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Keywords: maintenance, renewals, vector autoregression, rail infrastructure

JEL Codes: R48, L92

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Dynamics in rail infrastructure provision: maintenance and renewal costs in Sweden

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Abstract

In this paper we analyze the dynamics between rail infrastructure renewals and maintenance in Sweden, using a panel vector autoregressive model. The model estimation also comprises intertemporal effects for each of these activities. We find that past values of maintenance gives a better prediction of current renewal costs compared to only using past values of renewals as a predictor. Moreover, the results indicate intertemporal effects for both renewals and maintenance, where an increase in costs during a year predicts an increase in costs in the following year. The dynamic model also allows us to estimate equilibrium cost elasticities with respect to ton density, which are significantly larger than its static counterparts. Overall, this work highlights that dynamics in rail infrastructure costs are important to consider when setting track access charges with respect to the wear and tear caused by traffic.

1.0 Introduction

Infrastructure investments consume a large amount of resources. To reap the benefits of an investment, the infrastructure has to be maintained and renewed due to the wear and tear caused by traffic and to some extent weather conditions. In other words, maintenance and renewals will affect the performance and reliability of the infrastructure. The activities performed will also determine the level of maintenance and renewals that needs to be carried out in the future. Specifically, there may be an intertemporal effect for each of the activities; the amount of maintenance (renewals) carried out in year t can affect the amount of maintenance (renewals) carried out in year $t + s$. Moreover, the maintenance performed will determine when the infrastructure needs to be renewed and the size of the renewal, while a renewal can affect the level of maintenance carried out. We therefore expect interdependence between these activities.

The dynamics in maintenance and renewals implies that an infrastructure manager (IM) needs to strike a balance within and between these activities for a certain traffic level. A sudden increase in traffic may thus require an adjustment of these costs. This implies that the cost impact from traffic needs to be studied in a dynamic context.

The purpose of this paper is to provide empirical evidence on the interdependence between maintenance and renewals, as well as their intertemporal effects. The estimates can be used to calculate the marginal cost for traffic, which has become an important part of the track access charges that were introduced after the vertical separation between train operations and infrastructure management in Europe as of the 1990s.[1] Given that there are dynamic effects between different activities in infrastructure provision, the marginal cost estimates that takes these effects into account will be closer to the actual cost of running one extra unit of traffic on the railway, compared to the cost estimates based on static models for

[1] The Swedish reform took place in 1988, preceding the wider European reform.

maintenance (see for example Wheat et al. 2009) and renewals (see for example Andersson et al. 2012 and Andersson and Björklund 2012).

Knowledge on the intertemporal effects in rail infrastructure maintenance and renewals and the interdependence between these costs is scarce. A notable exception is the study by Wheat (2015), in which a vector autoregressive model (VAR) is estimated for both maintenance and renewal costs in ten zones in Britain over a 15 year period. The study finds evidence on intertemporal effects, yet not for a relationship between renewals and maintenance costs. An intertemporal effect is also found by Odolinski and Nilsson (2015) who estimate a dynamic model (system GMM) for maintenance. Similar to Wheat (2015), they find that an increase in maintenance costs in one year - due to for example a traffic increase – predicts an increase in maintenance costs in the next year. Other examples on research where the dynamics between maintenance and renewals are taken into account is Andersson (2008) and Odolinski and Smith (2016) who both use a dummy variable approach. However, it involves an arbitrary definition of major renewals and only allows for a stepwise effect of renewals on maintenance costs.

In this study we estimate a panel VAR model, which is an autoregressive model that considers several endogenous variables - renewals and maintenance in our case - in a multiple equation system. Our estimation approach is similar to Wheat's (2015), with the exception that we take the panel data structure into account. Hence, we are able to model unobserved individual heterogeneity, which in our case are unobserved effects specific for each contract area. Moreover, we have access to ton-km instead of train-km, where the former provides a better representation of wear and tear.

A central facet of the VAR model is to make structural analyses, in which identification of exogenous shocks in the system is required. In this paper, we make use of an impulse response analysis (IRA) to track how maintenance/renewal costs evolve over time due to an increase in lagged maintenance/renewal costs caused by an exogenous shock (due to for example an increase in traffic). The estimated effect a certain activity has on future activities will provide knowledge about the strategy currently used.

The paper is organized as follows. In section 2, we describe the methodology used. It also includes a subsection on the equilibrium cost elasticity with respect to traffic; an elasticity that can be used in a calculation of the marginal cost for the wear and tear of the infrastructure. Section 3 comprises a description of the data. We specify our model in section 4, where we also present results from a stability test. The estimation results are presented in section 5. Section 6 concludes.

2.0 Methodology

Sims (1980) proposed the VAR model as an alternative to the simultaneous equation macroeconomic models prevalent at the time, which he criticized for its problems with arbitrary identification. The (so called) exogenous variables in the models - used for example to identify an effect on either the demand or supply - were often not strictly exogenous due to expectations in the economy that can change the behavior of the consumer (the demand) in addition to the variable's direct effect on the supplier and vice versa. Hence, there is a problem of simultaneity in the outcomes, which is the same type of problem we have with maintenance and renewals.

The objective with a VAR model is to capture the effects of unexpected exogenous shocks via identification strategies which, if properly specified, can make the model useful for forecasting and policy analysis. One strategy is to make use of the temporal dependence between the variables – that is, how fast they react to a shock. Considering the endogeneity of the maintenance and renewals, where we expect the latter to react more slowly to a shock than the former, estimating a VAR model can be a fruitful approach for analyzing the dynamics in infrastructure provision.

We consider a panel VAR(p) model, where p denotes the lag length used in the model.[2] We have two endogenous variables: renewal costs (R_{it}) and maintenance costs (M_{it}), where $i = 1,2 \dots, N$ contract areas and $t = 1,2, \dots, T$ years. $\alpha_{1,i}$ and $\alpha_{2,i}$ are the unobserved individual-specific effects for the renewal and maintenance equations respectively, while $u_{1,it}$ and $u_{2,it}$ are their respective residuals, where $\left(u'_{1,it}, u_{2,it}\right) = \boldsymbol{u}_{it} \sim iid(0, \Sigma)$. Σ is the covariance matrix of the errors. We also include a vector of exogenous variables $\boldsymbol{X}_{it}$ with parameters $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_2$ for the maintenance and renewal equations respectively.

$$R_{it} = \alpha_{1,i} + \delta_{11} R_{it-1} + \theta_{11} M_{it-1} + \boldsymbol{\beta}'_1 \boldsymbol{X}_{it} + u_{1,it}$$
$$M_{it} = \alpha_{2,i} + \delta_{21} R_{it-1} + \theta_{21} M_{it-1} + \boldsymbol{\beta}'_2 \boldsymbol{X}_{it} + u_{2,it} \quad (1)$$

Lagged renewal and maintenance costs are included in both equations to capture the dynamics in maintenance and renewals, as well as the interdependence between these activities. We also consider a lagged traffic variable in the estimations.

