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THE EMPIRICAL IMPLICATIONS OF THE ZERO LOWER BOUND ON THE INTEREST RATE: THE CASE OF THE CZECH ECONOMY

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Abstract

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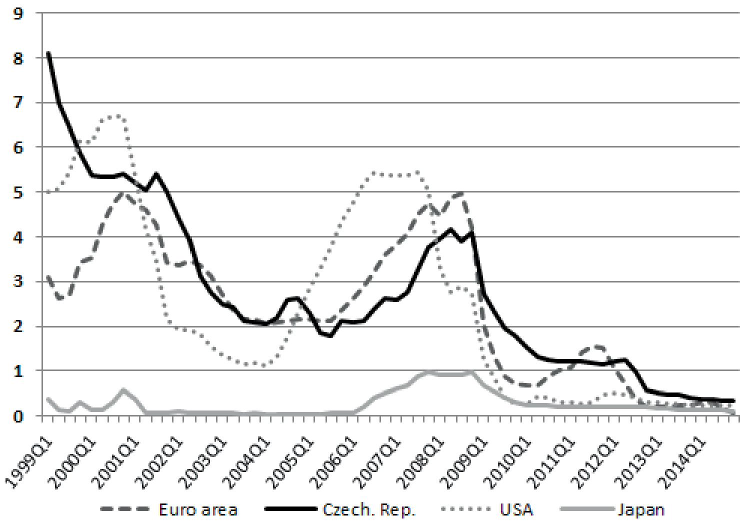
This paper uses an estimated DSGE model of the Czech economy to study the macroeconomic implications of various shocks when the interest rate is constrained by the zero lower bound. The goal is to identify which shocks represent threats for the economy and how large the distortions are. The results show that four single shocks can take the economy to the zero lower bound, and that of the four, productivity shock in the tradable sector is the most dangerous. The consequences for the behaviour of macroeconomic variables are nontrivial and, quite naturally, increase with the size of the shock and the frequency of occurrence. If the economy is subject to all model specific shocks, there are distortions in terms of lower average values of output and consumption (by more than one percentage point) and higher inflation volatility (by more than six percentage points). To reduce these costs, the central bank should give higher weight to inflation and lower weight to the output gap in monetary policy rule.

Keywords: zero lower bound on interest rate, DSGE model, occasionally binding constraint, monetary policy

INTRODUCTION

Many developed economies have experienced near-zero interest rates in the last few years. This is illustrated in Fig. 1. The United States and European countries (including the Czech Republic) have joined Japan, which has had consistently low interest rates since the 1990s. The situation in these economies is similar: they are slowly recovering from the recession and there are deflation pressures. This calls for expansionary economic policy to promote growth and increase prices. Monetary policy should respond by reducing interest rates, but this is not possible because the interest rates are near zero and cannot be negative.[1] This situation is called the liquidity trap or zero lower bound (ZLB) on interest rates. Naturally, it has consequences for the whole economy, which are worth exploring. The goal of this paper is to empirically assess the implications of the zero lower bound on the interest rate for macroeconomic variables in the Czech economy. Concretely, a DSGE model is estimated on Czech data by Bayesian techniques and a series of simulations is carried out. The types and sizes of disturbances that can push the interest rate to the zero lower bound are identified, as are the consequences this has for macroeconomic variables. The results show that for the interest rate conditions that prevail in mid-2015, four shocks could take the economy to the zero lower bound with a one-

1 Actually, recent experience show that some central banks really charge negative deposit rates. These examples includes central banks of Denmark, Sweden or Switzerland. However, the interest rate is only slightly negative, around minus 0.2 percent.



1: *Development of interest rates in selected economies*
Source: author's calculations, data: Eurostat

time impact. They are: productivity shock in the tradable sector, labour supply shock, monetary policy shock and productivity shock in the non-tradable sector. Of these, productivity shock in the tradable sector is the most "dangerous" and has nontrivial consequences for consumption, output and inflation behaviour. When a series of single shocks (similar in magnitude and persistence to those the Czech economy has experienced recently) is simulated, some other shocks arise as significant for the ZLB, but their impacts for macroeconomic variables are trivial. When a combination of all model specific shocks hits the economy, the output is lower by around 1.16 percentage points on average and its standard deviation increases by more than one percentage point. The impacts on consumption are even stronger. Quite surprisingly, average inflation is unchanged, but its volatility increases by more than six and half percentage points. To diminish these distortions, monetary policy should be more aggressive, placing greater weight on inflation, and should pursue strict inflation targeting (no weight on output).

LITERATURE REVIEW

The empirical consequences of the ZLB environment have been studied e.g. by Coenen *et al.* (2004), who ran a simulation of a small structural model subject to stochastic shocks similar in magnitude to those experienced in the U.S. during the 1980s and 1990s. They found that the ZLB constraint causes negligible distortions to macroeconomic variables if the inflation target is two percent. However, for inflation targets between zero and one, the volatility of output increases significantly and the volatility of inflation increases as well, albeit to a smaller extent. Gust *et al.* (2013) focus on the empirical implications of the ZLB in the U.S. economy during the Great Recession. They look at which shocks took the U.S. economy to the lower bound, and how much this constraint contributed to severity of the Great Recession. In a hypothetical situation in which monetary policy was not constrained, the GDP would have been one percent higher over the years 2009–2011. Ireland (2011) also argues that the U.S. economy would recover from the recession sooner and more quickly without this constraint on the interest rate.

Only a few papers have dealt with ZLB issues in relation to the Czech economy. Franta *et al.* (2014) discuss the use of exchange rate interventions as a solution for the situation of the zero lower bound on the interest rates. They confirm the suitability of this alternative monetary policy tool in the Czech economic conditions. Malovaná (2015) examines the effects of various shocks under different monetary policy regimes when the economy is at the ZLB. She finds that when the economy is at the ZLB, the volatility of the real and nominal variables is amplified in reaction to domestic demand shock, foreign demand and financial shocks and terms of trade shocks. When the central bank fixes nominal exchange rate at ZLB, it helps to mitigate deflationary pressures and to recover economic activity. Hloušek (2014) analyses a small open economy model estimated using Bayesian techniques on Czech data. The results show that the shocks likely to take the economy to the ZLB are domestic cost-push shock and foreign preference shock. The constraint on the interest rate has implications for consumption and output behaviour, but these are quantitatively small. This paper closely follows the strategy used in Hloušek (2014), but uses a larger model, extends the analysis for a broader combination of shocks, and discusses their impacts for monetary policy. Finally, Hloušek (2016) also deals with the impacts of the zero lower bound for the macroeconomy, but his research question is focused on inflation target setting by the central bank.

