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David Finck, Mathias Hoffmann, and Patrick Hürtgen

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Coordination: Bernd Hayo • Philipps-University Marburg
School of Business and Economics • Universitätsstraße 24, D-35032 Marburg
Tel: +49-6421-2823091, Fax: +49-6421-2823088, e-mail: hayo@wiwi.uni-marburg.de

On the Empirical Relevance of the Exchange Rate as a Shock Absorber at the Zero Lower Bound[*]

David Finck[†] Mathias Hoffmann[‡] Patrick Hürtgen[§]

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Abstract

The open economy New Keynesian model with flexible exchange rates postulates that the real exchange rate appreciates in response to an asymmetric negative demand shock in a zero lower bound (ZLB) scenario and exacerbates the adverse macroeconomic effects. However, when monetary policy is able to accommodate the adverse effects of the negative demand shock via unconventional measures, the model can generate a real depreciation at the ZLB. This paper examines these counteracting exchange rate channels empirically. We estimate the effect of a negative asymmetric demand shock on the real exchange rate and inflation expectations as well as output and prices by employing state-dependent and sign-restricted local projection methods for the euro area vis-à-vis the United States, Canada, and Japan. We find that the real exchange rate depreciates when interest rates are not at the ZLB but also when they are. Furthermore, our empirical results show that the real exchange rate can absorb considerable variations in output, confirming its shock-absorbing capacity before but also during the ZLB episode. The stabilizing role of the exchange rate is accompanied by a significant expansion of the ECBs balance sheet in the ZLB period, while it remained unaffected in the pre-ZLB period. Overall, our empirical results favor the open economy New Keynesian model with unconventional measures when interest rates are at the ZLB.

Keywords: Zero Lower Bound, Exchange Rate, Local Projections, State-dependent Effects

JEL classification: F31, E31, E37, C54

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[†]University of Giessen, email: david.finck@wirtschaft.uni-giessen.de

[‡]Deutsche Bundesbank, email: mathias.hoffmann@bundesbank.de

[§]Deutsche Bundesbank, email: patrick.huertgen@bundesbank.de

I Introduction

There is a traditional view starting with Friedman (1953) that regimes of flexible exchange rates allow the real exchange rate to depreciate in response to asymmetric negative demand disturbances.[1] This real depreciation then delivers efficient macroeconomic stabilization. However, when monetary policy is constrained by the ZLB, the New Keynesian argument is that flexible exchange rate regimes cannot stabilize cyclical developments in response to adverse demand shocks (see, for instance, Cook and Devereux, 2013; Cook and Devereux, 2016). However, when monetary policy is able to accommodate the adverse effects of the negative demand shock via unconventional measures, the model can generate a real depreciation when interest rates are at the ZLB.

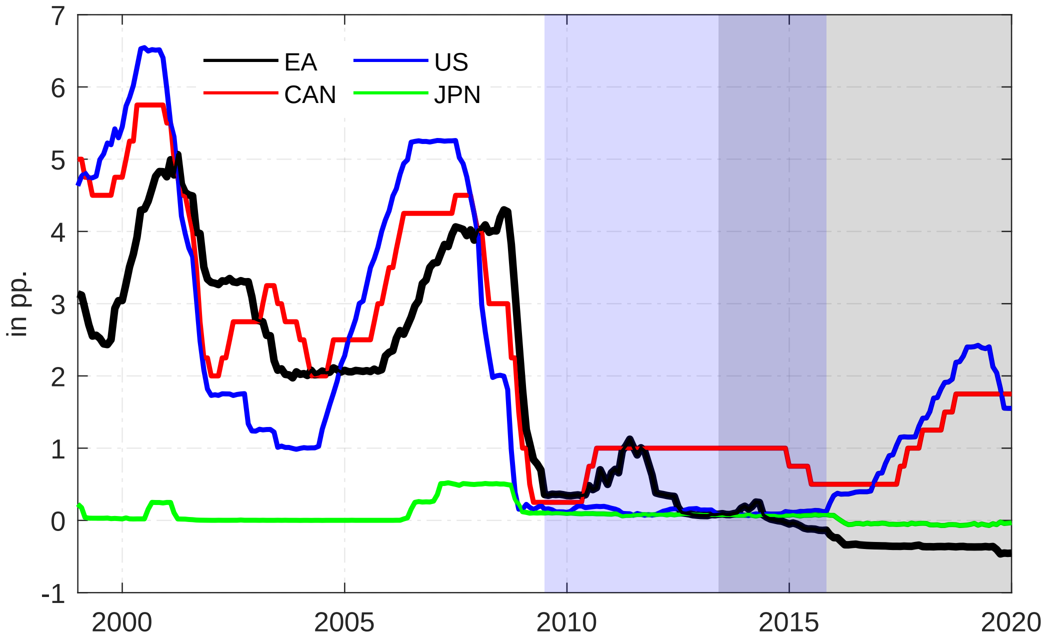
Given these opposing predictions, this paper studies the behavior of the exchange rate when interest rates are at the ZLB. To present the argument, we lay out a two-country New Keynesian model. The countries are highly integrated via financial markets but less than perfectly integrated in goods markets, so relative price adjustments across countries are required. In each country, firms set their prices in their own currencies, and the nominal exchange rate floats. The central banks follow a Taylor rule unless the ZLB binds. We examine the case of a severe global recession where either (i) both countries or (ii) one country is in a liquidity trap due to recessionary asymmetric demand shocks. We show that the driving forces for the real appreciation in a ZLB scenario are the strongly falling (relative) inflation expectations. Since the central bank cannot lower the policy rate, the falling inflation expectations cause a rise in the real interest rate differential in the ZLB-constrained country and, hence, a real appreciation.

In the light of the ZLB, many central banks have adopted unconventional policy measures to counteract the negative effects of the severe global recession and to stabilize inflation expectations.[2] Therefore, in a second step, we investigate the exchange rate response when interest rates are at the ZLB to an asymmetric demand shock in our two-country model when the central bank can stabilize inflation expectations via forward guidance. We show that when the liquidity-trapped country's monetary policy is sufficiently accommodative, inflation expectations are stabilized, and the real exchange rate can depreciate and absorb cyclical developments in response to an adverse demand shock during a ZLB period. Based on these two opposing exchange rate outcomes, in our third and main step, we aim to assess the empirical relevance of the exchange rate as a shock absorber when interest rates are at the ZLB. We utilize monthly data over the time horizon from

[1] When the zero lower bound (ZLB) is not binding, the central bank reduces its nominal interest rate in response to a negative demand shock. This interest rate cut causes a real depreciation, implying an expenditure switching towards cheaper goods.

[2] For a precise definition of unconventional monetary policy see also the speech by Smaghi (2009), which he gave as a member of the Executive Board of the ECB.

Figure 1: Policy rates from 1999-2020



Notes: Gray and blue-shaded areas indicate ZLB periods of the euro area and the United States, respectively.

1999 to 2020. We estimate the effect of a negative asymmetric demand shock on the real exchange rate and inflation expectations as well as output and prices in the euro area vis-à-vis Canada, Japan, and the US. We have chosen those countries to control for different foreign monetary policies when analyzing the empirical effects of a negative euro area demand shock during our estimation horizon. Figure (1) illustrates that Canada was the only economy among the G7 countries analyzed whose policy rate was not constrained by the ZLB over our estimation horizon. In contrast, Japan's interest rates have remained at the ZLB throughout the last two decades. Figure (1) also shows that since the Great Recession, the US experienced times when the policy rate was constrained at the ZLB or remained unconstrained. At the same time, interest rates in the euro area reached the ZLB shortly after those in the US did and have remained there ever since. Thus, analyzing the euro area vis-à-vis Canada, Japan, and the US allows us to empirically account for different foreign monetary policy stances when assessing the empirical relevance of the exchange rate as a shock absorber when interest rates are at the ZLB.

We employ state-dependent and sign-restricted local projection (LP) methods. As pointed out by Plagborg-Møller and Wolf (2021), LPs are conceptually not different from vector autoregressions (VARs), which are the most popular empirical approach in macroeconometrics to study the propagation of structural shocks. Instead, they are different linear projection techniques sharing the same estimand (in population) under different finite sample properties. Specifically, they show that VARs and LPs estimate the same impulse responses under an unrestricted lag structure. This seminal result implies that VAR-based structural identification, including short-run and sign restrictions, can be implemented equivalently within an LP framework. We extend the Plagborg-Møller and Wolf (2021) framework and allow the impulse responses obtained via sign restrictions to be different across the states of the economy. Our states are specified with respect to the euro area's monetary policy stance. In particular, we compare times where the ECB's policy rate was either unconstrained or constrained by the ZLB and assess the effect of a negative asymmetric demand shock on the real exchange rate, inflation expectations, output, and prices in the euro area vis-à-vis Canada, Japan, and the US.

In this respect, one could interpret our findings as evidence of how well the central bank's unconventional monetary policy reacted to a severe negative demand disturbance when the ZLB constraint was binding. If the exchange rate would depreciate in a ZLB scenario in response to such a shock, monetary policy would have been sufficiently accommodative to cushion the deflationary side-effects of the ZLB constraint on economic activity.

Our empirical findings show that the euro real exchange rate not only depreciates prior to the ZLB period but also during the ZLB episode. At the same time, inflation expectations do not react more strongly when the ZLB is binding.[3] We also find that output in the euro area vis-à-vis Canada, Japan, and the US does not fluctuate more in response to asymmetric negative demand disturbances than before the euro area's ZLB episode. Hence, our empirical results contrast with those of the standard New Keynesian model, which predicts that the real exchange rate appreciates in response to a negative demand shock during a ZLB period and that inflation and expected inflation are substantially more volatile when interest rates are at the ZLB. Nonetheless, they are in line with an extended version of the two-country New Keynesian model, which accounts for the ability of the central bank to allow for unconventional measures in a ZLB period to stabilize inflation expectations. Indeed, our empirical findings show that the ECB's balance sheet expanded significantly in response to the negative demand shock in the ZLB period, while it remained unaffected in the pre-ZLB period. Hence, the ECB's unconventional policies during the ZLB period supported a real depreciation, which helped to absorb cyclical developments in response to the adverse demand shock. Counterfactual variance decompositions show that, depending on the country pair, movements in the real exchange rate absorb at least eight percentage points of the variation in output. In this respect, the exchange rate plays an important role in stabilizing the economy when interest rates are at the ZLB.

We conduct a set of robustness checks of our empirical findings: first, we also estimate our model for the euro area vis-à-vis a broad set of trading partners, for which time-varying trade weights between the euro area and these countries are available all the way back to the launch of the euro. That is, we summarize the

[3] Corsetti et al. (2014) assess positive demand shocks for the US prior to the ZLB period, finding a real appreciation.

information for output and exchange rates for each of these countries and treat them as if they were one single country. Our results for this exercise are very similar to our main findings in that the trade-weighted euro real exchange rate depreciates in response to a negative demand shock both when interest rates are not at the ZLB and when they are. Second, note that the mere possibility of the ZLB being reached might affect economic decisions and expectations even before the ZLB becomes binding. Put differently, economic agents anticipate that the policy rate might reach the ZLB in the future, and their inflation expectations might already respond today. Hence, the consequences of the ZLB can be effective even before the short rate reaches zero. Moreover, there is no generally defined start date for the ZLB period. To account for these concerns, we also estimate our model in a smooth transition LP framework with the policy rate as a state variable so that the states are functions of the policy rate in the euro area. We find the same results as in our main specification. Third, we find that the results from a state-dependent VAR are qualitatively very similar to our benchmark results, although the VAR-based responses are smoother compared to the LP-based responses.

The work by Debortoli et al. (2020), Müller et al. (2022) and Stavrakeva and Tang (2020) is closely related to our analysis. The latter two papers also assess the importance of expectations for the exchange rate. However, the authors focus on the role of monetary policy shocks or broker-dealer relationships in the exchange rate market. Hence, the authors do not consider asymmetric demand disturbances across countries and do not assess the possible state-dependent macroeconomic effects due to the ZLB episode. The work by Debortoli et al. (2020) provides empirical evidence supporting the irrelevance hypothesis by illustrating that US output, inflation, and long-term rates are not affected by the ZLB episode. In contrast to their work, we assess the international dimension of liquidity traps and show empirically that the real exchange rate can depreciate in response to negative asymmetric demand shocks when interest rates are at the ZLB. In this respect, we can support the argument of flexible exchange rates by Friedman (1953), Mundell (1961), Obstfeld and Rogoff (2000), and Obstfeld and Rogoff (2002), i.e. that flexible exchange rates act as a shock absorber to country-specific shocks, such as negative demand shocks. We show that this is the case even if the ZLB constraint is binding but monetary policy is sufficiently accommodative. Thus, at the ZLB, a flexible exchange rate can allow for the adjustment of relative prices so that output and prices are stabilized in the ZLB-constrained country.

Our paper is also connected to a strand of the literature that examines exchange rate policies when the ZLB has been reached. Amongst these, Amador et al. (2020) assess an exchange rate policy that is inconsistent with interest rate parity because of a binding ZLB constraint. Coenen and Wieland (2004) investigate the effectiveness of an exchange rate peg and price level targeting regime in stimulating an economy in a liquidity trap. In a related work, Svensson (2001) argues that price-level targeting, a devaluation of the currency, and a temporary exchange rate peg can be employed to escape a liquidity trap. In relation to this work, we show that the ECB's unconventional monetary policy measures seem to have been sufficiently accommodative in the ZLB period for the real exchange rate to depreciate. We show that this real depreciation then supported a cushioning of the deflationary side-effects of the negative demand shock in the ZLB period.

The paper proceeds as follows: in section II, we lay out a two-country open economy model with sticky prices to show, in a nutshell, the theoretical considerations of a real appreciation or depreciation in a ZLB period. Based on this, in section III we present our empirical specification to assess the hypothesis of possibly opposing exchange rate outcomes in response to asymmetric demand shocks when interest rates are at the ZLB. Section IV outlines the empirical findings. Section V contains robustness checks. Section VI concludes.

II Assessing the Theoretical Mechanism

To depict the opposing real exchange rate outcomes of an appreciation versus a depreciation when interest rates are at the ZLB, we explore the two-country New Keynesian model as in Clarida et al. (2002). Following Engel (2011), we allow for less than perfectly integrated goods markets and extend the model by accounting for the ZLB. Here, we briefly outline the model to set the basis for the empirical analysis. The main ingredients of the model are two equally sized countries, home (H) and foreign (F), which are connected via trade in goods and state-contingent assets. In each of the economies there is a continuum of i households indexed by $i \epsilon [0, 1]$. Each household i consumes domestic and foreign goods, aggregated by a Cobb-Douglas technology, and faces a time preference shock ξ_i, which we also refer to as a demand shock. Our analysis focuses on a negative shock to ξ_i, which implies that households are willing to consume more in the future rather than today. Therefore, they increase savings and reduce their demand for goods. The time preference shock $\xi_{i,t}$ is unanticipated and follows a stochastic decay. In every period $t \geq 1$ it holds that $\xi_{i,t} = \xi_{i,t-1}$ with probability $\mu < 1$.[4] With probability $(1 - \mu)$ the time preference shock $\xi_{i,t}$ returns to zero. This occurs at the same period T for all households in the two countries. A continuum of monopolistically competitive sticky-price firms sells their goods in their own currency to home and foreign households. The monetary authorities decide on the underlying nominal interest rates while the country-specific fiscal authorities collect either lump-sum taxes or pay transfers to their residents. The full model and all optimality conditions are laid out in Hoffmann and Hürtgen (2021). In the following, we focus on the relevant equilibrium conditions to present the argument of a real appreciation versus depreciation when interest rates are at the ZLB.

[4] For $0 < \mu < 1$, the ZLB will expire in expectations, see Eggertson and Woodford (2003). This ensures that inflation today is pinned down by expectations that the stable manifold will determine future inflation.

A. *The Model's Equilibrium Relationships*

We log-linearize the model around its steady-state values. Lower case letters reflect log deviations from the variable X_t in the steady state X: $x_t = \log(X_t) - \log(X)$. We start with the evolution of consumption and output. We then discuss the determination of inflation, policy rates, and real exchange rates. In equilibrium, all households are identical and the individual's expectation equals average expectations $E_t^i = \overline{E}_t$. Then

$$c_t = \overline{E}_t \left[c_{t+1} - \frac{1}{\sigma} \left(\xi_{t+1} - \xi_t + r_t - \pi_{t+1} \right) \right] \tag{1}$$

is the Euler equation, with $\overline{E}_t [r_t - \pi_{t+1}]$ reflecting household's consumption-based real interest rate, which depends on consumer price inflation (CPI), π_t, as well as the policy rate, r_t. The intertemporal elasticity of substitution equals $1/\sigma$. A similar condition in the foreign economy is indexed by $*$. The Markov property of the time preference (i.e. demand) shocks ξ and ξ^* implies that under independent monetary policy and flexible exchange rates, there are no predetermined state variables. In expectation, all endogenous variables in the world economy will inherit the same persistence as the shock itself.

