conditions.

Our paper will proceed as follows. In section 2, we discuss the lower bound on nominal interest rates and the relevance of the bound in the Swedish case. We describe our econometric specifications for Taylor rules in the presence of a lower bound in section 3. In section 4, we report estimates of the models for the Riksbank. We offer concluding remarks in section 5.

[2] Kato and Nishiyama (2005) and Kim and Mizen (2010) have used the Tobit model to estimate the Bank of Japan's policy reaction function, while Kiesel and Wolters (2014) have used the Tobit model to estimate the policy reaction functions of the Bank of Japan, the Federal Reserve, and the European Central Bank.

2. Did the Riksbank Encounter a Lower Bound on Interest Rates?

The recession that began in 2007 produced large drops in real GDP in the United States and in other countries.[3] In Sweden, output began to plunge in late 2008, with a real-time estimate of the GDP gap reaching -8.15% in the fourth quarter of 2009.[4] The Riksbank cumulatively cut the target repo rate by 4.5 percentage points between October 2008 and July 2009 and reached a low of 0.25%. There is some question about whether this rate should be regarded as an effective lower bound, and the answer is important for the empirical investigation that follows in this paper. We will argue in the affirmative—the Riksbank's MPC (the Executive Board) regarded the 0.25% rate as a lower limit at that time.[5]

It is commonly accepted that nominal interest rates have a lower bound at zero. Because lenders have the option of holding currency and earning zero interest, they would not be expected to lend at rates that were lower. As a practical matter, holding and making transactions with cash can be cumbersome and risky, and many individuals would still hold bank deposits at slightly negative interest rates (Saunders 2000). Negative rates have occasionally been observed in repo markets as well (Fleming and Garbade 2003).

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[3] Williams (2009) examines the experience of the United States and other industrial countries as the financial crisis unfolded.

[4] This estimate was subsequently revised to -5.21%. Output gaps for the first, second, and third quarters of 2009 remained large after revisions, at -7.92%, -7.27%, and -6.71%. Estimates of the gap are from Sweden's National Institute of Economic Research (NIER).

[5] Our analysis employs data through 2012. By the end of 2012, Sweden's real GDP growth had slowed to near zero. Since then GDP growth has been positive, but inflation has persistently remained below its 2% target level. In October 2014, the Riksbank cut its policy interest rate (the repo rate) to zero. In February 2015, it was further lowered to -0.10, and the Riksbank has indicated that it expects to keep the rate negative for an extended period. We believe that this reflects a change in the lower bound, not an indication that a bound was never previously reached.

It is also possible that the effective lower bound on a central bank's target rate could exceed zero. Addressing the Swedish case, Beechey and Elmer (2009) argue that the marginal expansionary effect of lower rates may be very small when the target rate is already close to zero. Deposit rates are normally lower than central bank target rates, so taking target rates to zero is unlikely to produce a similar reduction in deposit rates. If deposit rates do not fall, lending rates are likely to be sticky as well. Moreover, if deposit and lending margins narrow, banks might respond by restricting the supply of credit.

Bernanke and Reinhart (2004) have suggested another worrisome possibility. As the target rate approaches zero, there could be disruptions in financial markets. They noted that, in the United States, rates in repo markets and for money market mutual fund deposits normally trade below the federal funds rate. With the funds rate nearing zero, these rates could be pushed to zero. As this happens, investors would seek alternatives. Funds could quickly flow out of money market mutual funds and into bank deposits, which would mean that those who had relied on money market mutual funds for financing (e.g., issuers of commercial paper) would need to find alternative sources of funds. For the Swedish case, Beechey and Elmer (2009, p. 3) have identified similar disruptions:

> Well-functioning financial markets enable changes in policy rates to be dispersed in the economy, both by way of effective pricing and through the intermediation of credit. When the policy rate approaches an unusually low level, there is a risk that these functions may deteriorate, with impaired pricing and lower activity as a consequence. Disruptions in

> financial markets could thus undermine the ability of monetary policy to affect the economy.

There is uncertainty about how serious the financial market disruptions might be in the vicinity of a zero target rate, but policymakers had reason to be hesitant about taking the rate all the way to zero. Minutes of meetings of the Riksbank's Executive Board suggest that this was the case for Sweden.