Model Economy

The model used in this paper is borrowed from Kolasa (2009). The model structure is described only verbally here, and the full model equations are to be found in the Appendix. It is a model of two open economies, which are treated identically, and differ only by their size, which is determined by the calibrated parameter *n*. The domestic economy represents the Czech economy, and the foreign economy is the Euro area.

There are two types of firm in every economy: producers of tradable goods and producers of non-tradable goods. The production function is Cobb-Douglas using capital and labour. The capital accumulation is subject to adjustment cost. The output is divided into consumption and investment goods. The tradable consumption and investment goods are combined with imports to make composite goods, a proportion of which are exported. There is assumed price rigidity at three stages of the production process. The rigidity is modelled in Calvo (1983) style and results in three price Phillips curves (for home tradable goods, non-tradable goods and composite consumption goods). Households consume a bundle of tradable and non-tradable goods, and decide about labour supply and bond purchases. There is an assumption of habit formation in consumption. Households have different labour skills, which gives them the power to influence wages. The wage setting is subject to rigidity, which is again modelled according to Calvo (1983).

The government collects lump-sum taxes to finance its expenditures and always has a balanced budget. The government expenditures consist of domestic non-tradable goods and are modelled as an AR(1) process. Monetary policy follows the Taylor rule with interest rate smoothing and attention to inflation and the output gap.

The model consists of forty structural equations and its dynamic is driven by seven exogenous shocks in each economy. Six of them follow AR(1): these are productivity shocks in the tradable sector and the non-tradable sector, a labour supply shock, an investment efficiency shock, a consumption preference shock and a government spending shock. Monetary policy shock is assumed *iid*.

DATA AND METHODS

The methodology of estimation closely follows Kolasa (2009). The model is estimated using data for fourteen variables – GDP, consumption, investment, inflation, real wages, nominal interest rate and internal exchange rate[2] each for both the domestic and foreign economies. These data series are chosen so that they correspond to model variables that could be observed; their number equals to the number of shocks in the model for the sake of identification purposes. The time series enter as the growth rates and are demeaned before estimation. Only the nominal interest rate and price inflation are used without transformation and are also demeaned. The data are quarterly and are taken from the Eurostat database, covering the time period 2001:Q2–2014:Q1. The time span is determined by the availability of data for the calculation of the internal exchange rate.

The model parameters are estimated using Bayesian techniques. A posterior distribution of the parameters is obtained by the Random Walk Chain Metropolis-Hastings algorithm. This generates 2,000,000 draws in two chains with 1,000,000 replications each; 90% of the replications are discarded so as to avoid any influence from initial conditions. MCMC diagnostics are used to verify the convergence. All computations are carried out using the Dynare toolbox (Adjemian *et al.*, 2000) in Matlab software.

The estimated model is then simulated using the *Occbin toolbox* developed by Guerrieri and Iacoviello (2015), who use a piecewise linear perturbation method that is able to solve dynamic models with an occasionally binding constraint. This method provides a very good approximation of a dynamic programming solution but is much easier to implement and is much faster even for models with many state variables. This algorithm captures nonlinearities that arise in models with two regimes – with and without a binding constraint. Therefore, it is suitable for studying the effects of attaining the zero lower bound on the nominal interest rate.

Calibration and Estimation Results

Thirteen structural parameters are calibrated according to the data of national accounts. Ten structural parameters, seven standard deviations of shocks and six autoregressive parameters are estimated for each economy. The domestic and foreign shocks are allowed to correlate and the correlation coefficient is also estimated. The priors of the estimated parameters are set according to Kolasa (2009) and Slanicay (2013).

The results of the estimation are reported in Tab. A.I and A.II in the Appendix. Here, we look at just a few of the most relevant estimated parameters. The parameters of monetary policy rule are as follows: the posterior mean of the interest rate smoothing parameter is $\rho = 0.85$, the weight to inflation is $\Psi\pi = 1.37$, and the weight to output gap is $\Psi_y = 0.07$. These estimates are quite comparable with the results of other empirical studies for the Czech economy. The persistence and volatility of the shocks are reported in Tab. A. II and are key to our analysis. The most persistent shock is domestic productivity shock in the tradable goods sector,

2 Calculated as price of tradable goods divided by price of non-tradable goods.

ρ_{a^H} = 0.91, while the least persistent is domestic productivity shock in the non-tradable goods sector, ρ_{a^N} = 0.45. The most volatile shock is domestic labour supply shock, with standard deviation σ_l = 0.345, while the least volatile is domestic monetary policy shock, σ_m = 0.002. Generally, the shocks in the Czech economy are more volatile than the shocks in the Euro area. A very high correlation was found between the two economies for monetary policy shocks.

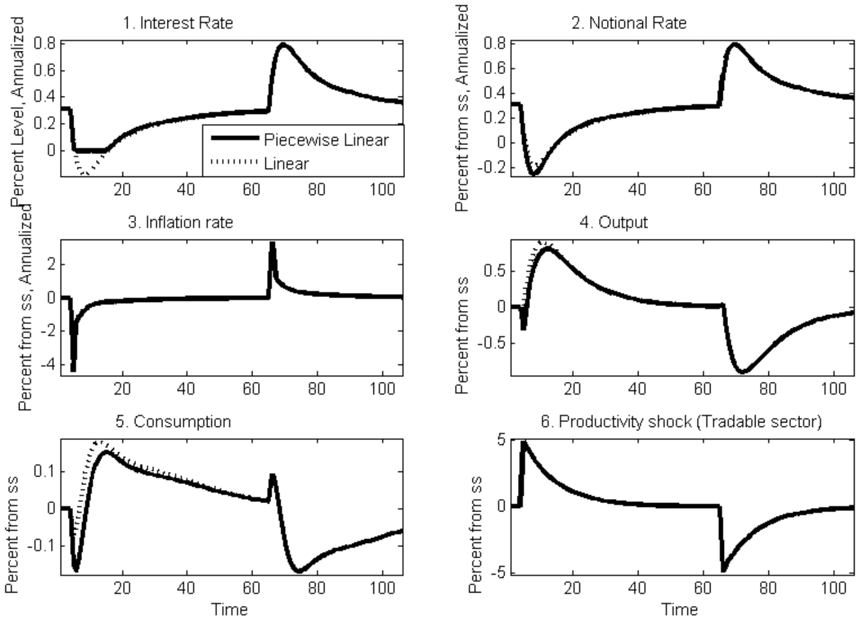
Results from Model Simulation

The shocks and their impact for model behaviour form the core of our analysis. First, impulse response functions are used to study the variables' reactions in response to positive and negative values of the shocks and the differences in the behaviour of these variables when the interest rate is and is not constrained by zero value is evaluated. Second, the model is simulated to a series of the shocks. The subject of interest is how often the interest rate is binding and what the average duration of the ZLB period is. As in the previous case, the reactions of the macroeconomic variables in terms of their average values and volatility are compared. This analysis is carried out for each shock and for a combination of all fourteen model shocks.