International linkages are expressed by the variable $x_t^R = \left(x_t - x_t^* \right)/2$, which denotes relative world variables. From the firms' resource constraints and households' demand conditions, aggregate output becomes

$$y_t = c_t + \left(1 - \frac{v-1}{\delta} \right) y_t^R - \frac{v(2-v)}{\delta} \xi_t^R. \tag{2}$$

The intensity of the home bias equals $0 \leq (v-1)/\delta \geq 1$, whereby $\delta \geq 1$ is a function of σ and v, with $v \geq 1$. If there is no home bias, $v = 1$ and $\delta = \sigma$. Given that goods markets are only imperfectly integrated, we set $v > 1$. From (1) and (2), a relation between interest rates, CPI, and output is obtained

$$r_t^R = \overline{E}_t \left[\pi_{t+1}^R + \sigma \frac{v-1}{\delta} \Delta y_{t+1}^R - \frac{(v-1)^2}{\delta} \Delta \xi_{t+1}^R \right], \tag{3}$$

with $\pi^R = \pi_H^R - (2-v) \left(\pi_H^R - r_{-1}^R \right)$ denoting relative CPI and π_H^R defining relative domestic price inflation. Equation (3) describes relative output in response to a demand shock. Expected CPI inflation equals

$$\overline{E}_t [\pi_{t+1}] = \overline{E}_t [\pi_{Ht+1}] + (2-v)\, \overline{E}_t [r_t^R - \pi_{Ht+1}^R], \tag{4}$$

with $\pi_{H,t} = \frac{\kappa}{2} y_t - \kappa_{(y-y^*)} y_t^R + \kappa_{(c-c^*)} \xi_t^R + \beta E_t [\pi_{Ht+1}]$ denoting gross domestic price inflation.[5] It holds that $\kappa > \kappa_{(y-y^*)} \geq \kappa_{(c-c^*)} \geq 0$, for $v \geq 1$. κ defines the responsiveness of domestic inflation to domestic output. The responsiveness to relative output is given by $\kappa_{(y-y^*)}$ and captures how strongly inflation adjusts to

[5] This follows Calvo (1983). For details see appendix A.1. in Hoffmann and Hürtgen (2021).

changes in relative output. The response to relative time preference conditions is determined by $\kappa_{(c-c^*)}$. The foreign country has similar conditions, with the second and third terms of the right-hand side of domestic price inflation taking opposite signs.

The monetary authorities adopt the following monetary policies by following a non-linear Taylor rule

$$r_t = \max\left\{-\ln(1/\beta), \phi\pi_{Ht}\right\} \text{ and } r_t^* = \max\left\{-\ln(1/\beta), \phi\pi_{Ft}^*\right\}, \tag{5}$$

with $r = \ln(1/\beta)$ and $\beta < 1$ being the household's discount factor. π_{Ht} denotes gross home producer price inflation. The Taylor principle holds, and the reaction on inflation is given by $\phi > 1$. Hence, the central banks' nominal interest rates react by more than the actual price change, pushing real interest rates in the desired direction. However, when interest rates are at the ZLB, the monetary authorities can lower the nominal rate up to $r_t = -\ln(1/\beta)$ and movements in the real interest rate would only depend on expected inflation.

From equations (1)-(3) and the respective foreign counterparts, we obtain a relationship between policy rates, relative inflation rates, and the real exchange rate q,

$$(v-1)\, r_t^R = \overline{E}_t\left[(v-1)\,\pi_{Ht+1}^R + \frac{\Delta q_{t+1}}{2}\right], \tag{6}$$

which mirrors the real UIP condition. From (6) it follows that changes in the real exchange rate are due to movements in the real interest rate differential between the home and foreign country, $\overline{E}_t\left[r_t^R - \pi_{t+1}^R\right]$. From the real UIP condition also becomes clear that when the Taylor rule (5) determines the nominal rate, monetary policy and inflation expectations determine the real exchange rate.

B. *The Effects of a Negative Asymmetric Demand Shock*

We examine the effects of negative demand shocks based on these equilibrium relationships. To set the stage, we focus on situations where interest rates are not at the ZLB and those where they are. This lays out the main mechanisms at work and explains how a real appreciation in a ZLB period occurs due to the decline in inflation expectations. Then, we show that a real appreciation can also occur if the ZLB is only binding in one country. We use this example to illustrate that with unconventional measures, such as forward guidance, inflation expectations are stabilized, and a real depreciation in a ZLB period can occur.

We consider equilibria where the variables are constant from the period the preference shock hits until the shock reverts back to zero, and the economy is in its non-stochastic steady state.[6] Since the time preference shocks ξ_i and ξ_i^* are unanticipated and follow a stochastic decay, expected consumption, output, inflation,

[6] This builds on the work by Eggertson and Woodford (2003) and Christiano et al. (2011).

and the real exchange rate inherit the Markov property of the demand shock. They take on the same values as long as the shock lasts and will revert to zero once the shock disappears.[7] Therefore, the time subscript t is replaced by the state subscript s. Then we can express the real UIP condition (6) by

$$\frac{q_{\mathrm{S}}}{2} = -\frac{(v-1)}{(1-\mu)}\left(r_{\mathrm{S}}^{R} - \left[\mu\pi_{H\mathrm{S}}^{R}\right]\right). \tag{7}$$

Thus, when the real interest rate differential $(v-1)\,(r_{\mathrm{S}}^{R} - [\mu\pi_{H\mathrm{S}}^{R}])$ falls, the real exchange rate depreciates, $q_{\mathrm{S}} > 0$, and vice versa. Consider now an asymmetric negative demand shock, which hits the home country more severely. This will lead to a (relative) fall in consumption, output, and, hence, prices as well as inflation expectations, $[\mu\pi_{H\mathrm{S}}^{R}] < 0$.

ZLB is (not) binding in both countries. When the ZLB is not binding, the central banks can use their policy rates to respond to the asymmetric negative demand shock.[8] Following the monetary policy rule (5), the policy rate will be reduced by more than the fall in inflation in response to the negative demand shock. This will cause a decline in the relative real interest rate by $(v-1)\left(\phi-\mu\right)[\mu\pi_{H\mathrm{S}}^{R}]/\mu < 0$. It follows from (7) that the decline in the real interest rate differential will lead to a real depreciation

$$\frac{q_{\mathrm{S}}}{2} = -\frac{(v-1)}{(1-\mu)}\frac{\phi-\mu}{\mu}\left[\mu\pi_{H\mathrm{S}}^{R}\right] > 0. \tag{8}$$

When the asymmetric demand shock is so severe that the ZLB is binding, the central banks cannot sufficiently use their policy rates to respond to it.[9] It follows that the fall in the relative inflation expectations will directly translate into a rise in the real interest rate differential, $-(v-1)\,[\mu\pi_{H\mathrm{S}}^{R}] > 0$, and, hence, a real appreciation

$$\frac{q_{\mathrm{S}}}{2} = \frac{v-1}{1-\mu}\left[\mu\pi_{H\mathrm{S}}^{R}\right] < 0. \tag{9}$$

Equations (8) and (9) illustrate that, without further monetary policy action, the real exchange rate appreciates in response to an asymmetric demand shock when interest rates are at the ZLB and that (relative) inflation expectations matter.

ZLB is binding only in the home country. Even in an environment where only the home country's interest rates are at the ZLB, and the foreign economy can use monetary policy to counteract the consequences of the home country's asymmetric negative demand shock, perverse responses of the real exchange rate can occur.[10] Based on the monetary policy rules (5) and the real UIP condition (7), the real

[7] Thus, in every period $0 \le t \le T-1$, the variables are constant but depend on the shocks.
[8] It holds that $\xi^{crit} < \xi_{\mathrm{S}} < 0$ and $\xi^{*crit} < \xi_{\mathrm{S}}^{*}$ with $\xi_{\mathrm{S}} < \xi_{\mathrm{S}}^{*}$, see Hoffmann and Hürtgen (2021).
[9] These conditions are satisfied for $\xi_{\mathrm{S}} < \xi^{crit}$ and $\xi_{\mathrm{S}}^{*} < \xi^{*crit}$, but $\xi_{\mathrm{S}} < \xi_{\mathrm{S}}^{*}$.
[10] In this case, it holds that $\xi_{\mathrm{S}} < \xi^{crit} < 0$, but $\xi^{*crit} < \xi_{\mathrm{S}}^{*}$.

exchange rate evolves by

$$\frac{q_s}{2} = \frac{v-1}{1-\mu}\left(\left[\mu\pi^R_{Hs}\right] + \frac{\ln(1/\beta) + \phi\pi^*_{Fs}}{2}\right). \tag{10}$$

Now not only relative inflation expectations $[\mu\pi^R_{Hs}]$ matter for the real interest rate differential and the real exchange rate, but also the foreign monetary policy and its ability to affect foreign inflation, $\phi\pi^*_{Fs}$. For example, a rise in foreign inflation π^*_{Fs} would cause a rise in the real exchange rate compared to (9), as this is accompanied by a rise in the foreign real interest rate, $(\phi-\mu)\pi^*_F > 0$.[11] But when the ZLB in the home country is binding, relative inflation (expectations) deteriorates, so that $[\mu\pi^R_{Hs}] < (\ln(1/\beta) + \phi\pi^*_{Fs})$. Hence, the real interest rate differential widens, and the real exchange rate appreciates. This situation occurs in a ZLB scenario when the difference between the home and foreign demand shock is sufficiently large.

Furthermore, Hoffmann and Hürtgen (2021) show that in all of the described situations, the decline in inflation expectations will be more severe when the ZLB is binding. The reason is that when interest rates are at the ZLB, firms want to lower their prices in response to the decline in consumption and output. However, since prices are sticky, some price adjustments will only occur in the future. Households will understand this and adjust their inflation expectations downwards accordingly. Without any monetary policy intervention, this will lead to a stronger rise in today's real interest rate and a real appreciation, amplifying the decline in consumption, output, and, hence, inflation expectations.

Unconventional measures: Forward guidance as an example. Smaghi (2009) argues that in stressful times for the global financial system, easing monetary policy by lowering policy rates towards the ZLB would not be enough to counteract the recessionary consequences of adverse demand shocks. Therefore, unconventional tools are needed. Via forward guidance – one manifestation of unconventional monetary policy – policymakers can directly influence expectations about future interest rates by resorting to a conditional commitment to maintaining policy rates at the lower bound for a significant period of time (e.g. Eggertson and Woodford, 2003). To align the future interest rate level in the market, the central bank needs to operate in the market for financial assets, such as government bonds. Those operations will then be reflected in a larger central bank balance sheet due to an expansion of monetary liabilities.

In this section, we focus on the effects of forward guidance on the real exchange rate. However, given the simplicity of our model, we refrain from assessing the effects on

[11] A rise in foreign inflation occurs when the foreign demand shock is sufficiently positive, i.e. $\xi^*_s > 0$. We will maintain this assumption. If the foreign demand shock were negative, i.e. $\xi^{*crit} < \xi^*_s < 0$, foreign inflation would also fall. From (10), a real appreciation occurs unambiguously in the home country.

the central bank's balance sheet here but will do so in section IV.B of our empirical analysis in more detail.

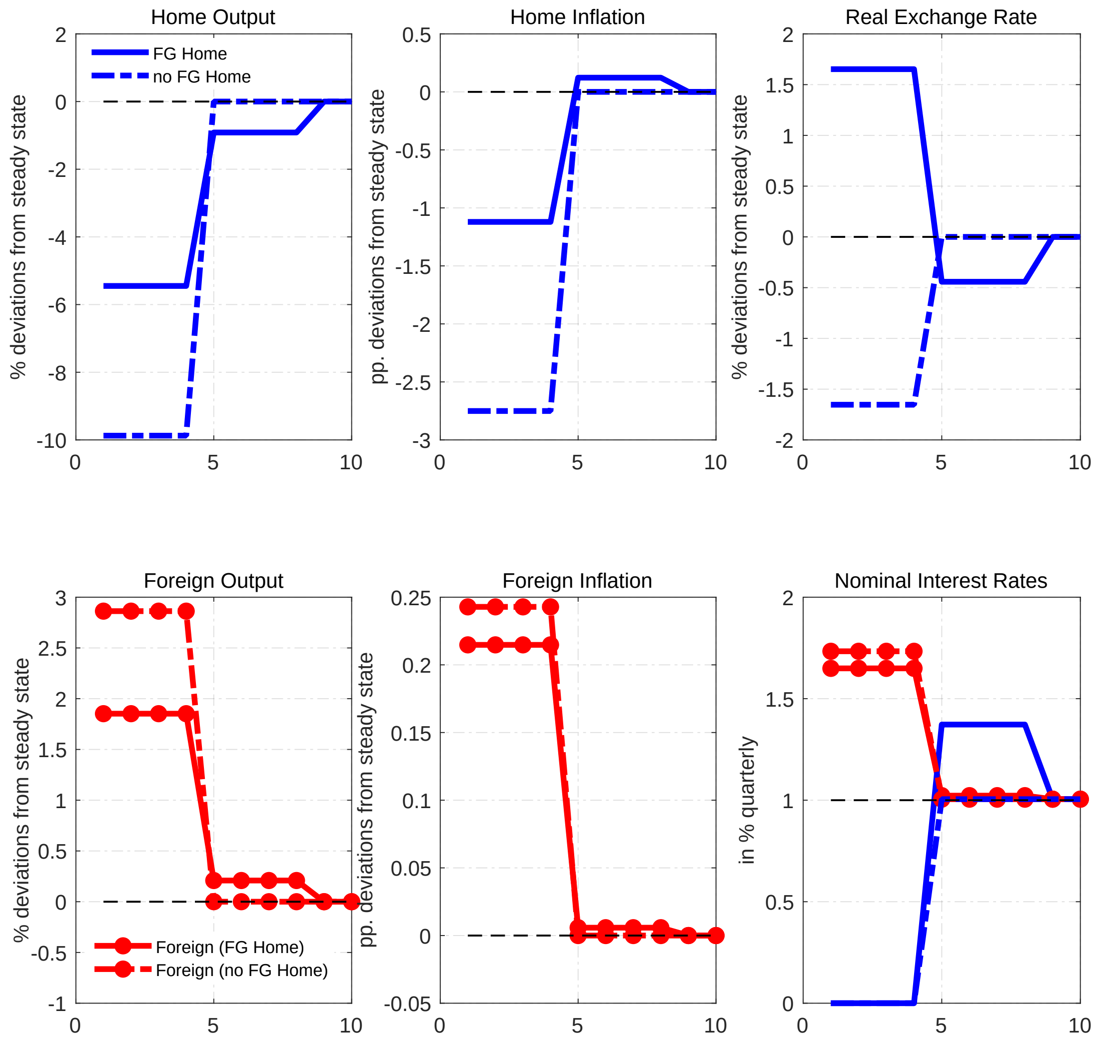
In line with our above analysis, we maintain the environment where the ZLB constrains only the home country. The foreign country pursues a policy of positive interest rates, following the Taylor rule, as described in (5). The home country's central bank announces in the ZLB state a path of the *future state*.[12] In particular, it will set the nominal interest rate in periods $t \geq T$ to achieve an inflation target of $\overline{\pi}_H > 0$, to raise inflation expectations in periods $t < T$. We assess the following scenario: At time $t = 1$, there is an asymmetric negative demand shock to the home country, which drives its policy rate to the ZLB. For illustrative purposes, we focus on a special case where the central bank has perfect foresight and knows that the preference shock will last for T periods. We assume that the shock persists for $T = 4$ periods, while the home country's central bank will set the $\overline{\pi}_H > 0$ to 40 basis points annually for $t = 8$ periods. We compare this scenario to the one where the home country does not follow any monetary policy action in a ZLB scenario, as described above.

The blue dashed (red dashed) lines in Figure (2) show the responses of the home (foreign) economy when the home country's interest rates are at the ZLB but it does not pursue forward guidance, and the foreign country's monetary policy is unconstrained. In such a situation, the real exchange rate would appreciate, as shown by the top-right panel of Figure (2). Furthermore, the figure shows in the upper panel a severe decline in output and inflation in the home economy in response to the negative asymmetric demand shock at home. These findings illustrate our discussion from above, namely that without further monetary policy intervention, the real exchange rate appreciates, and output and inflation decline strongly in the country that is constrained by the ZLB.

However, the solid blue (red) lines in Figure (2) show the responses of the home (foreign) country when the home country adopts forward guidance. Then, when the home country's policymakers commit to the future path of interest rates, it follows that a real exchange rate depreciation (blue-solid line) can be generated by announcing higher inflation today. This also impacts positively on output and inflation by mitigating its otherwise severe decline. The real depreciation also allows for an expenditure switching effect toward home-produced goods, as can be seen by the relatively stronger decline in foreign output by the bottom left panel of Figure (2), when the home country is at the ZLB, but it pursues a monetary policy of forward guidance.

[12] Note that many papers also examine the credibility of forward guidance announcements (see, for instance, Nakata and Sunakawa, 2022; Walsh, 2018; Finck, 2020). In these papers, forward guidance announcements are credible (sustainable) when fulfilling past promises is the central banks best strategy at any point until the promised lift-off date. A typical result in all these papers is that forward guidance can be credible only if recurrent ZLB episodes are possible, as assumed in this paper. We do not address possible credibility issues and assume no time inconsistency problem exists.