Once the repo rate reached 0.25%, one member of the committee, Deputy Governor Lars Svensson, repeatedly pressed the case for a further reduction to zero, arguing that monetary policy under the circumstances should err on the side of being too expansionary rather than too contractionary.[6] The minutes of the September 2009 meeting of the Executive Board record a typical example:

> If monetary policy were too expansionary it would be easy to adjust this later by raising the repo rate path. If monetary policy was too contractionary, however, it would be difficult to adjust this later, as one cannot cut the repo rate much more. Mr Svensson therefore felt that if mistakes were to be made, it would be better to err on the expansionary side rather than on the contractionary side. (Minutes of the Executive Board's Monetary Policy Meeting, No. 4, September 2, 2009, p. 12)

While other members of the committee were reluctant to counter Svensson's arguments directly, they were also clearly hesitant to take the rate lower. Some expressed doubts that

[6] Svensson (2003) and others (e.g., Bernanke and Reinhart 2004, Romer and Romer 2013, Williams 2009) have argued that policymakers need to adopt a broad set of policies to increase expected inflation when the policy rate is at or near the zero lower bound, since higher expected inflation will lower the real interest rate at the zero nominal interest rate and help stimulate the economy. Goodfriend (2000) and McCallum (2000) have also argued that monetary policy is far from powerless even if the policy rate is at or near the zero lower bound.

further reductions were needed or would be effective; however, there were also indications that the approaching boundary was a concern. The minutes report Deputy Governor Karolina Ekholm's remarks as follows:

> At the July meeting, as at the April meeting, Ms Ekholm's opinion was that the economic situation in principle justified even greater repo rate cuts, but that it was too risky to cut the policy rate even further when one did not really know how the financial markets would react to such low interest rates … she said that it is worthwhile for a central bank to act with some caution in areas where it does not have any previous experience to lean on. (Minutes of the Executive Board's Monetary Policy Meeting, No. 4, September 2, 2009, p. 14)

The minutes report that First Deputy Governor Svante Öberg agreed with Ekholm:

> … a central bank should exercise caution with regard to cutting the repo rate to very low levels. It is not possible to know very much about the effects it might have on the financial markets, as the repo rate has never been so low before. (Minutes of the Executive Board's Monetary Policy Meeting, No. 4, September 2, 2009, p. 20)

In the preceding meeting, Öberg had explicitly acknowledged that "with today's cut the repo rate has in practice reached its lower limit and that it should not be reduced more than this" (Minutes of the Executive Board's Monetary Policy Meeting, No. 3, July 1, 2009, p. 13). He had also indicated that a majority of the committee was in agreement:

> Mr Öberg also noted that the assessment of a majority of the members of the Executive Board is that, following the reduction to 0.25 per cent, the

repo rate has reached its lower level, that the situation on the financial markets is still not completely normal and that complementary measures are needed for monetary policy to have the intended effects. (Minutes of the Executive Board's Monetary Policy Meeting, No. 3, July 1, 2009, p. 13)

Öberg's last comment is noteworthy. While asserting that the repo rate should go no lower, he simultaneously acknowledged that the current policy stance was not sufficiently expansionary. Were it not for the boundary issues, a lower target rate would have been desired. The committee agreed with this assessment and adopted quantitative easing measures to complement the final downward interest rate move adopted at that meeting.[7] The Riksbank kept its target at 0.25% until June 2010, after the economy had begun a robust recovery.

Figure 1 provides a last piece of evidence suggesting the existence of a lower bound above zero. The chart shows Sweden's paths for historical inflation, the output gap, and the repo rate from 2000 through 2012. In the years preceding the Great Recession, the repo rate appears to track inflation. As the recession began, this continued—the target rate fell in step with lower inflation. At the same time, the output gap widened. After July 2009, inflation continued downward for several months while the target repo rate remained at 0.25%. During these months the ex post real rate of

[7] In July 2009, the Riksbank offered banks SEK 100 billion in loans at a low fixed rate with maturity of about 12 months. It made the same offer twice more between then and November 2009. These loans were intended to increase the supply of funds to banks and reduce banks' funding costs by making it cheaper to borrow from the Riksbank than in the market. These loans were also aimed at increasing market participants' confidence in the Riksbank's intention to maintain an accommodative policy stance until the autumn of 2010. The Riksbank did not use the purchase of securities as a crisis measure but rather as a supplemental tool. The repo rate remained the primary tool for monetary policy. For additional information about Swedish monetary policy during the financial crisis, see Elmer et al. (2012).

interest was increasing; effectively, monetary policy was tightening. Given the state of the economy and our knowledge of the thinking of the committee, it is unlikely that the Executive Board found this outcome desirable. We conclude that the Riksbank encountered a lower bound for the repo rate at 0.25% over the July 2009 to June 2010 interval. The econometric work that follows will explicitly incorporate that assumption.

