Charles University in Prague

Faculty of Social Sciences
Institute of Economic Studies

MASTER'S THESIS

The Exchange Rate Pass-Through at the Zero Lower Bound: The Evidence from the Czech Republic

Author: **Ing. Tomáš Šestořád**

Supervisor: **PhDr. Jaromír Baxa, Ph.D.**

Academic Year: **2016/2017**

Declaration of Authorship

The author hereby declares that he compiled this thesis independently, using only the listed resources and literature, and the thesis has not been used to obtain a different or the same degree.

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Prague, May 19, 2017

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Acknowledgments

I would like to express my deepest gratitude to PhDr. Jaromír Baxa, Ph.D. for supervising my work on this thesis, especially his dedication, positive attitude, encouragement and insightful comments were appreciated.

Abstract

The paper examines the hypothesis that the devaluation of the domestic currency leads to the higher exchange rate pass-through at the zero lower bound since the interest rate channel cannot offset effects of the depreciation in that situation. Time-varying vector autoregression with stochastic volatility is used to identify the development of the pass-through. The hypothesis is tested on the Czech dataset because the Czech Republic is considered as the prototypical small open economy with inflation targeting. The assumption of higher pass-through to consumer prices at the zero lower bound is rejected. Obtained results confirm that the deprecation stimulates output growth slightly more when the interest rate is close to zero. Our estimations imply that the exchange rate commitment of the Czech National Bank increased the price level by 0.116 % and contributed to the output growth by 0.781 %.

JEL Classification	C32, E52, F41
Keywords	exchange rate pass-through, zero lower bound, time-varying parameters, VAR

Author's e-mail	`65119440@fsv.cuni.cz`
Supervisor's e-mail	`jaromir.baxa@fsv.cuni.cz`

Abstrakt

Článek zkoumá hypotézu, zda depreciace při nulové nominální úrokové míře vede k většímu růstu cen a produktu než za normálních okolností. Stanovená hypotéza vychází z předpokladu, že při nulové nominální úrokové míře nemůže být reakce cen a produktu potlačena skrz zvýšení nominální úrokové míry. Hypotéza je testována pomocí vektorové autoregrese s proměnnými parametry v čase a se stochastickou volatilitou, která umožnuje určit, jak se transmise kurzového šoku mění v čase. Model je odhadnut pro Českou republiku, kterou lze považovat za ukázkový příklad malé otevřené ekonomiky dlouhodobě cílující inflaci. Výsledky ukazují, že k větší transmisi kurzového šoku při nulové úrokové míře dochází pouze do produktu. Kurzový závazek České národní banky vedl k navýšení inflace o 0,116 %. Produkt vzrostl v důsledku kurzového závazku o 0,781 %.

Klasifikace JEL	C32, E52, F41
Klíčová slova	transmisní mechanismus měnového kurzu, hranice nulové nominální úrokové míry, odhady měnící se v čase, VAR

E-mail autora	`65119440@fsv.cuni.cz`
E-mail vedoucího práce	`jaromir.baxa@fsv.cuni.cz`

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Acronyms

CNB Czech National Bank

CPI Consumer Price Index

CZK Czech koruna

ERPT Exchange Rate Pass-Through

GDP Gross Domestic Product

EUR Euro

IRF Impulse Response Function

MCMC Markov chain Monte Carlo

NEER Nominal Effective Exchange Rate

PRIBOR Prague InterBank Offered Rate

TVP-VAR-SV Time-Varying Vector Autoregression with Stochastic Volatility

USD United States Dollar

VAR Vector Autoregression

VECM Vector Error Correction Model

ZLB Zero Lower Bound

Master's Thesis Proposal

Author	Ing. Tomáš Šestořád
Supervisor	PhDr. Jaromír Baxa, Ph.D.
Proposed topic	The Exchange Rate Pass-Through at the Zero Lower Bound: The Evidence from the Czech Republic

Motivation The nominal interest rate had declined in developed countries during last two decades until the zero lower bound (ZLB) was reached after the Great Recession. Since the nominal interest rate has been traditionally considered as the main instrument of monetary policy (namely under inflation targeting regime), monetary authorities lost their main tool. In this situation, central banks are not able to stimulate output when the negative shock hits the economy. Therefore, it is necessary to find out a way how to increase low inflation and nominal interest rate by unconventional monetary tools. In case of a small open economy, Svensson (2001) suggests temporary exchange rate peg (devaluation) together with the adoption of price level targeting as one possible solution how inflation expectations can be increased. Since the impact of nominal exchange rate on inflation is measured by the exchange rate pass-through (ERPT), assessment of its dynamic is crucial in the evaluation of possible impact of devaluation. The theory suggests that ERPT is higher when the ZLB is binding because the central bank does not raise the nominal interest rate as a reaction to an exchange rate peg (Franta et al., 2014).

The purpose of this master thesis is to investigate whether the pass-through of devaluation to inflation is higher at the ZLB in comparison to normal circumstances. We expect the ERPT shall be higher because nominal weakening of currency leads to real depreciation and therefore to higher net export and output. At the same time the economy growth is not slowed down by rising nominal interest rate, because it remains close to zero.

The theory will be verified on the example of the Czech economy. Czechia is chosen because it is a small open economy where the exchange rate peg was introduced as a policy instrument when the ZLB was reached. This thesis will also examine a minor hypothesis if ERPT of the Czech economy had had declining trend in normal time as Taylor (2000) suggests. The reason for this research question is mixed empirical evidence among different papers considering ERPT to the inflation in the case of Czechia (Kukharchuk, 2007).

Finally, our intention is to identify the determinants of the ERPT over time. Since ERPT depends on the size of some macroeconomic variables in many countries, we want to find out whether and which macroeconomic variables can explain the ERPT in Czechia.

Hypotheses

Hypothesis #1: Is ERPT to inflation higher when zero interest rate is binding?

Hypothesis #2: Is exchange rate channel to aggregate demand higher at the ZLB?

Hypothesis #3: Was the size of exchange rate pass-through declined before reaching zero nominal interest rate as theory suggests (e.g. Taylor, 2000)?

Methodology We will use TVP VAR with stochastic volatility to estimate the effect of nominal weakening of currency on the inflation (consumer price index) and output gap. The magnitude of ERPT and exchange rate channel to output will be measured by impulse response functions (IRF). The time-varying approach is chosen because it allows the simulation of IRFs for each period separately. Therefore, it is possible to compare size and speed of ERPT for different periods. Estimation strategy will follow Primiceri (2004). The first two hypotheses will be verified by computation of difference between conditional IRF, where nominal interest rate will be set to zero, and unconditional IRF (Koop et al., 1996). The last hypothesis will be confirmed, if the cumulated IRFs to inflation will have declining trend in the period preceding the ZLB.

We will identify determinants of the ERPT by estimated dependent variable regression (Hanushek, 1974; Lewis and Linzer, 2005). The dependent variable will be estimated time-varying the ERPT. Appropriate macroeconomic variables according our literature review of nonlinear models will be chosen as explanatory variables. Weighted least square are the most probable technique how will be importance of determinants of the ERPT estimated.

Expected data sources are Czech Statistical Office, Czech National Bank and Eurostat. Monthly data between 1998 (the beginning of inflation targeting in Czechia) and 2015 will be used for estimation. The empirical part will be conducted in MATLAB.

Expected Contribution

1. Updating of previous research by prolonged dataset until 2015.
2. Quantification of the change of the ERPT to the inflation when the ZLB has started to be binding. Verification of theory that the ERPT and exchange rate channel to aggregate demand are higher at the ZLB.
3. The estimated dynamics of the ERPT can be used to ex-post evaluation of the effects of exchange rate interventions to inflation and also to provide insight into the future dynamics of inflation after expected appreciation of the exchange rate after the exit from exchange rate ceiling.
4. Identification of the determinants of the ERPT over time.

Outline

1. Introduction to ERPT and inflation targeting
2. Importance of nonlinearities in ERPT
3. ERPT at the ZLB (theoretical background/model)
4. Econometric model (TVP VAR with stochastic volatility)
5. Data description and transformation
6. Estimation of the size of exchange rate channel to aggregate demand and ERPT by simulation IRF (responses of positive shock to nominal ER)
7. Conclusion (answers to hypotheses)

Core bibliography

Franta, M., R. Horváth and M. Rusnák (2011): Evaluating Changes in the Monetary Transmission Mechanism in the Czech Republic. CNB Working Paper Series 13.

Franta, M., T. Holub, P. Král, I. Kubicová, K. Šmídková, and B. Vašíček (2014): The Exchange Rate as an Instrument at Zero Interest Rates: The Case of the Czech Republic. Research and Policy Notes 3.

Hanushek, E. A. (1974): Efficient Estimators for Regressing Regression Coefficients. The American Statistician (2), Vol. 28, 66-67.

Koop, G. and D. Korobilis (2009): Baysian Multivariate Time Series Methods for Empirical Macroeconomics. Foundations and Trends in Econometrics (4), Vol. 3, 267-358.

Koop, G., M. H. Pesaran and S. M. Potter (1996): Impulse response analysis in nonlinear multivariate models. Journal of econometrics (1), Vol. 74, 119-147.

Kukharchuk, O. B. (2007): Transmission of Exchange Rate Shocks into Domestic Inflation: The Case of the Czech Republic. CNB Working Paper Series 12.

Lewiss, J. B. and D. A. Linzer (2005): Estimating Regression Models in Which the Dependent Variable Is Based on Estimates. Political Analysis, Vol. 13, 345-364.

Primiceri, G. E. (2004): Time Varying Structural Vector Autoregressions and Monetary Policy. Review of Economic Studies 72, 821–852.

Svensson, L. E. O. (2001): The Zero Bound in an Open Economy: A Foolproof Way of Escaping from a Liquidity Trap. Monetary And Economic Studies (Special Edition), 277-312.

Taylor, J. B. (2000): Low inflation, pass-through, and the pricing power of firms. European Economic Review 44, 1389-1408.

Author | Supervisor

Chapter 1

Introduction

After the Great Recession, conventional monetary policy tools have become bounded by the zero nominal interest rate. Since central banks wanted to reach the inflation target, they had to experiment with unconventional instruments of monetary policy. In the case of small open economies, the exchange rate management seems to be an reasonable option. The devaluation of the domestic currency should lead to higher consumer prices since the change of the exchange rate won't be offset by the interest rate channel at the zero lower bound. Additionally, output might increase as another consequence of devaluation of domestic currency.

The main idea of the paper is to evaluate the proposed economic theory and find whether the pass-through is really higher at the zero lower bound since recent literature does not provide clear answer to this question. Economic models built within the New Keynesian framework predict higher inflation and output growth if the depreciation occurs during period of the zero lower bound (Svensson 2000). On the other hand, there is only weak empirical evidence which confirms findings of economic models. Most empirical studies find rather opposite, decreasing exchange rate pass-through at the zero lower bound (Özyurt 2016; Jašová *et al.* 2016). This leaves free room for our research.

The hypothesis is tested on the Czech data since the Czech Republic is a small open economy with long tradition of inflation targeting. Additionally, the Czech National Bank is the first central bank which adopted the exchange rate floor according to Svensson's proposal (2000). Our dataset covers period from January 1998 to November 2016 and includes four years of observations when the zero lower is prevailing. It allows to us properly investigate how the pass-through changed when the interest has become bounded by zero. Time-varying vector autoregression with stochastic volatility serves as the main estimation strategy since it is sufficiently flexible to capture changes in the transmission mechanism of the monetary policy. Virtue of used model is ability to assess the impact of the depreciation on the price level and output for each month separately. This allows to us evaluate the effectiveness of the exchange rate floor as the unconventional monetary policy tool introduced by the Czech National Bank in November 2013.

Both linear and time-varying models provide an evidence that the structural break in the transmission mechanism occurs when the zero lower bound is reached. Chow tests prove the existence of multiple structural breaks in the baseline linear model. Hence, time-varying vector autoregression is appropriate estimation strategy.

Using time-varying vector autoregression with stochastic volatility,we find that the exchange rate pass-through is rather fast and it is completed after less than two years for the most of observations. The exchange rate pass-through to consumer prices is declining together with inflation over time and this tendency did not change even when the zero lower bound was reached. Positive impact of the depreciation on output is slightly more distinctive for the end of sample when the low interest rate is prevailing. The response of output at the zero lower bound is less pronounced in time varying vector autoregression than in linear model. Obtained results confirm the assumption that the interest rate channel disappears in the situation when the interest rate is extremely low. According to our analysis, the output growth and the nominal interest rate seem to be the most important macroeconomic determinants of the size of the pass-through to consumer prices and output.

From the monetary policy perspective, the ability of the exchange rate management to stimulate inflation is limited. Unit depreciation of the currency is not able to increase the price level more than by 0.11 % after two years from the initial deprecation. Similarly, unit deprecation brings output growth lower than 0.1 %. We find that the 5 % depreciation in November 2013 contributed to price level by additional 0.116 % and increased output by 0.781 % after two years from the introduction of the exchange rate commitment[1].

The thesis is structured as follows: Chapter 2 gives deeper motivation to proposed topic and summarizes stylized facts about the exchange rate pass-through. Chapter 3 presents used estimation strategy. Chapter 4 covers basic information about used variables and their transformation. Chapter 5 de-

[1] Reported estimations correspond to the 5 % deprecation of CZK/EUR exchange rate.

scribes structural breaks in the data and shows how the transmission mechanism changed at the zero lower bound. Chapter 6 contains estimations of time varying exchange rate pass-through. Monetary policy implications are included in this chapter. Chapter 7 summarizes our findings and suggests possible extensions of the article for further research.

Chapter 2

Literature Review

2.1 Exchange Rate Peg as Unconventional Monetary Policy Tool

The nominal interest rate had declined in developed countries during last two decades until the zero lower bound (ZLB) was reached after the Great Recession. Since the nominal interest rate has been traditionally considered as the main instrument of monetary policy (namely under inflation targeting regime), monetary authorities lost their main tool. In this situation, central banks are not able to stimulate output by lowering the nominal interest rate when the negative shock hits the economy. Therefore, it is necessary to find out a way how to increase low inflation and the nominal interest rate by unconventional monetary policy tools.

The most common unconventional tools are qualitative and quantitative easing, forward guidance, negative nominal interest rate and exchange rate management. The other possibilities as helicopter money and switching monetary policy regime from inflation to price level targeting are discussed primarily on the theoretical level. Quantitative easing is used when the finance sector of the economy has insufficient amount of liquidity. Qualitative easing decreases the amount of risky assets on the market. These two tools are relevant only when the economy faces to problems on the financial markets. The lowering of the nominal interest rate significantly below zero brings great uncertainty about behaviour of economics agents (Bech & Malkhozov 2016). Clearly defined forward guidance is necessary for success of all others unconventional monetary tools because only then unconventional tools will become credible.

When the financial sector of a small open economy is in good condition, the exchange rate management and foreign interventions are only reasonable possibilities of the unconventional monetary policy. The main advocate of the exchange rate management at the zero lower bound is Svensson (2000) who suggests temporary exchange rate peg (devaluation) together with the adoption of price level targeting as a possible solution how inflation expectations can be increased.

The introduction of the exchange rate peg according to Svensson's proposal (2000) leads to the nominal depreciation of the domestic currency. The nominal depreciation influences price level and the development of real macroeconomic variables through direct and indirect effects (Savoie-Chabot & Khan 2015). The depreciation has two direct effects. Firstly, prices of finished imports are higher. Secondly, imported inputs become more expensive and production costs of domestic firms rise. Both direct effects increase price level. The main indirect consequence of the depreciation is less expensive domestic production relative to foreign producers. Cheaper production increases domestic and foreign demand for domestic goods. It implies the higher balance of trade and the stimulation of output growth (mainly in the case of the exporting economy). The high demand for the domestic production also influences labour market where firms hire more workers who get higher wage. Because of high demand for domestic goods and limited sources of inputs which become more expensive, firms have to increase their prices. Overall, the nominal depreciation brings higher inflation, output growth, export and lower unemployment and import.

Until now, we omit the central bank from the transmission mechanism. But the magnitude of the exchange rate shock on other macroeconomic variables depends on the policy of the central bank. In the case of inflation targeting, the main objective of the central bank is stable and positive inflation (output stability can be secondary aim for some central banks). Therefore, the central bank increases the policy rate as a reaction to the depreciation and expected inflationary pressure. This is a way how price stability will be ensured under normal circumstances when the nominal interest rate is above zero. Completely different situation is at the zero lower bound when the central bank wants to stimulate inflation. In that case, the central bank does not response to the depreciation by raising the nominal interest rate. Therefore, the depreciation should lead to higher inflation and output growth at the zero lower bound. From this description is clear how the exchange rate peg (devaluation) can serve as unconventional monetary policy tool when the zero nominal interest rate is reached. This argumentation is supported by Franta *et al.* (2014) and

Malovaná (2015) who mention that the introduction of the temporally exchange rate floor should be sufficient to stimulate inflation. Moreover, Malovaná (2015) proposes that the exchange rate floor is the most effective foreign intervention regime when the small open economy is facing deflationary pressures.

The most of literature studying the exchange rate pass-through at zero lower bound comes from Japan (Shioji 2012; 2015; Iwata & Wu 2006). Japan is the big open economy with the specific development in previous decades (Lost Decade) and therefore empirical evidence from Japan has very limited implication for a small open economy. Although Switzerland was the first country which used temporary exchange rate at the ZLB, the main motivation for nominal the exchange rate floor was strong pressure on the appreciation of Switzerland Frank (Franta *et al.* 2014). Hence, the Czech National Bank (CNB) was the first central bank which introduced temporary exchange rate commitment with aim to increase inflation according to Svensson's (2000) proposal. Therefore, this article particularly focuses on the pass-through in Czechia. Moreover, Czech Republic is widely considered as traditionally inflation targeting economy. For this reasons, it is useful to summarize the monetary policy of the CNB and recent literature which investigates the size of the pass-through in the Czech economy.

