Economics of Transportation 14 (2018) 21–30

Contents lists available at ScienceDirect

Economics of Transportation

journal homepage: www.elsevier.com/locate/ecotra

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

Kristofer Odolinski [a,*], Phill Wheat [b]

[a] The Swedish National Road and Transport Research Institute, Department of Transport Economics, Box 55685, 102 15 Stockholm, Sweden
[b] Institute for Transport Studies, University of Leeds, 36-40, University Road, Leeds LS2 9JT, United Kingdom

ARTICLE INFO

JEL codes:
R48
L92

Keywords:
Rail infrastructure
Renewal
Maintenance
Panel vector autoregression
Marginal cost
Impulse response analysis

ABSTRACT

In this paper, we extend to the literature on marginal wear and tear cost estimation in railways, by applying a panel vector autoregressive model to rail infrastructure renewals and maintenance costs, using an extensive dataset from Sweden. This study is significant given the inherent difficulties in modelling the substantial renewals element of infrastructure costs, as well as the need to account for the dynamics in renewals and maintenance. The dynamic model allows us to estimate equilibrium cost elasticities with respect to train usage, which are significantly larger than their 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. This is particularly important given several countries, for example France, Sweden and Switzerland, are now setting access charges at marginal costs based on econometric studies.

1. Introduction

Infrastructure investments consume a large amount of resources. To reap the benefits of an investment, the infrastructure must be maintained and renewed due to the wear and tear caused by traffic and to some extent weather conditions - that is, maintenance and renewals will affect the performance and reliability of the infrastructure. For a given traffic level, the objective of the infrastructure manager (IM) is to minimize whole life maintenance and renewal costs (as well as train delay costs). In doing this, the IM needs to consider the with-in year substitution possibilities and intertemporal relations in maintenance and renewal activities. This is because maintenance and renewal activities are input substitutes in the production of infrastructure services, both between each other and in their phasing over time. This is the basis of Life Cycle Asset Management. In general, a cost minimizing plan would imply that maintenance costs for a given asset would increase over time, until it is beneficial to renew the asset instead of letting the maintenance (and train delay) cost level increase any further. Hence, a renewal is likely to be preceded by high maintenance costs and then followed by low maintenance costs.[1] This also implies that a temporary deviation from the plan of maintenance and renewal activities, due to for example a change in traffic, will have an effect on the future pattern of these activities.

The dynamics in maintenance and renewals implies that an IM needs to strike a balance within and between these activities for a certain traffic level, and an increase in traffic may require an immediate as well as intertemporal adjustment of these costs. This implies that the cost impact from traffic needs to be studied in a dynamic context, which is the objective with this paper. Specifically, 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.[2]

In this study, we estimate a panel vector autoregressive (panel VAR) model. This is a dynamic model that considers several endogenous variables - renewals and maintenance in our case - in a multiple equation system. Our estimation approach is similar to that in Wheat (2015), with the contribution that we take the panel data structure into account. Hence, we are able to model unobserved individual heterogeneity, which

* Corresponding author.
E-mail addresses: kristofer.odolinski@vti.se (K. Odolinski), p.e.wheat@its.leeds.ac.uk (P. Wheat).

[1] However, we note that there may be reason to lower the level of preventive maintenance during a certain period before a renewal is made. Yet, this may be countered with a need for more corrective maintenance prior to the renewal.

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

https://doi.org/10.1016/j.ecotra.2018.01.001
Received 30 March 2017; Received in revised form 11 December 2017; Accepted 26 January 2018

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 relation to wear and tear.

A central facet of the VAR model is to make structural analyses, in which the response of the endogenous variables is traced through time following a 'shock' to the equation system. We make use of an impulse response analysis (IRA) to trace how maintenance/renewal costs evolve over time following a disruptive shock. This shock could be caused by a factor outside of the considered explanatory variables and thus captured as perturbing the error in the model. An example in this case is changes in the budget constraint or severe weather incidents. Alternatively, a shock can come from a change in the exogenous explanatory variables within the model e.g. traffic. Both of these shock types require the IM to adjust maintenance and renewal activities in response. To identify these shocks and their impact, we utilize the temporal dependence between maintenance and renewals, where we expect the latter to react more slowly than the former.

The paper is organized as follows. In section 2, we present the empirical context in which our study is positioned. The methodology used is described in section 3. It also includes a subsection in which we expand on the mechanisms behind the dynamics in rail infrastructure provision, as well as 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 4 comprises a description of the data. We specify our model in Section 5. The estimation results are presented in Section 6. Section 7 concludes.