3. Econometric Models for the Taylor Rule

The Taylor rule is conventionally written as

$$i_t = \pi_t + r_t^* + \alpha_\pi \left(\pi_t - \pi^*\right) + \alpha_y \left(y_t - \bar{y}_t\right) + e_t, \quad (1)$$

where i_t is a selected target interest rate, π_t is the rate of inflation, r_t^* is the real rate of interest, π^* is the target rate of inflation, y_t is the log of real GDP, $\bar{y}_t$ is the log of potential real GDP, and e_t is a normally distributed random variable with variance σ^2. The difference ($y_t - \bar{y}_t$) is usually referred to as the output gap. As originally proposed, this was a prescriptive rule, with parameter values specified as $r_t^* = 2$, $\pi^* = 2$, $\alpha_\pi = 0.5$, and $\alpha_y = 0.5$ (Taylor 1993).[8] In empirical applications, Taylor rule parameter values are estimated rather than prescribed. The specification is usually altered to include lagged dependent variables to account for inertia and to avoid problems with serial correlation (Orphanides 2004).

[8] Taylor and Williams (2011) report that simulation results from different macroeconomic models indicate that the better monetary policy rules have three general characteristics. First, an interest rate instrument performs better than a money supply instrument. Second, interest rate rules that react to both inflation and output perform better (as measured by inflation variability and output variability) than rules that react to either inflation alone or output alone. Third, interest rate rules that react to the exchange rate do not perform as well as rules that do not react to the exchange rate. The Taylor rule specification captures the spirit of this research.

Augmenting equation (1) with lagged dependent variables, we reformulate our empirical Taylor rule specification as

$$i_t = \alpha_0 + \sum_{j=1}^{J} \rho_j i_{t-j} + \alpha_\pi \left(\pi_t - \pi^*\right) + \alpha_y \left(y_t - \overline{y}_t\right) + e_t . \qquad (2)$$

The dependent variable is the repo rate (the rate of interest at which banks can borrow or deposit funds at the Riksbank for a period of seven days). Our measure of the output gap is a series published by Sweden's National Institute of Economic Research (NIER). We use the first available NIER estimate of the output gap for the current quarter. This series is a real-time measure for meetings in 2002 and later and an "almost" real-time measure for the earlier meetings.[9] Inflation is measured as the observed rate of consumer price inflation over the year ending in the month before the Executive Board meeting.[10] This is also an "almost" real-time measure that was typically available to the committee when its policy decisions were made. The Riksbank's inflation target is 2%. Our sample covers 92 meetings of the Executive Board between May 2000 and December 2012, with meetings occurring at roughly a bimonthly frequency. In each meeting, a target for the repo rate

[9] Since 2002, a current-quarter estimate of the output gap has been available in the current quarter. Before 2002, a current-quarter estimate of the output gap was available only with a lag (typically one quarter). While policymakers did not strictly have current-quarter estimates from NIER, it is reasonable to assume that they had most of the information NIER would ultimately use to produce the estimates. NIER uses a production function approach to measuring potential output.

[10] Some have suggested that a measure of expected future inflation should replace historically observed inflation in the Taylor rule. For several reasons, we have chosen not to do this. First, expected future inflation generally depends on the adopted policy and is therefore endogenous. Consider an extreme example: if a forecasting horizon is long, and if a central bank successfully targets inflation, then expected inflation will essentially be constant at the target rate. Reverse causality would also be an issue if forecasts were manipulated to justify a policy decision. Second, although the Riksbank developed inflation forecasts and considered them in its deliberations, it did not measure expected inflation in a consistent way over our sample period. Before October 2005, the inflation forecast assumed no change in interest rates over the forecast horizon. Beginning with October 2005, the forecast assumed that future interest rates would evolve in accord with market expectations embedded in forward rates. In February 2007, it was instead assumed that interest rates would follow a path that the Riksbank considered "well-balanced." Because of the changing assumptions, it is not clear that intertemporal variations in the Riksbank's inflation forecasts in our sample period are meaningful. Finally, we note that Taylor (1993) originally proposed that inflation be measured as an average over the year preceding the decision date.

was selected by a majority vote of the Executive Board, with the chairman serving as a tie-breaker.