The Czech National Bank resorted to an exchange rate policy in November 2013, when the floor of the exchange rate was fixed at 27 CZK/EUR. The nominal weakening of the Czech crown lasted until the beginning of April 2017. This weakening of the currency relied on the assumption that the pass-through is higher at the zero lower and therefore the exchange rate management can influence inflation and output as it was already described. Economists of the Czech National Bank (Lízal 2015; Tomšík 2016) repeatedly argue that the exchange rate peg has increased inflation and output growth remarkably. Lízal (2015) provides counterfactual analysis for different scenarios and show that the exchange rate management was only possible way how to overcome the deflationary threat. Tomšík (2016) assumes that 5 % depreciation[1] should increase consumer prices by 1.6 % in the long-term (it implies the pass-through just below one third). But when Tomšík (2016) compares development of price indexes in the euro area and in the Czech Republic for the period between December 2013 and October 2015, the differential is lower than it was expected. The wedge of the producer price index is 0.8 for given period. In the case of the

[1] 5 % depreciation corresponds to the size of the depreciation after the introduction of the exchange rate floor in November 2013.

consumer price index, the wedge is even lower (0.5; the pass-through is only 0.1 %). Low and insignificant impact of the exchange rate floor on consumer prices is also obtained by the synthetic control method (Opatrný 2016).

2.2 Exchange Rate Pass-Through

Evaluation of the impact of the exchange rate shock to price level and output is crucial when the exchange rate management is considered as possible unconventional monetary policy tool. Therefore, effectiveness of depreciations and appreciations is measured by the exchange rate pass-through (ERPT) which shows how much price level (and eventually output) responses to a one percentage change in the exchange rate (Goldberg & Knetter 1997). Stylized facts about the pass-through and its estimation are summarized in the following paragraphs.

According to a macroeconomic theory, the size of the pass-through moves between zero (none pass-through) and one (complete pass-through) (Goldberg & Knetter 1997). The pass-through is the highest to import prices and gradually declines along the distribution chain (McCarthy 1999). For instance, the pass-through to import prices is roughly 0.8 %, the pass through to producer prices reaches 0.6 % and the pass through to consumer prices is approximately lower than 0.2 % in the most important economies of the euro area (Comunale & Kunovac 2017). The pass-through to import prices is incomplete because firms internalize costs connected with the change in the nominal exchange rate into their mark-up rather than change prices completely. The type of goods also influences the size of the pass-through. The response of tradable goods is much higher to the exchange rate shock than response of nontradable goods such as services (Babecká 2007). Important determinant of the size of the pass-through to consumer prices is the sensitivity of domestic firms demanding foreign inputs to the exchange rate shock. In the case of the appreciation, less expensive foreign inputs of domestic producers influence consumer prices more than cheaper import of finished goods (Goldberg & Campa 2010). Taylor (2000) and his followers (for instance Takhtamanova 2008; Edwards 2006; Shintani *et al.* 2013) have pointed out that the size of the ERPT positively depends on the inflation rate and therefore the ERPT was declined during the period of Great Moderation. This finding is connected with the inflation targeting as a credible monetary policy regime (Takhtamanova 2008). Observation that the pass-through depends on inflation has implication also for cross-country differentials. Typically, emerging economies which have not adopted inflation targeting response to the exchange rate shock more than developed economies (Ca'Zorzi & Hahn 2007). But some differences in the pass-through also hold among similar advanced economies - the pass-through to consumer prices is higher in Spain and Italy than in France and Germany (Özyurt 2016).

Iwata & Wu (2006) investigate the difference in the transmission mechanism of foreign exchange interventions in Japan under normal circumstances and in the situation when the zero lower bound is reached. They use structural vector autoregressive model where the interest rate is specified by Tobit type of nonlinearity. The nominal interest rate is censored variable for periods when the zero is binding. This specification allows to estimate the transmission mechanism for separately both regimes. Iwata & Wu (2006) find that the effectiveness of foreign interventions is higher in normal times than at the zero lower bound. But according to their results, foreign interventions are still able to stimulate inflation and output although the zero nominal interest rate prevails in the economy. More recently, Jašová *et al.* (2016) estimate time-varying pass-through separately for advanced and emerging[2] economies before and after the crisis. Using one-equation rolling regression, they find stable pass-through for advanced economies and lower post-crisis pass-through in the case of emerging countries. The exchange rate pass-through dramatically dropped from 0.3 % to 0.22 % in the euro area in 2012 (Özyurt 2016). These results seem to be contradictory to Svensson's model (2000) which states that the pass-through is higher at the zero lower bound.

Several ways how the ERPT can be estimated exist. The first approach is simple ordinary least-squares regression. The backward looking Phillips curve for an open economy is used as the basic benchmark in this case. Shortcoming of this approach is that one equation model is not able to take into account monetary policy decision of the central bank as the response to the exchange rate shock. From econometric point of view, endogeneity problem is the main issue of single equation model (Devereux *et al.* 2003). Multivariate time series models such as the vector autoregression (VAR) overcome this issue (McCarthy 1999; Babecká 2007). On top of that, VAR allows contemporary interaction between chosen variables. The ERPT is measured by impulse response function (IRF). It identifies how inflation or other variables develops when the shock to the nominal exchange rate has occurred. IRF assesses the size of the short-term ERPT meanwhile the long-term ERPT is given by cumulated IRF. Vector er-

[2]Among emerging economies were also included Central European countries.

ror correction model (VECM) is an alternative technique how to estimate the ERPT. Its advantage is preservation of long term relationships between cointegrated variables. Hence, VECM assumes the existence of the macroeconomic equilibrium, where variables converge. Cointegrated models bring higher estimates of the ERPT than VAR models do (Beirne & Bijsterbosch 2011).

More up-to-date research focuses on nonlinearities in the ERPT using time-varying or threshold methodology. Especially threshold (vector) autoregression is used quite often. The main finding of threshold models is the verification of the presence of nonlinearities in several ways. Firstly, the price level reacts more to the depreciation than to the appreciation (Dellate & Lopez-Villavicencio 2013). In the case of the appreciation, domestic firms have not any strong incentive to reduce their prices because the change of the exchange rate leads to the higher profit of firms. Secondly, the size of the change in the nominal exchange rate has positive impact on the pass-through. Large changes in the exchange rate cannot be easily internalized as a smaller ones (Correa & Minella 2010; Caselli & Roitman 2016). For the same reason, expectations of the long-term change in the exchange rate increase the pass-through (Correa & Minella 2010; Ozkan & Erden 2015). What remains somehow unclear is the relationship between the output gap and the pass-through. For instance, Cheikh (2012) and Correa & Minella (2010) find the higher pass-through during expansions than in the situations of lower output growth. Cheikh (2012) argues that firms are more willingness to internalize costs of the devaluation in the recession than in the expansion, because they face low demand during the economic slowdown. On the other hand, Ozkan & Erden (2015) show the negative effect of output gap on the exchange rate transmission mechanism to consumer prices. They claim that the higher domestic production increases the output gap which reduces demand for imported goods and hence the pass-through has to decline. The possibility of ambivalent effect of output gap on the ERPT is also mentioned in Ghosh & Rajan (2009). Generally, the estimation of the ERPT by nonlinear model is significantly higher under some specific condition which linear models cannot take into account. This observation is important because it means that the EPRT is changing over time.

To track time-variation in the pass-through, models with time-varying parameters are used. Primiceri (2005) introduces famous framework of time-varying structural vector autoregression with stochastic volatility (TVP-VAR-SV). Time-varying VAR allows to capture effect of structural breaks, trends and other factors such as the effect of business cycles on the size of the ERPT (Koop

& Korobilis 2012). The disadvantage of time-varying VAR is large number of parameters and hence high uncertainty about estimations (Koop & Korobilis 2012). It implies wide confidence intervals for estimated parameters and their statistical insignificance. Using time-varying VAR, Sekine (2006) finds the declining ERPT in G7 countries in the pre-crisis period. Time-varying structural VAR for United Kingdom, euro area, Canada and Japan has brought similar results (Mumtaz & Sunder-Plassmann 2010). Another examples of time-varying VAR are Shioji (2012; 2015). In the case of Japanese economy, Shioji (2012) rejects the hypothesis of the higher ERPT at the zero lower bound. Opposite results brings his updated analysis. At the end of 2012, the ERPT has started to rise in Japan (Shioji 2015). Time-varying VECM is used rarely, because it is not able to provide reasonable results (Babecká 2007).

The exchange rate pass-through has been estimated several times for the Czech Republic in last years. Babecká (2007) finds that the long-term pasthrough is not higher than 30 % when different specifications of vector autoregressive model and its cointegrated counterpart are employed. Babecká *et al.* (2013) are not able to make clear conclusion about the development of the ERPT over time due to its sign instability and high volatility during Great Recession. Nevertheless, they suppose that the exchange rate channel had been weakened during Great Recession. But it is in contradiction with Hájek (2014) who finds the highest pass-through during periods of economic slowdown. Moreover, his estimation of time-varying VECM contra-intuitively suggests that the ERPT was declining in 2012 and 2013 when the nominal interest rate was already bounded by zero. But this result might be biased, because his dataset ends at the beginning of 2014 and the estimated ERPT is highly volatile. Franta *et al.* (2011) employ TVP-VAR-SV to estimate the ERPT between 1996 and 2010. According to their results, the response of consumer prices to the exchange rate shock remains stable over time, only at the end of the sample the ERPT has started to increase. Consumer prices react to the exchange rate shock two-times slower than in Babecká (2007). Notably, variation of ERPT is much lower in the case of Franta *et al.* (2011) than in Hájek (2014). The size of the estimated long-term ERPT moves between -20% and 60% in Hájek (2014), whereas Franta *et al.* (2011) provide much lower estimations which confirms the sensitiveness of results to used econometric approach.

Although some articles try to identify the impact of the CNB's exchange rate management, none of them estimate the size of the ERPT at the zero lower bound. Mixed evidence on effectiveness of the CNB's unconventional monetary policy and unclear development of the pass-through among economies are reasons why the further research is desirable.

Chapter 3

Methodology

3.1 Time-Varying VAR with Stochastic Volatility

Vector autoregressions are widely used to study transmission mechanisms of monetary and fiscal policies. It allows to investigate simultaneous interaction among time series. Since estimated vector autoregression includes many coefficients which have not straightforward interpretation, estimations are interpreted by impulse response functions. They show how each time series responses when exogenous shock hits given variable. In a standard linear vector autoregression, set of impulse responses is same for all considered time periods. This is the weaknesses of linear VAR because such model cannot capture any structural break or trend in the transmission mechanism between considered variables. Time-varying vector autoregression overcomes this shortcoming because it provides a unique set of impulse response functions for each time period in the dataset. The identification of impulse responses separately for each data point in the time allows to capture trend and structural breaks in the economy. Therefore, time-varying approach is suitable to assess the development of the pass-through over time regardless of the structural changes in the economy such as the reaching the zero lower bound. This chapter describes derivation and specification of time-varying VAR with stochastic volatility. The model assumes stochastic volatility because fluctuations of macroeconomic variables is changing over time. For instance, macroeconomic variables are usually more volatile during recession than during expansions (Koop & Korobilis 2012).

3.1.1 Model

In accordance with Primiceri (2005) and Nakajima (2011b), we construct following model:

$$A_t y_t = c_t + \sum_{i=1}^{p} F_{i,t} y_{t-i} + u_t, \tag{3.1}$$

where y_t is an $k \times 1$ vector of endogenous variables, c_t is an $k \times 1$ vector of time-varying intercepts, and $A_t, F_{i,t}$ for $i = 1, ..., p$ are $k \times k$ matrices of time-varying coefficients. The number of lags in the model is defined by p. The disturbance u_t is the $k \times 1$ structural shock, which follows normal distribution $u_t \sim N(0, \Sigma_t \Sigma_t)$, where

$$\Sigma_t = \begin{pmatrix} \sigma_{1,t} & 0 & \cdots & 0 \\ 0 & \sigma_{2,t} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \sigma_{k,t} \end{pmatrix}.$$

Simultaneous relations of the structural shock are defined recursively by the lower triangular matrix A_t,

$$A_t = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ a_{21,t} & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ a_{k1,t} & \cdots & a_{k\,k-1,t} & 1 \end{pmatrix}.$$

We can rewrite the structural model into its reduced form:

$$y_t = c_t + \sum_{i=1}^{p} B_{i,t} y_{t-i} + A_t^{-1} \Sigma_t \epsilon_t \qquad u_t = A_t^{-1} \Sigma_t \epsilon_t, \tag{3.2}$$

where $B_{i,t} = A_t^{-1} F_{i,t}$. Stacking intercepts c_t and matrices of coefficients $B_{i,t}$ for all t into a vector β_t of the length $k(kp+1)$, and defining $X_t = I_k \otimes (1, y'_{t-1}, ..., y'_{t-p})$, the model can be rewritten as

$$y_t = X_t \beta_t + A_t^{-1} \Sigma_t \epsilon_t. \tag{3.3}$$

In the next step, we define the evolution of time-varying parameters over time. Firstly, let stack unknown parameters of the lower triangular matrix A_t to a vector $\alpha_t = (a_{21,t}, a_{31,t}, a_{32,t}, a_{41,t}, ..., a_{k\,k-1,t})$ of the length $\frac{1}{2}(k-1)k$. Diagonal elements of Σ_t are logarithmically transformed $h_{jt} = \log \sigma_{jt}^2$ for $j = 1, ..., k$ and stacked into an $k \times 1$ vector $h_t = (h_{1t}, ..., h_{kt})$. Vectors β_t, α_t, h_t evolve for $t = s + 1, ..., n$ as random walk without drift:

$$\beta_{t+1} = \beta_t + u_{\beta,t+1}, \tag{3.4}$$

$$\alpha_{t+1} = \alpha_t + u_{\alpha,t+1}, \tag{3.5}$$

$$h_{t+1} = h_t + u_{h,t+1}. \tag{3.6}$$

From the equation (3.6) is visible that standard deviation σ_t evolves as geometric random walk, which belongs to the class of stochastic volatility model (Primiceri 2005). A vector of error terms ϵ_t and innovations of time-varying coefficients $u_{\alpha,t}, u_{\beta,t}, u_{h,t}$ are normally distributed

$$\begin{pmatrix} \epsilon_t \\ u_{\beta,t} \\ u_{\alpha,t} \\ u_{h,t} \end{pmatrix} \sim N \left(0, \begin{pmatrix} I_k & 0 & 0 & 0 \\ 0 & \Sigma_\beta & 0 & 0 \\ 0 & 0 & \Sigma_\alpha & 0 \\ 0 & 0 & 0 & \Sigma_h \end{pmatrix} \right),$$

where I_k is identity matrix of dimension $k \times k$. Matrix Σ_h is diagonal meanwhile matrices $\Sigma_\beta, \Sigma_\alpha$, depict the covariance structure of innovations.

Nakajima (2011a) suggests that TVP-VAR-SV without any technical modification is appropriate to investigate relationships among macroeconomic variables even at the zero lower bound.[1] To specify the model correctly when the zero nominal interest rate prevails in the economy, additional variable has to be added as a proxy for the monetary policy of the central bank. Nakajima (2011a) expects that the transmission mechanisms trough the interest rate channel disappears naturally due to nature of the time-varying model.

3.1.2 Bayesian Inference

Overparametrisation is serious issue of TVP-VAR-SV since large number of parameters have to be obtained for each observation. Bayesian estimation is a popular way how to deal with the overparametrisation and how to make impulse response more precise (Koop 2003). Bayesian econometrics combines two sources of information - empirically obtained likelihood and prior beliefs of

[1] Classical TVP-VAR-SV can provide misleading IRFs at the ZLB when the interest rate shock is considered. We do not discuss this issue in details since it has not any impact on our estimation strategy and results.

the researcher. These two factors together with probability distribution of the data form the posterior density of estimated parameters:

$$p(\theta|y) = \frac{p(y|\theta)p(\theta)}{p(y)}, \tag{3.7}$$

where y denotes the data and θ is the vector of parameters. The posterior density $p(\theta|y)$ is defined as multiplication of the likelihood $p(y|\theta)$ and priors $p(\theta)$ divided by the probability density of the data. The equation (3.7) is also known as the Bayesian' law. Since $p(y)$ does not depend on parameters of interest θ, the Bayesian' law can be simplified to

$$p(\theta|y) \propto p(y|\theta)p(\theta), \tag{3.8}$$

where $\propto$ means that the posterior density proportionally corresponds to the likelihood times priors. Point estimation of parameters θ can be obtained from the posterior distribution.

Analytical solution of the posterior distribution does not exists when the model is complicated and large. For this reason, numerical integrated methods based on Markov chain Monte Carlo (MCMC) simulation are employed. The convergence of draws to true values of parameters when the number of iterations becomes large is the main advantage of MCMC simulation. Weak law of large numbers holds for MCMC methods. Gibbs algorithm is commonly used to sample coefficients of time-varying VAR with stochastic volatility. Gibbs algorithm is used when it is possible to sample from conditional distributions (Greenberg 2008). Suppose we wish to sample from joint distribution $f(x_1, \ldots, x_d)$. Firstly, we have to specify initial values $x_2^0, \ldots, x_d^0$ and then we can start to sampling the first iteration for $x_1, \ldots, x_d$. The draw x_1^1 serves as the initial value for conditional draw x_2^1. Starting values for next draws $x_i; i \in \{1, \ldots, d\}$ are gradually updated. When the first iteration is finished, all starting values $x_2^0, \ldots, x_d^0$ are already replaced by draws of the first iteration $x_1^1, \ldots, x_d^1$. This process is repeated until the end of g-th iteration is reached. Sample average of these g draws corresponds to true mean value for each x_i when g is sufficiently large and firsts iterations are discarded because they are biased due to arbitrary choice of starting values $x_2^0, \ldots, x_d^0$. It is possible to summarize Gibbs algorithm by the scheme (Greenberg 2008):

1. Choose a starting values $x_2^{(0)}, \ldots x_d^{(0)}$

2. At the first iteration, draw
$x_1^{(1)}$ from $f\left(x_1|x_2^{(0)}, \dots x_d^{(0)}\right)$
$x_2^{(1)}$ from $f\left(x_2|x_1^{(1)}, x_3^{(0)}, \dots x_d^{(0)}\right)$
$\vdots$
$x_d^{(1)}$ from $f\left(x_d|x_1^{(1)}, \dots x_{d-1}^{(1)}\right)$

3. At the g-th iteration, draw
$x_1^{(g)}$ from $f\left(x_1|x_2^{(g-1)}, \dots x_d^{(g-1)}\right)$
$x_2^{(g)}$ from $f\left(x_2|x_1^{(g)}, x_3^{(g-1)}, \dots x_d^{(g-1)}\right)$
$\vdots$
$x_d^{(g)}$ from $f\left(x_d|x_1^{(g)}, \dots x_{d-1}^{(g)}\right)$

In the case of TVP-VAR-SV, Gibbs algorithm is used to generate joint posterior of A^T, B^T, Σ^T, v. Drawing process of one iteration consists of four parts. Draws are carried out in this order: drawing time varying coefficients (B^T), simultaneousness relations (A^T), volatilities (Σ^T) and hyperparameters V conditionally on data and the rest of parameters (Primiceri 2005). Interested readers can find more detailed description of the estimation procedure in Primiceri (2005).