We first perform model identification by making graphs of the data to spot trends and we also choose the lag order of the model based on model selection criteria. The lag order relates to autocorrelation in the residuals that can be removed by increasing the number of lags. For consistent estimation of the model parameters, $E(u'_{it}, u_{is}) = 0$, with $t \neq s$ i.e. no autocorrelation.

As a model check we perform a stability test, which can reveal if a stationary process is generated by the model. If the process is non-stationary, first differencing would be

[2] Here we present the VAR(1) model for expositional simplicity. We consider further lags in the model estimation.

required to avoid spurious results. However, the long-run relationship between the variables is eliminated when taking first differences. Moreover, if the variables are cointegrated (share a common trend), a vector-error correction model (VECM) is appropriate in order to analyze the long-run relationship between the variables (Heij et al. 2004). However, separating short-run and long-run relationships between maintenance and renewals is beyond the scope of this paper. We therefor only estimate the VAR model.

The model is estimated with generalized method of moments (GMM). Examples of studies that use this type of estimator for a VAR model are Love and Zicchino (2006), Tiwari (2011), Ahlfeldt et al. (2014) and Goés (2016). In doing this, we need to consider that the lagged variables are correlated with the contract area specific effects. To remove these effects, we use the transformation proposed by Arrelano and Bover (1995), which is forward orthogonal deviation, or Helmert transformation (examples of studies that use this transformation is Love and Zicchino (2006), Ahlfeldt et al. (2014) and Lee and Yu (2014)). More specifically, for each year and contract area, we subtract the mean of future observations.

We need to use instruments for the lagged variables, as these are correlated with the error terms. When including a set of lags as instruments, we use the method by Holz-Eakin et al. (1988), which basically substitutes missing values (created by increasing the lag length of the instruments) with zeros. This allows us to increase the lags of the instruments without losing the number of observations in the estimation.

2.1 Granger Causality and Impulse Response Analysis (IRA)

As a first test of interdependence between renewals and maintenance, we test whether lagged values of maintenance can improve the prediction of current values of renewals compared to only using lagged values of renewals (and vice versa). This approach of testing causal relations in time series is called a *Granger causality* test, proposed by Granger (1969).

A Granger causality test does however not reveal how exogenous changes in one variable affect another variable over time. To trace the effect of changes in renewals and maintenance costs, we make use of IRA, which requires identification of exogenous shocks ($\boldsymbol{\varepsilon}_{it}$). We assume these shocks to be a linear function of the residuals $\boldsymbol{u}_{it} = G\boldsymbol{\varepsilon}_{it}$, where G is a 2x2 matrix. Given our knowledge about the nature of renewals and maintenance, we choose *recursive identification* as the method to identify the shocks, which requires an ordering of the variables such that the G matrix can be calculated from the covariance matrix $\sum$ by using the Cholesky decomposition (see for example Sims 1989 and Christiano et al. 1999. For an overview of this method, see KVA 2011, p. 15-17). Simply put, the ordering should be constructed on the basis of how fast the variables respond, from slow to fast. In our case, renewals are ordered first as we assume that the only shock that can have an effect on current renewals is a shock in renewals, while current maintenance can be influenced by both a renewal shock and a maintenance shock. Notice that we only assume that a maintenance shock will not affect *current* renewals, while future renewals are likely to be influenced by maintenance shocks. In other words, maintenance expenditure is more agile to shocks than renewals, - that is, an IM responds first with a change in maintenance.

When the shocks have been identified, we can use them in an impulse response function (IRF):

$$\boldsymbol{C}_t = \sum_{k=0}^{K} H_k G \boldsymbol{\varepsilon}_{it-k} \qquad (2)$$

where $k = 1,2,\ldots,K$ is lag length and $\boldsymbol{C}_t = (R_{it}, M_{it})$. H_k are the weights, where $H_o = I$ (identity matrix). We use these weights in a plot to inspect how they vary with k. More specifically, we inspect how maintenance responds to a shock in either renewals or maintenance, and vice versa.

2.2 Equilibrium cost elasticity with respect to traffic

With lagged cost variables in our model, we are able to calculate the "equilibrium cost elasticity" with respect to traffic, both for renewals and maintenance.[3] For maintenance costs, the logic is that an increase in traffic in year $t-1$ will affect maintenance costs in year $t-1$, which in turn affects maintenance costs in year t. Moreover, maintenance costs that have adjusted into equilibrium imply $lnM_{it} = lnM_{it-1} = lnM_i^e$. The equation for maintenance costs in (1), with a logarithmic transformation and a traffic variable Q, is then

$$lnM_i^e = \alpha_{2,i} + \delta_{21} lnR_i^e + \theta_{21} lnM_i^e + \beta_{21} lnQ_i + \boldsymbol{\beta}_2' \boldsymbol{X}_i + u_{2,i} \quad (3)$$

which gives

$$lnM_i^e = \frac{\alpha_{2,i}}{1-\theta_{21}} + \frac{\delta_{21}}{1-\theta_{21}} lnR_i^e + \frac{\beta_{21}}{1-\theta_{21}} lnQ_i + \frac{\boldsymbol{\beta}_2'}{1-\theta_{21}} \boldsymbol{X}_i + \frac{u_{2,i}}{1-\theta_{21}} \quad (4)$$

The equilibrium cost elasticity with respect to traffic is then

$$\gamma_M^e = \frac{\partial lnM_i^e}{\partial lnQ_i} = \frac{\beta_{21}}{1-\theta_{21}} \quad (5)$$

The same logic applies for the renewal equation.

[3] The term long-run cost is often used in the literature, which requires that there are no fixed factors in the production. However, in our analysis, the rail infrastructure is mainly fixed. We therefore prefer the term equilibrium costs.

As noted by Wheat (2015), there is also a secondary effect that can be considered when estimating the cost elasticity with respect to traffic. If there is interdependence between our endogenous variables, then a change in traffic will have an impact on renewal (maintenance) costs, which in turn can have an effect on maintenance (renewal) costs, and vice versa.