The initial condition for the nominal interest rate is rather important for the results. As we are interested in the current situation of the Czech economy and the future possible cost of the zero lower bound constraint, the initial nominal interest rate is set to 0.3 percent annually, which corresponds to the 3M PRIBOR in the second quarter of 2015.

Impulse Responses

Fig. 2 shows the reaction of the model variables to a productivity shock in the tradable sector. The size of the shock is one standard deviation (posterior mean obtained from estimation). The y-axis shows the percentage deviation from the steady state, except for the first subgraph, which is in percent level. The dotted line depicts the linear solution which corresponds to a situation in which the nominal interest rate is allowed to be negative. The solid line depicts the piecewise linear solution and corresponds to the zero lower bound case. Let us examine the linear solution first. The economy is subject to positive productivity shock in period five. This causes inflation to decrease and output to increase. The central bank reacts to low inflation by lowering the interest rate. Consumption initially drops because the high real interest rate makes consumption more expensive and forces people to postpone it for the future. After this drop, consumption quickly rises above the steady state. In the piecewise linear solution, the central bank cannot decrease the nominal interest rate enough, because it hits the zero lower bound. The interest rate stays at zero value for ten periods and then moves in line with the linear solution. The constraint on the interest rate results in a larger initial drop in the inflation rate (by around one percentage point). There is also a difference in the reactions of output and especially consumption. There is a stronger initial drop, and the trajectory in the ZLB case is lower for a longer time compared to the unconstrained version. The top right panel in Fig. 2 shows the impulse responses of the notional interest rate. The linear version is the same as the



2: *Impulse responses to productivity shock in tradable sector (ZLB and noZLB case)*
Source: author's calculations

linear version for the nominal interest rate; the piecewise linear solution shows the interest rate's behaviour if the central bank reacts to variables in the piecewise linear solution (ZLB case). As the inflation rate decreases more, and because of the small initial drop in output, the central bank should respond with more expansionary monetary policy, i.e. by lowering the interest rate. After sixty periods, the variables are back at steady state. Then a negative productivity shock hits the economy in period sixty five. The reaction of the variables is a mirror image of the previous case, but now both solutions coincide, because the interest rate is not constrained.

This analysis is carried out for all fourteen shocks, and demonstrates that for four of them the interest rate is binding in at least one period. These are quoted in Tab. I together with the estimated standard deviation and number of periods when the interest rate was binding. Three sizes of shocks are assumed: one, two and three standard deviations.[3] The pattern is as expected: the larger the shock, the longer the interest rate is binding. Of these four shocks, productivity shock in the tradable sector is the most distinct, even though its estimated standard deviation is only 5 percent. An example of such a shock is technological improvement in the engineering industry, which causes more goods to be produced with given resources. Even if this shock increases output, which may be considered a positive impulse during the recession, it decreases inflation and thus forces the central bank to lower the interest rate, which becomes problematic at the ZLB.

Labour supply shock was estimated as the most volatile and is the second most "dangerous" shock in this analysis. Positive labour supply shock can be represented by a decrease in the weight of leisure in consumers' utility, or some exogenous increase in labour force. This shock translates into higher output and consumption, and lower wages. The lower wages decrease marginal costs and thus inflation, which is again a signal for the central bank to decrease the interest rate.

Monetary policy shock is the least volatile, but could take the economy to the ZLB for two periods. The reasoning is obvious: this shock directly influences the nominal interest rate. Productivity shock in the non-tradable sector only causes interest rate binding at larger values of this shock (two and three standard deviations).

As we have seen in Fig. 2, the zero lower bound can cause macroeconomic variables to behave differently in reaction to the shocks. First, we will quantify the difference at the peak (trough) of impulse responses. The upper panel of Fig. 3 shows the consumption reaction to different sizes of productivity shock in tradable sector, up to three standard deviations, for both positive and negative values of the shocks. The size of the shock is given on the x-axis. The y-axis measures the percentage deviation of consumption from the steady state for both the ZLB and noZLB cases. The lower panel shows the difference between the two trajectories from the upper panel. For an average size shock (one standard deviation) the difference is negligible, however it increases non-linearly with the size of the shock. The drop in consumption is greater by 1.6 percentage points for a shock of three standard deviations.

The differences for other shocks and other macroeconomic variables (output and inflation) are shown in Tab. II. The distortions correspond to the results from Tab. I. The productivity shock is the most "dangerous" and can cause significant costs – lower consumption, output and inflation.[4] For average values of the shock, the costs are moderate. However, when a shock as large as three standard deviations hits the economy, output is reduced by four percentage points and inflation by sixteen percentage points p.a. Such a situation is, of course, not very likely. Given the fact that innovations to the shocks are normally distributed, shocks bigger than three standard deviations are probable in just 0.3 % of cases. The costs caused by other shocks are much smaller, and correspond to the number of periods for which the economy stays at the ZLB.[5] Labour