2. Empirical context

Econometric analysis of railway maintenance and renewals costs is accepted by the European Commission as an appropriate methodology to set track access charges across EU member states (European Commission, 2015), and several countries, including Sweden, France and Switzerland have used econometric methods to inform the level of access charges within their countries. This motivates the empirical literature on marginal cost of railway infrastructure (see Link et al., 2008; Wheat et al., 2009), which has a wealth of research on the maintenance cost element (Munduch et al., 2002; Johansson and Nilsson, 2004; Wheat and Smith, 2008; Gaudry and Quinet, 2009). However, the econometric evidence on the marginal cost associated with renewals cost element is much less robust. Studies often add renewal costs to maintenance in the estimations (Andersson, 2006; Tervonen and Pekkarinen, 2007; Marti et al., 2009; Wheat and Smith, 2009), yet there are a couple of examples focusing on renewals only, although these use very disaggregate data by asset (Andersson et al., 2012; Andersson et al., 2016). The lack of evidence on renewals cost partly reflects the lumpy nature of renewals investments, which in turn implies a long time series is required to capture the evolution of renewals expenditure to changes in traffic (Link et al., 2008; Wheat et al., 2009).

Renewals expenditure accounts for roughly one third of the sum of maintenance and renewals expenditure in Sweden (Trafikverket, 2016) and so the significance of this cost category and its relationship with maintenance should not be understated.[3] In general, the importance of performing renewals and maintenance activities at the right time has generated a rather extensive literature on the optimization of these activities: Gaudry et al. (2016) and Andrade and Teixeira (2011) are railway examples, while Sathaye and Madanat (2011), De la Garza et al. (2011) and Gu et al. (2012) analyse the optimization of pavement maintenance and resurfacing activities (see Sharma and Yadava (2011) for a literature review on this area). Related to this literature is Small et al. (1989), who presents an equilibrium pricing and investment model, in which optimal road durability for a certain traffic volume is calculated together with the corresponding marginal costs.

Still, there is a lack of empirical evidence on the dynamics between and within maintenance and renewal activities (i.e. the interdependence and intertemporal effects as described in the introduction and more in depth in section 3.1), especially in the literature on rail infrastructure costs. A notable exception is the study by Wheat (2015), in which a VAR model 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 (2017) who estimate a dynamic model (system GMM) for maintenance costs only. 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.

Thus, econometric evidence on the dynamics in rail infrastructure provision is scarce, despite its relevance for track access charges. Ultimately, marginal cost estimates that take dynamic effects of renewals and maintenance 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 maintenance (see for example Wheat et al., 2009) and renewals (see for example Andersson et al., 2012; Andersson et al., 2016).

3. 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 behaviour 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 VAR framework dispenses with such arbitrary identification through the use of lagged explanatory variables which are by definition weakly exogenous even if the values in the current time period are endogenous.

The objective in using a VAR model is to capture the effects of 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 also 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, as explained further in section 3.1.

We consider a panel VAR(p) model, where p denotes the lag length used in the model.[4] We have two endogenous variables: renewal costs (R_{it}) and maintenance costs (M_{it}), where $i = 1, 2\ldots, N$ contract areas and $t = 1, 2, \ldots, T$ 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 $(u'_{1,it}, u_{2,it}) = \boldsymbol{u}_{it} \sim iid(0, \sum)$. $\sum$ 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. Importantly

[3] The share can be larger (or smaller) in other countries. See for example Grimes and Barkan (2006) for renewals as a proportion of total maintenance costs in the US during 1978–2002.

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

traffic is included in the vector of exogenous variables.

$$lnR_{it} = \alpha_{1,i} + \delta_{11} lnR_{it-1} + \theta_{11} lnM_{it-1} + \boldsymbol{\beta}_1^{'} \boldsymbol{lnX}_{it} + u_{1,it}$$

$$lnM_{it} = \alpha_{2,i} + \delta_{21} lnR_{it-1} + \theta_{21} lnM_{it-1} + \boldsymbol{\beta}_2^{'} \boldsymbol{lnX}_{it} + u_{2,it} \tag{1}$$

Lagged renewal and maintenance costs are included in both equations to capture the dynamics with-in maintenance and renewals, as well as the interdependence between these activities. We adopt a logarithmic functional form in keeping with the applied literature in this area (for example Munduch et al., 2002; Link et al., 2008; Wheat and Smith, 2008; Smith et al., 2010; Smith and Wheat, 2012; Odolinski and Nilsson, 2017).