With the equilibrium maintenance cost in (4) and the equilibrium renewal cost

$$lnR_i^e = \frac{\alpha_{1,i}}{1-\delta_{11}} + \frac{\theta_{11}}{1-\delta_{11}} lnM_i^e + \frac{\beta_{11}}{1-\delta_{11}} lnQ_i + \boldsymbol{\beta}_1' \boldsymbol{X}_i + \frac{u_{1,i}}{1-\delta_{11}} \quad (6)$$

we can derive the equilibrium maintenance cost elasticity with respect to traffic (γ_M^{e*}) that includes the secondary effect from the renewal equation:

$$\gamma_M^{e*} = \frac{\partial lnM_i^e}{\partial lnQ_i} = \frac{\beta_{21}}{1-\theta_{21}} + \frac{\delta_{21}}{1-\theta_{21}} \frac{\partial lnR_i^e}{\partial lnQ_i} \quad (7)$$

The last term in equation (7) is the equilibrium renewal cost elasticity with respect to traffic

$$\gamma_R^{e*} = \frac{\partial lnR_i^e}{\partial lnQ_i} = \frac{\beta_{11}}{1-\delta_{11}} + \frac{\theta_{11}}{1-\delta_{11}} \frac{\partial lnM_i^e}{\partial lnQ_i} \quad (8)$$

Putting this expression into (7) gives

$$\gamma_M^e = \frac{\partial lnM_i^e}{\partial lnQ_i} = \frac{\beta_{21}}{1-\theta_{21}} + \frac{\delta_{21}}{1-\theta_{21}} \left(\frac{\beta_{11}}{1-\delta_{11}} + \frac{\theta_{11}}{1-\delta_{11}} \frac{\partial lnM_i^e}{\partial lnQ_i} \right) \quad (9)$$

Rearranging, we have

$$\gamma_M^{e*} = \frac{\partial lnM_i^e}{\partial lnQ_i} = \frac{\beta_{21}(1-\delta_{11})+\delta_{21}\beta_{11}}{(1-\theta_{21})(1-\delta_{11})-\delta_{21}\theta_{11}} \quad (10)$$

We use equations (7) and (8) to get the corresponding renewal cost elasticity

$$\gamma_R^{e*} = \frac{\partial lnR_i^e}{\partial lnQ_i} = \frac{\beta_{11}(1-\theta_{21})+\theta_{11}\beta_{21}}{(1-\delta_{11})(1-\theta_{21})-\theta_{11}\delta_{21}} \quad (11)$$

It is straightforward to include more than one lag in the above derivations.

3.0 Data

Data has been obtained from the Swedish Transport Administration (the Infrastructure Manager; hereafter referred to as the IM), and consists of renewal and maintenance costs, traffic, and characteristics of the railway network such as track length and rail age. We also consider an input price variable (wages) in this study, which has been obtained from the Swedish Mediation Office (via Statistics Sweden). A complete list together with descriptive statistics is provided in Table 1 below.

Maintenance is activities performed to implement railway services according to the timetable and maintain the railway assets. As of 2007, snow removal is defined as maintenance and is included in the maintenance contracts. We are however able to pinpoint the snow removal costs in the data, and we exclude these costs due to its (stochastic) weather dependence. Renewals consist of replacements or refurbishments of the railway assets.

Maintenance and renewals are procured separately by the IM. The IM used in-house production of renewals until exposure to competition was introduced in 2001, while competitive tendering of maintenance services was introduced gradually in 2002.[4] The effect

[4] Already in 1999, about 45 per cent of the reinvestment projects were produced by private companies (Trafikverket 2012).

competitive tendering had on renewal costs in Sweden has not been studied. However, in terms of maintenance costs, Odolinski and Smith (2016) find an 11 per cent reduction due to competitive tendering over the period 1999-2011. This indicates a structural change in infrastructure provision that needs to be considered when analyzing the interdependence between maintenance and renewals. Hence, Table 1 includes dummy variables for competitive tendering of railway maintenance; *Mixtend* which indicates the first year a contract area is tendered in cases this year is a mix between not tendered and tendered in competition; and *Ctend* which indicates the subsequent years an area is tendered in competition. Tendering variables for renewals are not included in this study due to missing information.[5]

Table 1 – Descriptive statistics, 1999-2014 (480 obs.)

	Mean	St.dev.	Min	Max
Hourly wage, SEK*	156.7	11.7	128.9	187.4
MaintC (Maintenance costs), million SEK*	56.78	44.37	8.03	334.41
RenwC (Renewal costs), million SEK*	40.74	63.95	0.00	452.13
Route length, km	280	174	13	989
Track length, km	358	229	39	1203
Length of switches, km	8.68	6.62	0.58	37.67
Length of structures (tunnels and bridges), km	5.72	7.22	0.55	40.43
Average age of rails	18.83	5.83	3.76	38.98
Ton-density (ton-km/route-km), million	7.9	7.2	0.2	33.2
Mixtend	0.06	0.24	0	1
Ctend	0.47	0.50	0	1
Trend	8.45	4.50	1	16

* 2014 prices.

Data on infrastructure characteristics is available at a detailed level, while costs and traffic are reported at the more aggregate track section level. Moreover, each contract area for

[5] We do not think this is a significant issue for the estimation results as only one year in the estimation sample (2000) would include areas not tendered when using one lag in the model.

maintenance consists of several track sections. Considering that renewals can overlap adjacent track sections, we use contract areas as the identifier in our estimations. In that way, we have less artificial splits of renewal costs.

4.0 Model specification

To get a first impression of the main variables of interest, we make a graph of maintenance and renewal costs during years 1999 to 2014. We use costs per ton-km as data is missing for some track sections over this period. Both maintenance and renewal costs have an upward trend, yet renewal costs have a more lumpy nature with more variation during the studied period. Because in our dataset we aggregate to contract areas, the lumpy nature of renewals implies that our data have fewer observations with zero renewal costs compared to track sections (for example analyzed by Andersson et al. 2012).