3.1.3 Priors

It is necessary to specify priors about initial values of parameters and their expected variance overtime. Many different approaches how to specify prior beliefs about parameters exist. Review of possible approaches is available in (Koop & Korobilis 2012). We follow widely used strategy that priors are set according to estimations of linear VAR on the training sample (Primiceri 2005). Initial values of vectors β_t, α_t, h_t at $t = s + 1$ have normal distribution with mean and variance equal to estimations of linear VAR model on the training sample:

$$\beta_{s+1} \sim N(\hat{B}_{OLS}, 4 * V(\hat{B}_{OLS})), \tag{3.9}$$

$$\alpha_{s+1} \sim N(\hat{A}_{OLS}, 4 * V(\hat{A}_{OLS})), \tag{3.10}$$

$$h_{s+1} \sim N(\hat{h}_{OLS}, 4 * I_k), \tag{3.11}$$

where $\hat{A}_{OLS}, \hat{B}_{OLS}, \hat{h}_{OLS}$ are ordinary least squares estimations of linear vector autoregressive model for first τ observations. Variance of starting values is multiplied by arbitrary value of four to take into account uncertainty about initial values. Prior distribution of variance of innovations is defined in the following way:

$$\Sigma_\beta \sim IW\left(k_\beta^2 * \tau * V(\hat{B}_{OLS}), \tau\right), \tag{3.12}$$

$$\Sigma_h \sim IG\left(k_h^2 * (k+1) * I_k, k+1\right), \tag{3.13}$$

$$\Sigma_{\alpha,l} \sim IW\left(k_\alpha^2 * (1 + dim(\Sigma_{\alpha,l})) * V(\hat{A}_{l,OLS}), 1 + dim(\Sigma_{\alpha,l})\right), \tag{3.14}$$

where hyper-parameters k_α, k_β, k_h specify prior beliefs about the amount of time variation. Inverse-Wishart distribution of innovations is assumed. Prior beliefs about innovations of time-varying coefficients β become too tight when the training sample is long (Σ_β depends on τ, see the equation 3.12). This can resulted in underestimated time-variation of β coefficients. If this issue arises, higher value of k_β is an option how to obtain less tight priors. Innovations of simultaneous relations α are specified by blocked covariance matrices in the equation (3.14), where $l \in \{1, 2, ..., k-1\}$ and k is number of endogenous variables.

3.2 Specification of Model

3.2.1 Lag Selection

All estimated VAR models include four lags of endogenous variables. The number of lags is chosen with respect to the origin of data and the necessity to construct the smallest possible model. TVP-VAR-SV includes usually only two lags which is the lowest acceptable number to capture dynamic of the multivariate system (Nakajima 2011b). We have to use more lags since output is interpolated. Four lags ensure that the model contains sufficient information about interpolated output growth (estimation for each month includes of information from at least three original observations of quarterly GDP). Our choice of the number of lags is supported by information criteria for linear VAR which suggest three or more lags. More details about informations criteria are provided in Chapter 5.

3.2.2 Structural Identification of Model

We specify contemporary relations among variables recursively. Lower triangular Choleski decomposition of matrix A_t^{-1} is used. Ordering of variables matters when Choleski decomposition is utilized. The first variable does depend only on itself exogenous shock but the shock to the first variable influences immediately all remaining endogenous variables. The second variable is contemporaneously influenced by the shock from the first equation meanwhile its present value does not depend on shocks to other variables. The variable ordered as the last one is influenced immediately by the exogenous shock to any variable.

Variables are ordered in this way: output, price level, nominal interest rate and exchange rate. The exchage rate responses without any delay to all exogenous shock since the exchange rate can freely move on the market. Because the interest rate is set by the central bank according to the expected future performance of the economy, the central bank immediately takes into account information about shocks to output and inflation. Rigidities occur in responses of output and price level to exogenous shock from other variables. Price level contemporaneously reacts only on the shock to output. Following the econometric model, the vector of structural shocks u_t defined as $u_t = A_t^{-1}\Sigma_t\epsilon_t$ can be rewritten into full form:

$$\begin{pmatrix} u_{y,t} \\ u_{\pi,t} \\ u_{i,t} \\ u_{s,t} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ \alpha_{21,t} & 1 & 0 & 0 \\ \alpha_{31,t} & \alpha_{32,t} & 1 & 0 \\ \alpha_{41,t} & \alpha_{42,t} & \alpha_{43,t} & 1 \end{pmatrix} \begin{pmatrix} \sigma_{y,t} & 0 & 0 & 0 \\ 0 & \sigma_{\pi,t} & 0 & 0 \\ 0 & 0 & \sigma_{i,t} & 0 \\ 0 & 0 & 0 & \sigma_{s,t} \end{pmatrix} \begin{pmatrix} \epsilon_{y,t} \\ \epsilon_{\pi,t} \\ \epsilon_{i,t} \\ \epsilon_{s,t} \end{pmatrix}, \tag{3.15}$$

where lower indexes denotes variables: y is monthly growth rate of output, π is monthly inflation, i is the nominal interest rate and s is used for the exchange rate. Note that the exchange rate here also serves as a proxy for the monetary policy at the zero lower bound how Nakajima (2011a) suggests.

The recursive ordering is common for models describing big open economy (Christiano *et al.* 1996), but the application of Choleski decomposition to the small open economy is quite controversial (Kim & Roubini 2000). The recursive ordering is satisfying for our model because we expect that the central bank does not response to the exchange rate shock immediately. Lagged response of the interest rate to the exchange rate shock seems to be plausible since we use monthly data. The board of the central bank need some time to evaluate possible outcomes of the exchange rate shock before they make policy decision.

To identify the exchange rate pass-through, orthogonalized cumulated impulse responses are used. Time horizon for assessment of the long-term pass-through is set to two years since the exchange rate pass-through to other variables is fast in the Czech Republic Babecká (2007); Babecká *et al.* (2013). The exchange rate shock is defined as one percentage deprecation. One standard deviation serves as benchmark to asses statistical significance of impulse responses. 68 % credible intervals are computed from bootstrapped simulations. Median impulse responses are reported instead of average responses in the case of TVP-VAR-SV.

3.2.3 Training Sample and Priors

Priors are determined from linear VAR estimated on the whole sample instead of using training sample. We chose this option for two reasons. Firstly, we do not want to rely on the training sample which includes observations preceding to January 1998. The transmission mechanism of the monetary policy works quite differently before the adoption of inflation targeting and therefore obtained priors could be misleading for our model. Similarly, if the first two years of observations would be used as training sample, linear VAR would not be able to provide reasonable estimations of coefficients because the interest rate was high and quickly decreasing at that time as the consequence of the transition from the old to the new monetary policy regime.

Our choice of training sample is motivated by Canova (2003) who recommends to use all observations as training sample when the length of time series is too short. Since we have 227 available observations we are in slightly different position and we have to adjust prior beliefs about time variation of β coefficients because the length of time series (large τ) imposes unreasonable tight priors on time variation of coefficients (see equation 3.12). To solve this issue, we set a value of hyperparameters k_β loosely. Because time variation of results changes when different values of k_β are used, we estimate the model for three different values of hyperparameter: $k_\beta = \{0.1, 0.2, 0.3\}$. Hyperparameter k_β equal to 0.2 serves as baseline specification and other two values of k_β are used to assess robustness of results. We set values of k_α and κ_h to 0.05. Estimations are same when values of k_α and κ_h are changed.

Chapter 4

Data

4.1 Dataset

The dataset consists of six macroeconomic variables: gross domestic product (GDP), consumer price index (CPI), Prague InterBank Offered Rate (PRIBOR) and three alternative specifications of the exchange rate (nominal effective exchange rate (NEER) and bilateral exchange rates CZK/EUR and CZK/USD). All variables except the nominal interest rate are transformed into monthly growth rates to ensure the stability of linear VAR. Variable PRIBOR remains in levels. GDP measures the real economic activity of the economy. CPI shows how prices of consumed goods are changing overtime. The interest rate of the CNB, the main policy tool of inflation targeting, is depicted by PRIBOR (three months PRIBOR interest rate is used). Nominal exchange rates provide information how the Czech crown is valuable in comparison with other currencies. The increase of the NEER means the appreciation meanwhile the increase of bilateral exchange rates denotes the depreciation. For this reason, we multiple the growth rate of the NEER by minus one to obtain comparable interpretation of exchange rates. Database ARAD of the CNB serves as the main source of data. Values of the NEER are retrieved from the Bank for International Settlements.

Different specifications of the exchange rate are utilized for two reasons. Firstly, each specification of the exchange rate provides slightly different information. The nominal effective exchange rate is chosen as the core specification because it reflects exchange rates with main trade partners. The weight of the each foreign currency in the bundle is set according to the size of mutual trade with given country. The bilateral exchange rate CZK/EUR is chosen due to fact that the euro area is the main destination of the Czech export. Approximately two thirds of the Czech export goes to the euro area (Lízal 2014). The exchange rate CZK/USD identifies the importance of non-euro trade partners. Moreover, it takes into account the re-exportation of the Czech export to the euro area since the movement of CZK/USD exchange rate is closely related to the changes of USD/EUR exchange rate. Because 60 % of the Czech export consists of intermediates (Baldwin & Lopez-Gonzalez 2013), the deprecation of the euro to the dollar stimulates not only the world demand for the euro area production but also the demand for Czech inputs in the euro area. The second reason to estimate model with alternative definitions of the exchange rate is to evaluate the robustness of results.

Variables depict the condition of the Czech economy from January 1998 to November 2016 at monthly frequency. Dataset does not include observations before the adoption of inflation targeting because the transmission mechanism of the exchange rate shock worked quite differently at that time. Time series of the exchange rate CZK/EUR is available from January 1999 when the common European currency was introduced.

Time series of GDP and CPI are seasonally adjusted. Seasonality of consumer prices was removed by X-12-ARIMA procedure because original time series suffers from the strong periodicity of price growth in January. Seasonally adjusted GDP was obtained directly from ARAD. Since output is available only at quarterly frequency, we interpolated it into monthly data by cubic spline.

Output is interpolated by cubic spline with not-a-knot end conditions for the first and the last observation. Output observed in quarter frequency is substituted for month in the middle of quarter (February, May, August, November) and values for remaining months are interpolated. For this exercise, we use time series of GDP from the first quarter 1996 to the fourth quarter 2016. That allows to find GDP in January 1998 which would not be possible when time series started in 1998 would be used instead. Figure 4.1 depicts quarter growth rates of interpolated and original data.

Spline interpolation is preferred over polynomial interpolation because it provides smaller interpolation error (de Boor 1978). Cubic spline is the simplest specification of spline which ensures the minimization of the curvature of interpolated points. Since there is not sufficient information at the beginning and the end of sample, additional conditions have to be done. Not-a-knot end conditions are optimal when observations preceding and following to interpolated time range are not available (de Boor 1978).

Figure 4.1: Quarterly growth rates of interpolated output

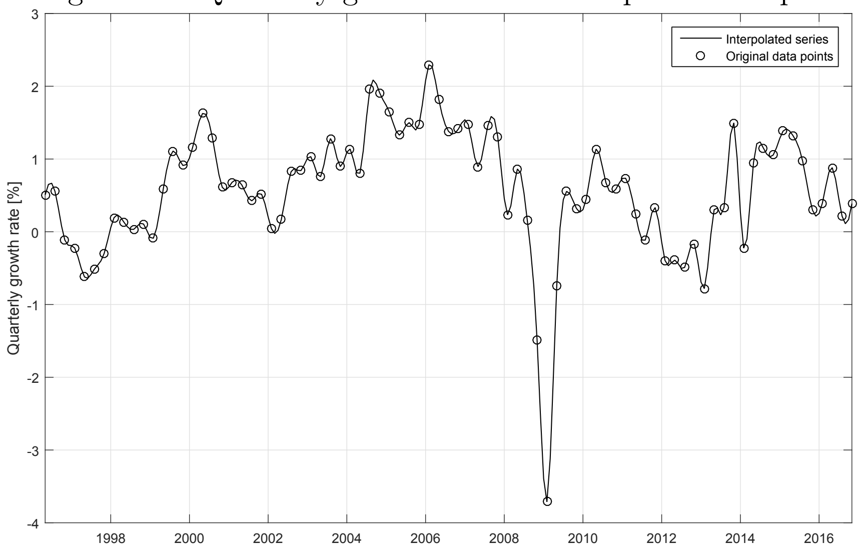


Table 4.1: Descriptive statistics (whole sample)

	Mean	Std. Dev.	Skewness	Kurtosis	Min	Max	n
ΔGDP	0.21	0.29	-1.88	10.41	-1.38	0.79	226
ΔCPI	0.19	0.31	1.23	10.21	-0.68	2.06	226
PRIBOR	3.00	3.09	2.31	9.19	0.28	16.06	226
ΔNEER	-0.19	1.65	0.04	5.12	-6.79	6.23	226
ΔCZK/EUR	-0.12	1.37	0.83	6.08	-4.32	5.76	213
ΔCZK/USD	-0.11	3.06	0.45	3.44	-7.06	9.59	226

Table 4.2: Descriptive statistics (split sample)

	Normal times			**Zero lower bound**		
	Mean	Std. Dev.	n	Mean	Std. Dev.	n
ΔGDP	0.22	0.31	177	0.20	0.21	49
ΔCPI	0.22	0.33	177	0.06	0.23	49
PRIBOR	3.73	3.12	177	0.36	0.07	49
ΔNEER	-0.29	1.75	177	0.16	1.20	49
ΔCZK/EUR	-0.21	1.46	164	0.17	0.93	49
ΔCZK/USD	-0.29	3.25	177	0.56	2.16	49

Descriptive statistics in Table 4.1 provides some basic overall information about macroeconomic development in Czechia during two last decades. The output growth is positive for the most of time. The output growth is negatively skewed - the stylized fact of the business cycles theory that crises are short and deep applies to the Czech economy. Average quarterly growth rate of output is 0.21 %. Average values of the monthly inflation rate and the nominal interest rate are positive. Consumer prices growths each month by 0.31 % in average. The Czech crown appreciated from 1998 to 2016. The exchange rate CZK/USD is more than two times volatile than the exchange rate CZK/EUR.

Interesting insight into development of macroeconomic variables we can obtain when the dataset is divided into two subsamples. First part of data, describes the economy in normal times between January 1998 and October 2012. The second subsample starts in November 2012 when the zero lower bound was reached and ends in November 2016. The dataset contains 177 observations in normal times[1] and 49 observations at the zero lower bound. Table 4.2 reports basic characteristics of variability for these two periods. The nominal interest rate and its variability is much more lower at the zero lower bound as it is expected. The interest rate close to zero also implies lower and more stable inflation than it is in normal times. The output growth is lower when the interest rate is bounded by zero. The Czech crown appreciates during normal times. The value of the Czech crown relative to other currencies decreased at zero lower bound which was caused by the unconventional monetary policy of the central bank. The exchange rate floor 27 Czech crowns per euro from November 2013 until the end of the sample implies low volatility of the exchange rate CZK/EUR. From November 2013, the development of the exchange rate CZK/USD is driven mainly by changes in the exchange rate USD/EUR. Different characteristics of variability under normal circumstances and at the zero lower bound suggest that the transmission mechanism of the monetary policy has changed dramatically. The structural break in the transmission mechanism is investigated in next chapters.

Figure 4.2 and 4.3 provide additional information about the development of macroeconomic variables. The Czech economy suffered from negative output growth during the Great Recession and between 2012 and 2013 when the fiscal policy was restrictive during economic slowdown. From Figure 4.2 we can see that inflation rate was decreasing over time with the peak before the Great

[1] The first subsample includes only 164 observations of the exchange rate CZK/EUR since the euro was introduced in 1999.