I: *Binding interest rate for selected shocks*

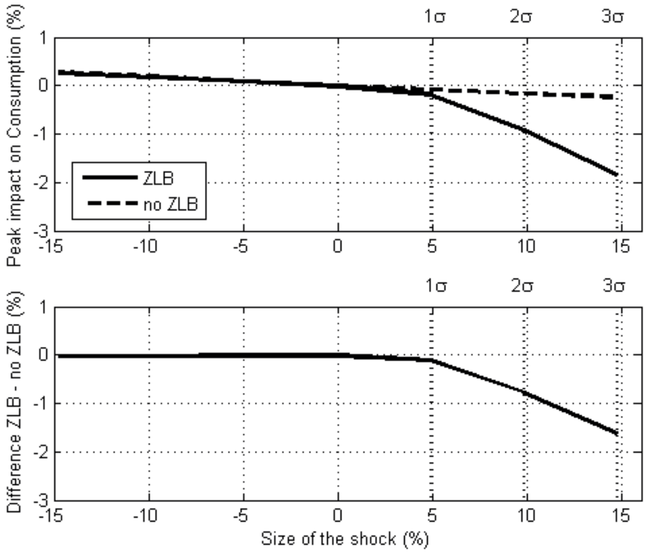
	Posterior mean of std	Interest rate is binding		
		1σ	2σ	3σ
Prod. shock – tradable sector	0.0491	10	17	20
Labour supply shock	0.3486	4	9	11
Monetary policy shock	0.0015	2	4	5
Prod. shock – non-tradable sector	0.0825	0	3	4

Source: author's calculations

3 As the shocks are assumed to have a normal distribution, the one standard deviation covers 68.3% of all shocks, two standard deviations cover 95.4% and three standard deviations cover 99.7% of shocks that occur statistically in the economy.

4 Lower inflation can be perceived as a beneficial result, however if the inflation is negative (deflation) it brings costs rather than benefits.

5 As indicated in Tab. I.



3: *Response of consumption to a productivity shock in the tradable sector*
Source: author's calculations

II: *Implications of the ZLB at impulse responses (difference ZLB – no ZLB in percentage points)*

	Impact on consumption			Impact on output			Impact on inflation (p.a.)		
	1σ	2σ	3σ	1σ	2σ	3σ	1σ	2σ	3σ
Prod. shock – T sector	–0.10	–0.76	–1.61	–0.27	–1.91	–4.04	–1.07	–7.72	–16.40
Labour supply shock	–0.01	–0.15	–0.33	–0.02	–0.49	–1.13	–0.11	–1.95	–4.46
Monetary policy shock	–0.02	–0.11	–0.22	–0.06	–0.32	–0.63	–0.22	–1.13	–2.26
Prod. shock – NT sector	0.00	0.00	–0.01	0.00	–0.03	–0.14	0.00	–0.09	–0.49

Source: author's calculations

supply shock and monetary policy shock have non-negligible consequences for macroeconomic variables only when these shocks are large, and productivity shocks in the non-tradable sector have only trivial impacts.

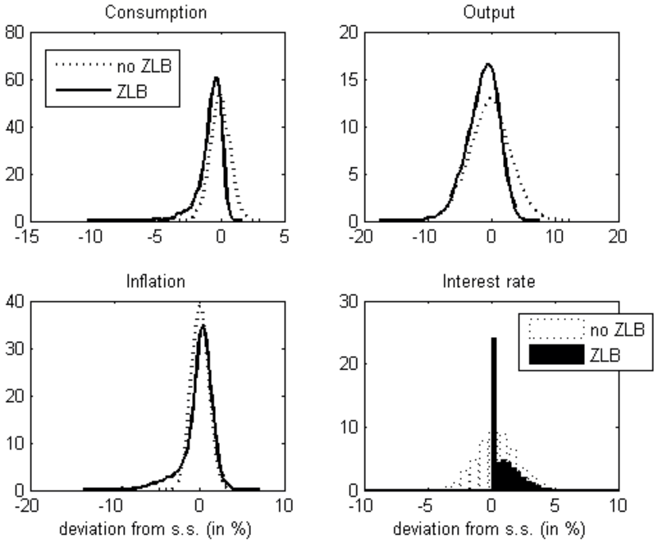
Simulation in the Presence of Single Shocks

The situation we have just examined assumed that the shocks hit the economy only once and that their effects fade out with time. The next exercise assumes, on the contrary, that each shock occurs in a large number of periods. Most of the shocks follow the AR(1) process:

e.g. $$\epsilon_{g,t} = \rho_g \epsilon_{g,t-1} + \mu_{g,t},$$

where the term "shock" is used for the variable $\epsilon_{g,t}$ and the term "innovation" for $\mu_{g,t}$ which has properties $\mu_{g,t} \sim N(0, \sigma_g)$. Concretely, five thousand random numbers from a normal distribution are generated and then multiplied by the estimated standard deviation of the particular shocks. These numbers correspond to the innovations. The shocks follow an autoregressive process with persistence parameters obtained from the estimation and the series of these innovations. Therefore, this construction should resemble the shocks that the Czech economy truly experienced during the estimated period. The empirical distribution from this simulation in the presence of productivity shocks in the tradable sector is shown in Fig. 4. The solid line depicts the distribution for the ZLB case, while the dotted line indicates the case with a non-binding interest rate (no ZLB). It is clear that the distribution in the ZLB case is shifted to the left for consumption and output, and to the right for inflation. It corresponds to the results obtained from impulse responses. Statistical properties and other characteristics for all important shocks are shown in Tab. III. The second column shows the probability of the interest rate binding to the ZLB, the third column shows the average duration of its spell at the ZLB, and the fourth to seventh columns show the impact for macroeconomic variables in terms of median differences between the ZLB and noZLB cases.

As the shocks are quite persistent and several successive adverse innovations can occur, the probability that the economy reaches the ZLB and stays there is higher compared to impulse responses. The interest rate is binding for productivity shocks in the tradable sector and for labour supply shocks, in almost 40 percent of cases. These two shocks also exhibit non–trivial losses in terms of lower consumption and output. Productivity shocks in the tradable sector reduce the average consumption and output by 0.54 and 0.94 percentage points,



4: *Empirical distribution for productivity shocks in the tradable sector*
Source: author's calculations

III: *Simulation of reaction to single shocks*

	Binding IR (in %)	Avg spell (periods)	difference of median (p.p.) (ZLB – noZLB)		
			C	Y	π (p.a.)
Prod. shock – T sector	38.7	13.2	–0.54	–0.94	0.72
Labour supply shock	38.1	8.6	–0.16	–0.23	0.24
Monetary policy shock	34.2	3.0	–0.06	–0.06	0.12
Prod. shock – NT sector	16.1	3.0	–0.01	–0.02	0.04
Investment efficiency shock	16.1	12.6	–0.01	–0.03	0.04
Fgn investment efficiency shock	7.0	31.9	–0.03	–0.01	0

Source: author's calculations

respectively, compared to the reduction with a non–binding interest rate. On the other hand, the impacts for inflation are modest; its average value is higher by 0.72 p.p. (in annual terms). The reason is that the central bank is primarily concerned with targeting of inflation and not output gap. Monetary policy shock also takes the economy to ZLB quite frequently, but its impacts for macroeconomic variables are trivial.