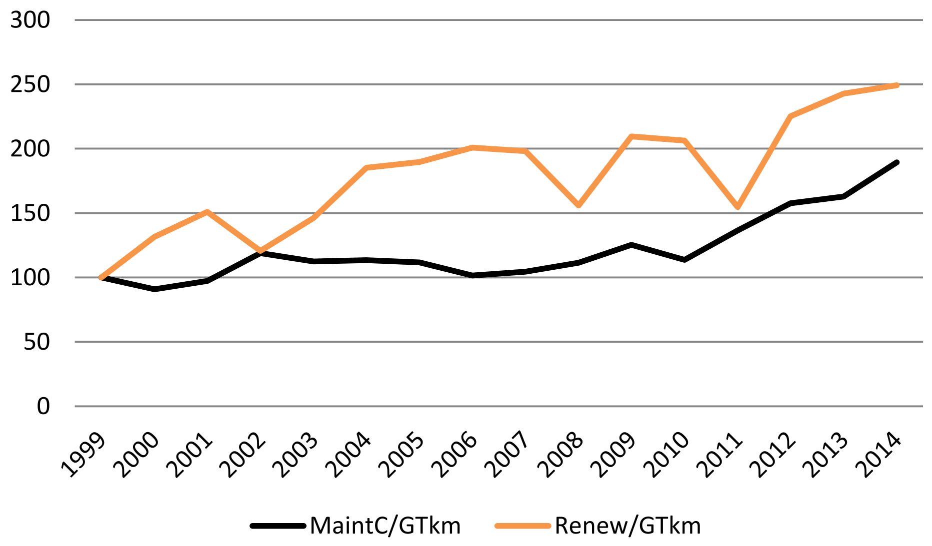

Figure 1 - Indices for maintenance (MaintC) and renewal costs (RenwC) per gross ton-km (GTkm), 1999-2014 (1999=100)

To control for fixed (time-invariant) effects in the variables, we time-demean the log transformed variables – that is, we subtract their group means: $ln\ddot{y}_{it} = lny_{it} - ln\bar{y}_i$, where $ln\bar{y}_i = T^{-1}\sum_{t=1}^{T} lny_{it}$. As previously noted, we also use a Helmert transformation in order to control for contract specific effects. Moreover, to impose linear homogeneity in input prices we divide maintenance and renewal costs with wages – that is, we normalize the costs with wages.

To determine the lag length of our model, we use the model fit criteria proposed by Andrews and Lu (2001), which are consistent moment and model selection criteria (MMSC) versions of the Akaike information criterion (AIC), the Bayesian information criterion (BIC), and the Hannan-Quin information criterion (HQIC).[6] We include the maximum number of lags in our model checks and choose the lag order with lowest values of the MMSC versions of AIC, BIC and HQIC. The test results show that the model with lag order 1 has the lowest values of AIC (-56.74), BIC (-262.57) and HQIC(-231.17) compared to the model with lag order 2, with the corresponding values -50.55, -234.62 and -208.55. However, we consider the second lag to be informative. We therefore also present results from models with lag order 2. Moreover, we also consider a lagged traffic variable to allow for a more flexible relationship between traffic and costs. Otherwise, the effect of past traffic is only picked up indirectly by lagged maintenance costs.

Finally, we test if the model estimations presented in the next section are stable. The modulus of each of the eigenvalues is below one, which implies that our estimated vector autoregressions are stable (Lütkepohl 2005, p.14-15).

[6] The formulations of the criteria in Abrigo and Love (2015) are used.

5.0 Results

Estimation results from Model 1 and Model 2 are presented in Table 2, where the former only includes the endogenous variables, and the latter includes a set of exogenous variables. The models are estimated with robust standard errors, using the iterative GMM estimator. All estimations are carried out with Stata 12 (StataCorp.2011) using the package provided by Abrigo and Love (2015). We also estimate the models with lag order 2, with the outputs presented in Table 3. We use the maximum lag length of the instruments (up to 14), which improves the efficiency of the model estimation; reducing the lag length to 12 or 11 for the instruments generates larger standard errors.

The results for lagged maintenance and renewals are similar in both models with respect to the signs of the coefficients for the lagged variables, yet the estimates for lagged maintenance in the maintenance equation are significantly lower when exogenous variables are included. This indicates that we may have omitted variable bias in Model 1. We focus on the results from Models 2a-d, which include variables for railway characteristics, ton density, dummy variables for competitive tendering and time trends.

The significance tests of the parameter estimates for lagged variables in the maintenance and renewal equations can be interpreted as Granger causality tests. The prediction of current renewals is improved by lagged values of renewals, with a coefficient at 0.3414 that is significant at the 1 per cent level (Model 2a). This may seem odd, but a possible explanation is that budget restrictions can make it difficult to complete renewals of the railway assets during one year, which leaves some of the required renewals for the next year. Moreover, the results from Model 2c with lag order 2 can be informative in this respect as the coefficient for renewals costs in year t-2 predicts a decrease in current renewals. More specifically, the coefficient is -0.0843, yet with p-value=0.124 (see appendix for the estimation results). The estimated intertemporal effects for renewals then suggests that renewals within a contract area are likely to overlap between two years, and seem to have the expected decreasing effect on renewal costs in the subsequent year.

Table 2 – Estimation results, models 1 and 2 (387 obs.)

		Model 1		*Model 2a*		*Model 2b*	
Equation	Variable	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
RenwC	RenwC_t-1	0.3449***	0.0600	0.3414***	0.0635	0.3417***	0.0635
	MaintC_t-1	-0.3714	0.2265	-0.3006	0.2497	-0.3026	0.2503
	Ton density	-	-	0.3727	0.3989	0.3796	0.3919
	Ton density_t-1	-	-	-	-	0.0308	0.3109
	Track length	-	-	0.6388	1.5237	0.6592	1.5226
	Rail age	-	-	0.3088	0.5070	0.3156	0.5083
	Switch length	-	-	-0.0358	0.7432	-0.0228	0.7461
	Length of struct.	-	-	1.2955**	0.6022	1.3385**	0.6303
	Trend	-	-	-0.1283	0.1934	-0.1483	0.2023
	Trend^2	-	-	0.0051	0.0179	0.0069	0.0185
	Mixtend	-	-	0.4959	0.3730	0.5062	0.3787
	Ctend	-	-	0.1260	0.4068	0.1468	0.4213
MaintC	RenwC_t-1	-0.0091	0.0091	0.0022	0.0096	0.0024	0.0097
	MaintC_t-1	0.5492***	0.0584	0.2746***	0.0553	0.2767***	0.0554
	Ton density	-	-	0.2449***	0.0841	0.2630***	0.0817
	Ton density_t-1	-	-	-	-	0.0641	0.0706
	Track length	-	-	0.3004	0.1872	0.2810	0.1904
	Rail age	-	-	0.1083	0.1033	0.0927	0.1048
	Switch length	-	-	0.3140***	0.1263	0.3186**	0.1277
	Length of struct.	-	-	0.2992***	0.1018	0.3265***	0.1135
	Trend	-	-	-0.0957***	0.0287	-0.1049***	0.0317
	Trend^2	-	-	0.0124***	0.0026	0.0132***	0.0029
	Mixtend	-	-	-0.0492	0.0633	-0.0370	0.0656
	Ctend	-	-	-0.0969	0.0682	-0.0843	0.0721