Figure 4.2: Core dataset (interest rate in levels, other variables in monthly growth rates)

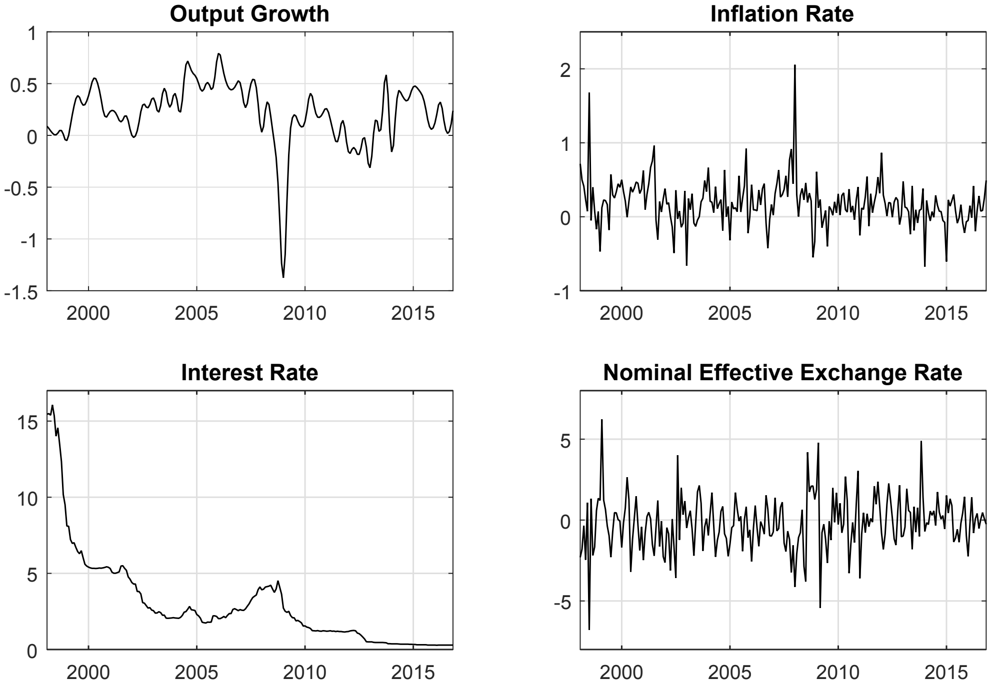
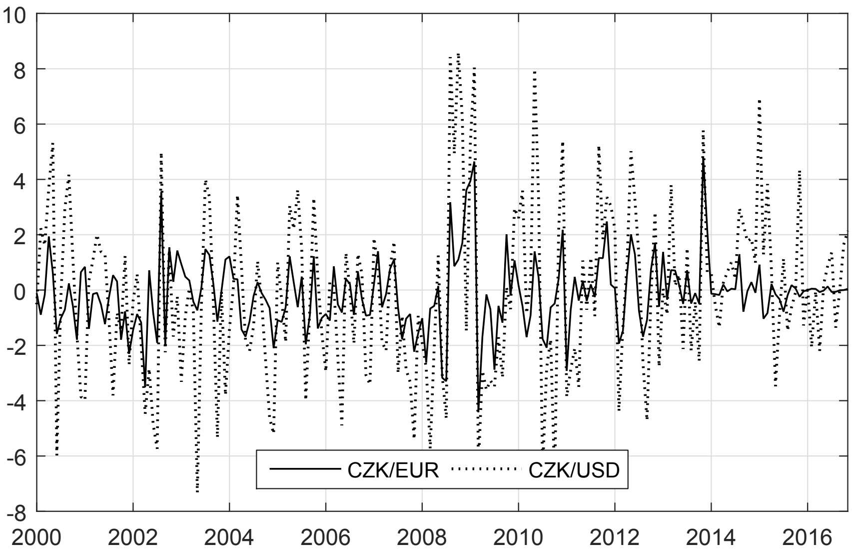


Figure 4.3: Alternative specifications of the exchange rate (monthly growth rates)



Recession. The interest rate declined from 1998 to 2005 as a consequence of inflation targeting monetary policy regime. Then the interest rate started to reflect macroeconomic conditions of the economy and at the end of 2012 has reached zero. In the long run, the Czech crown appreciates. Interventions of the CNB which was realized from the introduction of inflation targeting until 2003 did not influence the development of exchange rates significantly (Lízal & Schwarz 2013). From 2003 until November 2013 the CNB did not use innervations again. Short periods of natural depreciation took place always when the real economy activity was low. This finding is pronounced mainly during the Great Recession, when the Czech crown depreciated significantly.

4.2 Stationarity

Because we want to show that classical linear VAR is inappropriate for the estimation of the ERPT in Czechia, we investigate whether structural breaks are present in linear VAR later in the article. Since the stability of VAR is assumed, we analyse stationarity of used time series. For this purpose, some of variables are transformed to growth rates which ensure the stability of multivariate time series models. Transformed data also allows easier interpretation. Note that stationarity is not necessary for all considered time series, only stability of the whole system matters (Enders 1995). Moreover, there is not any restriction regarding to the stationarity of data for TVP-VAR-SV since it is estimated within Bayesian framework (Sims *et al.* 1990).

Table 4.3: P-values of augmented Dickey-Fuller test

Lags	0	1	2
ΔGDP	0.08	0.00	0.15
ΔCPI	0.00	0.00	0.00
PRIBOR	0.00	0.00	0.00
ΔNEER	0.00	0.00	0.00
ΔCZK/EUR	0.00	0.00	0.00
ΔCZK/USD	0.00	0.00	0.00

Augmented Dickey-Fuller test and KPSS test are estimated to provide complete overview about stationarity of data. Null hypothesis of augmented

Table 4.4: P-values of KPSS test (p-value $\in [0.01; 0.1]$)

Lags	12	13	14	15	16	17	18
ΔGDP	0.10	0.10	0.10	0.10	0.10	0.10	0.10
ΔCPI	0.10	0.10	0.10	0.10	0.10	0.10	0.10
PRIBOR	0.01	0.01	0.01	0.01	0.01	0.01	0.01
ΔNEER	0.08	0.07	0.07	0.07	0.07	0.07	0.07
ΔCZK/EUR	0.10	0.10	0.10	0.10	0.10	0.10	0.10
ΔCZK/USD	0.10	0.10	0.10	0.10	0.10	0.10	0.10

Dickey-Fuller test with drift states the model with unit root

$$x_t = x_{t-1} + \sum_{j=1}^{p} \beta_j \Delta x_{t-j} + \varepsilon_t \tag{4.1}$$

against the alternative of autoregressive model with constant c

$$x_t = c + \phi x_{t-1} + \sum_{j=1}^{p} \beta_j \Delta x_{t-j} + \varepsilon_t, \tag{4.2}$$

where x is considered variable, p is total number of lags, and ϕ is autoregressive coefficient lower or higher than one. P-values of augmented Dickey-Fuller test are summarized in Table 4.3.

Because alternative hypothesis of augmented Dickey-Fuller test is not able to reject possibility of explosive behaviour of time series, the verification of stationarity by KPSS test is necessary. KPSS test estimates structural model

$$x_t = c_t + u_{1,t} \tag{4.3}$$

$$c_t = c_{t-1} + u_{2,t}, \tag{4.4}$$

where $u_{1,t}$ is a stationary process, $u_{2,t}$ is an independent and identically distributed process with mean 0 and variance σ^2. The null hypothesis states that process is stationary ($\sigma^2 = 0$). Alternative hypothesis assumes a nonstationary unit root process. Following Kwiatkowski *et al.* (1992), we include approximately $\sqrt{T}$ lags in estimation process, where T is the length of time series. Result are reported in Table 4.4.

Augmented Dickey-Fuller test rejects the null hypothesis of the presence unit root for all variables. But KPSS test shows that the interest rate develops as nonstationary process. Note that the interest rate develops as the nonstationary process even when the deterministic trend is included into structural model (equations 4.3 and 4.4). Hence, except the nominal interest rate, all time series are stationary.

Chapter 5

Structural Break at the Zero Lower Bound

The discussion of results obtained by linear vector autoreggresion is provided before we move to estimations of the time-varying pass-through. Particularly, we prove the presence of structural breaks in the linear multivariate model in this chapter. Further, the original sample is dived into two parts to find out whether the transmission mechanism of the exchange rate shock has changed when the zero lower bound is reached. Estimations confirm that the transmission mechanism changed although differently than we expected. Obtained impulse responses suggest that the interest rate and consumer prices do not response to the exchange rate shock when zero nominal interest rate is reached. Higher response of output is obtained at the zero lower bound.

5.1 Linear Vector Autoregression

Linear VAR is simplified version of the model introduced in chapter 2. The linear model provides only one set of estimated coefficients. The model can be written as

$$y_t = c + \sum_{i=1}^{p} B_i y_{t-i} + A^{-1}\Sigma\epsilon_t \qquad u_t = A^{-1}\Sigma\epsilon_t, \tag{5.1}$$

where y is vector of endogenous variables, c is vector of constants, B is matrix of lagged coefficients, p is number of lags, Σ denotes variance matrix, u_t is vector of structural errors, ϵ_t is independently and normally distributed noise and lower triangular matrix A captures contemporaneous relation among variables.

Output growth, inflation rate, nominal interest rate and the growth rate of

Table 5.1: Lag selection criteria for different specifications of the model: Akaike information criterion (AIC), Hannan–Quinn information criterion (HQ), Schwarz information criterion (SC), final prediction error (FPE)

Exchange rate	Period	AIC	HQ	SC	FPE
	1998M01-2016M11	13	7	3	7
NEER & CZK/USD	1998M01-2012M10	12	4	3	12
	2012M11-2016M11	7	7	7	8
	1998M01-2016M11	13	7	3	13
CZK/EUR	1998M01-2012M10	14	4	3	12
	2012M11-2016M11	7	7	7	8

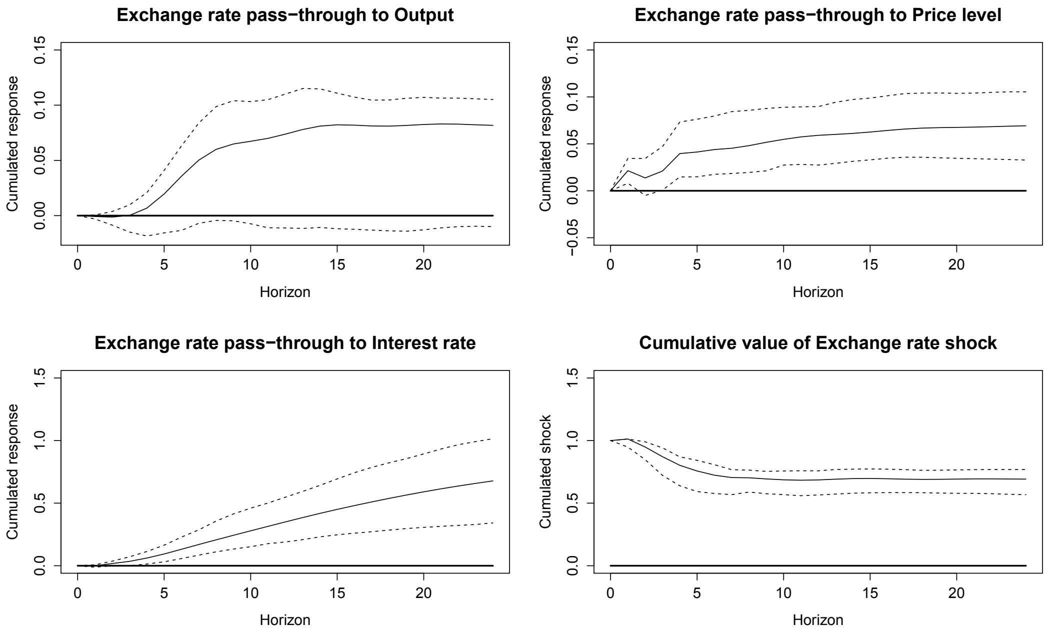
the nominal effective exchange rate are used as endogenous variables. Model is estimated with four lags which is close to the minimal optimal number of lags how they are computed by information criteria. Schwarz information criterion suggests only three lags as the best option, but this number can be slightly underestimated since Schwarz information criterion punishes heavily large models. Remaining information criteria prefer model with more lags than we used (see first row in Table 5.1). Therefore, we also estimated model with more lags, but impulse responses and estimates of the pass-through show excessive volatility that is rather counterintuitive. We do not include trend[1] and exogenous variables[2] into model since there are not present in the time-varying model. Moreover, results remain unchanged when trend and the foreign price level are included into model.

Obtained impulse responses after the depreciation develop in accordance with the economic theory. The central bank increases the nominal interest rate to offset the effect of the depreciation on the inflation rate and output. Despite the reaction of the central bank, the deprecation stimulates output growth and inflation. Only response of output is not statistical significant. Although the ERPT to consumer prices is positive, its value is far away from the complete pass-through. In the case of 1 % depreciation, average response of consumer prices is only 0.069 %. The interest rate is raised by 0.678 % and out increases by 0.082 % in average when a unit shock to the exchange rate occurs. The pass-through to consumer prices (and output) is fast. Majority of the pass-through is realised during the first year after the exchange rate shock. The development

[1]Decreasing nominal interest rate in the Czech Republic is the reason why the specification of the model with deterministic trend is considered.

[2]Harmonised price index of the euro area is commonly used in VAR models for the Czech Republic (see for instance Babecká 2007; Hájek 2014).

Figure 5.1: Exchange rate pass-through (linear VAR)



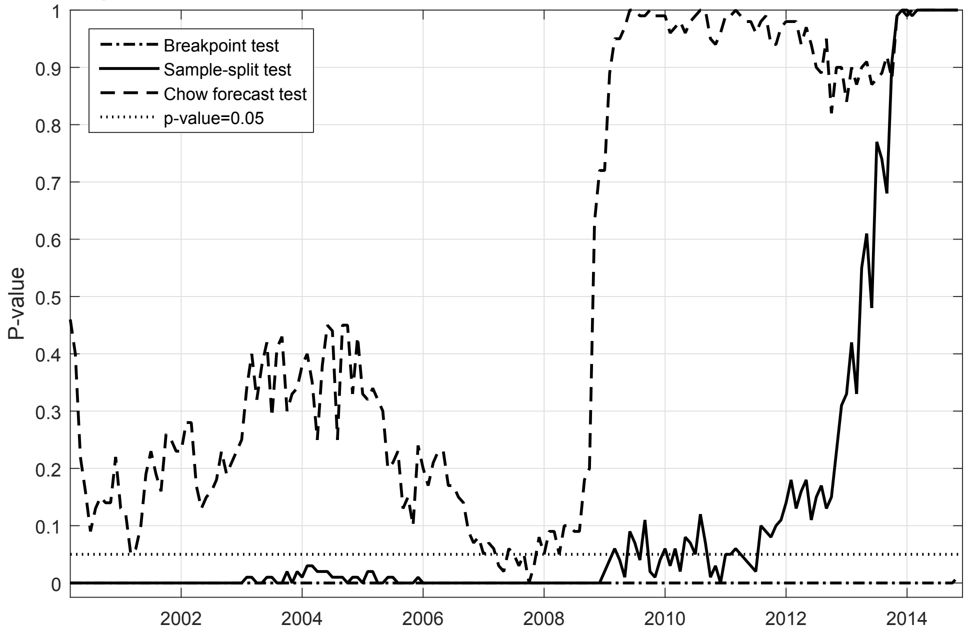
of cumulated impulse responses after a unit depreciation is depicted in Figure 5.1.

The model do not pass multivariate ARCH-LM test which states the constant variance as the null hypothesis. We reject the null hypothesis of homoskedasticity at all levels of significance. VAR with stochastic volatility seems to be appropriate solution to this issue.

5.2 Chow Tests

Since we assume different transmission mechanism of the exchange rate shock at the zero lower bound and under normal circumstances, we run set of Chow tests intended for multivariate models. We estimate breakpoint test, sample-split test and Chow forecast test. All tests are specified in the way that the null hypothesis represents stability of system and alternative hypothesis proposes time variation in coefficients. Tests are estimated for each observation between January 2002 and December 2014. Boostraped p-values are utilized because distributions of the test statistics under the null hypothesis may be quite different from the asymptotic χ^2 or F-distributions when the number of observations is not large relative to the number of parameters in the model (Candelon & Lütkepohl 2001). One hundred of bootstrapped replication is computed for each test.

Figure 5.2: Bootstrapped p-values of Chow multivariate tests



The break point test examines whether some structural break occurs in the sample at given time. No structural break is expected under null hypothesis. The rejection of the null hypothesis implies the presence of the structural break at considered period. The possibility of different parameters in the white noise covariance matrix is also counted in test statistics. The null hypothesis of the sample-split test relies on the assumption that the residual covariance matrix is constant. The test is checked against the alternative that the VAR coefficients may vary. The Chow forecast test tests against the alternative hypothesis that all coefficients including the residual covariance matrix may vary.

The obtained results for the break point tests suggest the presence of the structural break for all data points between January 1998 and December 2014. According to sample split tests, VAR coefficients are not constant for the most of observations. When Chow forecast tests are considered, the break in parameters occurs at the beginning of the Financial crisis of 2007-2008. To sum up, there is strong evidence that VAR coefficients are time-varying.

5.3 Structural Break in Transmission Mechanism

Because multivariate Chow tests deny single linear VAR as the appropriate model and the economic theory expects the structural break at zero lower bound, we decided to estimate vector autoregressive model separately for two subsamples. The break point in the sample is dedicated to November 2012, when the CNB decreased the nominal interest rate to technical zero.

The comparison of obtained impulse responses for both subsamples confirm that the transmission mechanism of the exchange rate shock changed significantly after November 2012. Cumulated impulse responses are depicted in Figures 5.3 and 5.4. Results for the first subsample are similar to the model which considers whole sample. Specifically, all variables responses to unit depreciation slightly more when only the sample until November 2012 is used. Average value of cumulated responses after two years from initial shock are reported in Table (5.2).

The estimated model for the subsample at the ZLB provides much more interesting findings. The exchange rate pass-through to consumer prices is insignificant and close to zero although the transmission of the depreciation through the interest rate channel practically disappeared as we expected. The long-term ERPT to price level is 0.028 % at the zero lower bound (0.076 % under normal circumstances). It means that the average response of consumer prices to the exchange rate shock decreased more than by 63 %. Results show that the entire transmission of the exchange rate shock goes only through the output growth[3]. Two years after a unit depreciation, output increases by 0.117 % when the nominal interest rate si bounded. Under normal circumstances output increases by 0.109 %.

Although after the division of the sample, linear VAR is able to capture the structural break of the transmission mechanism at the zero lower, more flexible approach is desirable. Multivariate ARCH-LM test denies the constance of variance in the case of the first subsample. Furthermore, splitting the sample into two parts does not take into account existence of other structural breaks which Chow tests identified. These issues are solved by time-varying estimation of the pass-through in Chapter 6.

5.4 Results for Alternative Specifications

To provide complete evidence for linear VAR, the results with alternative specifications of the exchange rate are also reported in Tables 5.1, 5.2 and 5.3. The exchange rate pass-through to consumer prices is lower for both bilateral exchange rates and it completely dispersers at the zero lower bound. The interest

[3]Due to small number of observations,the long-term ERPT to output is not statistically significant for the second subsample.