Figure 2: The ZLB-constrained home country with and without forward guidance



Notes: It holds that $\xi_S < \xi^{crit} < 0$ and $\xi^{*crit} < 0 < \xi^*_S$ and $\mu = 0.8$, whereby $\sigma = 2$, $v = 1.5$, $\delta = 1.75$, $\kappa = 2.5$, $\kappa_{(y-y^*)} = 1.64$ and $\kappa_{(c-c^*)} = 0.25$.

In summary, when the ZLB is binding in at least one country and monetary policy cannot sufficiently accommodate negative demand shocks, no expenditure switching is possible via the real exchange rate since a real appreciation occurs for the country in which the ZLB is binding. This effect is caused by a strong decline in (relative) inflation expectations in the country which is hit most severely by the asymmetric negative demand shock. The model also predicts that output, inflation (expectations), and the real exchange rate are substantially more volatile when interest rates are at the ZLB. However, our model also shows that when monetary policy can stabilize inflation expectations in a ZLB scenario via unconventional measures, such as forward guidance, the real exchange rate can depreciate and stabilize movements in output and prices.[13] The next section assesses these opposing predictions empirically.

[13]When accounting for the so-called forward guidance puzzle, Hoffmann and Hürtgen (2021) show that the effects would remain but in a mitigated manner.

III State-Dependent Local Projections

This section empirically explores the exchange rate arguments by estimating a sign-restricted state-dependent local projection model. First, we lay out the econometric model and explain its state-dependent structure. Second, we discuss the data used to estimate our empirical model and show how we differentiate the two monetary states of a non-binding and binding ZLB. Third, we explain our identification strategy. Finally, the statistical inference is laid out to draw the structural impulse responses.

A. *Specification*

We set up a non-linear model based on sign restrictions to distinguish the possible state-dependent real exchange rate effects. In particular, we estimate a state-dependent LP model to empirically investigate the role of the exchange rate as a shock absorber in a ZLB scenario.

As pointed out by Plagborg-Møller and Wolf (2021), LPs are conceptually not different from VARs. In fact, they are different linear projection techniques sharing the same estimand under different finite sample properties. This result implies that VAR-based structural identification, including short-run and sign restrictions, can be implemented equivalently within an LP framework.[14] We empirically utilize this finding when assessing the propagation of asymmetric demand shocks and extend the idea of Plagborg-Møller and Wolf (2021) to a non-linear framework. More precisely, we condition the effect of the demand shock on whether the ZLB is binding or not. To fix notation, first, consider the linear model

$$y_{i,t+h} = \alpha_{i,h} + \beta_{i,h} y_t' + \gamma_{i,h} x_t' + u_{i,h,t},$$

where $y_{i,t+h}$ is the ith endogenous variable in the vector y_t at horizon $t+h$ and $\alpha_{i,h}$, $\beta_{i,h}$, $\gamma_{i,h}$ contain the projection coefficients for the control variables in y_t and x_t, respectively. Specifically, the $n \times p + 1$ vector $\gamma_{i,h} = \left[\phi_{i,h,1}, ..., \phi_{n,h,1}, \phi_{i,h,2}, ..., \phi_{n,h,p}, \delta_{i,h}\right]$ contains the stacked coefficients for the covariates in $x_t = \left[y_{t-1}, ..., y_{t-p}, t\right]$. Finally, $u_{i,h,t}$ corresponds to the projection residual of variable i at horizon h in t with (strictly) positive variance. Based on this, we set up a non-linear model to distinguish between the possible state-dependent effects of the ZLB. Thus, we allow for different projection coefficients across two states for all variables:

$$y_{i,t+h} = (1-\lambda_t)\left[\alpha^{I}_{i,h} + \beta^{I}_{i,h} y_t + \gamma^{I}_{i,h} x_t\right] + \lambda_t\left[\alpha^{II}_{i,h} + \beta^{II}_{i,h} y_t + \gamma^{II}_{i,h} x_t\right] + u_{i,h,t}.$$

The superscripts I and II distinguish between state *I=pre-ZLB* and *II=ZLB*, respectively. Hence, λ_t is equal to zero when in t the economy is in state *I=pre-ZLB* and equal to one when the economy is in state *II=ZLB*.

[14] LPs could also accommodate other identification schemes such as narrative sign restrictions as in Antolín-Díaz and Rubio-Ramírez (2018), or long-run restrictions as in Blanchard and Quah (1989).

It has to be noted that, even though VARs might be as robust to misspecifications as LPs *in population*, this is not the case when one is forced to use a finite lag structure, saying that the impulse responses might in general differ *in sample*. However, the consensus in the literature is that impulse responses in an LP framework under a finite lag length are more robust to misspecification than in a VAR framework. This is because iterated forecasts in a VAR can increase the misspecifications as the horizon expands. This is not the case in an LP framework since we estimate the reduced-form coefficients separately for each $h = 0, ..., H$.

Moreover, VARs implicitly assume no changes in the state of the economy (see, for instance, Tenreyro and Thwaites, 2016; Alpanda and Zubairy, 2019; and Alpanda et al., 2021). That is, based on the fact that VAR-based impulse responses rely on iterated forecasts, one implicitly assumes that once the shock occurs in state j, the economy will stay forever in this state. This is not the case within a state-dependent LP framework, where the reduced-form impulse response coefficients reflect the average effect of shocks as a function of the state of the economy within the same period the shock hits. Hence, it also comprises the average effect of the shock on future changes in the state of the economy.[15]

B. *Data*

We estimate our baseline model for the euro area vis-à-vis Canada, the US, and Japan. We use six variables for each country pair to estimate our empirical model. The first four variables only pertain to the euro area: (1) industrial production (excl. construction), (2) the Harmonised Index of Consumer Prices (HICP), (3) one-year-ahead inflation expectations from Consensus Economics, (4) and the (shadow) short rate.[16] The (shadow) short rate is included for the following three reasons: Firstly, in the euro area, there is no generally defined start date for the ZLB period. Therefore, we assess when the Wu and Xia (2016) shadow interest rate for the euro area is below 0 and set the indicator variable in our local projection model for the ZLB-state λ_t to 1 from June 2013 onward. Secondly, the shadow short rate is also meant to capture the unconventional policy measures conducted by the ECB, such as forward guidance and quantitative easing, which in our theoretical model play an important role in generating a possible real depreciation when interest rates are at the ZLB. Finally, the (shadow) short rate will help us to distinguish demand

[15]Note that this point is even more important when one specifies a model with frequent changes between the states. As far as the presence of the ZLB as a state is concerned, this point is more relevant than before, at least since the COVID-19 pandemic. This is based on the observation that many central banks lowered their policy rates in response to the pandemic and returned to the ZLB for a second time after the Great Recession.

[16]Consensus Economics forecasts for the euro area have only been available since December 2002, so we approximate the forecasts from January 1999 to November 2002 by real GDP-weighted forecasts from Germany, the Netherlands, Spain, France, and Italy. For the period in which the forecasts for the euro area are also available, we find a very similar pattern with a correlation of 88.4%.

from monetary policy shocks when identifying a country-specific negative demand shock. The last two variables contain both domestic (euro area) and foreign information: (5) the bilateral real exchange rate and (6) relative industrial production, i.e. domestic production relative to foreign industrial production. The latter is also needed to identify a domestic demand shock.[17]

Industrial production, consumer prices, and the exchange rate are included in logs. The impulse responses for these variables are therefore understood as percentage changes. Both inflation expectations and the short rate are expressed in percentage points. Our sample starts in January 1999 and ends in February 2020 to avoid possible asymmetries in the propagation of the extremely large structural shocks during the ongoing pandemic.[18] Our baseline specification includes $p = 2$ lags of the endogenous variables. However, in the robustness section, we show that our results are robust to different lag choices.

C. *Identification of a Country-Specific Demand Shock*

We identify a domestic demand shock by means of sign restrictions, which are summarized in Table (1).

Table 1: Sign restrictions of a country-specific demand shock

ip	*prices*	*short rate*	*relative ip*	*exp. inflation*	*real exchange rate*
–	–	–	–		

Notes: The restrictions on industrial production, prices, and the (shadow) short rate hold on impact and for five consecutive months. The restriction on relative industrial production holds on impact.

Our theoretical model of section II suggests, as illustrated in Figure (2), that an adverse demand shock leads to a decline in domestic production and prices. However, we would expect the same reactions of production and prices following a contractionary monetary policy shock. To separate demand shocks from monetary policy shocks, we include in our identification strategy the (shadow) short rate in our empirical model to account for a reduction in the policy rate to counteract deflationary pressure from a negative demand shock.

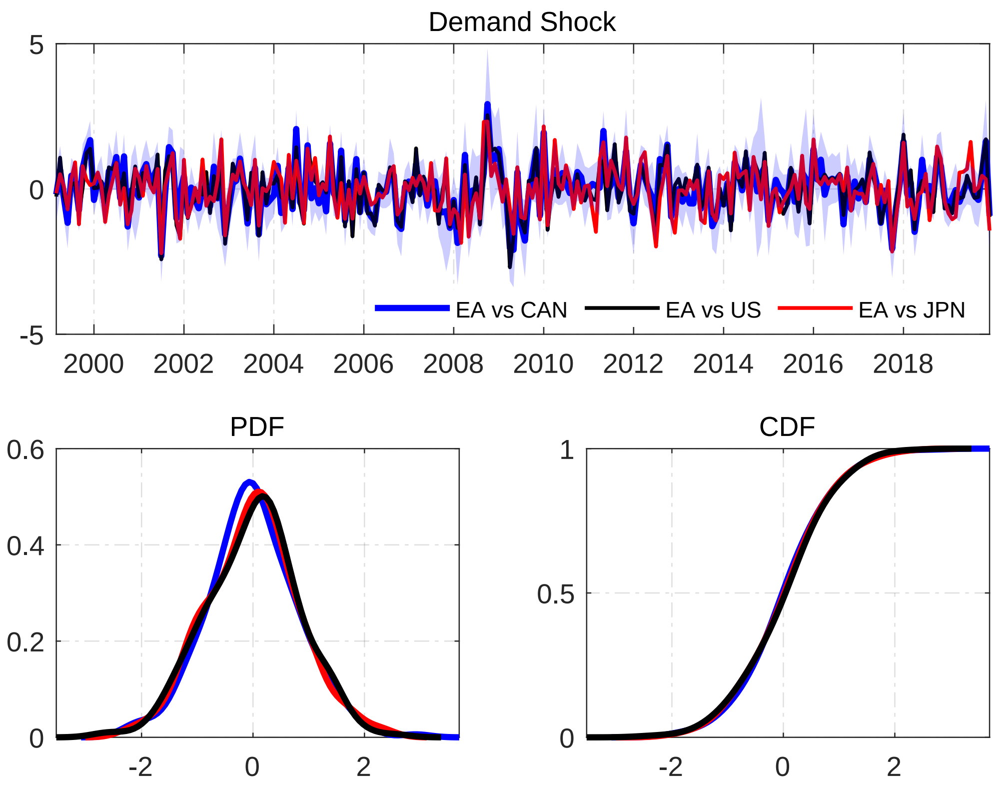
Moreover, as shown in Figure (2), our model predicts that production in the euro area should fall more strongly than in the foreign country in response to a negative asymmetric euro area demand shock. This finding also allows for separating domestic from foreign demand shocks. The distinction can be especially important when two open economies are particularly strongly connected, and a shock from abroad also has effects on domestic variables (see Bobeica and Jarociński, 2019 and Corsetti et al.,

[17] In this paper, the real exchange rates are derived such that an increase refers to a depreciation, while a decrease refers to an appreciation.

[18] See Lenza and Primiceri (2020) for a thorough discussion and suggestions on how to handle a sequence of extreme observations such as those recorded during the COVID-19 pandemic.

2014). In other words, with this identification strategy, we ensure that the reaction of domestic variables is not a spillover effect due to foreign shocks. As shown in Table (1), we leave the response of inflation expectations and the real exchange rate unrestricted, which are our key variables of interest.

Figure 3: Shocks across different country pairs



Notes: The upper panel shows the median shocks for all three country pairs: euro area vis-à-vis Canada (blue line), euro area vis-à-vis the US (black line), and euro area vis-à-vis Japan (red line). The blue-shaded areas correspond to the 5*th* and 95*th* percentiles for the euro area vis-à-vis Canada model. For all three country pairs, the lower panels show the cumulative distribution functions (left panel) and the probability density functions (right panel) over the full sample.

Figure (3) shows the shock distribution of the euro area demand shock across the different country pairs. The upper panel illustrates the median shock for the euro area vis-à-vis Canada (blue line), the US (black line), and Japan (red line). The figure shows that the obtained asymmetric demand shock across the three country pairs, which originates in the euro area, are well aligned. This is confirmed by the second panel of Figure (3), which shows that their cumulative distributions and the probability densities are very similar. Based on this, we now turn to the inference of the structural impulse responses.

D. *Inference*

This section outlines our procedure to draw structural impulse response functions from our sign-restricted state-dependent LP model. Sign and zero restrictions are easy to implement and well understood in VAR frameworks (see, for instance, Rubio-Ramirez et al., 2010; Arias et al., 2018; Uhlig, 2005). Plagborg-Møller and Wolf (2021) show that sign and zero restrictions can also be easily implemented within an LP framework. The idea relies on the finding that the projection coefficients from an LP framework are the reduced-form impulse responses of y_t with respect to VAR-based Wold innovations $e_t = y_t - E\left(y_t | \{y_\tau\}_{\tau<t}\right)$ at horizon h and that the projection residuals $u_{1,1,t} \dots u_{n,1,t}$ equal these Wold innovations. As a result, the variance-covariance matrix Σ obtained within an LP framework contains the same information as obtained from a VAR framework. As regards the implementation of zero and sign restrictions within an LP framework, the procedure can be sketched as follows. In a first step, for each horizon $h = 0 \dots H$, we estimate the model and store the coefficients $\beta^I_{i,h}$ for state *I=pre-ZLB* and $\beta^{II}_{i,h}$ for state *II=ZLB* in appropriate vectors $C^I_h = \left[\beta^I_{1,h}\ \beta^I_{2,h} \dots \beta^I_{n,h}\right]$ and $C^{II}_h = \left[\beta^{II}_{1,h}\ \beta^{II}_{2,h} \dots \beta^{II}_{n,h}\right]$, respectively. Plagborg-Møller and Wolf (2021) show that structural impulse functions at horizon h can be derived as

$$\Theta^j_h\left(Q, C^j_h, f(\Sigma)\right) = C^j_h f(\Sigma) Q,$$

where $f(\Sigma)$ is an appropriate decomposition (e.g. Cholesky) of the horizon-1 projection residuals $Var(u_{1,1,t} \dots u_{n,1,t}) = f(\Sigma) f(\Sigma)'$ and Q is an orthogonal matrix with $QQ' = Q'Q = I_n$. The boundaries of the identified set for the impulse responses for the ith variable at horizon h can be easily approximated numerically through random draws of orthogonal matrices Q as in Arias et al. (2018), which are subject to

$$\mathbf{S}_k \Theta^j\left(Q, C^j, f(\Sigma)\right) e_k \geq 0$$
$$\mathbf{Z}_k \Theta^j\left(Q, C^j, f(\Sigma)\right) e_k = 0,$$

where $\Theta^I = \left[\Theta'^I_0\ \Theta'^I_1 \dots \Theta'^I_H\right]$ and $\Theta^{II} = \left[\Theta'^{II}_0\ \Theta'^{II}_1 \dots \Theta'^{II}_H\right]$ are the $n(H+1) \times n$ matrices of stacked impulse response coefficients in state I and state II, respectively, and the $n(H+1) \times n(H+1)$-dimensional matrices $\mathbf{S}_k$ and $\mathbf{Z}_k$ are set as in Rubio-Ramirez et al. (2010) with e_k being the kth column of the identity matrix.

Inference on the impulse responses is based on various percentiles over all draws that satisfy our zero and sign restrictions. As pointed out by Fry and Pagan (2011), this procedure does not report sampling (estimation) uncertainty as is typically done in a conventional LP approach using robust standard errors. Instead, it reports the distribution across the models that satisfy the set of zero and sign restrictions. Note that our algorithm ensures we use the same draws for Q in both states. In other words, we discard the draw when a candidate for Q satisfies all sign and zero restrictions in state *I=pre-ZLB* but not in state *II=ZLB*, and vice-versa.

IV Results

In this section, we assess the responses of the euro area to a negative domestic demand shock. In the first step, we present the results from our main specification by country pairs, as discussed in the previous section. In a second step, we assess the reaction of the ECB's balance sheet to the negative domestic demand shock to further understand the role of unconventional policy measures in accommodating the negative disturbance when interest rates are at the ZLB. Finally, we explore the importance of the real exchange rate response to the negative demand shock for output through forecast error variance decompositions.

A. *Main Results*

Since the Canadian economy was not bound by the ZLB, we can draw a clear inference regarding the effects of the euro area's ZLB period on the real exchange rate and inflation expectations. We then compare the results to those of the euro area vis-à-vis Japan and the US.