***, **, * : Significance at the 1%, 5%, and 10% level, respectively.

A lagged value of maintenance does not improve the prediction of current values of renewals compared to only using lagged values of renewals. However, the estimation results from Model 2c with lag order 2 (presented in Table 3) show that maintenance cost in year t-2 predicts an increase in renewals ($MaintC_{t-2}$ is 0.5776, with p-value 0.018). Hence, this model suggests that a shock in maintenance may increase a need for renewals in the second year, while it is unlikely to occur in the first year (coefficient is -0.1671 with p-value 0.540). The impact on renewals is rather intuitive considering that renewals should be preceded by large (corrective) maintenance costs as this is what generally motivates a renewal. Figure 3 in section 5.1 provides an illustration of this relationship.

When it comes to lagged values of renewals in the maintenance equation, we do not find a significant Granger causality, and the estimate is close to zero. However, lagged maintenance costs predict an increase in current maintenance, with a coefficient at 0.2746 (p-value= 0.000) in Model 2a. This estimate is somewhat higher than the coefficient in Odolinski and Nilsson (2015), who estimated a system GMM on Swedish data at the track section level (more observations available compared to the contract area level), generating a coefficient for lagged maintenance costs at 0.1825.

Traffic is a key driver of cost. Therefore, the cost elasticities with respect to ton density are of particular interest which, together with coefficients for lagged costs, allows us to estimate equilibrium cost elasticities. In Model 2a (excludes a lagged traffic variable), the parameter estimate for ton density in the maintenance equation is 0.2449 (p-value=0.004), which is in line with previous results on Swedish data (see for example Odolinski and Nilsson 2015 or Andersson 2008). In the renewal equation the coefficient for ton density is 0.3727, which is lower than previous estimates on Swedish data (however, our estimate is not significantly different from zero, p-value = 0.350); Andersson et al. (2012) find a cost elasticity with respect to ton density at 0.547, and Yarmukhamedov et al. (2016) find elasticities between 0.5258 and 0.5646. St

We also include lagged traffic to allow for more flexibility in the model, where a change in traffic might generate renewal and/or maintenance activities in the next year other than that implied by the lagged dependent structure. Including a lagged traffic mainly had an impact on the maintenance equation. The coefficient for current traffic's impact on maintenance costs is now 0.2630 (p-value 0.001), while the estimate for lagged traffic is 0.0641 (p-value=0.364).

Table 3 – Estimation results, Models 1b and 2c-d, with order 2 lags (342 obs.)

		Model 1b		*Model 2c*		*Model 2d*	
Equation	Variable	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
RenwC	RenwC_t-1	0.3361***	0.0655	0.3193***	0.0678	0.3201***	0.0676
	RenwC_t-2	-0.0718	0.0521	-0.0848	0.0544	-0.0843	0.0549
	MaintC_t-1	-0.3918	0.2645	-0.1671	0.2729	-0.1660	0.2728
	MaintC_t-2	0.2535	0.2829	0.5776**	0.2436	0.5719**	0.2412
	Ton density	-	-	0.2633	0.3885	0.2479	0.3806
	Ton density_t-1	-	-	-	-	0.0992	0.2759
	Track length	-	-	2.2840	1.6545	2.2257	1.6528
	Rail age	-	-	-0.0591	0.6446	-0.0720	0.6451
	Switch length	-	-	-0.6738	0.9885	-0.6616	0.9857
	Length of struct.	-	-	0.6425	0.6824	0.6690	0.7281
	Trend	-	-	0.0263	0.2142	0.0236	0.2254
	Trend^2	-	-	-0.0104	0.0199	-0.0103	0.0208
	Mixtend	-	-	0.3549	0.3445	0.3603	0.3453
	Ctend	-	-	0.0734	0.3759	0.0830	0.3862
MaintC	RenwC_t-1	-0.0107	0.0099	0.0044	0.0106	0.0037	0.0105
	RenwC_t-2	-0.0021	0.0094	0.0091	0.0093	0.0087	0.0092
	MaintC_t-1	0.4665***	0.0570	0.3032***	0.0560	0.3005***	0.0557
	MaintC_t-2	0.1530***	0.0522	0.0065	0.0503	0.0066	0.0503
	Ton density	-	-	0.2330***	0.0901	0.2067**	0.0901
	Ton density_t-1	-	-	-	-	-0.0475	0.0754
	Track length	-	-	0.2181	0.2151	0.2519	0.2164
	Rail age	-	-	0.1617	0.1109	0.1729	0.1121
	Switch length	-	-	0.3765***	0.1331	0.3684***	0.1338
	Length of struct.	-	-	0.3852***	0.1323	0.3462**	0.1376
	Trend	-	-	-0.1339***	0.0325	-0.1250***	0.0345
	Trend^2	-	-	0.0157***	0.0030	0.0149***	0.0031
	Mixtend	-	-	-0.0694	0.0639	-0.0798	0.0638
	Ctend	-	-	-0.1145*	0.0695	-0.1231*	0.0701

***, **, * : Significance at the 1%, 5%, and 10% level, respectively.

We calculate the equilibrium cost elasticities with respect to ton-density for both renewals and maintenance. These are presented in Table 4, where γ^{e} denotes equilibrium cost elasticity and γ^{es} equilibrium cost elasticity including secondary effects. In Models 2a and 2b, the elasticity for renewals is not significant at the 10 per cent level, while the estimates for maintenance are significant at the 1 per cent level.