Figure 5.3: Exchange rate pass-through in normal times

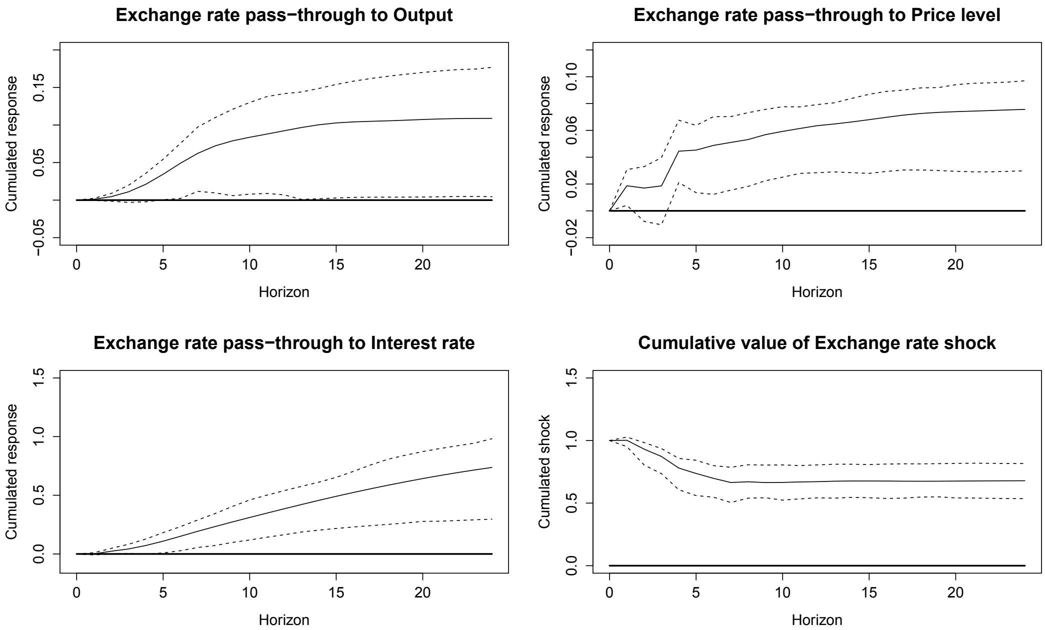


Figure 5.4: Exchange rate pass-through at the zero lower bound

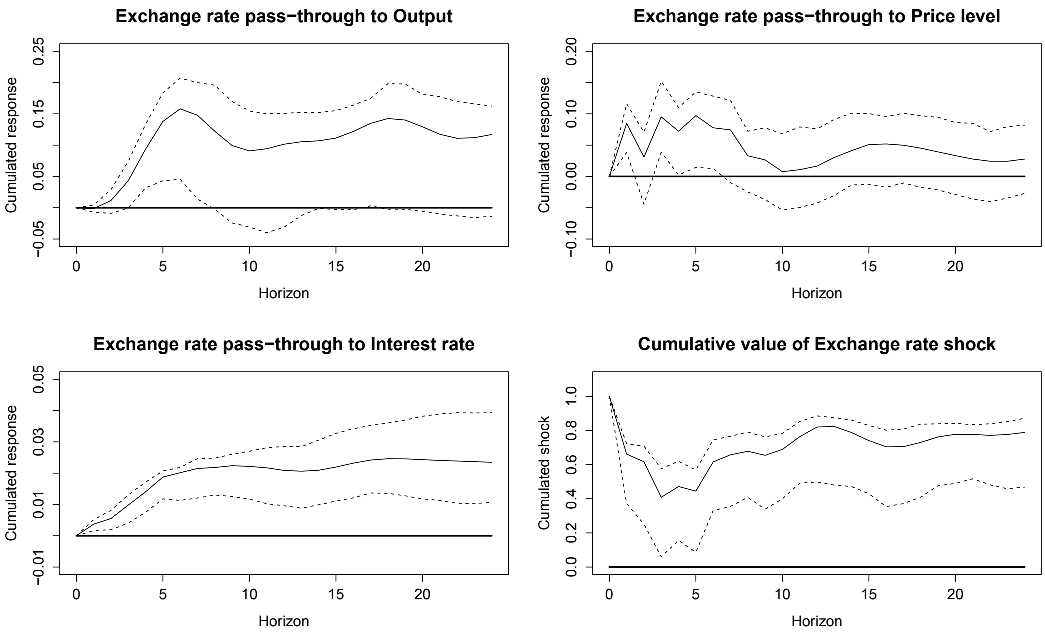


Table 5.2: Cumulated impulse responses after two years from initial shock

Exchange rate	Period	GDP	CPI	PRIBOR	ER
NEER	1998M01-2016M11	0.082	0.069	0.678	0.692
	1998M01-2012M10	0.109	0.076	0.737	0.679
	2012M11-2016M11	0.117	0.028	0.023	0.789
CZK/USD	1998M01-2016M11	0.028	0.025	0.345	1.136
	1998M01-2012M10	0.031	0.028	0.407	1.076
	2012M11-2016M11	0.171	-0.004	0.008	1.824
CZK/EUR	1998M01-2016M11	0.215	0.059	0.754	0.739
	1998M01-2012M10	0.262	0.078	0.931	0.662
	2012M11-2016M11	0.189	-0.040	-0.004	0.806

Table 5.3: Multivariate ARCH-LM test

Period	NEER	CZK/USD	CZK/EUR
1998M01-2016M11	0.0000	0.0000	0.0000
1998M01-2012M10	0.0000	0.0000	0.0000
2012M11-2016M11	0.9996	0.9996	0.9996

rate channel works only under normal circumstances. Unit depreciation of the exchange rate CZK/USD has much bigger long-term impact on output at the ZLB (0.171 %) than in normal times (0.031 %). This sharp change in the response of output at the zero lower bound can be explained by the exchange rate floor committed by the CNB for the most of observations in the second sample. Since the exchange rate CZK/USD closely follows the development of the bilateral exchange rate USD/EUR, the depreciation of the Czech crown relative to the dollar actually means the depreciation of the euro relative to the dollar. the deprecation of the euro to the dollar stimulates the world demand for the euro area production. The deprecation of CZK/USD has indirect positive impact on the Czech output since the export from the euro area becomes relative cheaper on the world market, and hence the demand for Czech inputs in the euro area is higher. It is worthy to note that described indirect effect of CZK/USD depreciation on output exists even when the exchange rate floor is not committed, but it is not so strong.

Surprisingly, a unit depreciation of the Czech crown to the euro brings relative smaller output stimulation at the ZLB (0.262 %) than under normal circumstances (0.189 %). The limited time-variation of the exchange rate after the adoption of the exchange rate commitment by the CNB can serve as possible explanation why obtained results are different when the exchange rate CZK/EUR is used.

Chapter 6

Time-Varying Exchange Rate Pass-Through

This chapter presents estimated time-varying exchange rate pass-through to inflation and output. Obtained results deny hypothesis which assumed higher pass-through to consumer prices when the interest rate is bounded by zero. The depreciation stimulates output only slightly more at the zero lower bound than under normal circumstances. As we expected, the interest rate channel has disappeared completely when the nominal interest rate approached to zero. Main features of the development of time varying pass-through correspond to estimations obtained by linear VAR for normal times and period of the zero lower bound. Our results are similar to conclusions of other empirical articles (Iwata & Wu 2006; Jašová *et al.* 2016; Özyurt 2016) which do not find the support for the hypothesis that the pass-through to inflation is higher at the zero lower bound how economic models predict (Lízal & Schwarz 2013).

The model with time-varying parameters is separately estimated for three alternative specifications of the exchange rate. Markov-switching Monte Carlo simulation, specifically Gibbs sampler, is used to obtain parameters of interest. The estimation process for each model consists of 20,000 simulations. First 10,000 iterations are discarded to allow for convergence. Moreover, to minimize autocorrelation of draws, only each fifth iteration is retained. Reported results are based on the 2,000 remaining iterations.

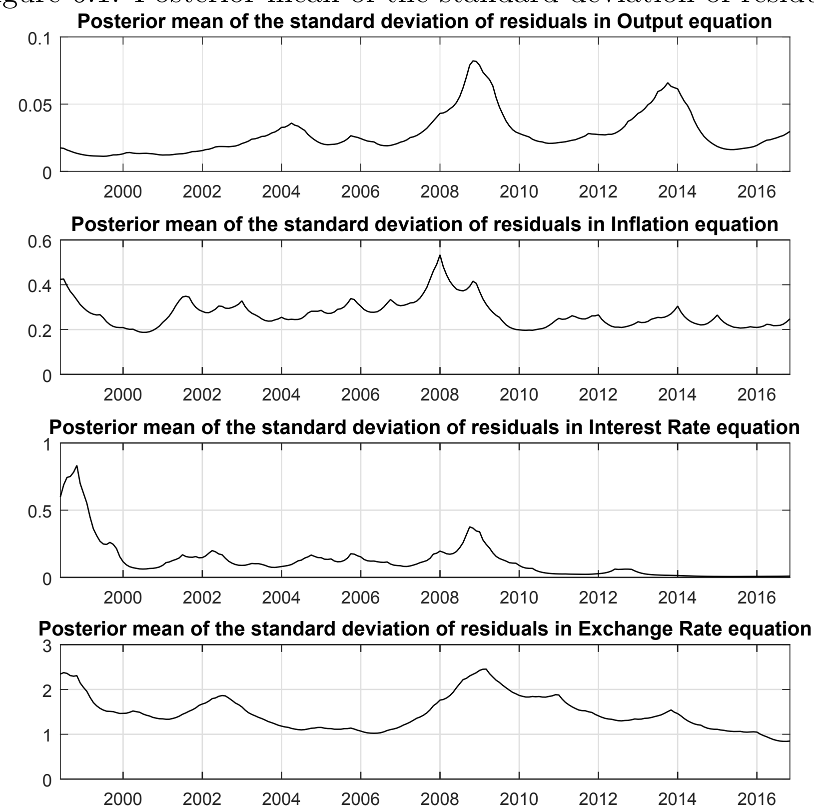
6.1 Nominal Effective Exchange Rate

In the baseline model, the exchange rate is specified by the NEER which reflects exchange rates between the Czech crown and other currencies according to importance of mutual trade balance.

6.1.1 Stochastic volatility

Posterior mean of standard deviation of residuals depicted in Figure 6.1 justifies why stochastic volatility is incorporated into the model. We can clearly see that the standard deviation process is not constant for any variable. In output equation, two major peaks occur during economic crises. First exceed in the volatility is dated to 2008 when the Czech economy was hit by the Great Recession. Second peak can be find in 2013 when the restrictive fiscal policy and low economic activity caused economic crises. Inflation exhibits periods of higher volatility before and during the Great Recession. From 2010, the volatility is stabilized at the lower value than which one prevailed before the crisis in 2008-2009. Note that volatility was considerable higher at the beginning of the

Figure 6.1: Posterior mean of the standard deviation of residuals



sample when inflation targeting was adopted. The nominal interest rate experienced highest volatility in the late 90's as a consequence rapidly decreasing interest rate due to stabilization of inflation around its target. Another peak in the standard deviation process in the interest rate equation is visible during the Great Recession when the CNB tried to offset negative demand shock by the lowering the policy rate.

The model correctly captures zero volatility at the zero lower bound. The NEER is the most volatile variable in the model. Visible peaks occurs during periods of large appreciations (1999,2002) and depreciation (Great Recession, the beginning of the exchange rate commitment in 2013) of the Czech crown. Overall, residuals are more volatile primarily during Great Recession. The stabilisation of monetary policy between 1998 and 2000 is the important source of volatility for nominal variables.

6.1.2 Exchange Rate Pass-Through

Estimated median impulse responses to the exchange rate shocks (deprecation) are presented in Figure 6.2. Median time-varying exchange rate pass-through for different horizons is depicted in Figure 6.3. Obtained time-varying pass-through is fast. More than half of the pass-through to output and consumer prices is realized during first six months after a unit exchange rate shock. Furthermore, the pass-though to output is almost finished after one year. The interest rate responses to the exchange rate shock slower than other variables since the it is specified in levels.

We find that the pass-through to the consumer price index is incomplete and decreasing over time as Taylor (2000) suggests. Prices response no more than by 0.11 % after a unit depreciation at the beginning of the sample. The pass-through was decreasing until 2011 when its value was stabilized around 0.05 %. The hypothesis that the exchange rate pass-through to the price level is higher at the zero lower bound is clearly rejected. Our results corresponds to Jašová *et al.* (2016) who find lower pass-through in emerging economies after the Great recession. Similarly, Özyurt (2016) observes sharp decline in the ability of the exchange rate shock to stimulate inflation in the euro area in 2012.

The development of the pass-through to output is more complicated. Time-varying estimations suggest temporary deep drop of the pass-through between 2000 and 2008 with the through in 2002. Responses of output to exchange rate

Figure 6.2: Impulse responses to a 1 % exchange rate shock (NEER, depreciation)

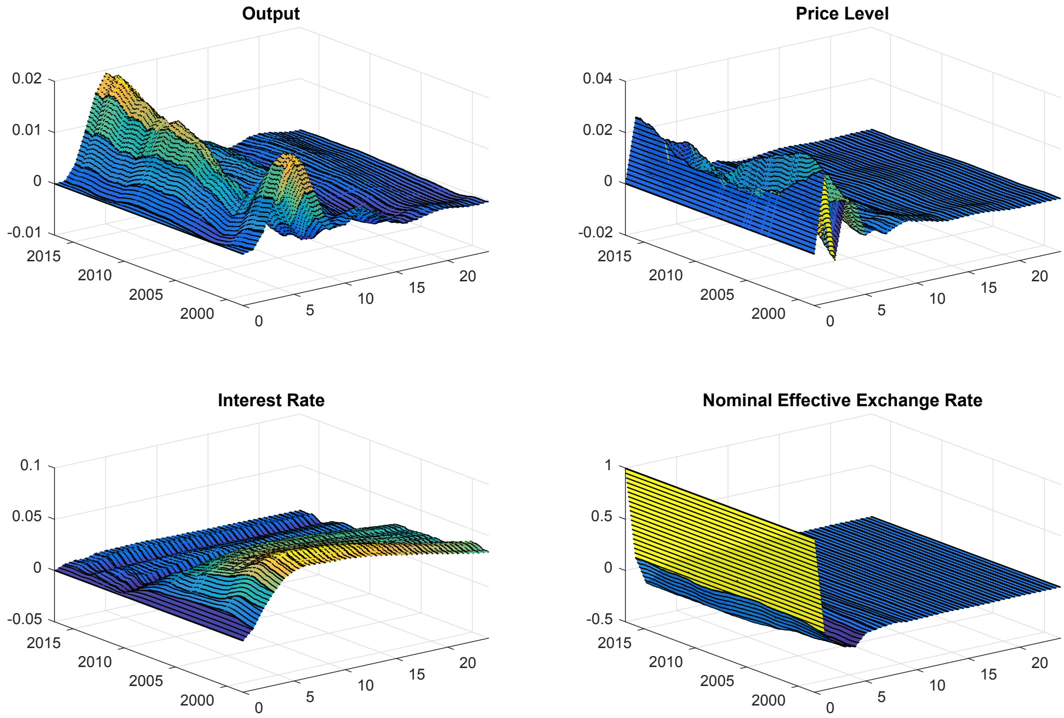
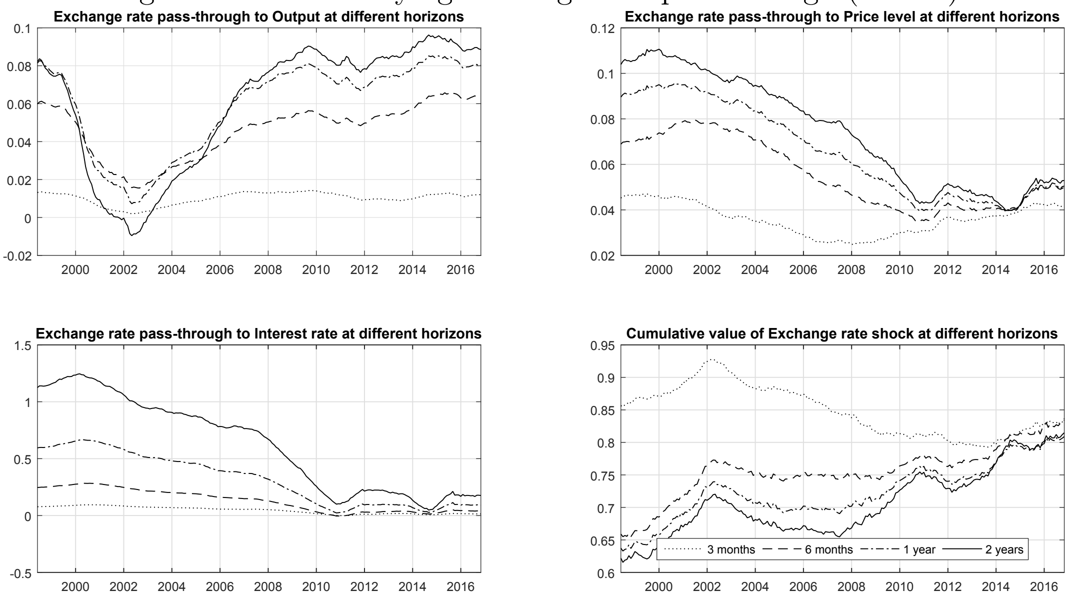


Figure 6.3: Time-varying exchange rate pass-through (NEER)



shocks look to be stable for remaining observations, although at the end of the sample we can notice slightly higher pass-through. A unit exchange rate shock is not able to stimulate output growth no more than by 0.1 % and the pass-through is zero or even negative in 2002. Clear explanation why output did not response to the exchange rate shocks in 2002 does not exist. We assume that the obtained estimations for this period are given by atypical development of macroeconomic variables in Czechia - the Czech crown appreciated significantly although the output growth was close to zero. To compare, Franta *et al.* (2011) do not identify any temporal change in the pass-through to output in 2002. Instead of it, Franta *et al.* (2011) conclude that the pass-through to output is stable over time.

The importance of the interest rate channel was declined from the beginning of the sample until 2010. According to our results, the central bank increased the policy rate by 1.2 % in a reaction to a 1 % depreciation in 2000. However, the interest rate was increased only by 0.15 % if a 1 % deprecation occurred in 2010 or later. This corresponds to the reality that the interest rate was set to zero after the Great Recession, and therefore the central bank has any reason to offset the exchange rates shocks since its objective is to stimulate inflation which is below target. Hence, time-varying VAR with stochastic volatility allows to capture the transmission mechanism at the zero lower bound without any additional modification as Nakajima (2011a) points out.