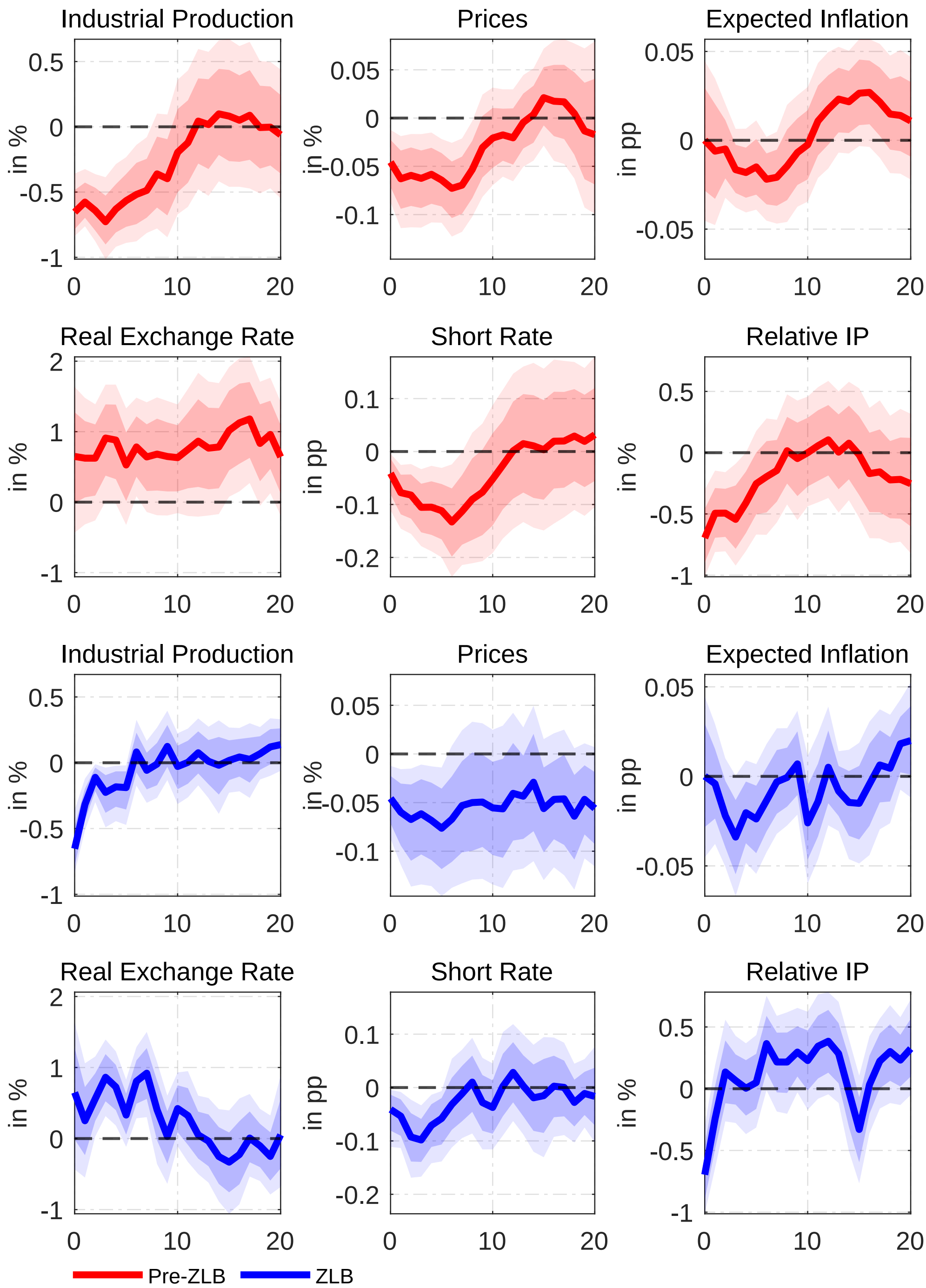
Figure (4) shows our results for the euro area vis-à-vis Canada. Across all panels, the solid blue line shows the responses for the state in which the ZLB is binding, while the solid red line shows the responses for the state in which it is not. The blue (red) shaded areas cover the 5*th* and 95*th* percentiles. Hence, we report 90% confidence bands.

A few things stand out. First, we find that, following an unexpected demand shock, industrial production falls and reverts much faster to its expected value when the economy's interest rates are at the ZLB compared to when they are not. More precisely, after an initial drop in industrial production of about 0.7 percent, it takes about seven months until industrial production reverts to its mean when the ZLB is binding, while the mean reversion takes 13 months when the ZLB is not binding, therefore resulting in a higher overall cumulative effect in state *I*. This can probably explain why the reaction of the (shadow) short rate is found to be stronger in state *I* than in state *II*, as the central bank cuts the short rate by more (in absolute terms) to compensate for the larger drop in industrial production.[19]

Second, we find that the reaction of both prices and one-year-ahead inflation expectations is very similar across both states. Although the response of expected inflation is somewhat noisier in a ZLB scenario than in a non-ZLB scenario, both impulse responses show a similar picture. Interestingly, this implies that the decline in inflation expectations in the ZLB period is not stronger than in the pre-ZLB

[19]Note that the confidence bands around the response of industrial production are somewhat wider in state *I* than in state *II*. A candidate explanation would be the high volatility around the Great Recession, for which we do not explicitly account. We have therefore re-estimated all models and included the OECD-based Recession Indicators as an additional explanatory variable in the model to increase the in-sample fit in periods marked as recessions. However, we find that even in this case, the uncertainty in state *I* is still noticeably higher than in state *II*.

Figure 4: Results for the euro area vis-à-vis Canada



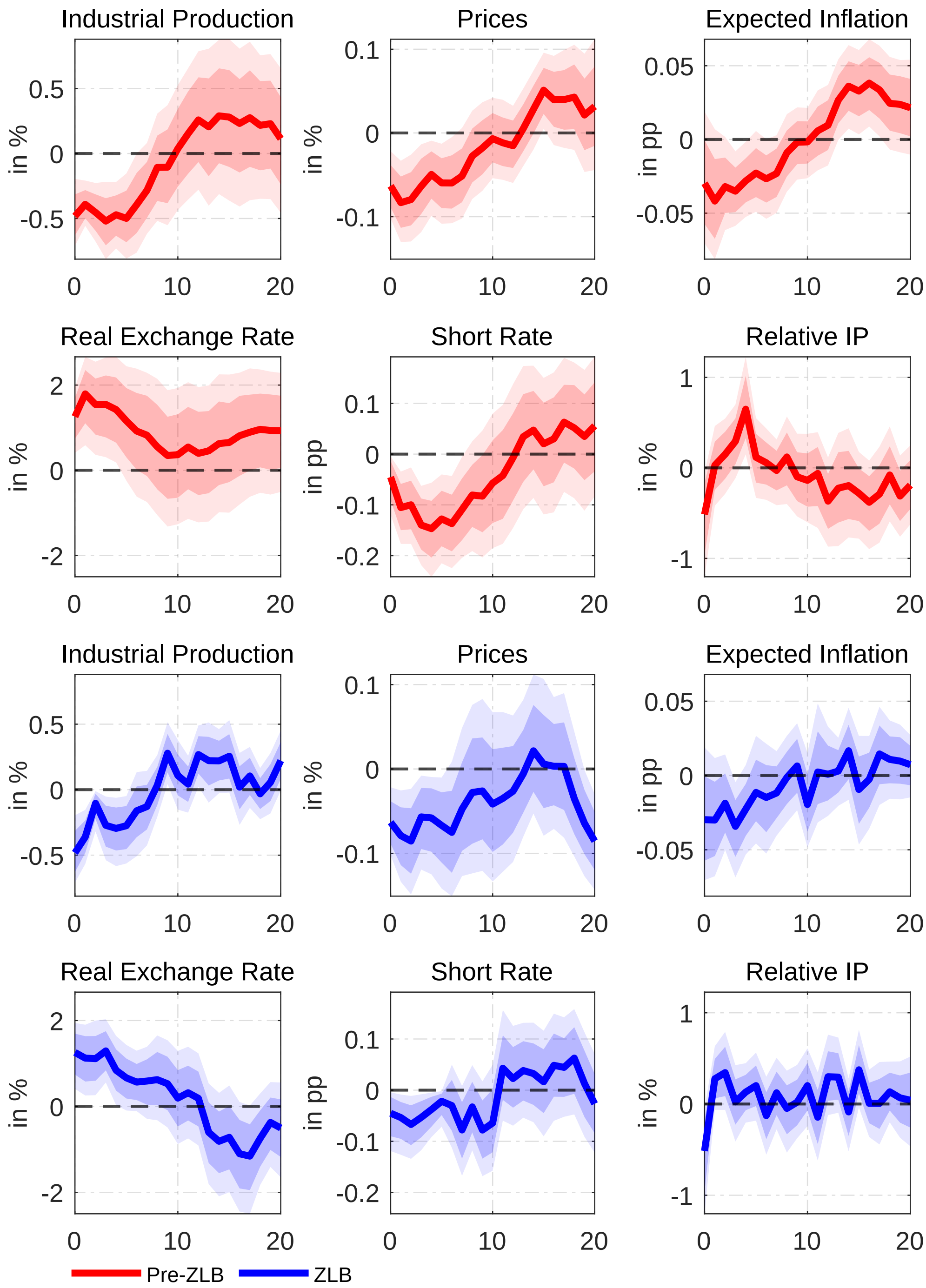
Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.

period. We find that the decline in both sub-samples is around two basis points within the first quarter and that, in both states, inflation expectations return to their mean after ten months or so. Note that these findings are more in line with the results of the open economy New Keynesian model in section II, which predicts that both inflation and expected inflation are less volatile in a ZLB scenario when monetary policy can counteract the negative demand shock through unconventional monetary policy measures.

Third, the real exchange rate depreciates significantly in both samples, i.e. both before the ZLB has been reached and once the ZLB has been reached. The size of the real depreciation is very similar and amounts to one percent in both samples after the first quarter. As before, we find that the uncertainty for the impulse responses in a non-ZLB period is larger than for the responses in a ZLB period. Moreover, we again find that mean reversion occurs much faster when interest rates are at the ZLB than when the ZLB is not binding. The real exchange rate depreciation in a ZLB scenario is contrary to the appreciation predicted by the model in section II, where monetary policy would not respond beyond the ZLB constraint. However, the real depreciation is in line with the model extension, where monetary policy can counteract the negative demand shock by unconventional policy measures. Similar to the reactions of prices and expected inflation, the reaction of the real exchange rate when interest rates are at the ZLB is not stronger than when interest rates are not at the ZLB.

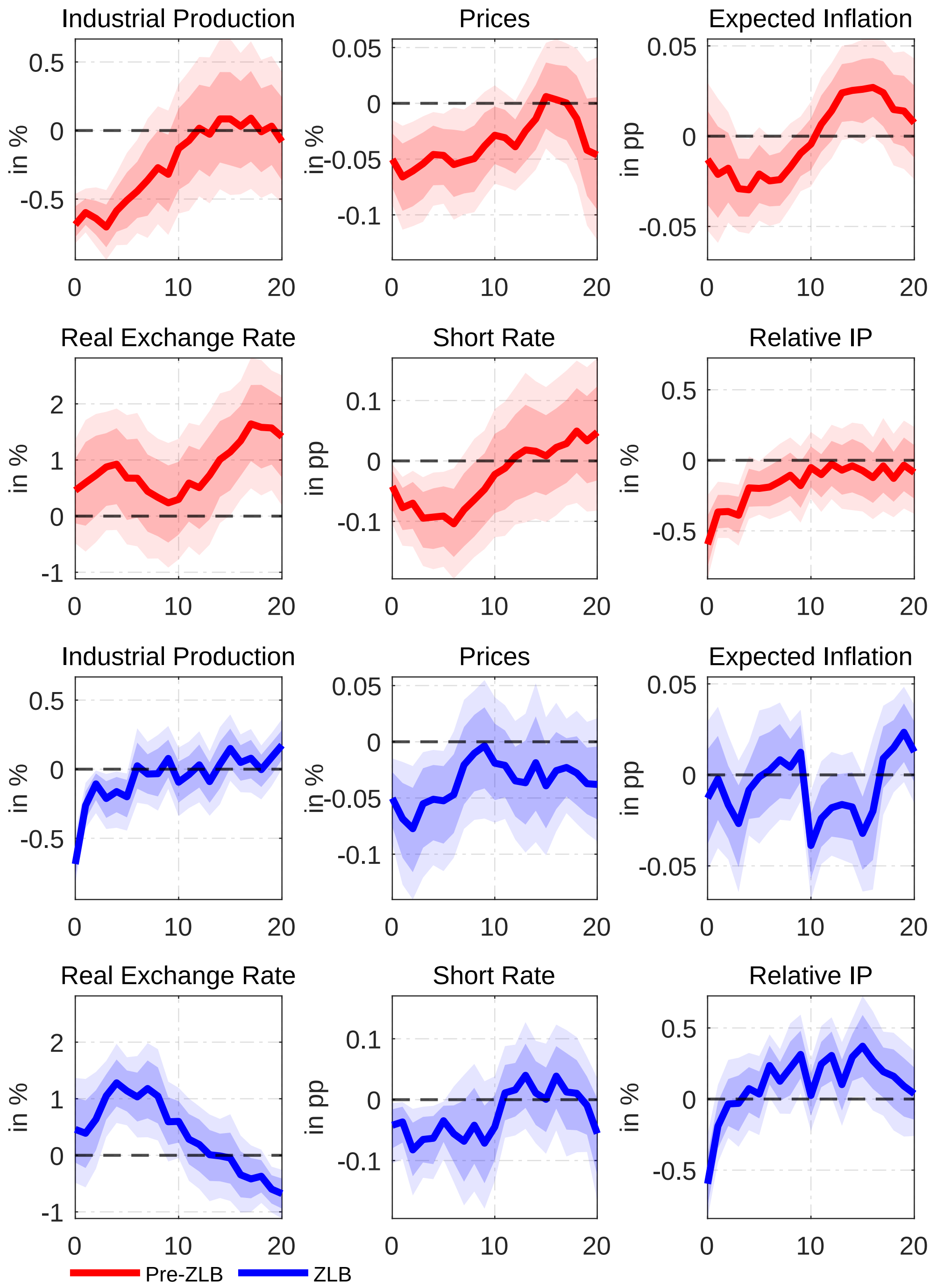
Figure (5) shows our findings of the euro area vis-à-vis Japan. Throughout our estimation period from January 1999 until February 2020, Japan's interest rates remained at the ZLB, as illustrated by Figure (1). Therefore, Japan offers a clean counterpart to our assessment of the euro area vis-à-vis Canada. Note that in this case, too, we find that the reactions of both industrial production and the (shadow) short rate show a pattern that is very similar to the first country pair, although the difference in the responses of industrial production across both regimes is less pronounced. Most importantly, we find again that a negative euro area demand shock leads to a decline in both prices and expected inflation, as well as a real depreciation of the euro exchange rate. This real depreciation occurs within both monetary policy regimes i.e. in the pre-ZLB period and once interest rates are at the ZLB. Figure (5) illustrates that prices, expected inflation, and the real exchange rate move very closely in both monetary policy regimes for the first 12 months. Importantly, however, the decline in prices and inflation expectations is not more accentuated when the negative demand shocks when interest rates are at the ZLB. At the same time, we find that the real exchange rate does not react more strongly when the economy's interest rates are at the ZLB. Figure (6) provides the impulse responses of the euro area vis-à-vis the US. In contrast to Japan, the US economy switched policy regimes. Since the Great Recession, the US has experienced times when the policy rate was constrained by the ZLB or remained unconstrained, as shown by Figure (1). To keep things short, our main findings are qualitatively

Figure 5: Results for the euro area vis-à-vis Japan



Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.

Figure 6: Results for the euro area vis-à-vis the US



Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.

robust for this country pair. Regardless of the euro area's state of being constrained or not constrained by the ZLB, we find a depreciation of the real exchange rate and the responses of prices and inflation expectations are within the two regimes' confidence bands.

B. *Unconventional Monetary Policy*

In the next step, we assess the ECB's balance sheet response to understand the role of unconventional policy measures in accommodating the negative disturbance when interest rates are at the ZLB. The motivation for this assessment can be seen in Figure (11) in the appendix. Before the ZLB was binding, the ECB's balance sheet grew modestly over time. However, from June 2014 onwards, the ECB's balance sheet increased tremendously. The reason was the ECB's large-scale asset purchases, which were mirrored in the ECB's balance sheet as part of the ECB's forward guidance, as outlined in section II.

We re-estimate our model for each country pair by adding the ECB's balance sheet as a seventh variable (in logs), keeping everything else to the benchmark specification. Importantly, we also leave the balance sheet response unrestricted. As discussed in section II, the large-scale asset purchases were conducted during the ZLB period to reduce long-term interest rates by driving down the yields on the securities the ECB was purchasing to meet their forward guidance. This should lead to lower interest rates throughout the economy and stimulate economic activity. Therefore, in our empirical assessment, we should expect a significant rise in the ECB's balance sheet to counteract the ZLB constraint during our ZLB state, while we would only expect an unincisive reaction of the balance sheet in the pre-ZLB period.