In six of the meetings in our sample—those between July 2009 and April 2010—the repo rate was set at 0.25%. As we have noted, a majority of the committee appeared to view this as an effective lower bound. In the presence of a lower bound, a Tobit model can provide an appropriate empirical specification for the Taylor rule. According to the Tobit model, the MPC has a latent desired target rate, i_t^*, which is not subject to a lower bound. When i_t^* equals or exceeds the boundary value of 0.25%, then the actual target rate, i_t, is equal to the desired rate, i_t^*; however, when i_t^* is less than 0.25%, then i_t^* is not observed and the target rate is set at the boundary level.[11]

The Tobit reformulation of the Taylor rule therefore becomes

$$i_t^* = \alpha_0 + \sum_{j=1}^{J} \rho_j i_{t-j} + \alpha_\pi \left(\pi_t - \pi^*\right) + \alpha_y \left(y_t - \bar{y}_t\right) + e_t \tag{3a}$$

with

$$i_t = i_t^* \text{ if } i_t^* \geq 0.25 \tag{3b}$$

and

$$i_t = 0.25\% \text{ if } i_t^* < 0.25 . \tag{3c}$$

Lags of the observed target rate, i_t, appear on the right-hand side in (3a), but a compelling alternative specification would instead place lags of the latent dependent variable on the right-hand side:

$$i_t^* = \alpha_0 + \sum_{j=1}^{J} \rho_j i_{t-j}^* + \alpha_\pi \left(\pi_t - \pi^*\right) + \alpha_y \left(y_t - \bar{y}_t\right) + e_t . \tag{3a$'$}$$

[11] Kim and Mizen (2010) estimate Tobit models for the Bank of Japan assuming positive threshold values at which monetary policy was effectively at the zero lower bound.

The distinction between equations (3a) and (3a') appears to be modest but is, in fact, substantive. Interest rate smoothing occurs when policymakers do not immediately adjust the target interest rate to the rate that is perceived to be optimal at a moment in time. Smoothed rates could be innately desirable because stability in financial markets is valued (Goodfriend 1991). In this spirit, Cukierman (1991) has proposed a formal model in which interest rate smoothing arises as the central bank's effort to guarantee financial stability prompts it to make interest rates as predictable as possible. Smoothing could also be appropriate when uncertainty is pervasive (Bernanke 2004). If the central bank is uncertain about the effect its actions will have on the economy, then it may be appropriate for it to adjust policy more cautiously and in smaller steps than it would if it had precise knowledge of the effects of its policy actions. By adjusting policy in small increments, the central bank gives itself the opportunity to assess the effects of its actions and refine its views about how large a policy change will ultimately be needed. Furthermore, smoothing could be appropriate because it can magnify the effect of a given policy shift by signaling persistence (Goodfriend 1991, Woodford 1999, 2003). Because output and inflation respond to variations in longer-term interest rates, the central bank can achieve its stabilization goals only to the extent that its policy actions affect longer-term interest rates. Longer-term interest rates should be determined, in part, by market expectations of future short-term interest rates, so the central bank needs to communicate a credible commitment to changing the future path of short-term interest rates. It can do this by following initial small changes in the policy rate with additional small changes in the same direction. This approach to policy should give the central bank significant leverage over aggregate demand without requiring excessive volatility in short-term interest rates. Thus, one argument for the observed inertia in policymaking is that interest rates are purposely smoothed.

Rudebusch (2002) argues that the term structure of interest rates provides little predictive information about the future path of short-term rates beyond a horizon of three months, but interest rate smoothing implies that rates should be predictable well beyond that horizon. He has proposed that optimal rates themselves have moved slowly because they were responding to inertial movements in variables omitted from the Taylor rule specification. He argues that when important omitted variables are serially correlated, this is likely to result in misleadingly large coefficients on the lagged dependent variables in an estimated Taylor Rule.[12] Moreover, he goes on to show that a policy rule without interest rate smoothing but with highly serially correlated shocks is more consistent with the evidence from the term structure. Thus, a second argument for the observed inertia in policymaking is that the optimal rate itself moves slowly, perhaps because policymakers' preferences evolve slowly in response to key variables that have been omitted from the specification of the policy rule.