Exchange rate shocks are not persistent since cumulated values of impulse responses are lower than one. It implies that deprecation shocks are followed by periods of appreciations. Cumulated values of exchange rates shocks slowly increase over time.

Similarities in results of baseline linear and time-varying models occur. The interest rate channel disappeared at the zero lower bound in both models. Simultaneously, we find lower pass-through to consumer prices when interest rate reached zero. However, time-varying pass-through gives us some important additional insight to the development of transmission mechanism. Firstly, the interest rate channel and the pass-through to inflation were diminishing gradually. Moreover, we identify the temporary change of the pass-though to output between 2000 and 2008.

Figure 6.4: Dependence of the pass-through on prior beliefs (NEER)

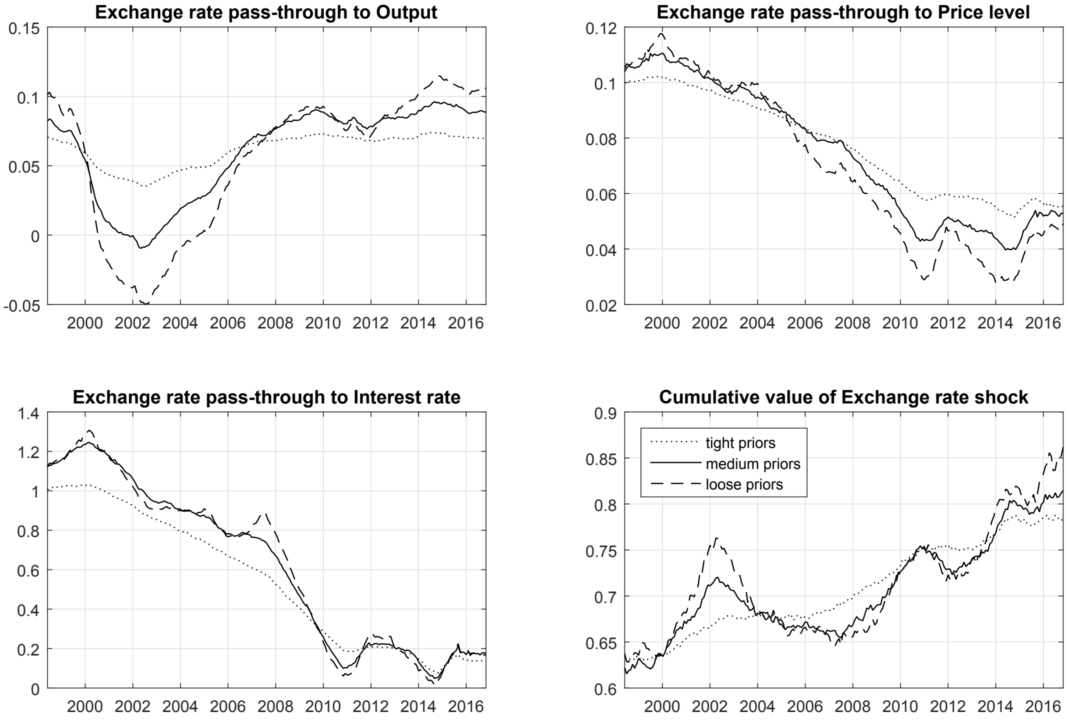
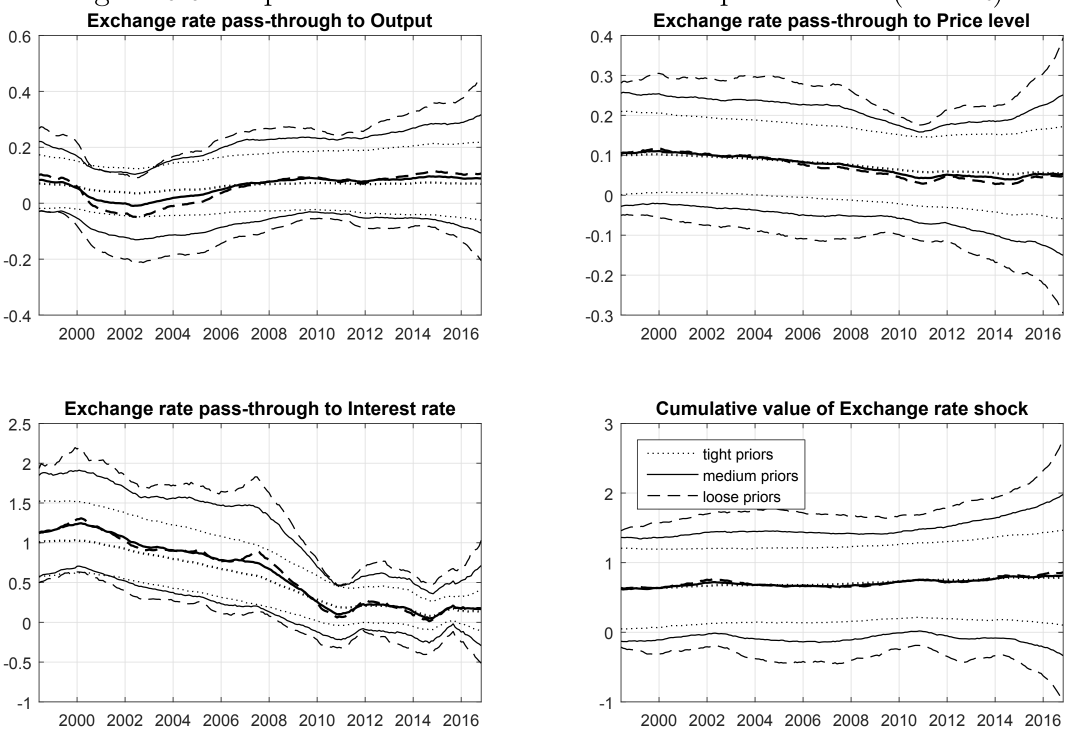


Figure 6.5: Dependence of credible intervals on prior beliefs (NEER)



6.1.3 Sensitiveness of Results to Priors

To provide sensitiveness check of priors, we also estimated the model for tighter and looser specifications of prior beliefs. Cumulated impulse responses after two years from the initial shocks to the exchange rate are provided in Figure 6.4. When higher prior volatility is introduced into the system, the pass-through to output in the absolute value is higher at the beginning of the sample, in 2002 and at the zero lower bound. It implies that the pass-through to output might be higher at the zero lower bound how the economic theory predicts. Tight priors naturally lead to smoother estimation of the pass-through which does not provide any additional information.

Figure 6.5 shows estimations of time varying pass-through with 68 % credible intervals for different priors. We can see that higher time variation costs precision of results. When priors are specified less tight, credible intervals are wider. Large uncertainty of the size of the pass-through is at the end of the sample because cumulative values of exchange rate shocks has become more volatile when the CNB began to commit the exchange rate floor. Intuitively, credible intervals are narrower for responses of the interest rate to depreciations at the zero lower because the central bank have no reason to raise the policy rate since it wants to stimulate inflation which is below the target.

6.2 Exchange Rate CZK/EUR

Posterior mean of the standard deviation for output, inflation and interest rate equation evolves almost equally when bilateral exchange rates are used instead of the NEER. Peaks in stochastic volatility in the exchange rate equation are more pronounced when the exchange rate CZK/EUR is used instead of the

Figure 6.6: Posterior mean of the standard deviation of residuals (CZK/EUR)

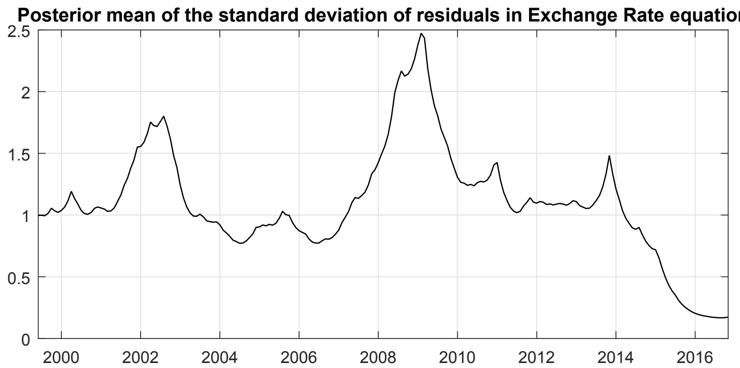


Figure 6.7: Impulse responses to a 1 % exchange rate shock (CZK/EUR, depreciation)

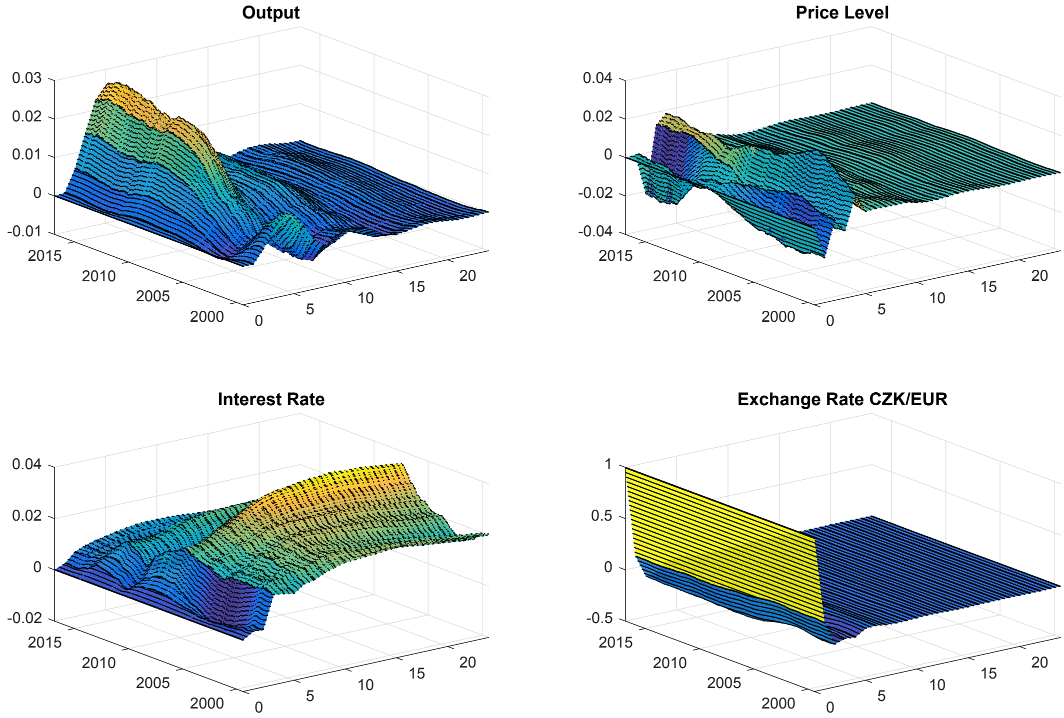
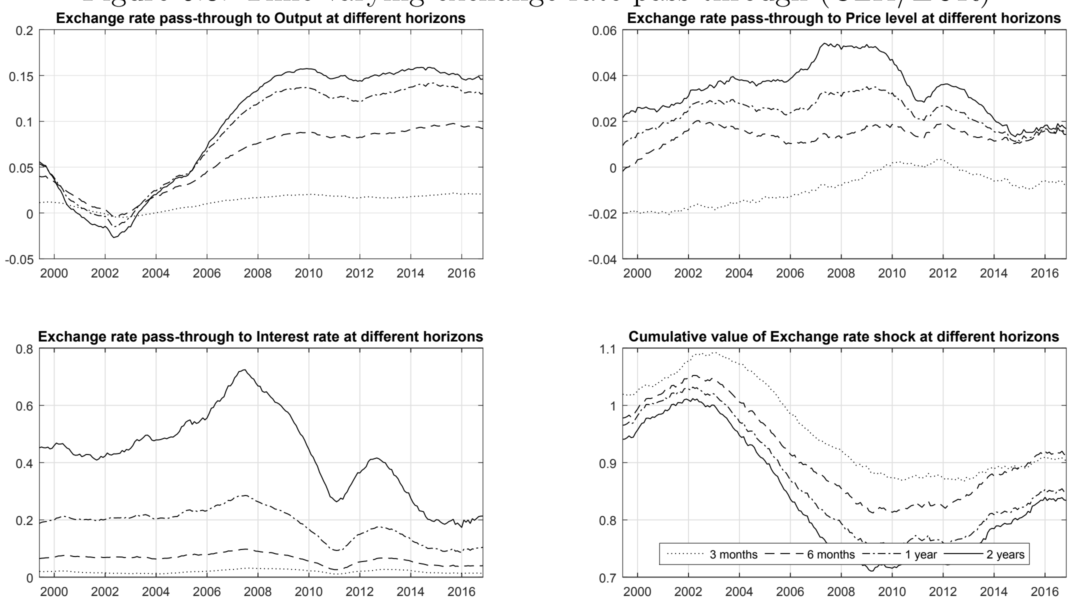


Figure 6.8: Time-varying exchange rate pass-through (CZK/EUR)



NEER. The highest volatility was during the Great Recession. Considerably higher volatility in exchange rate was also in 2002 and 2013 when the CNB introduced the exchange rate floor as unconventional monetary policy tool. The model correctly estimates very small volatility of the exchange rate when it was de facto fixed by the CNB.

Estimations for the exchange rate CZK/EUR are depicted in Figures 6.7 and 6.8. The pass-through to consumer prices varies less when we use CZK/EUR exchange rate instead of the NEER. The pass-through is highest during the Great Recession (approximately 0.05 %) and then it decreased below 0.02 %. Output at the beginning of the sample responses to depreciations much less then during Great Recession and period of the zero lower bound. The temporary change in the pass-through to output is also confirmed for this specification. Higher pass-through to output and inflation at the zero lower bound is rejected.

Some issues are related to obtained results. The interest rate channel did not disappeared at the zero lower bound, and hence estimated pass-through is based on incorrect assumption that central bank increases its interest rate if the exchange rate depreciates. Furthermore, the short-term pass-through to the price level is negative.

6.3 Exchange Rate CZK/USD

The posterior mean of standard deviation of residuals in the exchange rate equation is high in comparison to other specifications of the exchange rate. The highest volatility of the exchange rate was during the Great Recession.

Figures 6.10 and 6.11 present obtained results. The pass-through to output is increasing over time with exception between years 2000 and 2004, when the

Figure 6.9: Posterior mean of the standard deviation of residuals (CZK/USD, depreciation)

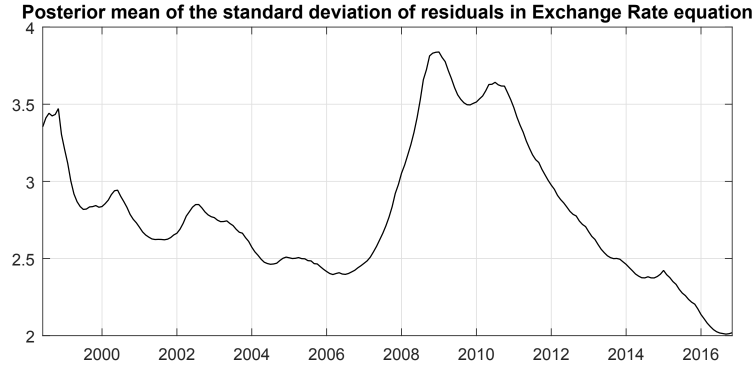


Figure 6.10: Impulse responses to a 1 % exchange rate shock (CZK/USD)

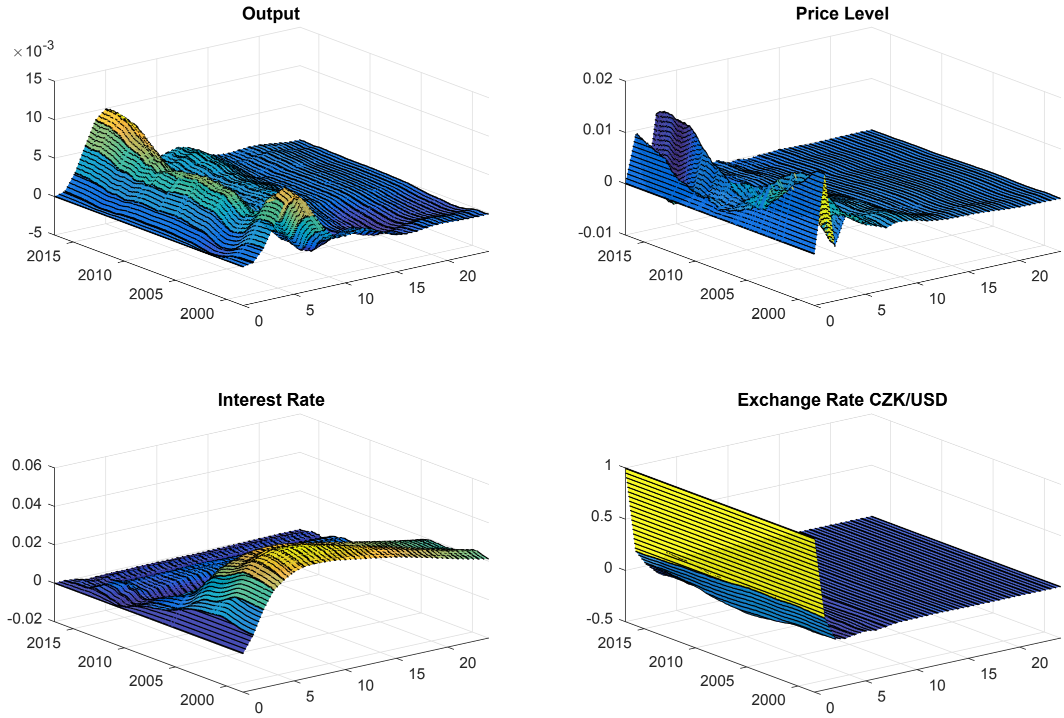
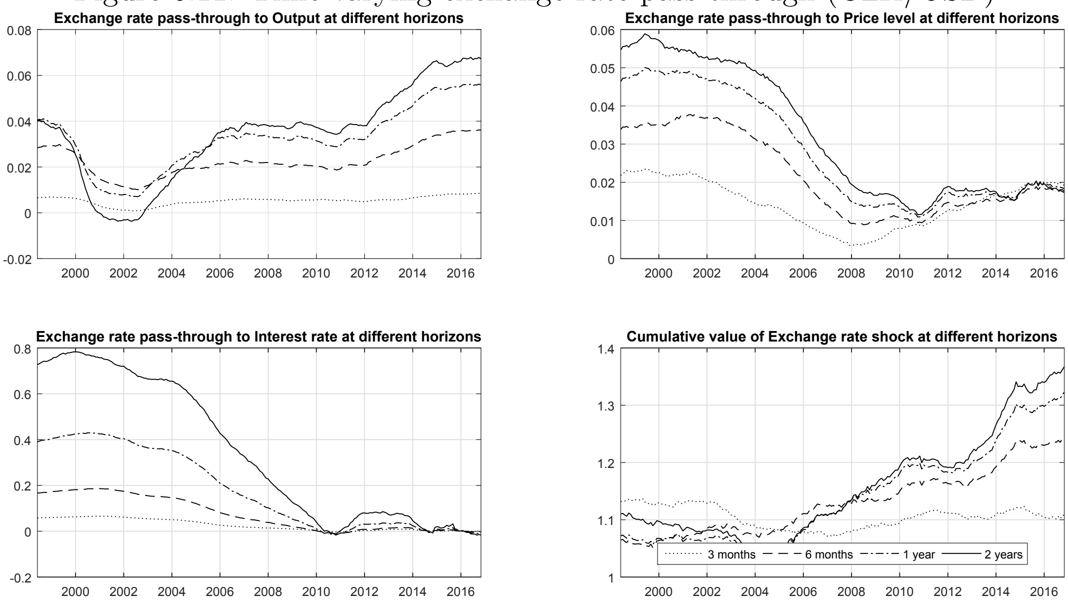


Figure 6.11: Time-varying exchange rate pass-through (CZK/USD)



impact of the exchange rate on output was negligible. Hence, hypothesis which states that the pass-through to output is higher at the zero lower bound is confirmed. Note that although the output responses more to the depreciation at the zero lower bound, the pass-though is still less than 0.07 % (two times lower than for CZK/EUR exchange rate).