Figure (7) reports the results for this exercise. Since all the remaining impulse responses look similar to those in our baseline specification, we show the balance sheet response for all three country pairs. It stands out that only when interest rates are at the ZLB do we see a significant, expansionary balance sheet response. More specifically, the balance sheet rises significantly in all three cases after a demand shock, peaking at around two percent after about ten months.

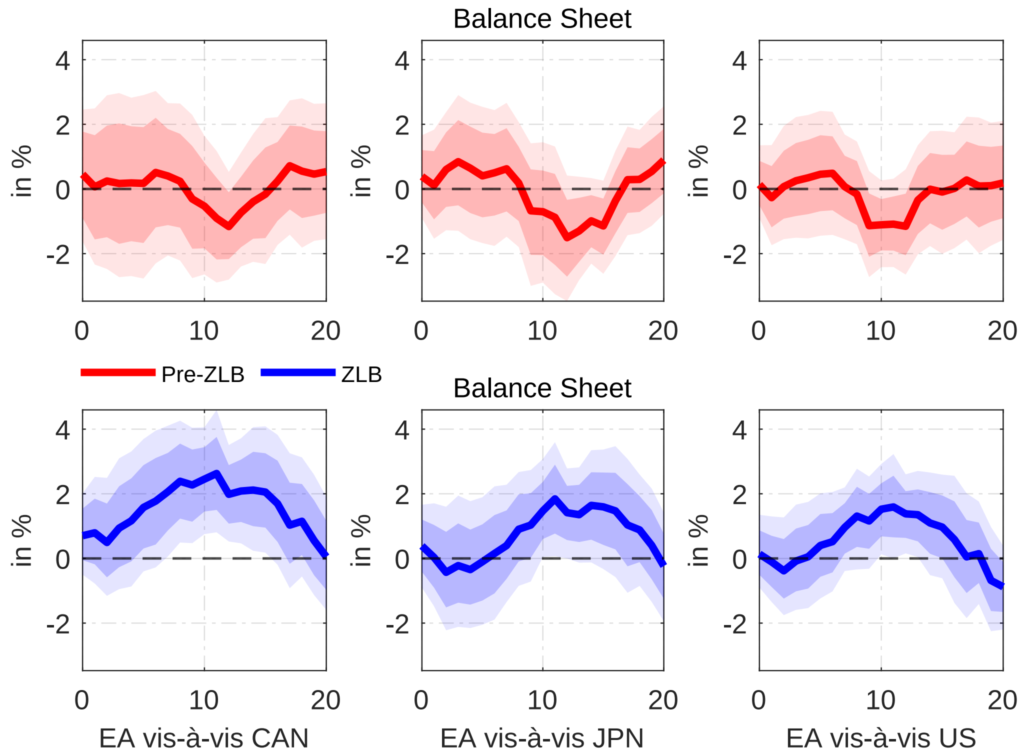
In non-ZLB scenarios, on the other hand, we do not observe any significant balance sheet reaction. The responses fluctuate around zero for all three country pairs and even show negative values after about ten months. However, these responses are not significant.

Overall, the balance sheet responses during the ZLB period are one good explanation for the accommodative decline of the shadow short rate in our baseline model in reaction to the negative demand disturbance.

C. *Quantifying the Role of the Real Exchange Rate as a Shock Absorber*

In this section, we quantify the potential of the exchange rate as a shock absorber. More specifically, we assess by how much the depreciation of the real exchange rate

Figure 7: State-dependent response of the ECB's balance sheet



Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.

cushions the effects of the adverse demand shocks on output and prices.

To do so, we proceed in two steps. Firstly, we simulate a counterfactual scenario by extracting the feedback effect of the response of the exchange rate on the response of the other endogenous variables. An appropriate environment for such an exercise relies on restricting the lag polynomials in the exchange rate equation to zero, except for its own lags. Thus, we assume that the exchange rate does not respond to past movements of all remaining endogenous variables. This, in addition to a zero restriction on the response on impact, guarantees that the exchange rate does not react to the demand shock over the entire projection horizon $h = 0, 1 \ldots H$. Our approach is in line with Bachmann and Sims (2012), who analyze the role of consumer confidence in the propagation of government spending shocks by isolating the feedback effects from the response of confidence on the response of the remaining endogenous variables.

Secondly, we calculate the forecast error variance decomposition (FEVD) for the baseline specification and the counterfactual scenario. Note that the FEVD tells us how important the demand shock is in explaining the variations of the variables in the model. It is important to note that the differences between the FEVDs must come from the suppressed feedback effect of the exchange rate on the other variables. Hence, the difference in the FEVDs tells us how much the depreciation of the real exchange

Table 2: Forecast error variance decompositions

	euro area vis-à-vis Canada					
		Pre-ZLB			*ZLB*	
	benchmark	*counterfactual*	*difference*	*benchmark*	*counterfactual*	*difference*
$h = 0$	67.2	77.7	10.5	67.2	77.7	10.5
$h = 3$	63.3	71.7	8.4	39.3	41.0	1.7
$h = 6$	52.9	60.7	7.8	30.3	30.8	0.5
$h = 12$	29.6	35.3	5.7	21.0	20.2	-0.8

	euro area vis-à-vis Japan					
		Pre-ZLB			*ZLB*	
	benchmark	*counterfactual*	*difference*	*benchmark*	*counterfactual*	*difference*
$h = 0$	46.7	75.5	28.8	46.7	75.5	28.8
$h = 3$	45.8	55.0	9.2	30.3	37.5	7.2
$h = 6$	38.4	39.5	1.1	24.7	23.2	-1.5
$h = 12$	20.7	22.1	1.4	20.4	15.9	-4.6

	euro area vis-à-vis the US					
		Pre-ZLB			*ZLB*	
	benchmark	*counterfactual*	*difference*	*benchmark*	*counterfactual*	*difference*
$h = 0$	73.7	81.2	7.5	73.7	81.2	7.5
$h = 3$	58.8	70.4	1.6	39.2	44.5	5.3
$h = 6$	54.0	52.6	-1.4	27.5	30.3	2.7
$h = 12$	26.6	24.8	-1.8	19.8	21.2	1.4

Notes: All values are based on the median estimates and are rounded to one decimal point.

rate cushions the effects of the adverse demand shocks.

Table (2) reports the results for this exercise. A few things stand out. First, the exchange rate can cushion much of the adverse effects of the demand shock, especially in the first few months after the shock occurs. We find for all three country pairs that the explanatory power of the demand shock on industrial production would be much higher if the exchange rate could not respond. For example, for the country pair euro area vis-à-vis the US, we find that in the baseline specification on impact, 73.7 percent of the forecast errors are explained by the demand shock in both states. In the counterfactual scenario, on the other hand, this value is 81.2 percent, i.e. around eight percentage points more. We also find a qualitatively similar picture and an even higher absorbing effect of the real exchange rate for the other two country pairs. Second, the absorbing effect of the exchange rate seems to be relatively short-lived. We find for all country pairs that the absorbing effect of the exchange rate fades after six months.

In conclusion, our empirical results in Table (2) show that the real exchange rate can absorb a considerable amount of variations in output, confirming its shock-absorbing capacity before and during the ZLB episode.

V Robustness Checks

In this section, we assess the robustness of our findings. To do so, we proceed as follows: First, we re-estimate our model for a broad set of 16 countries. Second, we investigate how our results change when we allow for smooth transitions between the states of the economy. Third, we compare our results from the LP to the empirical evidence from a state-dependent VAR. Finally, we compare the effects from different lag structures.

A. *Considering a Broad Set of Countries*

Our main results rely on three country pairs representing different monetary policy stances. In this subsection, we re-estimate our model for the euro area vis-à-vis a broader set of countries, namely 16 different trading partners for which trade weights are available. These countries consist of the 15 trading partners considered by the Bank of International Settlement (BIS) for the calculation of the *narrow index of the real effective* exchange rate, as well as China.[20] Based on the time-varying trade weights, as reported in Table (3), we calculate the real effective exchange rate for this set of countries.

Moreover, we use the same trade weights to calculate a weighted time series for industrial production in these countries. Hence, we summarize the information for all 16 countries and treat them as a single country. Finally, we calculate the share of industrial production in the euro area to this weighted industrial production series. By doing so, we are fully consistent with our baseline identification strategy.

We calculate the trade-weighted industrial production for the set of countries as

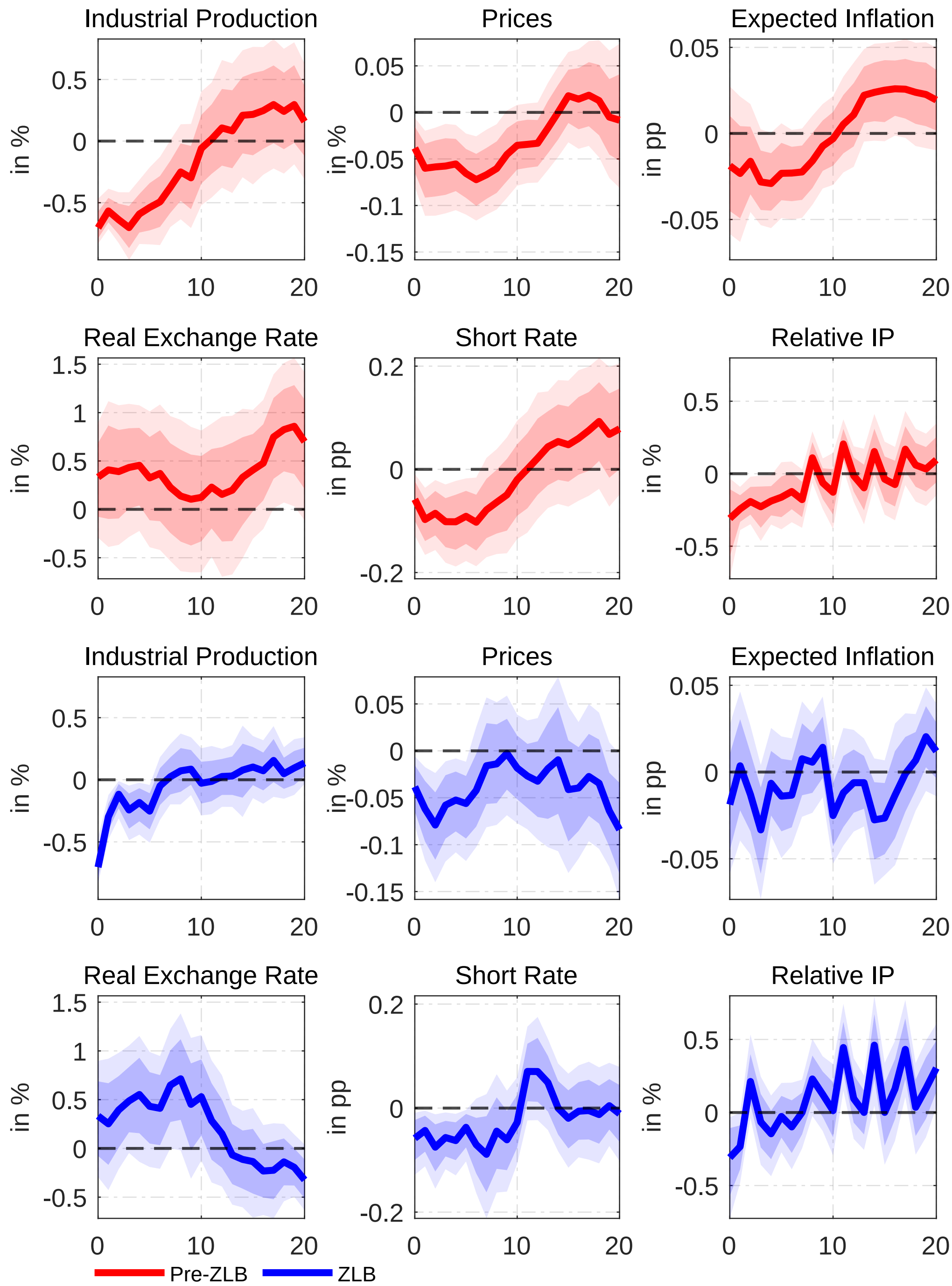
$$\overline{ip}_t = \chi_t^{1,ea} ip_{1,t} + \chi_t^{2,ea} ip_{2,t} + \ldots + \chi_t^{16,ea} ip_{16,t},$$

where $\chi_t^{j,ea}$ is the trade weight for country $j = 1, \ldots, 16$ in the real effective exchange rate, and $ip_{j,t}$ refers to the seasonally adjusted industrial production index of country j in period t.[21] Figure (8) shows the impulse responses for this exercise. Two things stand out. First, the impulse responses look similar to those presented in section IV. In particular, we observe a very similar pattern for the responses of industrial production, prices, expected inflation, and the (shadow) short rate. Second, we find again that the exchange rate depreciates both when interest rates are at the ZLB and when they are not. More precisely, the exchange rate response looks very similar to the responses of

[20] These countries comprise Australia, Canada, Taiwan, Denmark, Hong Kong, Japan, Korea, Mexico, New Zealand, Norway, Singapore, Sweden, Switzerland, the United Kingdom, and the United States. Importantly, we rescaled the trade weights for the 15 countries included in the narrow index of the real effective exchange rate such that the trade weights of these countries and China sum up to 100.

[21] Note that for Australia, New Zealand, and Switzerland, industrial production is only available on a quarterly basis. We, therefore, interpolate these series in order to get monthly data.

Figure 8: Results for the euro area vis-à-vis 16 trading partners



Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.

Table 3: Trade weights

Country \Years	1999–2001	2002–2004	2005–2007	2008–2010	2011–2013	2014–2020
			Asia			
China	7.5	12.0	17.5	23.6	26.2	26.9
Hong Kong	0.8	0.6	0.5	0.4	0.5	0.4
Japan	11.5	10.3	9.2	8.4	7.7	6.5
Korea	3.2	3.7	4.3	4.2	4.1	4.0
Singapore	2.1	2.0	2.0	1.9	2.0	1.8
Taiwan	2.9	2.6	2.5	2.4	2.3	2.2
			America			
Canada	2.2	2.1	2.1	2.0	2.0	1.9
Mexico	1.6	1.6	1.6	1.7	2.0	2.1
United States	26.3	23.6	21.4	19.9	19.5	21.3
			Europe			
Denmark	3.0	3.1	3.1	2.9	2.5	2.5
Norway	1.5	1.6	1.7	1.7	1.5	1.3
Sweden	5.5	5.6	5.6	5.2	5.1	4.6
Switzerland	8.1	8.4	8.0	8.7	8.6	8.1
United Kingdom	22.8	21.7	19.3	15.9	14.7	15.3
			Oceania			
Australia	0.9	1.0	1.0	1.1	1.1	0.9
New Zealand	0.2	0.2	0.2	0.2	0.2	0.2
Sum Σ	100	100	100	100	100	100

Notes: All values are taken from the Bank of International Settlement. Values are rounded to one decimal point.

our model for the euro area vis-à-vis the US. That is, the exchange rate significantly depreciates after half a year or so in the ZLB period, while the same is true after one year when the ZLB is not binding.

Table (4) reports the results from the same counterfactual exercise as in section C. As can be seen, the exchange rate also absorbs a considerable part of the adverse

Table 4: FEVD for the euro area vis-à-vis 16 trading partners

	Pre-ZLB			*ZLB*		
	benchmark	*counterfactual*	*difference*	*benchmark*	*counterfactual*	*difference*
$h = 0$	78.7	85.3	6.6	78.7	85.3	6.6
$h = 3$	74.2	76.6	2.4	43.1	46.9	3.8
$h = 6$	63.0	62.9	-0.1	31.4	32.6	1.2
$h = 12$	35.7	35.1	-0.6	18.0	18.2	0.2

Notes: All values are based on the median estimates and are rounded to one decimal point.

effects caused by the demand shock. However, as for the three country pairs in section IV, this effect lasts only a few months. In particular, our results indicate that the effect disappears after six months and the values for the baseline specification and the counterfactual scenario are almost identical.

Overall, we find that both the impulse responses and the role of the exchange rate as a shock absorber are very similar to the results from the previous section.