Table 4 – Equilibrium cost elasticities with respect to ton density

Model 2a			
	Cost elasticity	Coef.	Std. Err.
	$\gamma^{e}_{Maintenance}$	0.3375***	0.1144
	$\gamma^{e}_{Renewals}$	0.5660	0.6065
Including secondary effect	$\gamma^{es}_{Maintenance}$	0.3388***	0.1154
	$\gamma^{es}_{Renewals}$	0.4113	0.5955

Model 2b (with lagged traffic)			
	Cost elasticity	Coef.	Std. Err.
	$\gamma^{e}_{Maintenance}$	0.4522***	0.1667
	$\gamma^{e}_{Renewals}$	0.6235	0.7860
Including secondary effect	$\gamma^{es}_{Maintenance}$	0.4536***	0.1671
	$\gamma^{es}_{Renewals}$	0.4149	0.7871

***, **, * : Significance at the 1%, 5%, and 10% level, respectively.

Including the secondary effect generates similar results for maintenance (0.3388 with p-value=0.003), while the elasticity becomes smaller for renewals (0.4113 with p-value=0.490), due to the negative (yet, not statistically significant) coefficient for lagged maintenance costs in the renewal equation. The equilibrium cost elasticities changes for maintenance when lagged traffic is included (Model 2b); it is 0.4536 (p-value = 0.007) for maintenance when the secondary effect is included, which is quite high compared to the estimates for current traffic's impact on current maintenance cost that are common in the literature (estimates on Swedish data are in the interval 0.17-0.26; see Odolinski and Nilsson (2015)).

The equilibrium cost elasticities from models with lag order 2 are presented in Table 5 in appendix. Moreover, in appendix we also present equilibrium cost elasticities when using a two-step GMM estimator (as opposed to the iterative GMM estimator, where we also used the assumption that moment equations are independent). The equilibrium cost elasticities for maintenance are somewhat lower, while the cost elasticities for renewals are remarkably high. However, the lagged coefficients for maintenance and renewals are similar in both estimations.

The dummy variable for tendering of maintenance contracts shows that maintenance costs decreased with about 8 to 9 per cent[7], similar to the results in Odolinski and Smith (2016). However, the coefficients are not significant at the 10 per cent level (p-values are 0.155 and 0.242, respectively).[8] In the renewal equation, the estimate for competitive tendering of maintenance is not significantly different from zero. In one way, this is not surprising considering that a decision to renew is not likely to be directly connected to the introduction of tendering of maintenance; the decision to renew ought to be more connected to the condition of the railway assets and how costly infrastructure failures are for society on a certain part of the network. However, the amount and/or type of maintenance carried out - which may have changed due to competitive tendering - is certainly connected to the condition of the railway assets, which affects the need for renewals. Still, as previously noted, the results do not indicate that competitive tendering of maintenance has affected the renewal costs.

Finally, we note that the estimates for track length, average rail age, and length of structures have the expected signs in both the renewal and maintenance equations. The

[7] exp(-0.0969)-1= -0.0923 and exp(-0.0843)-1 = -0.0809 in Model 2a and Model 2b, respectively.

[8] Yet, these coefficients are significant at the 10 per cent level in the model with lag order 2 (see Table 3).

estimate for switch length is close to zero in the renewal equation, and not statistically significant. It is only the coefficients for switches and structures in the maintenance equation that is statistically significant, while length of structures is also significant in the renewal equation (indicating a rather large increase in renewal costs due to the length of tunnels and bridges). Using lag order 2 does not change these coefficients in the maintenance equation significantly. However, we note that the coefficients for rail age and length of switches are negative (still, not significant), while the coefficient for track length becomes remarkably large.

5.1 Impulse response analysis

We make use of IRA to trace the effect a shock in maintenance or renewals have on future costs of these activities, which is shown in Figure 2 below. We use one standard deviation shocks and trace its effects in each of the two equations in Model 2a (similar results are generated by Model 2b). The model including lags of order 2 generated more intuitive results with respect to lagged maintenance costs in the renewal equation. We therefore present the IRF for this relationship in Figure 3. The horizontal axis in both figures represent years. The dashed lines are 90 per cent confidence intervals based on 200 Monte Carlo draws from Model 2 (relies on repeated resampling).

The top left graph in Figure 2 shows how a shock in maintenance costs affects future maintenance costs, while the top right graph shows how a shock in maintenance costs affects future renewal costs. The lower graphs in Figure 2 show how a shock in renewal cost affects the different cost categories. As noted in section 2, we use recursive identification of the shocks, where we assume that current renewals can be affected by a shock in renewals but not by a contemporaneous shock in maintenance. Still, past shocks in maintenance may have an effect on renewals according to this assumption. For comparison, we estimate the impulse response function (IRF) with the opposite (wrong) ordering in the recursive identification of the shocks. These functions are presented in Figure 4 in appendix, showing that the IRFs for maintenance vs. renewals and renewals vs. maintenance are different with respect to levels and shapes, compared to the corresponding graphs in Figure 2. As expected, the IRFs for maintenance vs. maintenance and renewals vs. renewals do not change with the ordering in the identification method.