When we compare the development of the pass-through to output among alternative specifications of the exchange rate, we find that the pass-through increased at the zero lower bound the most when the exchange rate CZK/USD is used for the estimation. Oppositely, the zero lower bound did not affect the pass-through to output if CZK/EUR exchange rate is used in the model. In the case of the NEER, we obtain slight increase of the pass-through at the zero lower bound. These time-varying estimations are analogous to results of linear VAR (split sample) in Chapter 5.

Responses of other considered variables are similar to the core model which includes the NEER. The transmission of the exchange rate shocks through the interest rate channel completely disappeared when the interest rate has reached zero. The pass-through to consumer prices is decreasing over time, and hence we can clearly conclude that Svensson (2000)'s assumption of higher pass-through at the zero lower bound does not hold for the Czech Republic. This conclusion is robusts among different definitions of the exchange rate. Moreover, similar results are also obtained by linear VAR.

6.4 Monetary Policy Implications

Our findings have important momentary policy implications since the effectiveness of the CNB's unconventional monetary policy depends on the size of the exchange rate pass-through. Specifically, the CNB committed the exchange rate floor from November 2013 to April 2017 with objection to achieve the inflation target. Because the introduction of the exchange rate floor 27 Czech crowns per the euro implied 5 % depreciation in November 2013, we summarize expected contribution of 5 % depreciation to the price level and output in Table 6.1. Reported values are cumulative impulse response to 5% exchange rate shock in November 2013. Time horizon of cumulated impulse responses is two years.

Since the commitment is related to the euro, we primarily consider the model with CZK/EUR exchange rate. We find that 5 % depreciation increased the price level after two years only by 0.116 %. The commitment stimulated the

Table 6.1: Cumulated responses of output and the price level to the 5 % depreciation shock in November 2013

	Response of	
Exchange rate	GDP	CPI
NEER	0.435 %	0.229 %
CZK/EUR	0.781 %	0.116 %
CZK/USD	0.274 %	0.088 %

output growth by 0.781 %. Both estimations are statistically insignificant due to wide credible intervals which are typical for employed methodology. However, our policy implication that the exchange rate commitment stimulated output more than inflation corresponds to Opatrný (2016) who finds insignificant positive effect of the CNB's commitment on the price level and slightly positive and statistically significant impact on output. Possibility of the smaller pass-through than it was initially expected is also admitted in Tomšík (2016). When other specifications of the exchange rate are considered, the 5 % depreciation led to lower contribution to the output growth. Additionally, when the NEER is used, the impact of the 5% exchange rate shock on the price level is nearly two times higher than for the model with CZK/EUR exchange rate. To conclude, estimated effect of the 5 % depreciation is far away from expected outcome of the exchange rate commitment as unconventional monetary policy (Tomšík 2016).

Since the CNB terminated the exchange rate floor in April 2017, we are interested in the future development of prices and output if some significant appreciations of the Czech crown will occur. For this purpose, estimations for the last observation (November 2016) can serve as reference value for future macroeconomic development. According to our results, we assume that the possible appreciation does not represent large threat to the future development of prices or output because the pass-through was quite low in November 2016. However, the pass-through might be slightly higher now than in November 2013 when the exchange rate commitment was introduced.

The investigation how the size of the pass-through depends on macroeconomic variables can serve to the deeper understanding of the pass-through. Simultaneously, when the monetary authority knows correlation relationships between pass-through and macroeconomic condition, it can easier predict expected impact of the exchange rate management. Table 6.2 reports results of

Table 6.2: Pearson's product-moment correlation of the pass-through and macroeconomic variables (* denotes p-value< 0.05)

Macroeconomic variable	Exchange rate pass-through to GDP	Exchange rate pass-through to CPI
ΔGDP	-0.267^*	0.248^*
ΔCPI	-0.059	0.164^*
PRIBOR	-0.263^*	0.730^*
ΔNEER	0.112	-0.121
ΔHICP	-0.218^*	0.173^*

simple correlation analysis[1]. Except of already described variables, we also include the Harmonised Indices of Consumer Prices (HICP)[2] to our analysis since Mumtaz & Surico (2012) point out that international common factor explains the historical decline in the level of inflation in developed economies.

The pass-through to consumer prices is significantly[3] correlated with output growth, interest rate, domestic and foreign inflation rate. Contradictory to Hájek (2014), we find positive relationships between output growth and the pass-through to inflation. Our finding can be explained by higher willingness of firms to internalize costs of depreciations during recession than in periods of expansions (Cheikh 2012). Obtained positive correlation coefficients of the pass-through to the price level and inflation (domestic and foreign) and the nominal interest rate are in the accordance with economic theories (Taylor 2000; Takhtamanova 2008; Mumtaz & Surico 2012). Especially, the pass-through to the price level is closely associated with the nominal interest rate (correlation coefficient is 0.73).

The pass-through to output is significantly negatively correlated with these variables: output growth, interest rate and foreign inflation. From obtained correlation coefficients we can see that the pass-through to output is higher in situations when the pass-through to the price level is rather low. From this point of view, the substitution effect between the pass-through to inflation and output is present.

[1]Reported correlations are computed for the baseline time-varying model with the NEER.
[2]The HICP is transformed to the monthly growth rate.
[3]Pearson moment correlation test is used to assess statistical significance ($\alpha = 0.05$) of correlations.

Chapter 7

Conclusion

The paper has provided insight to the development of the exchange rate pass-through in the Czech Republic during two lasts decades. The proposed hypothesis that the pass-through to consumer prices is higher at zero lower bound has been rejected. According to our results, output responses only slightly more to the exchange rate shock when the interest rate is close to zero than under normal circumstances. Despite the rejection of the main hypothesis, the structural break in the transmission mechanism has been identified at the zero lower bound as we expected. Existence of multiple structural breaks has confirmed the necessity to estimate the time-varying pass-through. The main benefit of used methodology is an opportunity to determine the size of the pass-through for each month separately.

The evaluation of the effectiveness of the exchange rate management on macroeconomic variables is the main contribution of this article to recent literature. Our results are similar to other empirical studies (Iwata & Wu 2006; Jašová *et al.* 2016; Özyurt 2016), which find only limited support for the higher pass-through at the zero lower bound. From this point of view, there has remained unsolved discrepancy between empirical findings and the prediction of economic models which promote the exchange rate floor as a appropriate unconventional monetary policy tool for small open economies (Svensson 2000; Malovaná 2015). Obtained time-varying estimations have also important monetary policy implications. They can serve to the evaluation of the exchange rate commitment of the Czech National Bank introduced in November 2013. Furthermore, the estimation of the pass-through for the last observation in our sample (November 2016) can be viewed as the suggestion what happens to inflation and output growth if the Czech crown will appreciate after the termination of the exchange rate commitment in April 2017.

The identification of determinants of the pass-through is a possible extension of this paper. How important is re-exportation of the Czech export and whether the depreciation of the euro can significantly stimulated the demand for the Czech intermediates in the euro are is another option for further research. Although time-varying estimation of the pass-through is quite flexible, there are still open questions related to the exchange rate pass-through in the Czech Republic which cannot be answered by this methodology. For instance, the different impact of depreciations and appreciations on the size of the pass-through cannot be identified by time-varying VAR. Similarly, we do not know from obtained results whether the pass-through differs for small and large exchange rate shocks.

Bibliography

Babecká, O. K. (2007): "Transmission of Exchange Rate Shocks into Domestic Inflation: The Case of the Czech Republic." *CNB Working Paper Series 12*, Czech National Bank.

Babecká, O. K., M. Franta, D. Hájková, P. Král, I. Kubicová, A. Podpiera, & B. Saxa (2013): "What We Know About Monetary Policy Transmission in the Czech Republic: Collection of Empirical Results." *CNB Research and Policy Notes 1*, Czech National Bank.

Baldwin, R. & J. Lopez-Gonzalez (2013): "Supply-Chain Trade: A Portrait of Global Patterns and Several Testable Hypotheses." *NBER Working Paper 18957*, National Bureau of Economic Research, Inc.

Bech, M. L. & A. Malkhozov (2016): "How have central banks implemented negative policy rates?" *BIS Quarterly Review 1*, Bank for International Settlements.

Beirne, J. & M. Bijsterbosch (2011): "Exchange rate pass-through in central and eastern European EU Member States." *Journal of Policy Modeling* **3(2)**: pp. 241–254.

de Boor, C. (1978): *A Practical Guide to Splines.* Springer-Verlag.

Candelon, B. & H. Lütkepohl (2001): "On the reliability of Chow-type tests for parameter constancy in multivariate dynamic models." *Economics Letters* **73(2)**: pp. 155–160.

Canova, F. (2003): *Methods for applied macroeconomic research.* Princeton University Press.

Caselli, F. G. & A. Roitman (2016): "Non-Linear Exchange Rate Pass-Through in Emerging Markets." *IMF Working Paper 1*, International Monetary Fund.

Ca'Zorzi, M. & E. Hahn (2007): "Exchange Rate Pass-Through In Emerging Markets." *Working Paper Series 739*, European Central Bank.

Cheikh, N. B. (2012): "Asymmetric Exchange Rate Pass-Through in the Euro Area: New Evidence from Smooth Transition Models." *The Open-Access, Open-Assessment E-Journal* **6(39)**: pp. 1–28.

Christiano, L. J., M. Eichenbaum, & C. L. Evans (1996): "The Effects of Monetary Policy Shocks: Evidence from the Flow of Funds." *Review of Economics and Statistics* **78(1)**: pp. 16–34.

Comunale, M. & D. Kunovac (2017): "Exchange rate pass-through in the euro area." *Working Paper Series 2003*, European Central Bank.

Correa, A. D. & A. Minella (2010): "Nonlinear Mechanisms of the Exchange Rate Pass-Through: A Phillips Curve Model with Threshold for Brazil." *Revista Brasileira de Economia* **64(3)**.

Dellate, A. L. & A. Lopez-Villavicencio (2013): "Nonlinearity of the inflation-output trade-off and time-varying price rigidity." *EconomiX Working Papers 1*, Czech National Bank.

Devereux, M. B., C. Engel, & P. E. Storgaard (2003): "Endogenous Exchange Rate Pass-through When Nominal Prices are Set in Advance." *NBER Working Paper 9543*, National Bureau of Economic Research, Inc.

Edwards, S. (2006): "The Relationship Between Exchange Rates and Inflation Targeting Revisited." *NBER Working Paper 12163*, National Bureau of Economic Research, Inc.

Enders, W. (1995): *Applied Econometric Time Series.* Wiley.

Franta, M., T. Holub, P. Král, I. Kubicová, K. Šmídková, & B. Vašíček (2014): "The Exchange Rate as an Instrument at Zero Interest Rates: The Case of the Czech Republic." *CNB Research and Policy Notes 3*, Czech National Bank.

Franta, M., R. Horváth, & M. Rusnák (2011): "Evaluating Changes in the Monetary Transmission Mechanism in the Czech Republic." *CNB Working Paper Series 13*, Czech National Bank.

Ghosh, A. & R. Rajan (2009): "Exchange rate pass-through in Korea and Thailand: Trends and determinants." *Japan and the World Economy* **21(1)**: pp. 55–70.

Goldberg, L. & J. M. Campa (2010): "The Sensitivity of the CPI to Exchange Rates: Distribution Margins, Imported Inputs, and Trade Exposure." *The Review of Economics and Statistics* **92(2)**: pp. 392–407.

Goldberg, P. K. & M. M. Knetter (1997): "Goods prices and exchange rates: What have we learned?" *Journal of Economic Literature* **35(3)**: pp. 1243–1272.

Greenberg, E. (2008): *Introduction to Bayesian Econometrics*. Cambridge University Press.

Hájek, J. (2014): "Exchange Rate Pass-Through to Domestic Prices: The Case of the Czech Republic." *Rigorous thesis*, Institute of Economic Studies, Charles University in Prague.

Iwata, S. & S. Wu (2006): "Estimating monetary policy effects when interest rates are close to zero." *Journal of Monetary Economics* **53**: pp. 1395–1408.

Jašová, M., R. Moessner, & E. Takáts (2016): "Exchange rate passthrough: What has changed since the crisis?" *BIS Working Papers 583*, Bank for International Settlements.

Kim, S. & N. Roubini (2000): "Exchange Rate Anomalies in the Industrial Countries: A Solution with a Structural VAR Approach." *Journal of Monetary Economics* **45(3)**: pp. 561–586.

Koop, G. (2003): *Bayesian Econometrics*. Wiley-Interscience.

Koop, G. & D. Korobilis (2012): "Baysian Multivariate Time Series Methods for Empirical Macroeconomics." *Foundations and Trends in Econometrics* **3(4)**: pp. 267–358.

Kwiatkowski, D., P. C. B. Phillips, P. Schmidt, & Y. Shin (1992): "Testing the Null Hypothesis of Stationarity against the Alternative of a Unit Root." *Journal of Econometrics* **54**: pp. 159–178.

Lízal, L. (2014): "Export, motivace tuzemské ekonomiky." *Žofínské fórum*, Czech National Bank.

LÍZAL, L. (2015): "Foreign Exchange Interventions as an (Un)conventional Monetary Policy Tool: Mid-Term Evaluation." *11th international conference challenges of europe: Growth, competitiveness and inequality*, Czech National Bank.

LÍZAL, L. & J. SCHWARZ (2013): "Foreign exchange interventions as an (un)conventional monetary policy tool." *BIS Papers 73*, Bank for International Settlements.

MALOVANÁ, S. (2015): "Foreign Exchange Interventions at the Zero Lower Bound in the Czech Economy: A DSGE Approach." *IES Working Papers* **(13)**.

MCCARTHY, J. (1999): "Pass-Through of Exchange Rates and Import Prices to Domestic Inflation in Some Industrialized Economies." *BIS Working Paper 79*, Bank for International Settlements.

MUMTAZ, H. & L. SUNDER-PLASSMANN (2010): "Time-varying dynamics of the real exchange rate. A structural VAR analysis." *Working Paper 382*, Bank of England.

MUMTAZ, H. & P. SURICO (2012): "Evolving International Inflation Dynamics: World And Country-Specific Factors." *Journal of the European Economic Association* **10(4)**: pp. 716–734.

NAKAJIMA, J. (2011a): "Monetary Policy Transmission under Zero Interest Rates: An Extended Time-Varying Parameter Vector Autoregression Approach." *IMES Discussion Paper Series 2011-E-8*, Bank of Japan.

NAKAJIMA, J. (2011b): "Time-varying parameter VAR model with stochastic volatility: An overview of methodology and empirical applications." *Monetary and Economic Studies* **29**: pp. 107–142.

OPATRNÝ, M. (2016): "Quantifying the Effects of the CNB's Exchange Rate Commitment: A Synthetic Control Method Approach." *IES Working Paper 17*, Institute of Economic Studies, Charles University.

OZKAN, I. & L. ERDEN (2015): "Time-varying nature and macroeconomic determinants of exchange rate pass-through." *International Review of Economics and Finance* **38(C)**: pp. 56–66.

PRIMICERI, G. E. (2005): "Time Varying Structural Vector Autoregressions and Monetary Policy." *Review of Economic Studies* **72**: pp. 821–852.

SAVOIE-CHABOT, L. & M. KHAN (2015): "Exchange Rate Pass-Through to Consumer Prices: Theory and Recent Evidence." *Discussion Paper 9*, Bank of Canada.

SEKINE, T. (2006): "Time-Varying Exchange Rate Pass-Through: Experiences of Some Industrial Countries." *BIS Working Paper 202*, Bank for International Settlements.

SHINTANI, M., A. HAGIWARA, & T. YABU (2013): "Exchange rate pass-through and inflation: A nonlinear time series analysis." *Journal of International Money and Finance* **32(C)**: pp. 512–527.

SHIOJI, E. (2012): "The Evolution of the Exchange Rate Pass-Through in Japan: A Re-evaluation Based on Time-Varying Parameter VARs." *Public Policy Review* **8(1)**: pp. 67–92.

SHIOJI, E. (2015): "Time varying pass-through: Will the yen depreciation help Japan hit the inflation target?" *Journal of the Japanese and International Economies (Abenomics: A New Unconventional Economic Policy Regime in Japan)* **37**: pp. 43–58.

SIMS, C. A., J. H. STOCK, & M. W. WATSON (1990): "Inference in Linear Time Series Models with Some Unit Roots." *Econometrica* **58(1)**: pp. 113–144.