B. *Allowing for Smooth Transitions*

An important assumption in our analysis is that the economy jumps instantly from one state to another. However, the possibility of the ZLB being reached might affect economic decisions and expectations even before the ZLB becomes binding. If economic agents anticipate that the policy rate might reach the ZLB in the future, their inflation expectations might already react today. Hence, the economic consequences of the ZLB can already be effective even before the short rate reaches zero. We acknowledge this by allowing for a smooth transition between the two regimes *I=pre-ZLB* and *II=ZLB*. The model then reads as

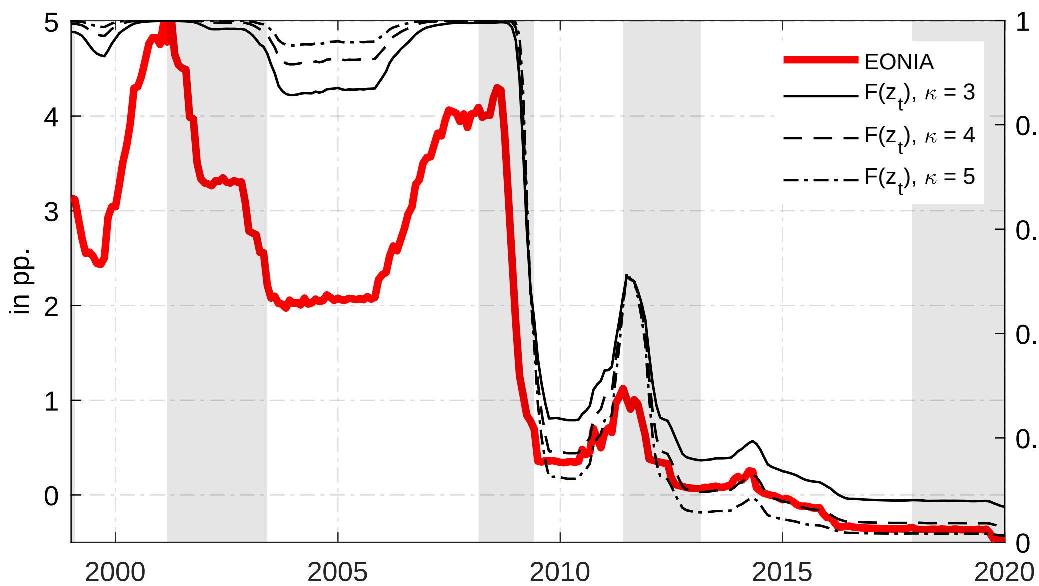
$$y_{i,t+h} = (1 - F(z_t))\left(\alpha^{I}_{i,h} + \beta^{I}_{i,h} y_t + \gamma^{I}_{i,h} x_t\right) + F(z_t)\left(\alpha^{II}_{i,h} + \beta^{II}_{i,h} y_t + \gamma^{II}_{i,h} x_t\right) + u_{i,h,t},$$

where everything is kept similar to the benchmark case, except that we replace λ_t with a logistic transition function $F(z_t)$ of the form

$$F(z_t) = \frac{\exp\left(\kappa \frac{z_t - \mu}{\sigma_z}\right)}{1 + \exp\left(\kappa \frac{z_t - \mu}{\sigma_z}\right)},$$

where μ is used to control the proportion of the sample the economy spends in either state, and σ_z is the sample standard deviation of the state variable z_t. Finally, the parameter κ controls how abruptly the economy switches from one state to the other following movements of the state variable z_t. As regards the choice of μ, we

Figure 9: Evolution of the state variable over time



Notes: The red line corresponds to the EONIA short-term rate (left axis), while the black lines correspond to the evolution of the state variable for $\kappa \in [3, 4, 5]$ (right axis).

choose the median value of the policy rate. This is based on the fact that, within our observation sample, the euro area policy rate was below one percentage point for 49.6% of the time. We choose three different values for κ, namely $\kappa \in [3, 4, 5]$. These values indicate an intermediate degree of intensity of the regime-switching behavior (see, for instance, Auerbach and Gorodnichenko, 2012; Tenreyro and Thwaites, 2016). Figure (9) shows the evolution of the state variable for all three parameters for κ over time. As can be seen, there is now a smooth transition to the ZLB state rather than the abrupt switch as in the baseline specification.

Figures (15) to (17) in the appendix show the results for this exercise together with the baseline results. Two things stand out. First, the results for all three country pairs are similar to those from the baseline specification with quasi-observable states. Second, the choice of κ does not seem to play a major role either, as the differences between impulse responses for different κ are negligible. While we do not plot the confidence bands for all individual impulse responses in order to avoid an unnecessarily crowded graph, we can make similar statements about significance as in our main results. This being said, here, too, we find a significant exchange rate depreciation after an adverse demand shock in both states.

Finally, one has to recognize that this result is also interesting in that the determination of the exact timing of the ZLB is not clearly defined. The methodology in this exercise circumvents this problem by dividing the proportions of states into periods in which the policy rate is either below or above one percentage point.

C. *Evidence From a State-Dependent SVAR*

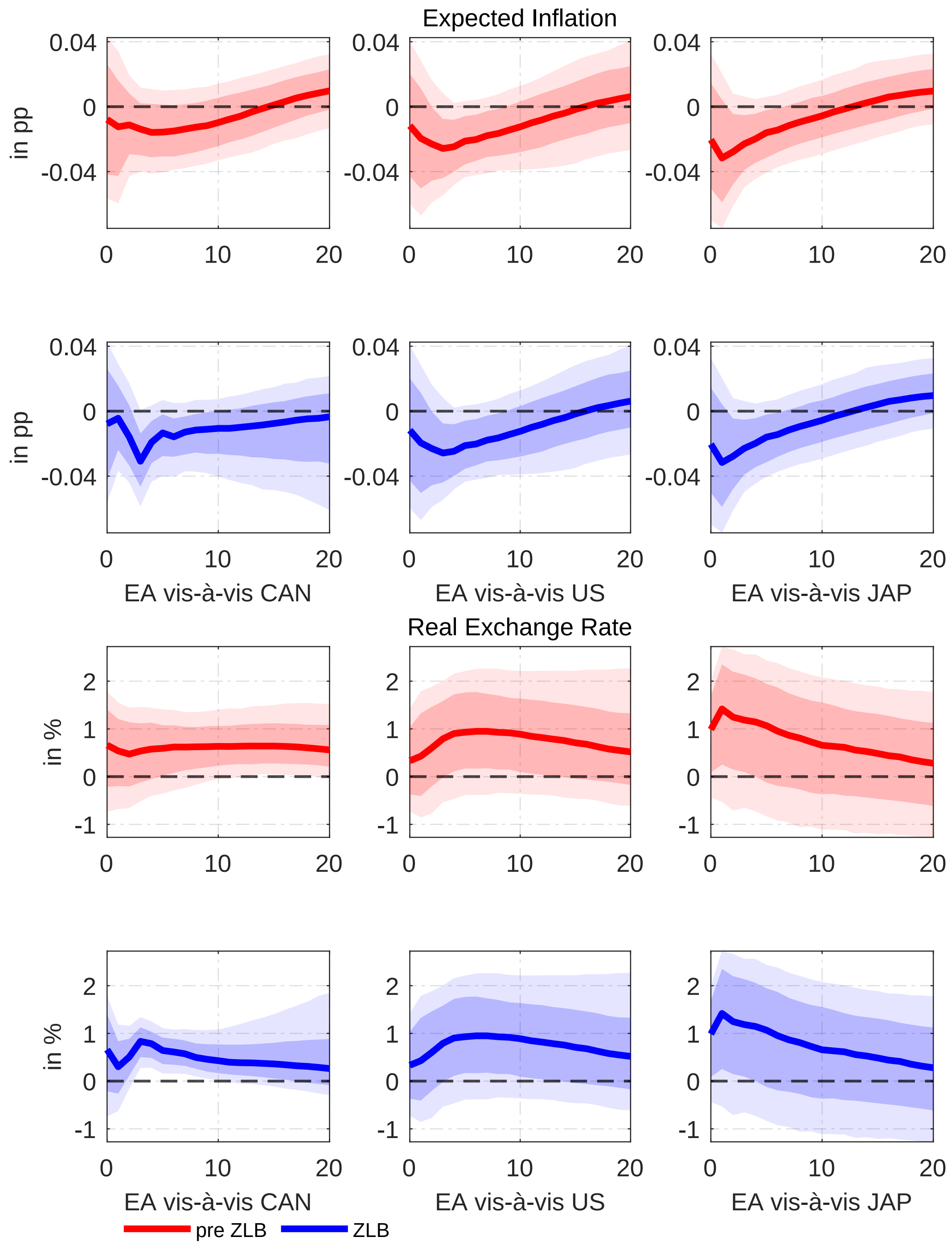
As a further robustness check, for each country pair, we estimate a state-dependent SVAR. We use the same endogenous variables in $\mathbf{y}_t$ and rely on the same identification strategy as in the baseline model. The state-dependent VAR, in its reduced form, reads

$$\mathbf{y}_t = (1 - \lambda_t)\, \mathbf{B}^I \mathbf{x}_t + \lambda_t \mathbf{B}^{II} \mathbf{x}_t + \mathbf{e}_t,$$

where $\mathbf{y}_t$ is an $n \times 1$ vector of endogenous variables, $\mathbf{x}_t = \left[\mathbf{y}_{t-1}, \ldots, \mathbf{y}_{t-p}, 1, t\right]$ is an $n \times np + 2$ matrix of control variables, $\mathbf{B}^j = \left[\phi_1^j, \ldots, \phi_p^j, \mathbf{c}, \delta\right]$ contains the reduced-form VAR coefficients and $\mathbf{e}_t$ is an $n \times 1$ vector of reduced-form error terms. Similar to the LP framework, the vector λ_t is equal to zero when the economy in period t is in state I and equal to one when the economy is in state II, respectively. We use the same identification strategy as in the LP framework, and for each model, we use $p = 2$ lags. This lag length is preferred by the AIC.

We find that the impulse responses are qualitatively similar to our benchmark results, although the VAR-based responses are somewhat smoother than the LP-based responses. On the one hand, this shows that our results are robust to the model specification, but on the other hand, it also shows that LPs and VARs produce qualitatively similar results even in a state-dependent framework (see, for instance, Plagborg-Møller and Wolf, 2021). Figure (10) illustrates those findings for the real

Figure 10: Results from a state-dependent SVAR



Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.

exchange rate and inflation expectations for the euro area vis-à-vis Canada, Japan, and the US. From the VAR-based assessment, we highlight two main findings: first, the real exchange rate depreciates significantly in both samples, i.e. prior to the ZLB being reached and once it has been reached for all country pairs. As for the LP analysis, the real exchange rate depreciation in the ZLB period contrasts with the predictions of the New Keynesian model outlined in section II. Secondly, the decline in inflation expectations in the ZLB period is not stronger than in the pre-ZLB period, thereby again confirming our findings from the state-dependent LP. As mentioned above, the findings align with the predictions of the extended New Keynesian model of section II, which allows the central bank to counteract the ZLB constraint through unconventional measures, in contrast to the version of the model in which unconventional policy measures do not feature.

The full set of results for state-dependent SVAR can be found in Figures (18) and (20).[22] They also confirm our findings from section IV concerning the evolution of industrial production and prices across the three country pairs.

D. *Different Lag Specifications*

It is well known that the dynamic properties of impulse responses may depend on the lag order of the underlying model fitted to the data, both for VAR and LP frameworks. This subsection reports our baseline results for different lag-length specifications.[23] For each country pair, we, therefore, show impulse responses for the case where the baseline model is estimated for $p = 1$ to $p = 4$ lags. To best compare the results, each model starts with the fifth observation, including the baseline specification estimated with two lags.

Figures (12) to (14) in the appendix report the corresponding results for this exercise. Note that, for all country pairs and all endogenous variables, the estimated impulse responses for $p = 1, 3, 4$ follow our baseline results very closely and always lie within the confidence bands of our baseline specification of $p = 2$. We conclude that our results are robust concerning the chosen lag length.

[22]These figures also show the impulse responses from the baseline specifications obtained by local projections. Importantly, the impulse responses from the VAR and the LPs mostly overlap for the restricted variables over the restricted projection horizon. Thus, we can confirm the finding of Plagborg-Møller and Wolf (2021) also for a state-dependent model.

[23]We also re-estimated our models where we take the past value of the state variable λ_t, as is often recommended in the literature. The results do not change in any way. Concerning state-dependent local projections using external shocks, Gonçalves et al. (2022) discuss conditions under which the state-dependent local projections estimator can be expected to recover the true population impulse responses. They show that in the case of endogenous state variables, the state variable has to be a function of the number of lags of the endogenous variable being equal to the projection horizon. In our approach, we identify the structural shock within the model instead of using external shocks. We also do not explicitly model the state variable based on current and past realizations of the endogenous variables.

VI Conclusion

According to the standard New Keynesian argument, the exchange rate cannot work as a shock absorber in response to an adverse demand shock when interest rates are at the ZLB. However, allowing for forward guidance as an additional policy tool suggests that the exchange rate could, in fact, also depreciate in a ZLB scenario. Our main contribution is to test this hypothesis empirically. We identify an adverse demand shock using sign restrictions and show that the real exchange rate depreciates both when interest rates are at the ZLB and when they are not. We find that the exchange rate fulfills its role as a shock absorber even when interest rates are at the ZLB, and output and inflation (expectations) are not significantly more volatile.

Our findings are robust for different country pairs: euro area vis-à-vis Canada, Japan, and the US. These countries represent different monetary stances among G7 countries. Furthermore, our empirical results show that the real exchange rate can absorb considerable variations in output, confirming its shock-absorbing capacity before and during the ZLB episode. Our findings are accompanied by a significant expansion of the ECB's balance sheet during the ZLB spell, while it remained unaffected in the pre-ZLB period. Overall, our empirical results support an open economy New Keynesian model with unconventional measures when interest rates are at the ZLB.

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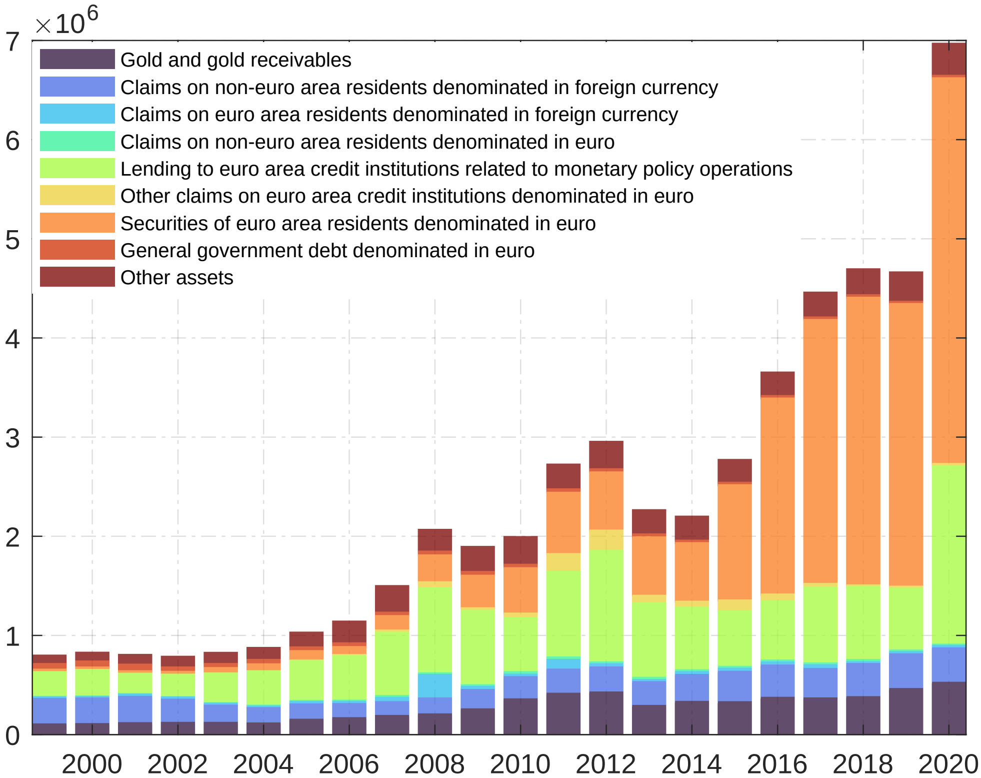
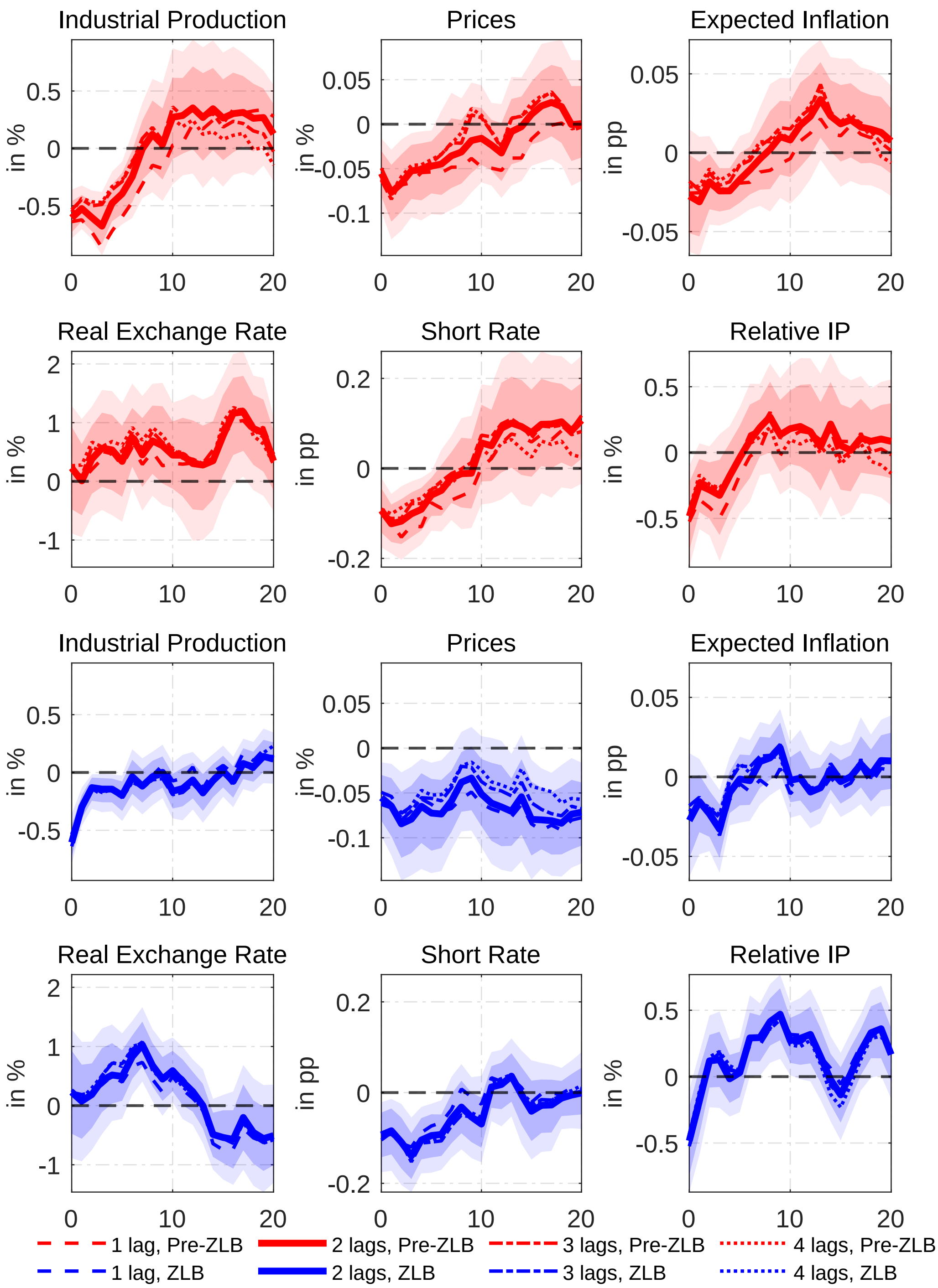
Figure 11: Consolidated balance sheet of the Eurosystem