Furthermore, two new shocks play a role: investment efficiency shocks in the domestic and foreign economies.[6] However, compared to the shocks described above, their macroeconomic consequences are quite small and are comparable to the impacts of productivity shocks in the non-tradable sector. The longest average duration at the ZLB is around eight years, with a foreign investment efficiency shock. This is quite surprising, because this shock does not take the interest rate to the ZLB so frequently. However, this outcome is robust to a number of simulations. Empirically, it can only be compared to the situation of Japan, whose economy has been at the ZLB for such a long time. The average spell at the ZLB for the other shocks ranges from three quarters of a year to three years, which is a much more acceptable duration.

Before moving on to the last set of simulations, it is worth comparing these results with other empirical studies. Gust *et al.* (2013) also documented that productivity shocks played an important role for output decline during the Great Recession. Discount rate shocks had quite important consequences, but only for the behaviour of inflation. Discount rate shocks correspond to preference shocks in our model, and they turned out to be unimportant in the analysis. This could be because the model used by Gust *et al.* contained only three types of shocks. Fernández-Villaverde *et al.* (2012) uses a small calibrated New Keynesian model with four shocks. The main source of distortions at the ZLB is ascribed to technology and discount

6 In fact, constraint on interest rate was also binding for five other shocks (domestic and foreign preference shock, government spending shock, foreign monetary policy shock, and foreign labour supply shocks). However, the ZLB was detected in only a few cases and the consequences for macroeconomic variables were virtually nil.

IV: *Differences between descriptive statistics ZLB – noZLB*

	Binding IR	Avg spell	Difference of median (p.p.)			Difference of std (p.p.)		
			C	Y	π (p.a.)	C	Y	π(p.a.)
Benchmark MR	48.5	10.0	–1.72	–1.16	0.01	1.05	0.56	6.52
$\Psi_y = 0.03$	44.1	8.3	–1.29	–1.16	–0.03	–0.51	–0.14	3.69
$\Psi_\pi = 1.94$	47.0	9.2	–1.24	–1.14	0.00	–1.00	–0.17	3.08

Source: author's calculations

factor shocks, which both have similarly large impacts for macroeconomic variables. Hloušek (2014) found that, for the Czech economy, domestic cost-push shock, monetary policy shock and foreign preference shocks are the most significant sources of welfare losses at ZLB. Contrary to his results, foreign shocks are not found to be important in taking the economy to the ZLB in our model. Malovaná (2015) identified for the Czech economy that various demand shocks (both domestic and foreign) increase volatility of real and nominal variables at ZLB. Similarly to our results, positive domestic productivity shock weakens economic expansion at ZLB and thus leads to economic losses.

Simulation in the Presence of All Shocks

The results from the previous section can be seen as a lower bound, because the economy may be subject to a combination of several shocks. We will therefore explore the situation again, using a stochastic simulation, but this time the economy will be subject to all fourteen shocks. The results are shown in Tab. IV, which also shows the differences in volatilities between the ZLB and noZLB distributions. The first row indicates that the interest rate is binding in almost half of the cases, and the average spell for which the economy stays at the ZLB is ten periods. The implications of the ZLB for macroeconomic variables are nontrivial. Consumption is lower by 1.72 percentage points on average, and output by 1.16 p.p. On the other hand, the average value of inflation is almost unchanged. Regarding the volatilities of the variables, consumption is more volatile by one percentage point, output by half a percentage point and inflation by as much as 6.52 p.p.

In sum, these results show that the empirical consequences of the ZLB are quite substantial, which raises the question as to whether anything can be done about it. To answer this question, we focus on the central bank's behaviour, more concretely on different settings of monetary policy rule. The last two rows in Tab. IV show the results of the simulation for different parameter values of the Taylor rule. First, the weight to output, parameter ψ_y, is decreased from benchmark value $\psi_y = 0.07$ to 0.03, which is the lowest value found for the Czech economy in empirical papers, concretely in Ryšánek *et al.* (2012). The results of the simulation show that the ZLB occurs in fewer cases under these conditions. Quite surprisingly, the difference in the average values of output is unchanged, but there is improvement in consumption, whose average value in the ZLB case is lower by only 1.29 percentage points. Another improvement is in the volatility of consumption and output: the ZLB distribution for these two variables is now less volatile compared to the unrestricted version. Regarding inflation, its average value is almost unchanged, but the difference in volatility has decreased compared to the benchmark. In other words, these results indicate that some form of strict inflation targeting is beneficial for the economy in an environment of low interest rates.

Next, we focus on increasing the weight to inflation in monetary policy rule. It is increased from benchmark value $\psi_\pi = 1.37$ to 1.94, which is the highest estimate for the Czech economy, again obtained from Ryšánek *et al.* (2012).[7] The third row in Tab. IV shows the results of this simulation. The ZLB constraint binds in fewer cases compared to the benchmark, but only slightly. The other results are similar to the results with lower weight to output: a smaller difference in average values of consumption and almost no change for output and inflation. Consumption is less volatile in the ZLB case by one percentage point and output is also somewhat less volatile. Inflation is more volatile in the ZLB case, but there is improvement against the benchmark. The message of this experiment is that monetary policy that behaves more aggressively (higher weight to inflation) lowers the distortions connected with the zero lower bound.

7 The range of estimates for the Taylor rule parameters in the literature is quite wide. The inflation parameter varies from 1.16 (Tonner *et al.*, 2011) to 1.94 (Ryšánek *et al.*, 2012) and the output gap parameter ranges from 0.03 (Ryšánek *et al.*, 2012) to 0.47 (Brázdik, 2011). Here, we focus only on changes to the parameters that lower the cost connected with the ZLB.

CONCLUSION

This paper has explored the empirical consequences of attaining the zero lower bound on the interest rate in the Czech economy, using an estimated DSGE model. Of the fourteen model specific shocks, four shocks turned out to be important in determining the behaviour of the interest rate near the ZLB. They are: productivity shock in the tradable sector, labour supply shock, monetary policy shock and productivity shock in the non-tradable sector. The most significant is the first – productivity shock in the tradable sector, which means that more output can be produced with given inputs. In the case of the Czech economy, this can be represented e.g. by technological improvements in the engineering industry.