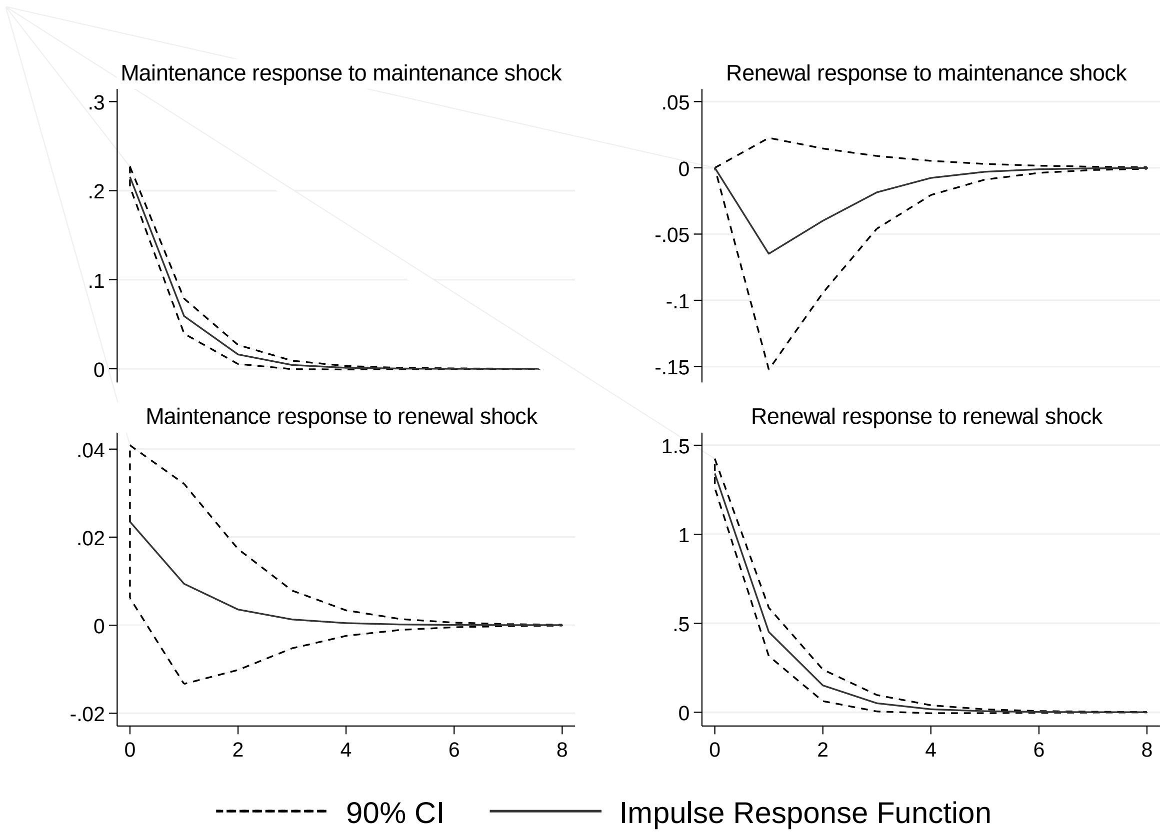

Figure 2 – Impulse response functions

As noted earlier, we found a Granger causality between lagged renewals and current renewals. The IRF indicates that a shock in renewals seems to be accompanied by more renewal costs within one year (and to some extent two years). This is not very surprising given budget restrictions and the lumpy nature of renewals - that is, these costs will probably stretch over more than one year in the accounting system.

From the upper left graph in Figure 2, we can see that a shock in maintenance costs has a direct impact on maintenance cost within a year, but not the second year. This suggests that the IM adjusts rather quickly to a sudden increase in traffic, without making an over-investment in preventive maintenance.[9] An over-investment would manifest itself as a decrease in maintenance cost for at least one year, and then adjust back to zero in the IRF.

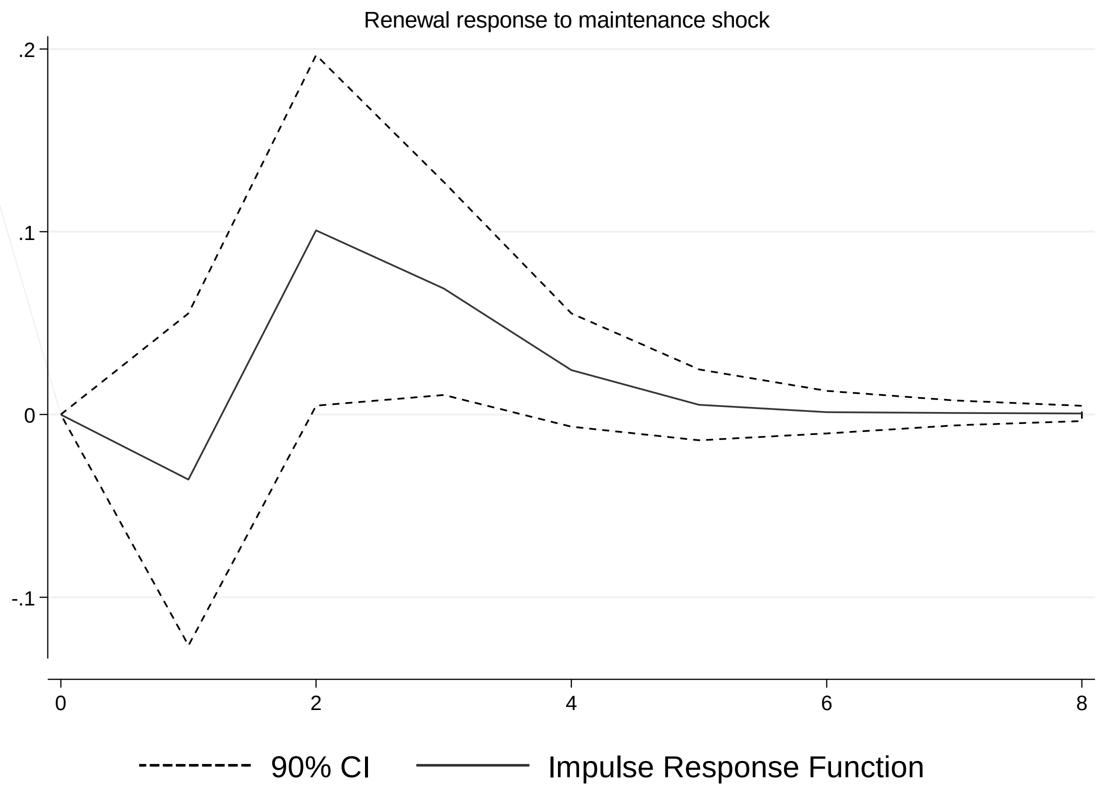

Figure 3 – Impulse response function, model with lag order 2

An impulse response function for the response in renewals from a maintenance shock is illustrated in Figure 3. In line with the upper right graph in Figure 2, a shock in maintenance predicts a decrease in renewals (yet, it is not significantly different from zero). However, in

[9] Note that the IRF would probably be different with user costs, to which the statement on over-investment may be sensitive.

the second year, the maintenance shock results in an increase in renewal costs. This suggests that an increase in maintenance costs may be a signal that it can be costly to continue with maintenance activities, and that a renewal is warranted. A renewal activity can be difficult to perform within a year due to the planning procedures required (procurement of the project and getting access to the tracks), making it more probable that the renewal response to a shock in maintenance mainly occurs in the second year.

6.0 Conclusions

In this paper we have estimated a panel VAR model on rail infrastructure costs in Sweden. The results provide empirical evidence on the relationship between maintenance and renewals, as well as evidence on intertemporal effects for each of these activities. The results show that past maintenance costs can improve the prediction of current values of renewals compared to only using past values of renewals. We also found intertemporal effects for both renewal and maintenance costs; an increase in renewals (maintenance) during one year predicts an increase in renewals (maintenance) during the next.

Our IRA shows how the intertemporal effects evolve over time, where the IM seems to adjust the maintenance costs quickly to a sudden increase in for example ton-density. The IRF for renewals has a similar shape, indicating that a renewal during one year is followed by additional renewal costs in the next year. It is probably the lumpy nature of renewals together with budget restrictions that makes it difficult to completely serve a need to renew the railway assets during one year in a contract area, leaving some of the required renewals to be made in the next year.