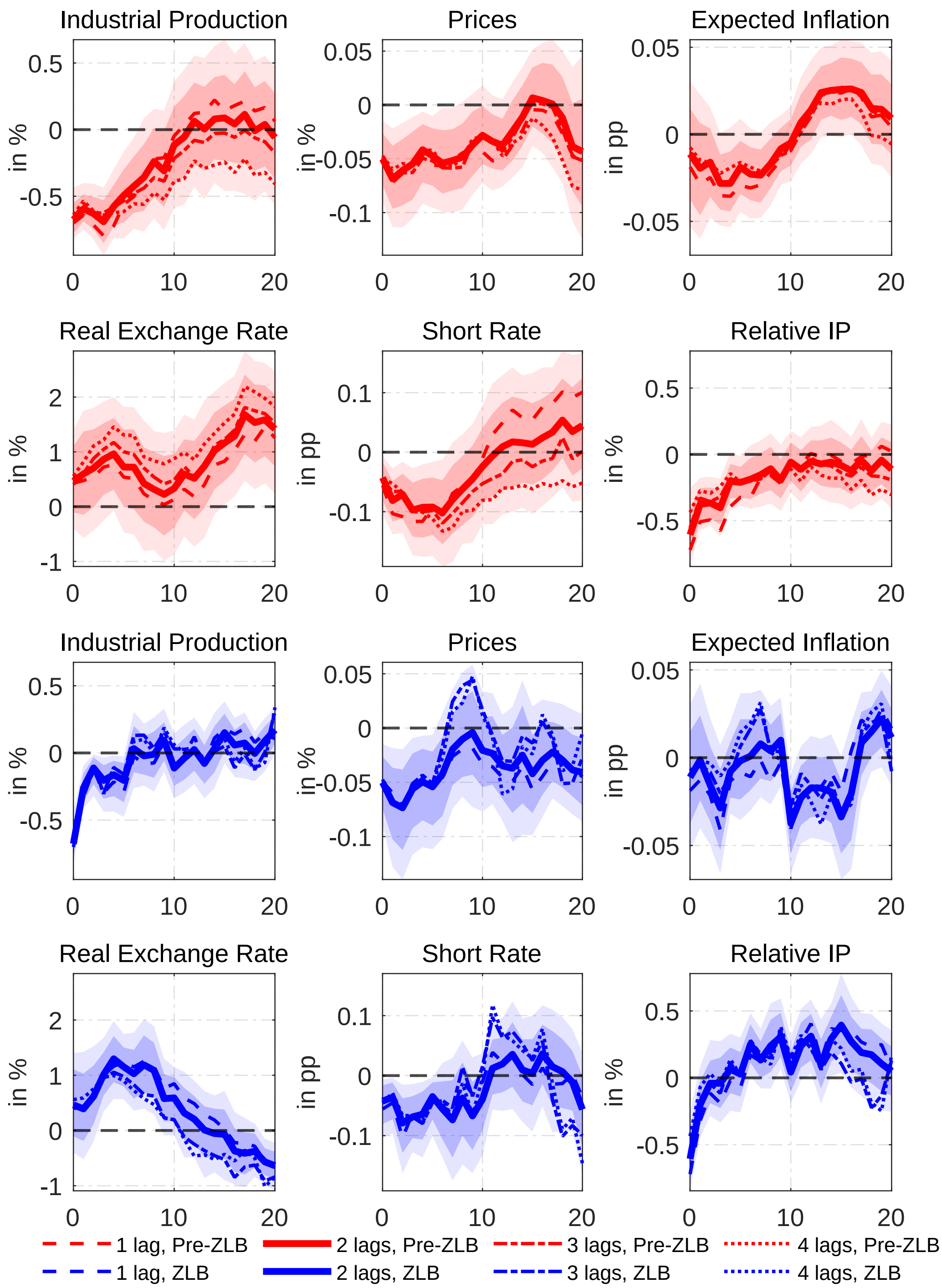
Notes: In million euros.

Figure 12: Different lag structure | euro area vis-à-vis Canada



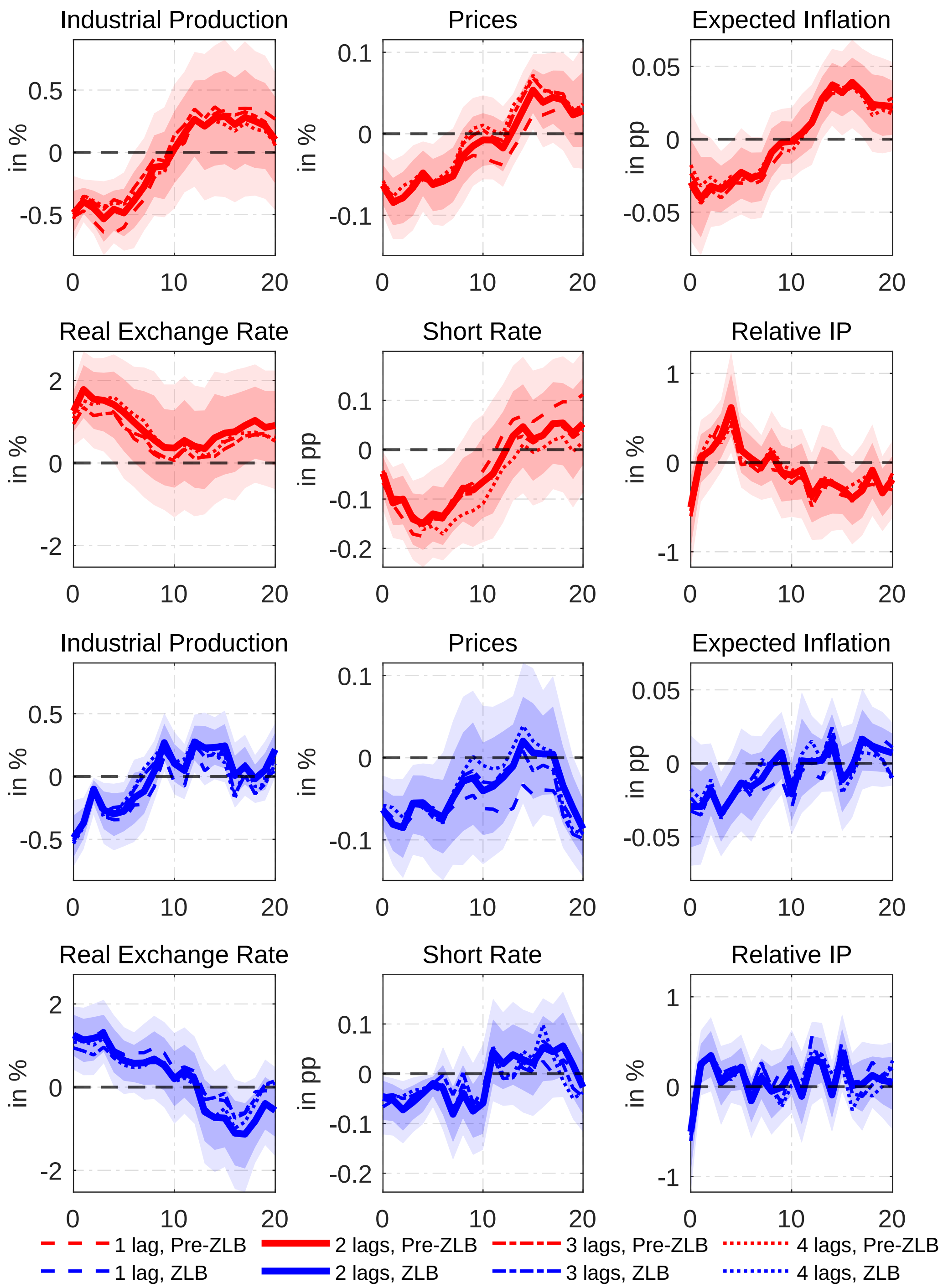
Notes: Median impulse response coefficients for different lag specifications. For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles of the baseline specification with $p = 2$ lags.

Figure 13: Different lag structure | euro area vis-à-vis the US



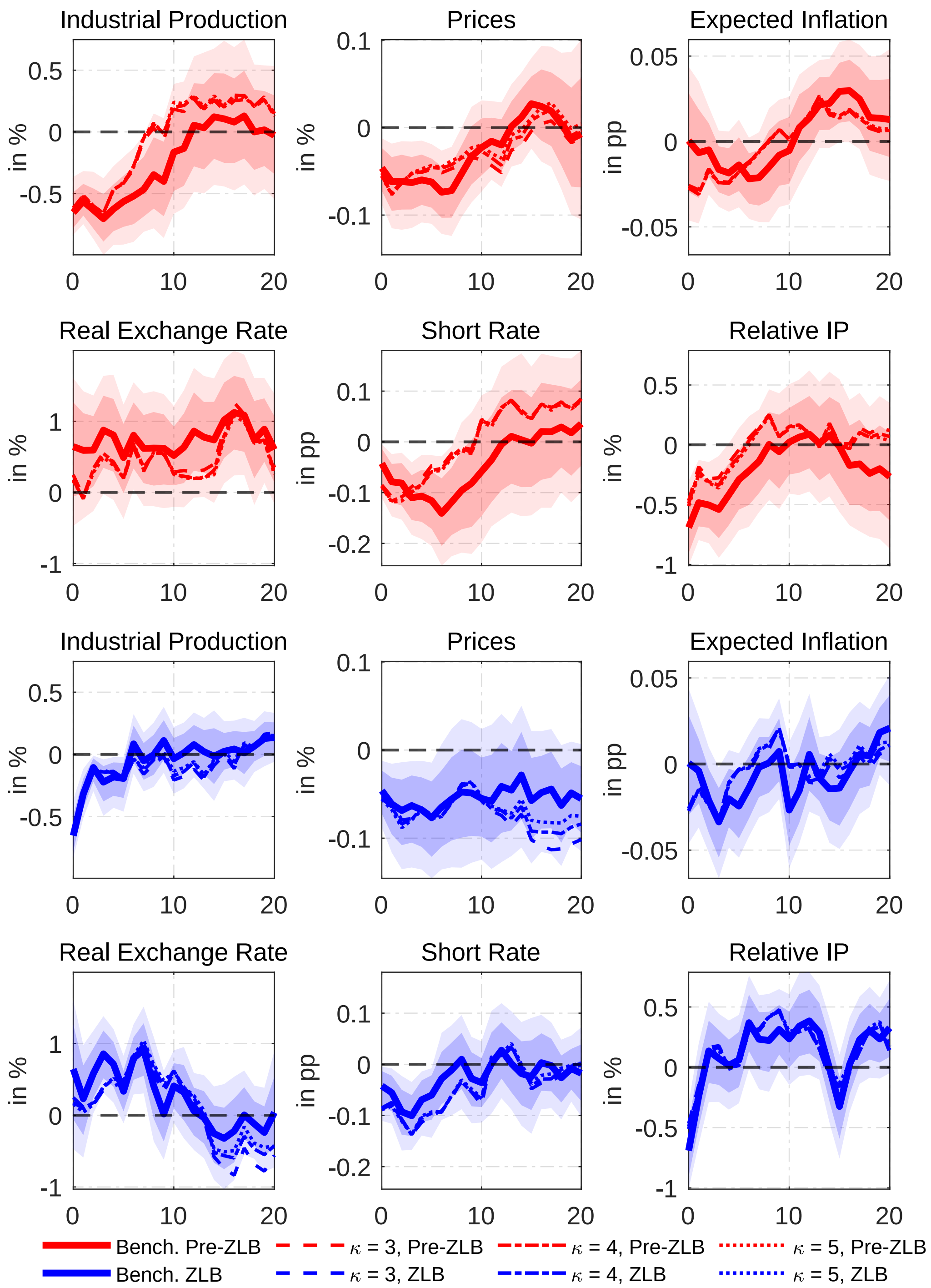
Notes: Median impulse response coefficients for different lag specifications. For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles of the baseline specification with $p = 2$ lags.

Figure 14: Different lag structure | euro area vis-à-vis Japan



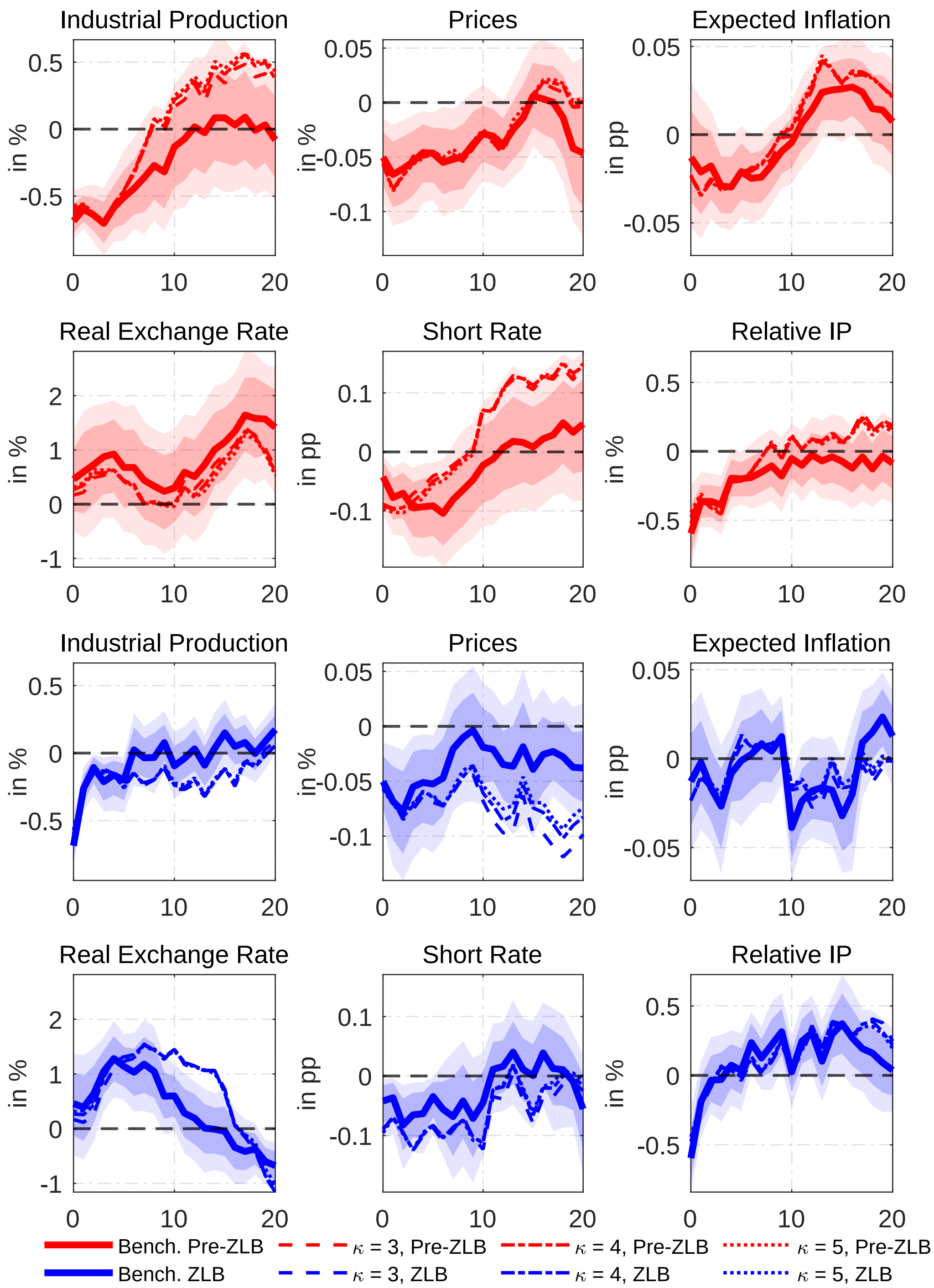
Notes: Median impulse response coefficients for different lag specifications. For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles of the baseline specification with $p = 2$ lags.