Individual shocks produce quite small welfare losses at one time impact. The costs become important only for shocks of very high magnitude (two or three standard deviations) or when shocks occur more frequently. E.g. if the economy is subject to a series of productivity shocks in the tradable sector, output could be lower by almost one percentage point and consumption by half a percentage point on average. If the economy is subject to a series of all fourteen shocks, the losses connected with the ZLB are even higher: average output is lower by 1.7 percentage points and consumption by 1.2 percentage points. Although the average value of inflation is almost unchanged, its volatility (measured by standard deviation) increases by 6.5 percentage points annually in this situation.

In summary, this analysis has shown that the costs connected with the zero lower bound are quite substantial. The recommendation for monetary policy is therefore to pursue more aggressive behaviour and strict inflation targeting (i.e. giving higher weight to inflation and lower weight to output). There can be also room for unconventional policies, such as exchange rate interventions that can eliminate cost connected with zero lower bound. Exploration of their possible impacts on the economy is left for further research.

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Appendix

This Appendix briefly describes the structure of the domestic economy. The foreign economy has an identical structure. Parameters with an asterisk relate to the foreign economy. For further details about the model and log-linearized version, see Kolasa (2009).

Households

Households in a domestic economy are homogenous and maximize the expected utility function

$$U_t(j) = E_t \sum_{k=0}^{\infty} \beta^k \left[\frac{\varepsilon_{d,t+k}}{1-\sigma} (C_{t+k}(j) - H_{t+k})^{1-\sigma} - \frac{\varepsilon_{l,t+k}}{1+\phi} L_{t+k}(j)^{1+\phi} \right],$$

where E_t denotes expectations in the period t, β is a discount factor, σ is an inverse elasticity of intertemporal substitution in consumption, $H_t = hC_{t-1}$ is an external habit taken by the household as exogenous, h is a parameter of habit formation, C_t is a composite consumption index (to be defined later), ϕ is an inverse Frisch elasticity of labor supply, $\varepsilon_{d,t}$ is a preference shock in the period t, which influences intertemporal decisions about consumption and $\varepsilon_{l,t}$ is a labor supply shock in the period t.

Households maximize the utility function subject to a budget constraint

$$P_{C,t}C_t(j) + P_{I,t}I_t(j) + E_t\{\Upsilon_{t,t+1}B_{t+1}(j)\} = B_t(j) + W_t(j)L_t(j) +$$

$$+ R_{K,t}K_t(j) + \Pi_{H,t}(j) + \Pi_{N,t}(j) + T_t(j), \qquad \text{for } t = 0, 1, 2, \dots,$$

where $P_{C,t}$ denotes the price of the consumption C_t, $P_{I,t}$ is the price of investment goods I_t, B_{t+1} is the nominal payoff in period $t + 1$ of the portfolio held at the end of period t, W_t is the nominal wage, $R_{K,t}$ denotes income of households achieved from renting capital K_t, $\Pi_{H,t}$ and $\Pi_{N,t}$ are dividends from tradable and non-tradable goods producers and T_t denotes lump sum government transfers net of lump sum taxes. $\Upsilon_{t,t+1}$ is the stochastic discount factor for nominal payoffs, such that $E_t\Upsilon_{t,t+1} = R_t^{-1}$, where R_t is the gross return on a riskless one-period bond.

Consumption index C_t consists of final tradable goods index $C_{T,t}$ and non-tradable goods index $C_{N,t}$ which are aggregated according to

$$C_t = \frac{C_{T,t}^{\gamma_c} C_{N,t}^{1-\gamma_c}}{\gamma_c^{\gamma_c}(1-\gamma_c)^{1-\gamma_c}},$$

where γ_c denotes the share of final tradable goods in the consumption basket of households. It is assumed that consumption of a final tradable good requires ω units of distribution services $Y_{D,t}$, which implies

$$C_{T,t} = \min\{C_{R,t}; \omega^{-1}Y_{D,t}\}.$$

The consumption index of raw tradable goods is defined as

$$C_{R,t} = \frac{C_{H,t}^{\alpha} C_{F,t}^{1-\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}},$$

where α denotes share of domestic goods in the domestic basket of tradable goods, $C_{H,t}$ is an index of home-made tradable goods and $C_{F,t}$ is an index of foreign-made tradable goods, both consumed in the domestic economy and defined as

$$C_{H,t} = \left[\left(\frac{1}{n}\right)^{\frac{1}{\phi_H}} \int_0^n C_t(z_H)^{\frac{\phi_H - 1}{\phi_H}} dz_H \right]^{\frac{\phi_H}{\phi_H - 1}},$$

$$C_{F,t} = \left[\left(\frac{1}{1-n}\right)^{\frac{1}{\phi_F}} \int_n^1 C_t(z_F)^{\frac{\phi_F - 1}{\phi_F}} dz_F \right]^{\frac{\phi_F}{\phi_F - 1}},$$

where ϕ_H (ϕ_F) is an elasticity of substitution between domestic (foreign) tradable goods, consumed in the domestic economy. Analogously, the consumption index of non-tradable goods is defined as

$$C_{N,t} = \left[\left(\frac{1}{n}\right)^{\frac{1}{\phi_N}} \int_0^n C_t(z_N)^{\frac{\phi_N - 1}{\phi_N}} dz_N \right]^{\frac{\phi_N}{\phi_N - 1}}$$

where ϕ_N is an elasticity of substitution between domestic non-tradable goods.

Households use part of their income to accumulate capital K_t which is assumed to be homogenous and is rented to firms. Capital is accumulated according to the formula

$$K_{t+1} = (1-\tau)K_t + \varepsilon_{i,t}\left(1 - S\left(\frac{I_t}{I_{t-1}}\right)\right)I_t,$$

where τ is a depreciation rate of capital and I_t denotes investment in the period t. Capital accumulation is subject to investment specific technology shock $\varepsilon_{i,t}$ and adjustment costs represented by function $S(\cdot)$. This function satisfies following properties $S(1) = S'(1) = 0$ and $S''(\cdot) = S'' > 0$.