A particular purpose of estimating the dynamics in infrastructure costs is that it allows us to take these effects into account when assessing the cost impact of traffic. The estimated cost elasticity with respect to traffic is different in our dynamic model compared to static models that are frequently used in the literature on rail infrastructure costs. In particular, we used information on the dynamics between renewals and maintenance in order to estimate equilibrium cost elasticities. This type of elasticity can be used in the calculation of marginal cost (which is the product of average costs and the cost elasticity), with the aim of providing a better representation of the cost impact of an additional ton-km, considering that a traffic increase gives rise to costs in both the current year and subsequent years. Still, future work may benefit from longer panels which can provide more robust estimates (for example, the cost elasticity with respect to traffic in the renewal equation is not statistically significant). Such estimates could be used by infrastructure managers in Europe who need to set track access charges for the wear and tear caused by traffic.

The type of results provided in this paper can also be a useful demonstration of the maintenance and renewal strategy currently used. Stripping out the effects from the current strategy is essential for making improvements, where a proper balance between maintenance and renewal activities can generate higher benefits at a lower cost. For example, the estimate for the second order lag of maintenance cost in the renewal equation gives us a hint on how sensitive renewal costs are to prior increases in maintenance. Moreover, the intertemporal effect for maintenance reveals how quickly this cost adjusts to equilibrium. Still, there is more to be done in this research area in addition to providing more robust estimates. For example, the analysis in this paper is not able to answer whether the quick adjustment in maintenance costs is avoiding an over-investment - that is, doing more than is necessary to uphold the performance of the infrastructure. In fact, the IM may well be over- or under-investing in maintenance after a sudden increase in traffic. User costs (values of train delays for passengers and freight companies) must be considered in this type of analysis. That is, with access to data on train delaying failures and delay costs for passengers and freight companies, it could be a step towards a cost-benefit analysis of maintenance and renewals which in turn can generate economically efficient levels of these activities. This is an area for future research.

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Appendix

Table 5 – Equilibrium cost elasticities with respect to ton density, with order 2 lags

Model 2c			
	Cost elasticity	Coef.	Std. Err.
Including secondary effect	$\gamma^{e}_{Maintenance}$	0.3376**	0.1352
	$\gamma^{e}_{Renewals}$	0.3439	0.5173
	$\gamma^{es}_{Maintenance}$	0.3492**	0.1435
	$\gamma^{es}_{Renewals}$	0.5324	0.5697
Model 2d (with lagged traffic)			
	Cost elasticity	Coef.	Std. Err.
Including secondary effect	$\gamma^{e}_{Maintenance}$	0.2297	0.1778
	$\gamma^{e}_{Renewals}$	0.4553	0.6771
	$\gamma^{es}_{Maintenance}$	0.2410	0.1845
	$\gamma^{es}_{Renewals}$	0.5839	0.7035

***, **, * : Significance at the 1%, 5%, and 10% level, respectively.

Table 6 – Equilibrium cost elasticities with respect to ton density, using the two-step GMM estimator

Model 2c			
	Cost elasticity	Coef.	Std. Err.
Including secondary effect	$\gamma^{e}_{Maintenance}$	0.2372**	0.0961
	$\gamma^{e}_{Renewals}$	0.9451	0.5909
	$\gamma^{es}_{Maintenance}$	0.2397**	0.0982
	$\gamma^{es}_{Renewals}$	0.8277	0.5830
Model 2d (with lagged traffic)			
	Cost elasticity	Coef.	Std. Err.
Including secondary effect	$\gamma^{e}_{Maintenance}$	0.3535**	0.1491
	$\gamma^{e}_{Renewals}$	1.4678**	0.7170
	$\gamma^{es}_{Maintenance}$	0.3574**	0.1519
	$\gamma^{es}_{Renewals}$	1.2951*	0.7060

***, **, * : Significance at the 1%, 5%, and 10% level, respectively.

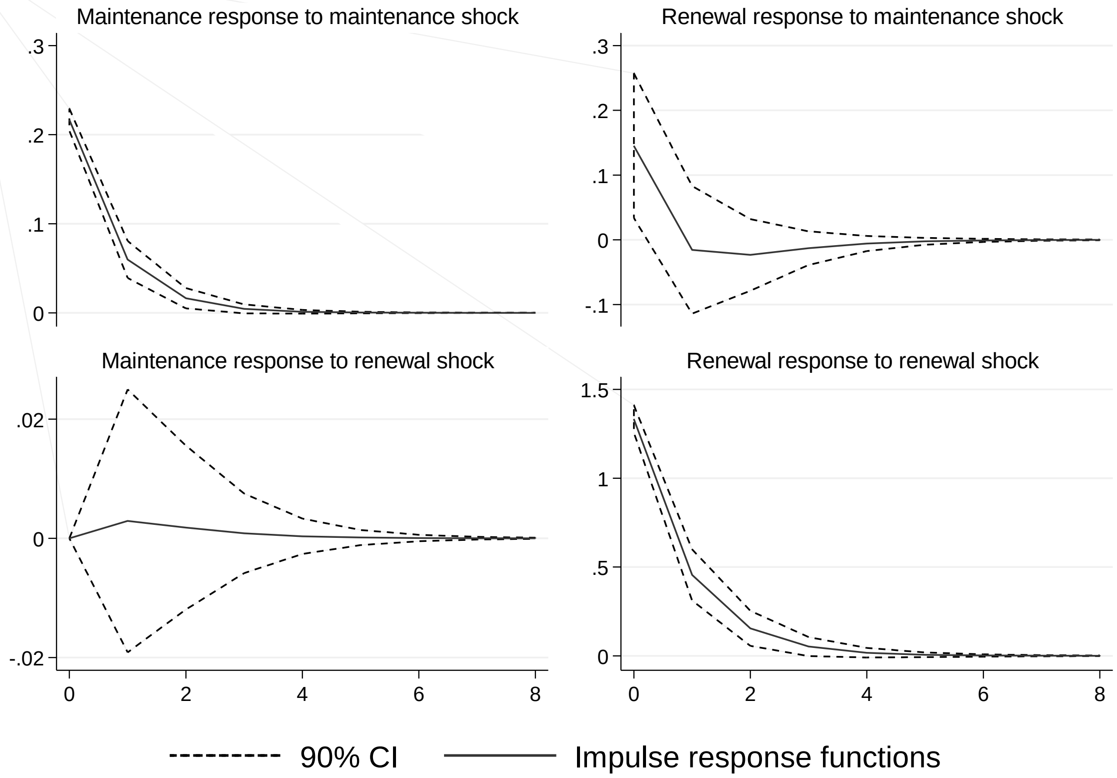

Figure 4 – IRFs with wrong ordering in the recursive identification