SVENSSON, L. E. O. (2000): "The Zero Bound in an Open Economy: A Foolproof Way of Escaping from a Liquidity Trap." *NBER Working Papers 7957*, National Bureau of Economic Research, Inc.

TAKHTAMANOVA, Y. (2008): "Understanding Changes in Exchange Rate Pass-Through." *Woking Paper Series 13*, Federal Reserve Bank of San Francisco.

TAYLOR, J. B. (2000): "Low inflation, pass-through, and the pricing power of firms." **44**: pp. 1389–1408.

TOMŠÍK, V. (2016): "Impact of the CNB's Exchange Rate Commitment: Pass-Through to Inflation." *BIS Emerging Market Deputy Governors Meeting*, Czech National Bank.

ÖZYURT, S. (2016): "Has the exchange rate pass through recently declined in the euro area?" *Working Paper Series 1955*, European Central Bank.

Appendix A

Supplement Figures

Linear VAR

Exchange Rate CZK/EUR

Figure A.1: Exchange rate pass-through (CZK/EUR)

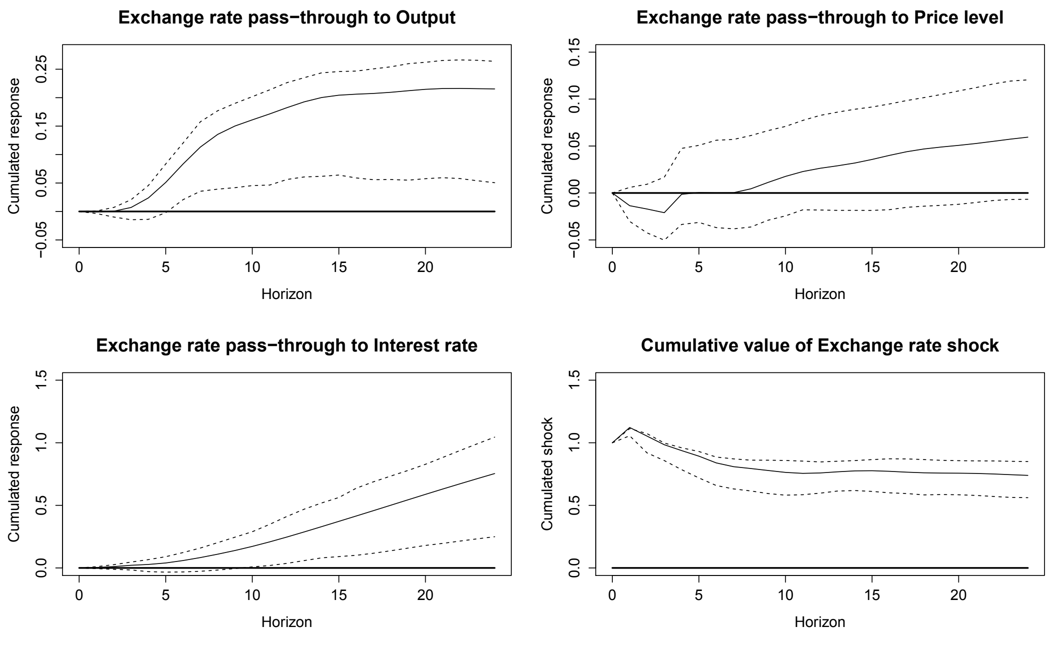


Figure A.2: Exchange rate pass-through in normal times (CZK/EUR)

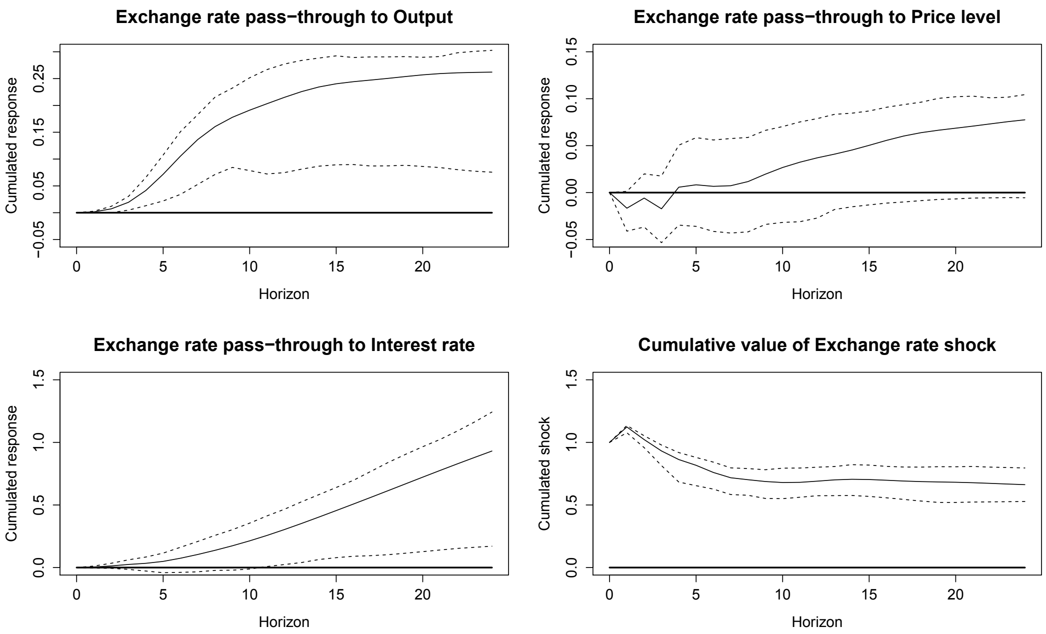
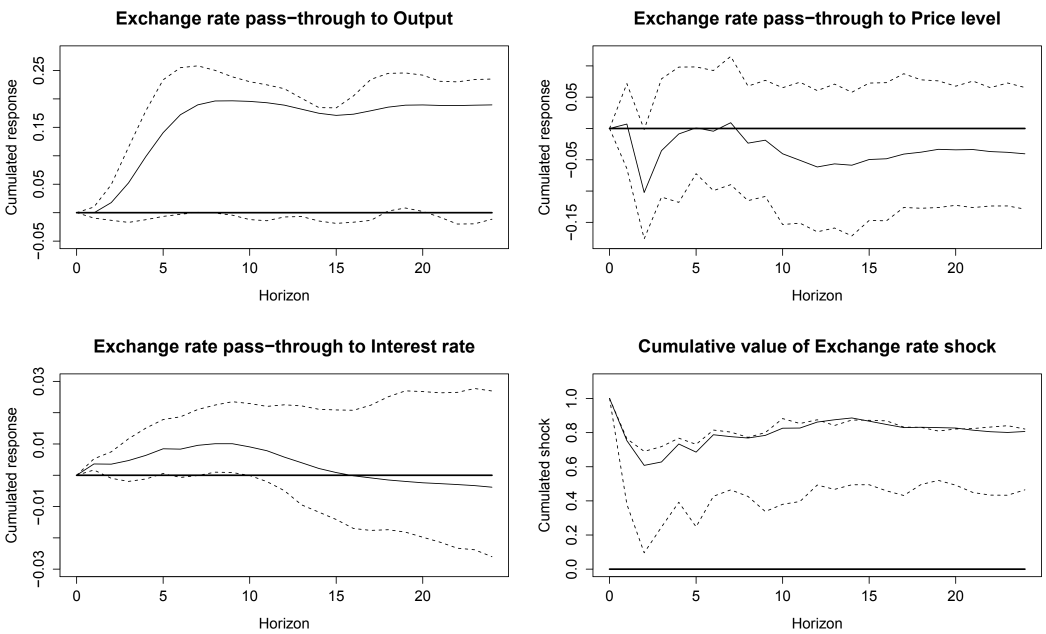


Figure A.3: Exchange rate pass-through at the zero lower bound (CZK/EUR)



Exchange Rate CZK/USD

Figure A.4: Exchange rate pass-through (CZK/USD)

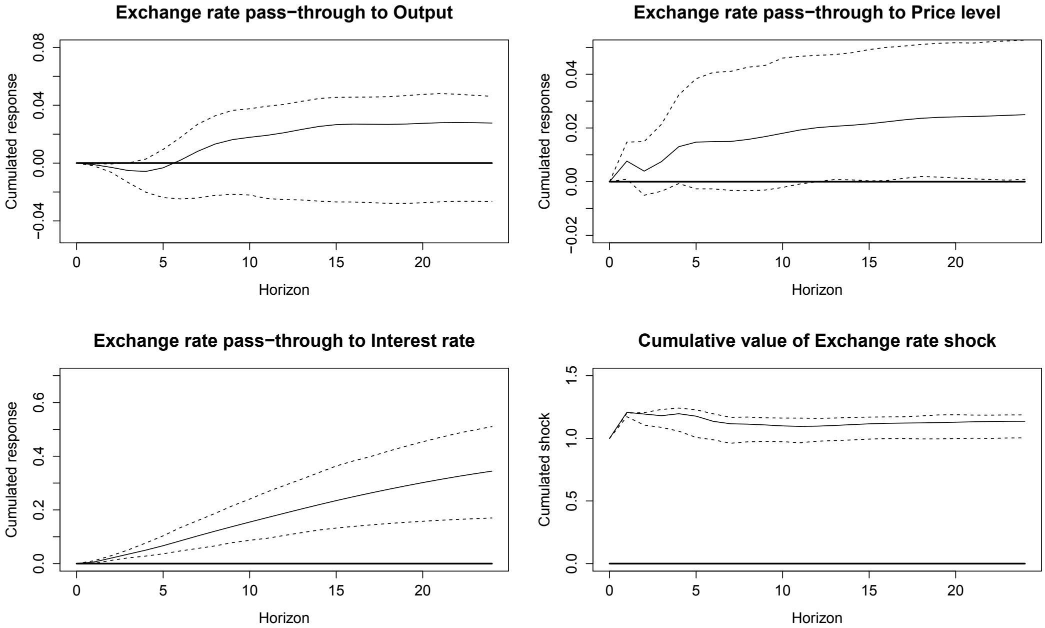


Figure A.5: Exchange rate pass-through in normal times (CZK/USD)

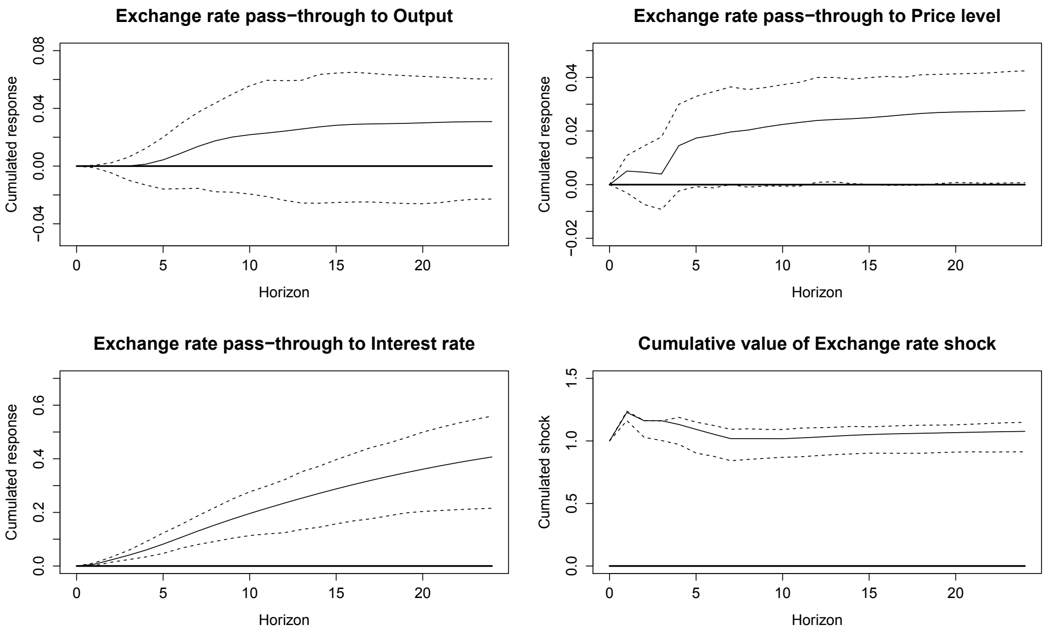
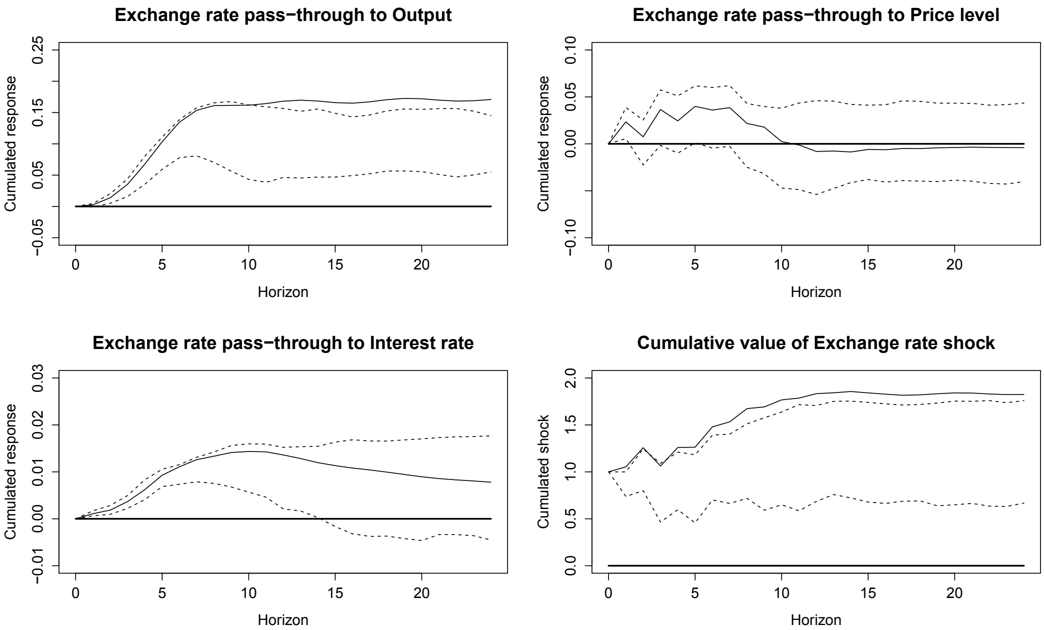


Figure A.6: Exchange rate pass-through at the zero lower bound (CZK/USD)



Long-Term Time-Varying Pass-Through

Figure A.7: Exchange rate pass-through with 68 % credible intervals (NEER)

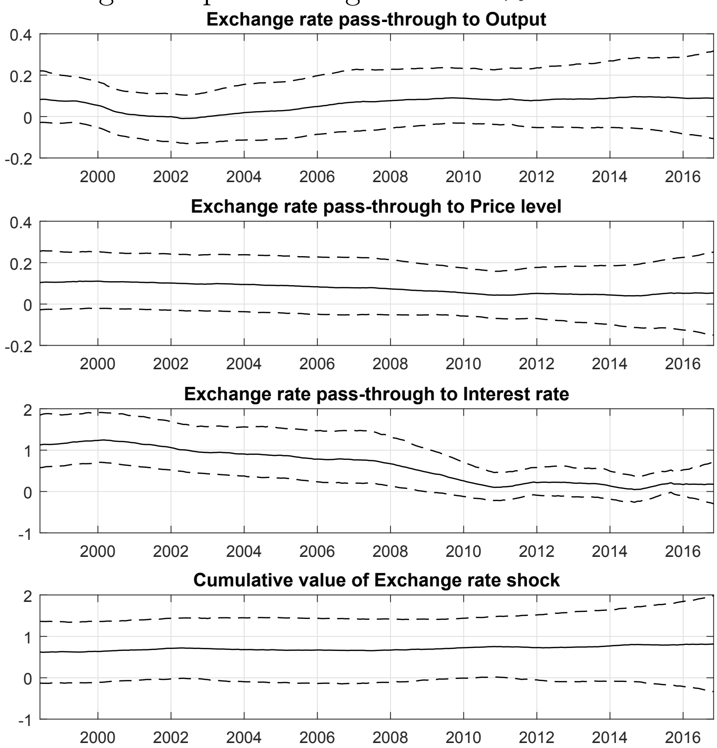


Figure A.8: Exchange rate pass-through with 68 % credible intervals (CZK/EUR)

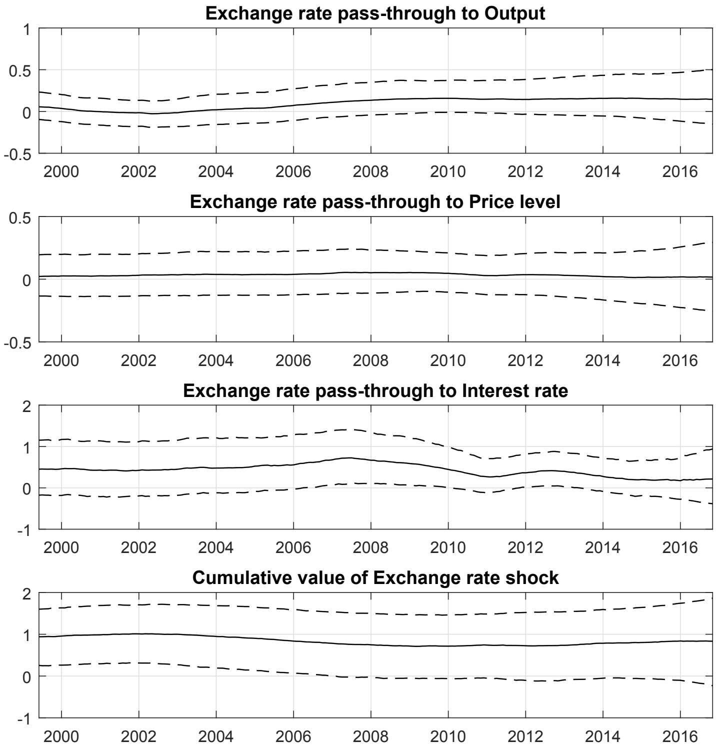


Figure A.9: Exchange rate pass-through with 68 % credible intervals (CZK/USD)