Figure 15: Smooth transitions | euro area vis-à-vis Canada



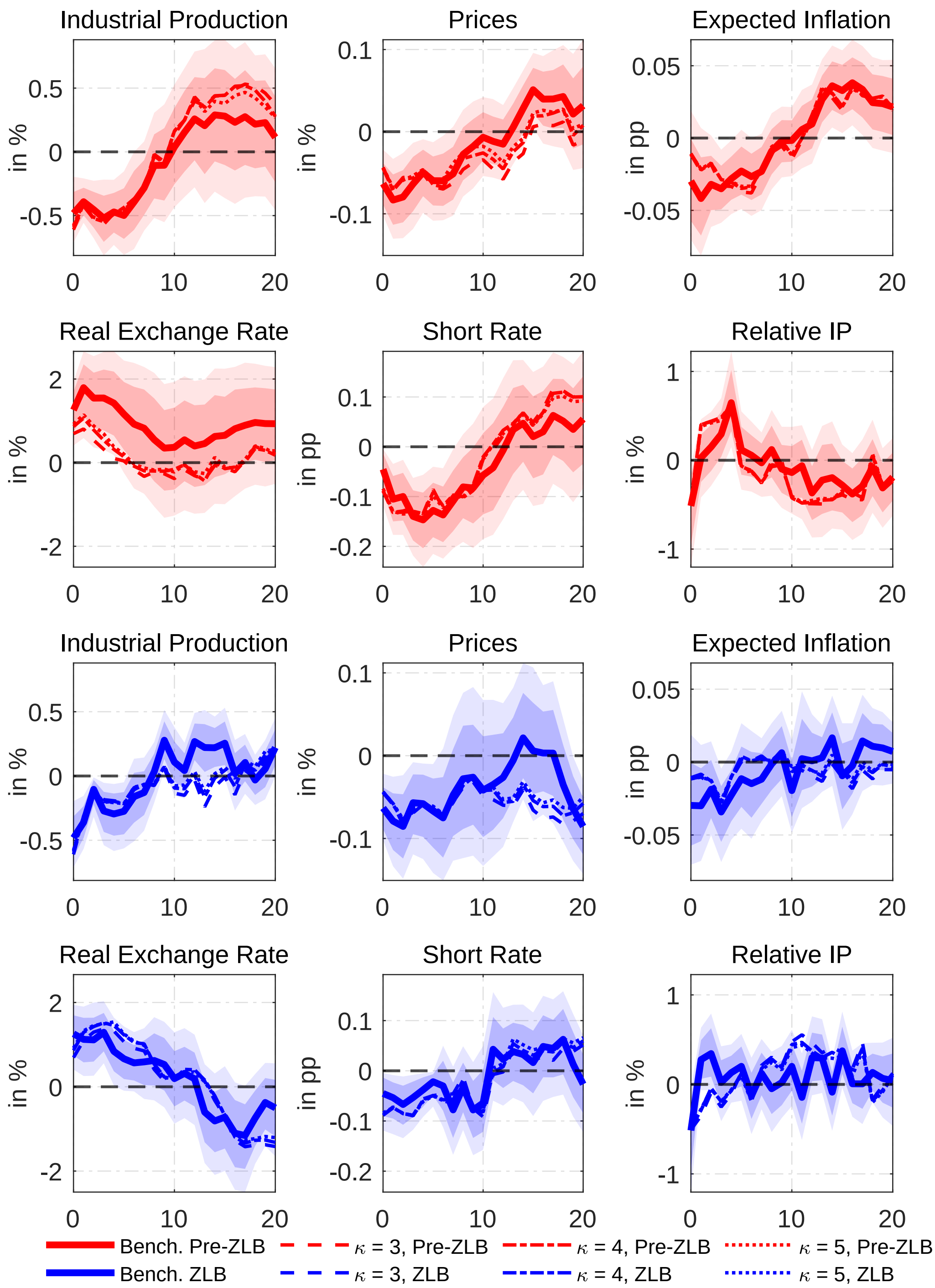
Notes: Median impulse response coefficients for different values for κ. For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles of the baseline specification.

Figure 16: Smooth transitions | euro area vis-à-vis the US



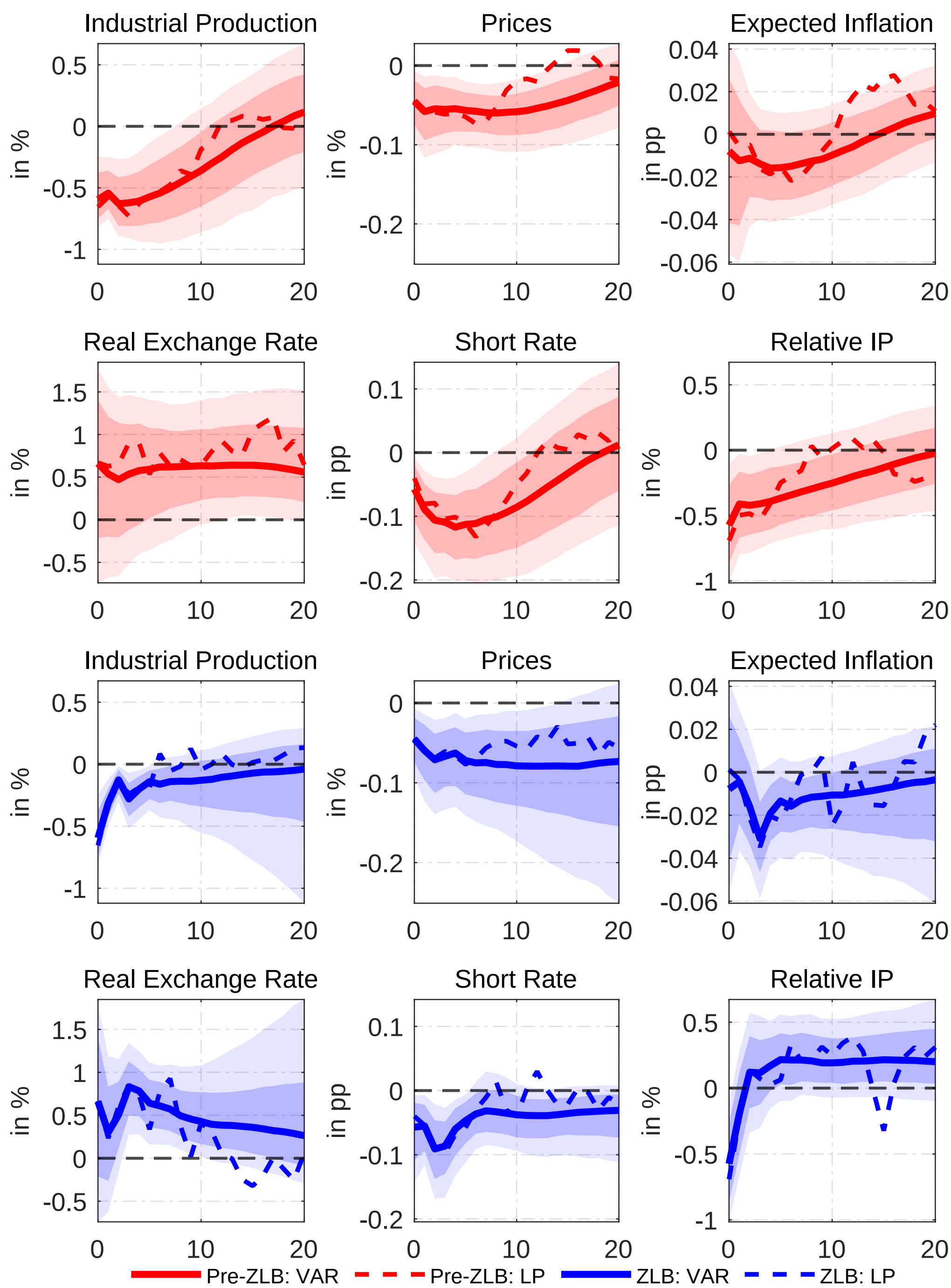
Notes: Median impulse response coefficients for different values for κ. For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles of the baseline specification.

Figure 17: Smooth transitions | euro area vis-à-vis Japan



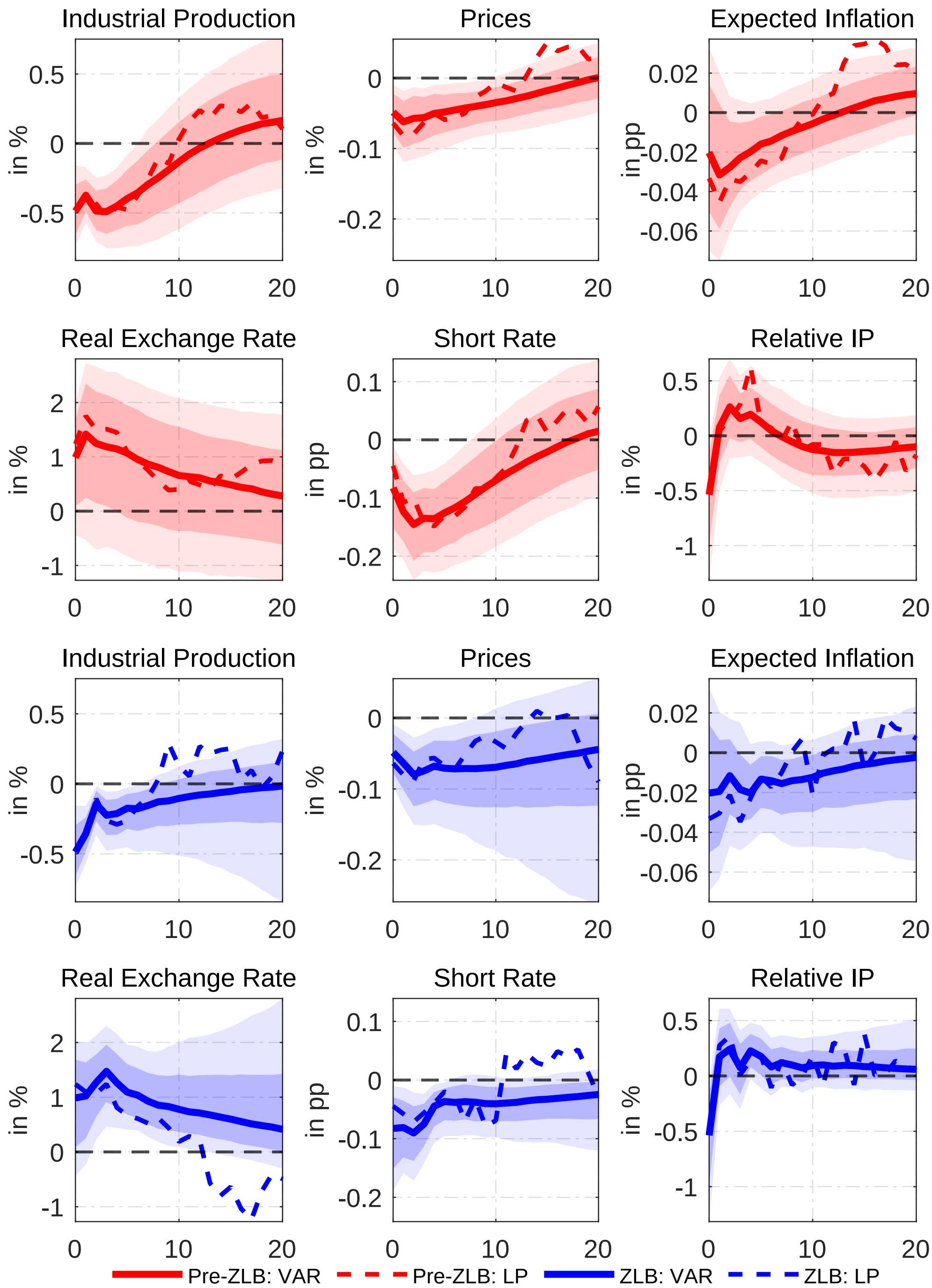
Notes: Median impulse response coefficients for different values for κ. For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles of the baseline specification.

Figure 18: Results from a state-dependent SVAR for the euro area vis-à-vis Canada



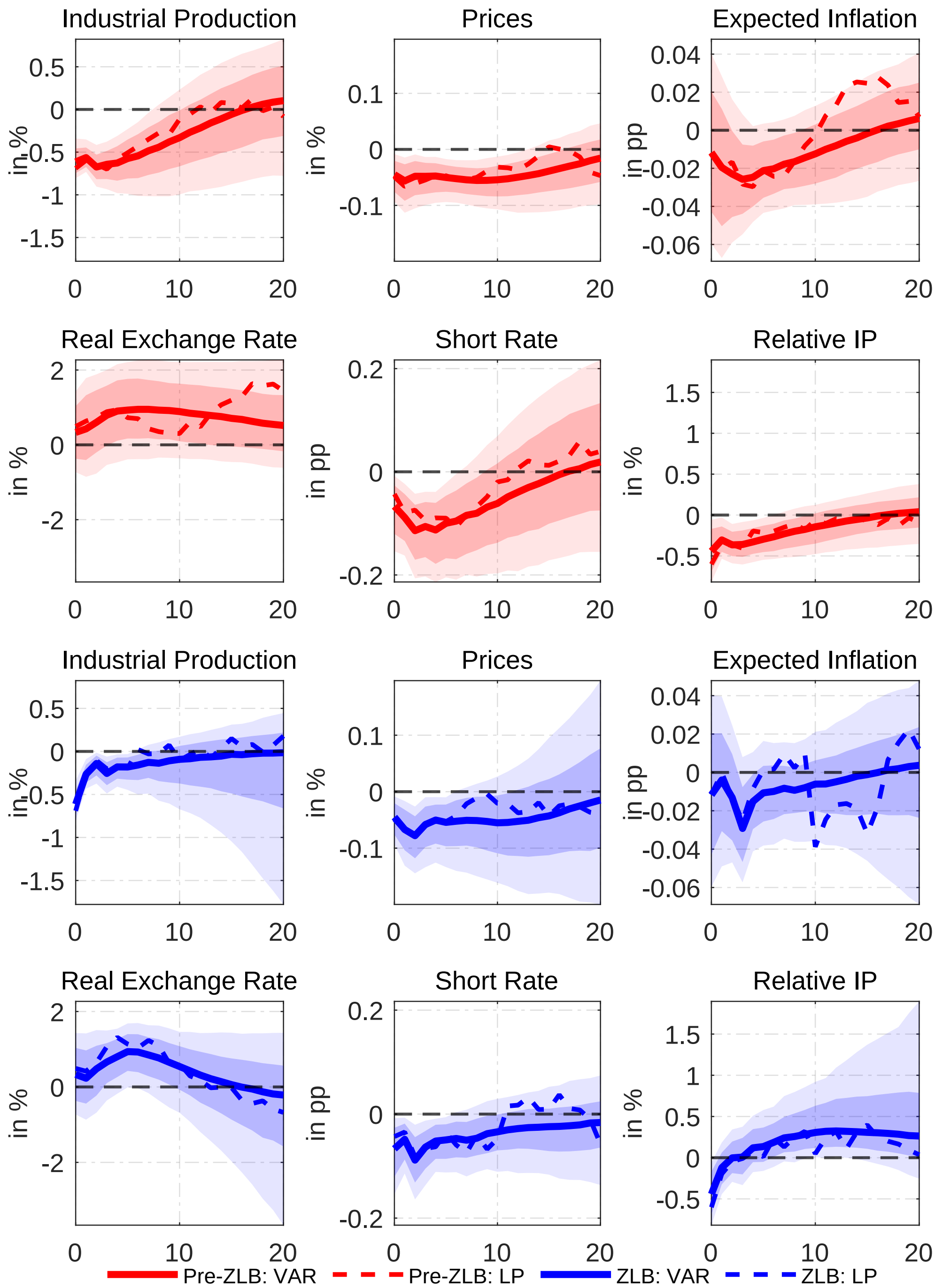
Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.

Figure 19: Results from a state-dependent SVAR for the euro area vis-à-vis Japan



Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.

Figure 20: Results from a state-dependent SVAR for the euro area vis-à-vis the US



Notes: Median impulse response for the pre-ZLB period (red line) and the ZLB period (blue line). For both states, the shaded areas correspond to the 5*th* (95*th*) and the 16*th* (84*th*) percentiles.