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 (see Section 5). 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, where stability implies stationarity. If the process is non-stationary, first differencing would be required to avoid spurious results. The modulus of each of the eigenvalues is below one in our estimated models, which implies that our vector autoregressions are stable and therefore stationary (see Lütkepohl, 2005, p.14–15). The moduli are presented in output Table 2.

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 Góes (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 Arellano 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. In absence of good instruments outside our dataset, we use further lags of the endogenous lagged variables as instruments. These are valid instruments as we use forward orthogonal deviation, where past values are not included in the transformation (see Arellano and Bover, 1995; Roodman, 2009; Baltagi, 2013). Using a longer set of lags as instruments can improve estimation efficiency (yield more precise estimates). In doing so, we use the method by Holtz-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 (one should, however, be aware that using a large set of instruments may overfit the endogenous variables - see Roodman, 2009 for details - and we therefore also estimate the models with a restricted number of instruments, i.e. reduce the number of lags). This approach is valid under the standard assumption that our instruments are not correlated with the error terms.

3.1. Mechanisms behind the dynamics in rail infrastructure provision

The mechanisms under study in this paper can be described by introducing examples of changes in exogenous factors into the cost minimizing maintenance and renewal plan. Some of these can be exogenous shocks captured in the error, i.e. representing the impact of potential omitted variables (examples are given below, whereas how this type of shock can be used for identification is described in section 3.2), while others are changes in the explanatory variables, for example traffic. The dynamic effects depend on the exogenous change and the initial response taken by the IM, where it is useful to distinguish between preventive maintenance and corrective maintenance. The examples are as follows.

If the IM deviates from the maintenance and renewal plan by increasing preventive maintenance in the current year (due to relaxation of an exogenous budget constraint, i.e. shock in error term), it can lower the level of maintenance required in subsequent year(s) relative to the original plan, *ceteris paribus*, and vice versa. An increase in preventive maintenance can also make it possible to postpone a renewal.

If there instead is a (sudden) change in a cost driver such as traffic, it can result in a direct increase in corrective maintenance as well as additional maintenance activities in subsequent year(s), i.e. it takes time for the IM to adjust its cost minimizing maintenance and renewal plan in the current year (this effect was found by Wheat, 2015; Odolinski and Nilsson, 2017). This may also front-load and/or increase the level of planned renewals. On the other hand, the IM may respond to the increase in traffic directly with (front-loading) preventive maintenance activities, which in the short-run can create a lower than average maintenance cost level in the subsequent period(s) (this type of effect was found by Andersson, 2008).

In the case of renewals, one may expect that increased renewals in the current year will always indicate less (if any) renewals being made in the subsequent year. However, a set of renewal (or maintenance) activities in an area may need to be performed during two years due to organisational constraints (for example inflexible inputs in the production). Hence, increased renewal (maintenance) costs in the current year can also indicate that further renewals (maintenance) will be made in the next year.

In short, a change in an exogenous factor can have an impact on the future pattern of maintenance and renewal activities, where there may be changes both with-in and between maintenance and renewals considering that these activities are input substitutes in the production of infrastructure services. The exact relationships are a priori ambiguous as explained above and our model is flexible enough to reveal through estimation which process dominates in our data. The use of lagged maintenance and renewal costs is our main approach for capturing the patterns of adjustment. Note that the impact on future maintenance and renewal costs due to a sudden change in an exogenous regressor is picked up by the lagged cost variables through recursive back substitution. Furthermore, we also consider a lagged traffic variable to allow for a different pattern of adjustment for traffic vis-a-vis other shocks. This could be important as IMs may respond differently over time to an unexpected change in traffic as opposed to an unexpected change in other factors. Importantly we test for whether this alternative dynamic pattern of adjustment exists.

The mechanisms that we describe are likely to apply to other countries outside of Sweden but the balance between them may be different, and thus there can be different empirical findings on the dynamic patterns. For example, in Britain, the analysis by Wheat (2015) for the time period which included the nationalized infrastructure manager, high maintenance and high renewals expenditures were found to persist for a number of years following a shock. This is likely to reflect the lumpiness and unpredictability of the (politically determined) budget constraint the organization operated within over that period.