[12] According to Coibion and Gorodnichenko (2012), once allowance is made for higher order interest rate smoothing, it is possible to discriminate between the interest rate smoothing explanation of interest rate persistence and the persistent shocks explanation of interest rate persistence. Their evidence favors the interest rate smoothing explanation. Coibion and Gorodnichenko (2012) also find that the Fed is able to predict future interest rate changes better than the private sector and argue that the Fed's greater predictive success is consistent with the presence of significant policy inertia. The inability of private sector forecasters to predict interest rates as well as the Fed reflects their more limited information sets and their uncertainty about the policy rule. As the Fed has become more transparent over time, private sector interest rate predictions have improved in a way that is consistent with the presence of policy inertia. Söderström et al. (2005) use an empirical New Keynesian model to estimate the central bank's preference parameters, the degree of forward-looking behavior in the determination of output and inflation, and the variance of output and inflation to match broad characteristics of U.S. data. Explaining the observed behavior of the interest rate (and hence monetary policy) requires a large weight on interest rate smoothing, a large degree of forward-looking behavior in the determination of output, and a small degree of forward-looking behavior in the setting of prices.

Arguments for interest rate smoothing apply to actual target interest rates, not to latent desired rates. The interest rate smoothing hypothesis therefore suggests that equation (3a) provides the appropriate specification. The Rudebusch argument implies that apparent inertia is derived from movements in omitted variables that drive slowly changing optimal rates. Those omitted variables would continue to affect latent desired rates when actual rates are bounded, and variations in the lagged latent rates would continue to reflect inertial forces. Therefore, equation $(3a')$ should better capture inertia of the Rudebusch variety.

The specification in (3a) is a standard Tobit model, but the specification in $(3a')$ is complicated by the appearance of unobserved variables on both sides of the equation. Kiesel and Wolters (2014) estimate dynamic Tobit models for the Bank of Japan, the Federal Reserve, and the European Central Bank, but they do not place lags of the latent dependent variable on the right-hand side of the specification; to our knowledge, we are the first to consider this alternative dynamic Tobit specification.[13] To estimate the model implied by $(3a')$, we use the maximum simulated likelihood (MSL) method.[14] For each observation in the sample, missing values of the unobserved right-hand-side variables are simulated repeatedly according to the process specified by equation $(3a')$. The likelihood function is then calculated for each simulated observation, and the likelihood for a sample observation is calculated as the average of the simulated values. Standard numerical

[13] In an examination of whether Federal Reserve Chairman Alan Greenspan influenced the FOMC voting behavior of Federal Reserve Bank presidents, El-Shagi and Jung (2015) estimated reaction functions for the 12 district Federal Reserve Banks that included both the lagged Committee target rate and the difference between the lagged individual interest rate preference and the Committee target rate. Inclusion of the latter term does not improve on the results obtained from a specification that includes only the lagged Committee target rate.

[14] See Chang (2011) for a detailed description of simulation methods for estimating dynamic Tobit models.

methods are then used to locate the maximum of the likelihood function. The programming is complex because the required simulations vary according to the precise configuration of observed and unobserved variables. The dependent variable can be observed or unobserved, and one or more lagged latent variables can be observed or unobserved.

Estimation is also computationally intensive. In MSL applications, it is desirable to use the same set of simulated error terms in each evaluation of the likelihood function. When this practice is followed, only variations in parameters produce variation in the likelihood function, which makes locating a maximum easier. In our application, simulated values for unobserved variables are drawn conditionally—we know that if a latent variable is unobserved, its value is below the threshold boundary. However, under differing parameters, the same random errors may not always produce a match with the required condition for an observation (i.e., that the value of the latent variable be above or below the threshold). It is therefore not possible to use the same set of simulated errors for each evaluation of the likelihood function. Our solution to this problem is to use a very large number of simulated observations (up to one million) to evaluate the likelihood function for each observation with lagged latent variables. By using sufficiently large numbers of simulated observations, we can calculate the likelihood function with acceptable precision.[15]

4. Model Estimates

In this section, we present estimated Taylor rules for the Riksbank. Our discussion will focus on how parameter estimates differ across pre-recession and recession/recovery

[15] See the appendix for additional information about our estimation procedures.

sample periods and how results vary for model specifications that include lagged actual dependent variables or lagged latent dependent variables.