Homogenous investment goods are produced in the same way as final consumption goods, which implies the following definitions

$$I_t = \frac{I_{R,t}^{\gamma_i} I_{N,t}^{1-\gamma_i}}{\gamma_i^{\gamma_i}(1-\gamma_i)^{1-\gamma_i}},$$

$$I_{R,t} = \frac{I_{H,t}^{\alpha} I_{F,t}^{1-\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}}.$$

It is assumed that the composition of consumption and investment baskets in a given economy can differ, i.e. parameters γ_c and γ_i can be different, and that the composition of tradable baskets is identical, i.e. parameter α is the same for both tradable consumption goods and tradable investment goods in the given economy.

Each household is specialized in a different type of labour $L_t(j)$, which it supplies in a monopolistically competitive labour market. All supplied labour types are aggregated into homogenous labour input L_t according to the formula

$$L_t = \left[\left(\frac{1}{n}\right)^{\frac{1}{\phi_W}} \int_0^n L_t(j)^{\frac{\phi_W - 1}{\phi_W}} dj \right]^{\frac{\phi_W}{\phi_W - 1}},$$

where ϕ_W is the elasticity of substitution between different labour types. A corresponding aggregate wage index is then defined as

$$W_t = \left[\frac{1}{n} \int_0^n W_t(j)^{1-\phi_W} dj \right]^{\frac{1}{1-\phi_W}},$$

where $W_t(j)$ denotes the wage of household j.

The setting of wages assumes Calvo (1983) mechanism. According to this set-up, every period only $1 - \theta_W$ portion of households (randomly chosen) can reset their wages optimally, while the remaining portion of households θ_W leave their wages unchanged.

Firms

There is a continuum of homogenous, monopolistic competitive firms in the tradable and non-tradable sectors of the domestic economy. The production function of firms is assumed to be Cobb-Douglas function with constant returns to scale with respect to capital and labour

$$Y_t(z_N) = \varepsilon_{a^N,t} L_t(z_N)^{1-\eta} K_t(z_N)^{\eta},$$

$$Y_t(z_H) = \varepsilon_{a^H,t} L_t(z_H)^{1-\eta} K_t(z_H)^{\eta},$$

where η is the elasticity of output with respect to capital (common to both sectors, but potentially different in individual countries), and $\varepsilon_{a^H,t}$ ($\varepsilon_{a^N,t}$) is a productivity shock in the tradable (non-tradable) sector.

Firms set their prices in order to maximize their profits. It is assumed that firms face Calvo (1983) pricing restriction. According to this restriction, every period only $1 - \theta$ portion of firms (randomly chosen) have the opportunity to reset their prices optimally, while θ portion of firms leave their prices unchanged.

It is assumed that prices are set in the producer's currency and that the international law of one price holds for intermediate tradable goods. Thus, prices of domestic goods sold in the foreign economy and prices of foreign goods sold in the domestic economy are given by

$$P_t^*(z_H) = ER_t^{-1} P_t(z_H), \qquad P_t(z_F) = ER_t P_t^*(z_F),$$

where ER_t is the nominal exchange rate expressed as units of domestic currency per one unit of foreign currency.

International Risk Sharing

The assumption of complete financial markets implies that expected nominal returns on domestic and foreign bonds must be the same, which implies the following condition

$$Q_t = \kappa \frac{\varepsilon_{d,t}^*}{\varepsilon_{d,t}} \frac{(C_t^* - h^* C_{t-1}^*)^{-\sigma^*}}{(C_t - h C_{t-1})^{-\sigma}},$$

where κ is a constant depending on initial conditions and Q_t is a real exchange rate defined as

$$Q_t = \frac{ER_t P_{C,t}^*}{P_{C,t}}.$$

The real exchange rate can deviate from purchasing power parity because of changes in the relative prices of tradable and non-tradable goods, changes in relative distribution costs and changes in terms of trade, as long as there is a difference between household preferences among countries, i.e. $\alpha \neq 1 - \alpha^*$.

$$Q_t = S_t^{\alpha + \alpha^* - 1} \frac{1 + \omega^* D_t^*}{1 + \omega D_t} \frac{X_t^{*1-\gamma_c^*}}{X_t^{1-\gamma_c}},$$

where S_t are the terms of trade defined as domestic import prices relative to domestic export prices[8]

$$S_t = \frac{ER_t P_{F,t}^*}{P_{H,t}}.$$

X_t and X_t^* are internal exchange rates defined as prices of non-tradable goods relative to prices of tradable goods

$$X_t = \frac{P_{N,t}}{P_{T,t}}, \qquad X_t^* = \frac{P_{N,t}^*}{P_{T,t}^*}$$

and D_t and D_t^* are relative distribution costs, defined as prices of non-tradable goods relative to prices of raw tradable goods

$$D_t = \frac{P_{N,t}}{P_{R,t}}, \qquad D_t^* = \frac{P_{N,t}^*}{P_{R,t}^*}.$$

8 The assumption of law of one price for tradable goods implies $S_t^* = S_t^{-1}$.

Monetary and Fiscal Authorities

The behaviour of the central bank is described by a variant of the Taylor rule

$$R_t = R_{t-1}^{\rho}\left[E_t\left\{\left(\frac{Y_{t+1}}{\bar{Y}}\right)^{\psi_y}\left(\frac{P_{C,t+1}}{(1+\bar{\pi})P_{C,t}}\right)^{\psi_\pi}\right\}\right]^{1-\rho}\varepsilon_{m,t},$$

where ρ is a parameter of interest rate smoothing, Y_t is a total output in the economy, $\bar{Y}_t$ denotes a steady state level of this output, $\bar{\pi}$ is a steady state level of inflation, ϕ_y is an elasticity of the interest rate to the output, ϕ_π is an elasticity of the interest rate to inflation and $\varepsilon_{m,t}$ is a monetary policy shock.

Fiscal policy is modeled in a simple way. Government expenditures and transfers to households are fully financed by lump-sum taxes so that the state budget is balanced every period. Government expenditures consist only of non-tradable domestic goods and are modeled as a stochastic AR(1) process $\varepsilon_{g,t}$. Given the assumptions about households, Ricardian equivalence holds in this model.