Table 1 provides OLS estimates of Taylor rules for three different sample periods. Column 1 presents estimates for the pre-recession period (May 2000 through December 2007), column 2 gives estimates for the recession/recovery period (February 2008 through December 2012), and column 3 shows results for the full sample period. In these and all subsequently reported estimations, the empirical specification includes two lags of the dependent variable. With two lagged dependent variables, Breusch-Godfrey tests for OLS estimations failed to reject the hypothesis of no serial correlation of the error terms.[16]

There are several important findings. First, for the pre-recession sample, policymaking seems to have been highly inertial. The sum of the coefficients on the repo rate lags is large (0.92) and evidence of responses to macroeconomic conditions is weak. Both the inflation and output gap coefficients have positive signs, but only that for inflation is marginally significant ($p = 0.070$). An F test fails to reject the hypothesis that the inflation and output gap coefficients jointly equal zero ($p = 0.167$). Given that the Riksbank was directed to target inflation, and given the stability of both output and inflation over this period, these results should not be surprising.

The estimation results for the recession/recovery period (February 2008 through December 2012) continue to show evidence of policymaking inertia, although the sum of the coefficients on the repo rate lags is now lower, at 0.84. Coefficients for the output gap and inflation are positive but do not differ significantly from zero, either individually or

[16] Evidence presented by Coibion and Gorodnichenko (2012) also favors Taylor rule specifications with two lags of the dependent variable.

jointly ($p = 0.247$). The results for the complete sample also show strong inertial effects, with the sum of the lagged repo rate coefficients again at 0.92. The inflation and output gap coefficients are positive, with the gap coefficient marginally significant (p = 0.076). An F test again fails to reject the hypothesis that the inflation and output gap coefficients jointly equal zero ($p = 0.171$).

As we have noted, it appears that a lower limit of 0.25% on the repo rate was binding in six meetings beginning with July 2009 and extending through April 2010. Consequently, a Tobit specification is preferred for samples including those observations. Table 2 provides Tobit model estimates for the full sample period and for the recession/recovery period. The first two columns include two lags of the actual target interest rate (i_{t-1} and i_{t-2}) on the right-hand side, while the third and fourth columns include two lags of the Tobit model's unobserved latent variable (i^*_{t-1} and i^*_{t-2}).

Using the full sample and lagged observed target rates, there are notable differences between Tobit and OLS results. The estimation now implies a large and significant effect of the output gap in the Taylor rule ($p = 0.001$). The inflation rate coefficient estimate is also positive but falls short of significance ($p = 0.114$). A likelihood ratio test now strongly rejects the hypothesis that the output gap and inflation coefficients jointly equal zero ($p = 0.001$).

In the recession/recovery period, the results are again broadly similar, but there is less evidence of policy inertia. The sum of the lagged target rate coefficients now falls to 0.75. The output gap and inflation coefficient estimates are both positive, and that for the gap differs significantly from zero ($p = 0.036$). A likelihood ratio test strongly rejects the hypothesis that the output gap and inflation coefficients jointly equal zero $(p = 0.012)$.

These results make it clear that the Tobit specification is important for detecting both decreased inertia and increased responsiveness of monetary policy to macroeconomic conditions, implying that the six observations when the repo rate was at its effective lower bound are highly informative.

The third and fourth columns of Table 2 provide estimates of Tobit models in which lags of the unobserved latent dependent variable (i^*_{t-1} and i^*_{t-2}) appear on the right-hand side instead of lags of the actual target interest rate. The estimates are qualitatively similar to those for the Tobit with actual lagged target rate values, but there are two noticeable differences. First, for the recession/recovery sample, the sum of the coefficients on the lagged latent variables is yet lower, at 0.60. Second, in both sample periods, the fit of the model (based on values of the likelihood function) with lagged latent variables is notably inferior to that of the model with lagged actual target rates. Based on our earlier argument, this suggests that a desire to smooth interest rates may provide a better explanation for policy inertia than the hypothesis that optimal rates are themselves evolving slowly.[17] Since we also see less evidence of inertia in the recession/recovery sample, there is some support for the view that some pre-recession inertia was illusory, perhaps driven by persistent shocks.

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[17] The Riksbank's website also provides support for the interest rate smoothing argument:

> A desirable monetary policy should also be predictable in order to make it easier for households and companies to adapt to new economic conditions. Changes in the repo rate should therefore normally be made gradually and not in large steps. Moreover, changing the interest rate gradually provides an opportunity to await and analyse new economic data. Since it is difficult to know exactly how the economy functions and how monetary policy acts it is also beneficial that one normally proceeds cautiously in changing interest rates. (http://www.riksbank.se/en/Monetary-policy/Forecasts-and-interest-rate-decisions/What-factors-influence-an-interest-rate-decision-/, accessed January 14, 2014)

5. Conclusions

We have estimated Taylor rules for Sweden's Riksbank over a period extending from May 2000 through December 2012. This period is interesting because it includes the late years of the Great Moderation, a severe recession, and a robust recovery. It also includes a brief period in which the Riksbank's target interest rate encountered a lower bound. These circumstances provide an environment which should be informative about the sources of inertia in monetary policymaking.

In the pre-recession years, when output and inflation were stable, estimates of the Riksbank's Taylor rule were characterized by high levels of inertia with little apparent response to either inflation or the output gap. When the sample is extended to include the recession and recovery years, we observe important differences. Although policy still appears to be inertial, it is less so in the recession/recovery period.[18] Adding observations from the recession/recovery period also strengthens evidence that the Riksbank actively responded to the output gap.

Because the Riksbank encountered a lower bound on interest rates in the recession period, we employed Tobit specifications for samples including the recession observations. Two variants of the Tobit model were estimated. One variant included actual lags of the dependent variable (the repo rate target) as explanatory variables; the other included unobserved lagged latent variables. The former specification is appropriate under the interest rate smoothing argument, while the latter is appropriate when persistent shocks are prevalent. We find that specifications with actual lagged target rates provide

[18] Gerlach and Lewis (2014) find that the European Central Bank reduced interest rates during the financial crisis more rapidly than would have been expected based on its "normal" reaction function.

better fits to the data. This favors interest rate smoothing over persistent shocks as an explanation for policymaking inertia.

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Appendix: Maximum Simulated Likelihood Estimation of the Dynamic Tobit Model

This appendix describes computational procedures followed in estimating dynamic Tobit models when lags of the latent dependent variable appear on the right-hand side of the equation, as in equation $(3a')$ from the text:

$$i_t^* = \alpha_0 + \sum_{j=1}^{J} \rho_j i_{t-j}^* + \alpha_\pi \left(\pi_t - \pi^*\right) + \alpha_y \left(y_t - \overline{y}_t\right) + e_t .$$

To make the description concrete, our discussion refers to the specific data used in our application. In our sample, the committee first encountered the boundary level of 0.25 in July 2009. This was the 71st meeting in our sample. The rate remained at that boundary level until June 2010, the 77th meeting in our sample. Table A1 below shows the pattern of observation "types" over the course of our sample by noting when i_t^* or its lags were unobserved.

Table A1. Distribution of Observation Types for Latent Dependent Variable and Its Lags

Observation Numbers	i_t^*	i_{t-1}^*	i_{t-2}^*	Case
1-70				1
71	Unobserved			2
72	Unobserved	Unobserved		3
73-76	Unobserved	Unobserved	Unobserved	4
77		Unobserved	Unobserved	5
78			Unobserved	6
79-92				1

We now describe the calculation of the likelihood function for observations falling into each of the six cases according to observation type.

Case 1: For case 1, i_t^*, i_{t-1}^*, and i_{t-2}^* are all observed, so the likelihood function for an observation takes the OLS form. No simulations are required.

Case 2: For case 2, which is encountered in meeting 71, the lower bound is encountered, but both i_{t-1}^{*}, and i_{t-2}^{*} are observed, so the likelihood function takes the usual Tobit form. No simulations are required.

Case 3: This case is encountered in meeting 72. Note that in meeting 71, the lower bound was encountered. This means that in meeting 72, the first lag of the latent dependent variable, i_{t-1}^{*}, is unobserved. If i_{t-1}^{*} *were* observed, the likelihood function would take the Tobit form. Our strategy is to replace the unobserved value i_{t-1}^{*} with a simulated value. For given parameter values (including σ^2), we simulate a value for the dependent variable of equation ($3a'$) for $t = 71$, while randomly drawing a random error from a normal distribution with variance σ^2. This simulation provides a lagged dependent variable for $t = 72$. At this point we must check that the simulated value for i_{t-1}^{*} is actually below the threshold level of 0.25 (as we know is the case for this observation). If it is not, the simulation is rejected and repeated. This procedure ensures that errors are being drawn from the correct conditional distribution. Having obtained a simulated value for i_{t-1}^{*}, we can now calculate the likelihood, using the Tobit form, for the simulated observation. This simulation procedure is repeated *N* times, where *N* is a large number, and the average value of the likelihood across the *N* repetitions provides the value of the likelihood function for this observation.