Market Clearing Conditions

The model is closed by the market clearing conditions. Goods market clearing requires that the output of each firm producing non-tradable goods is either consumed by households in the domestic economy, spent on investment, used for distribution services or purchased by the government. Similarly, the output of firms producing tradable goods is either consumed or invested in the domestic or foreign economy. Formally

$$Y_{N,t} = C_{N,t} + I_{N,t} + Y_{D,t} + G_t,$$

$$Y_{H,t} = C_{H,t} + C^*_{H,t} + I_{H,t} + I^*_{H,t}.$$

The total output in the economy is given by the sum of output in tradable and non-tradable sectors

$$Y_t = Y_{N,t} + Y_{H,t}.$$

Finally, market clearing conditions for factor markets requires

$$L_t = \int_0^n L_t(z_N)dz_N + \int_0^n L_t(z_H)dz_H,$$

$$K_t = \int_0^n K_t(z_N)dz_N + \int_0^n K_t(z_H)dz_H.$$

Exogenous Shocks

The business cycle behaviour of the model is driven by seven structural shocks in each economy:

- productivity shocks in the tradable sector ($\varepsilon_{a^H,t}$ and $\varepsilon^*_{a^F,t}$),
- productivity shocks in the non-tradable sector ($\varepsilon_{a^N,t}$ and $\varepsilon^*_{a^N,t}$),
- labour supply shocks ($\varepsilon_{l,t}$ and $\varepsilon^*_{l,t}$),
- investment efficiency shocks ($\varepsilon_{i,t}$ and $\varepsilon^*_{i,t}$), consumption preference shocks ($\varepsilon_{d,t}$ and $\varepsilon^*_{d,t}$),
- government spending shocks ($\varepsilon_{g,t}$ and $\varepsilon^*_{g,t}$) and
- monetary policy shocks ($\varepsilon_{m,t}$ and $\varepsilon^*_{m,t}$).

Except for monetary policy shocks, which are represented by *iid* processes, all other shocks follow AR(1) processes in the log-linearised version of the model. The shocks are allowed to be correlated across the countries.

A.I: Estimated parameters

Parameter	Prior distribution			Posterior distribution		
	Density	Mean	S.D.	Mean	2.5%	97.5%
Habit formation						
h	beta	0.7	0.1	0.65	0.50	0.81
h^*	beta	0.7	0.1	0.73	0.60	0.86
Elasticity of intertemporal subst.						
σ	gamma	1	0.7	1.28	0.50	2.01
σ^*	gamma	1	0.7	2.52	1.24	3.76
Frisch elasticity of labour supply						
ϕ	gamma	1	0.7	0.37	0.01	0.78
ϕ^*	gamma	1	0.7	0.97	0.23	1.71
Investment adjustment cost						
S'	norm	4	1.5	3.40	1.25	5.51
S'^*	norm	4	1.5	4.73	2.69	6.59
Calvo parameters						
θ_H	beta	0.7	0.05	0.75	0.69	0.81
θ_F^*	beta	0.7	0.05	0.73	0.67	0.78
θ_N	beta	0.7	0.05	0.77	0.72	0.82
θ_N^*	beta	0.7	0.05	0.63	0.57	0.69
θ_W	beta	0.7	0.05	0.73	0.65	0.80
θ_W^*	beta	0.7	0.05	0.78	0.73	0.84
Monetary policy rule						
ρ	beta	0.7	0.15	0.85	0.82	0.88
ρ^*	beta	0.7	0.15	0.84	0.81	0.88
Ψ_y	gamma	0.25	0.1	0.07	0.05	0.09
Ψ_y^*	gamma	0.25	0.1	0.13	0.07	0.18
Ψ_π	gamma	1.3	0.15	1.37	1.18	1.55
Ψ_π^*	gamma	1.3	0.15	1.41	1.21	1.62

A.II: Estimated shocks

	Prior distribution			Posterior distribution		
Param.	**Density**	**Mean**	**S.D.**	**Mean**	**2.5 %**	**97.5 %**
			Volatility			
σ_{a^H}	invg	0.01	Inf	0.049	0.032	0.065
$\sigma^*_{a^F}$	invg	0.01	Inf	0.023	0.014	0.033
σ_{a^N}	invg	0.01	Inf	0.083	0.044	0.119
$\sigma^*_{a^N}$	invg	0.01	Inf	0.022	0.014	0.029
σ_d	invg	0.01	Inf	0.038	0.015	0.060
σ^*_d	invg	0.01	Inf	0.040	0.018	0.061
σ_l	invg	0.01	Inf	0.349	0.085	0.653
σ^*_l	invg	0.01	Inf	0.168	0.044	0.298
σ_g	invg	0.01	Inf	0.032	0.027	0.037
σ^*_g	invg	0.01	Inf	0.013	0.011	0.015
σ_i	invg	0.01	Inf	0.073	0.026	0.116
σ^*_i	invg	0.01	Inf	0.033	0.020	0.044
σ_m	invg	0.01	Inf	0.002	0.001	0.002
σ^*_m	invg	0.01	Inf	0.002	0.002	0.002
			Persistence of shocks			
ρ_{a^H}	beta	0.7	0.1	0.91	0.82	0.93
$\rho^*_{a^F}$	beta	0.7	0.1	0.63	0.62	0.96
ρ_{a^N}	beta	0.7	0.1	0.45	0.89	0.97
$\rho^*_{a^N}$	beta	0.7	0.1	0.57	0.91	0.98
ρ_d	beta	0.7	0.1	0.77	0.63	0.88
ρ^*_d	beta	0.7	0.1	0.73	0.63	0.86
ρ_l	beta	0.7	0.1	0.45	0.28	0.67
ρ^*_l	beta	0.7	0.1	0.49	0.56	0.88
ρ_g	beta	0.7	0.1	0.78	0.69	0.85
ρ^*_g	beta	0.7	0.1	0.81	0.73	0.89
ρ_i	beta	0.7	0.1	0.66	0.48	0.82
ρ^*_i	beta	0.7	0.1	0.74	0.68	0.88
			Correlation of shocks			
$corr_{a_H,a^*_F}$	norm	0	0.4	–0.02	–0.23	0.18
$corr_{a_N,a^*_N}$	norm	0	0.4	0.24	0.05	0.44
$corr_{d,d*}$	norm	0	0.4	0.23	0.02	0.45
$corr_{l,l*}$	norm	0	0.4	0.12	–0.08	0.33
$corr_{g,g*}$	norm	0	0.4	0.12	–0.07	0.33
$corr_{i,i*}$	norm	0	0.4	0.18	–0.01	0.39
$corr_{m,m*}$	norm	0	0.4	0.92	0.88	0.96

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