Case 4: This case is first encountered in meeting 73. In meetings 71 and 72, the lower bound was encountered, which implies that i_{t-1}^{*} and i_{t-2}^{*} are both unobserved at $t = 73$. For given parameter values, we dynamically simulate equation ($3a'$) forward from observation $t = 71$, obtaining simulated values for the dependent variable for $t = 71$ and

$t = 72$. This provides simulated values of i^*_{t-1} and i^*_{t-2} for observation 73. We again check that each of the simulated values is below the threshold value of 0.25 (as we know is the case) and reject and repeat the simulation as needed. Having obtained simulated values for i^*_{t-1} and i^*_{t-2}, we calculate the likelihood, using the Tobit form, for the simulated observation. This simulation procedure is again repeated *N* times, and the average value of the likelihood across the *N* repetitions provides the value of the likelihood function for this observation.

Case 5: Case 5 is encountered in meeting 77. In this instance, the dependent variable is now above the boundary level and is observed, but both lags of the dependent variable are unobserved. As in case 4, we simulate forward dynamically from $t = 71$ to obtain simulated values for i^*_{t-1} and i^*_{t-2} at $t = 77$, rejecting and re-simulating as needed to meet the required conditions for the observation. Given the simulated values, the likelihood for the observation is calculated using the OLS form. Again the simulation is repeated *N* times, and the average value of the likelihood across the repetitions provides the value of the likelihood function for this observation.

Case 6: Case 6, which is encountered in meeting 78, is similar to case 5, except that the required simulation replaces only one lagged dependent variable.

At this point, we have a method for calculating the value of the likelihood function for any observation given arbitrary parameter values. The log-likelihood for the sample is the sum of the log-likelihoods over all observations. Using the MLPROC command in TSP, we are able to locate parameter values that maximize the log-likelihood function using standard numerical optimization methods.

In applications of maximum simulated likelihood, it is normally desirable to draw the same random errors when calculating the likelihood function for differing parameter values. This is done so that only the changes in parameter values (not changes in the random draws) cause changes in the likelihood function. In our application, this was not feasible. Some draws of random error terms resulted in “rejected” simulations (meaning simulated values were not compatible with requirements for the case of that observation) under some parameter values, but not others. To get satisfactory precision under these circumstances, we used extremely large values for N (as high as 1,000,000).

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Table 1. OLS Estimates of Riksbank Taylor Rule

Variable	May 2000 through December 2007	February 2008 through December 2012	May 2000 through December 2012
Constant	0.296	0.352	0.256
	(0.032)	(0.143)	(0.027)
i_{t-1}	1.279	1.404	1.459
	(0.000)	(0.000)	(0.000)
i_{t-2}	-0.361	-0.569	-0.539
	(0.006)	(0.002)	(0.000)
$(y_t - \bar{y}_t)$	0.023	0.022	0.030
	(0.697)	(0.597)	(0.076)
$(\pi_t - \pi^*)$	0.070	0.072	0.019
	(0.070)	(0.416)	(0.517)
Additional Hypothesis Test: $\alpha_\pi = \alpha_y = 0$			
F Statistic	1.961	1.405	1.907
	(0.167)	(0.247)	(0.171)
$\bar{R}^2$	0.963	0.952	0.967
Sample Size	61	31	92

Note: *p*-values in parentheses.

Table 2. Tobit Estimates of Riksbank Taylor Rule

Variable	February 2008 through December 2012	May 2000 through December 2012	February 2008 through December 2012	May 2000 through December 2012
Constant	0.734 (0.032)	0.380 (0.002)	1.033 (0.006)	0.396 (0.032)
i_{t-1}	1.061 (0.000)	1.338 (0.000)		
i_{t-2}	-0.315 (0.105)	-0.443 (0.000)		
i^*_{t-1}			0.731 (0.030)	1.192 (0.000)
i^*_{t-2}			-0.129 (0.656)	-0.310 (0.000)
$\left(y_t - \overline{y}_t\right)$	0.110 (0.036)	0.074 (0.001)	0.103 (0.217)	0.053 (0.005)
$\left(\pi_t - \pi^*\right)$	0.126 (0.125)	0.049 (0.114)	0.233 (0.067)	0.046 (0.243)
Additional Hypothesis Test: $\alpha_\pi = \alpha_y = 0$				
χ^2 *Statistic*	8.794 (0.012)	13.043 (0.001)	14.482 (0.001)	11.376 (0.003)
Log-Likelihood	-6.862	3.220	-8.368	-4.631
Sample Size	31	92	31	92

Note: *p*-values in parentheses.

Figure 1. The Swedish Inflation Rate, Output Gap, and Repo Rate, By Executive Board Meeting Date, 2000–2012