3.2. 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 ($\boldsymbol{\varepsilon}_{it}$), which simply put are changes in either renewals or maintenance caused by factors outside the known variable system in the model – that is, omitted factors such as changes in budget constraints or severe weather incidents. Given our knowledge about the nature of renewals and maintenance, we choose *recursive identification* as the method to identify the relationship between the errors in the same time period as the time of a shock. Shocks are assumed to be a linear function of the residuals $\boldsymbol{u}_{it} = G\boldsymbol{\varepsilon}_{it}$, where G is a 2×2 matrix. An ordering of the variables is required such that the G matrix can be calculated from the covariance matrix $\sum$ by using the Cholesky decomposition (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 impact on current renewals is a shock in renewals, while current maintenance can be influenced by both a renewal shock and a maintenance shock. This assumption only implies that a maintenance shock will not affect *current* renewals, while future renewals are allowed to be influenced by the maintenance shock. In other words, maintenance expenditure is more agile to shocks than renewals – that is, an IM responds first with a change in maintenance. Note that this does not discard the possibility of a renewal shock influencing the current (or future) level of maintenance.

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

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

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.

3.3. Equilibrium cost elasticity with respect to traffic

With lagged cost variables in our model, we can calculate the 'equilibrium cost elasticity' with respect to traffic, both for renewals and maintenance. We use the term 'equilibrium cost' to describe a situation in which there is no tendency to change maintenance or renewals costs, *ceteris paribus*. This is important because we consider that the IM's objective is to reach a level of maintenance and renewals that minimizes these costs with respect to different cost drivers (traffic, asset condition etc.). However, the IM is subject to short term budget and scheduling restrictions, which mean it cannot adjust to an unexpected change in traffic completely in a single time period. Thus it takes time for the full impact of a traffic change to influence cost. The equilibrium cost elasticity with respect to traffic represents this full change and so is (at least what the IM considers to be) the change required to minimize costs when traffic changes – that is, to adjust to the IM's desired equilibrium maintenance and renewal cost level.[5] This argument is similar to the widely applied "Partial Adjustment Model" (see for example Doran, 1989 or Baltagi, 2011).

From an econometric point of view, it is essential that we adopt our dynamic modelling approach if there are such lags in the IM responding to unexpected shocks. This is because, if we ignore these factors and do not include a lagged dependent variable (or more generally a lagged endogenous variable) as explanatory factors, then we assume that the IM responds instantly to unexpected changes (in for example traffic). If lags in the IM's response exist in our cost data, we would introduce bias if we ignore them in our model estimation.

Furthermore, if the estimates for the lagged dependent variables indicate that the short run impacts diminish over time, then we can interpret this as an adjustment towards an equilibrium in response to an unexpected shock. As such, information on equilibrium can be gleaned from our cost data even if in reality there is always some departure between the observed data and equilibrium (because there will also be new shocks impacting on the system).

Turning to how to calculate the equilibrium cost elasticity, using equation (1) and separating out traffic, Q, from the general vector of exogenous factors, we have:

$$lnR_{it} = \alpha_{1,i} + \delta_{11} lnR_{it-1} + \theta_{11} lnM_{it-1} + \beta_{11} lnQ_{it} + \boldsymbol{\beta}_1^{'} \boldsymbol{lnX}_{it} + u_{1,it}$$

$$lnM_{it} = \alpha_{2,i} + \delta_{21} lnR_{it-1} + \theta_{21} lnM_{it-1} + \beta_{21} lnQ_{it} + \boldsymbol{\beta}_2^{'} \boldsymbol{lnX}_{it} + u_{2,it} \tag{3}$$

which is the VAR model we estimate. Here it should be noted that we control for other cost drivers ($\boldsymbol{X}_{it}$) such as rail age (proxy for asset condition) and to some extent, planned traffic changes, via inclusion of the time trend variables (since these adjust the equilibrium over time to reflect a general trend in the cost drivers for the railway as a whole).

The definition of equilibrium is no tendency to change. As such, in equilibrium $\boldsymbol{lnR}_{it-1} = \boldsymbol{lnR}_{it} = \boldsymbol{lnR}_i^e$ and $\boldsymbol{lnM}_{it-1} = \boldsymbol{lnM}_{it} = \boldsymbol{lnM}_i^e$. Substituting these relations into equation (3), we have

$$lnR_i^e = \alpha_{1,i} + \delta_{11} lnR_i^e + \theta_{11} lnM_i^e + \beta_{11} lnQ_i + \boldsymbol{\beta}_1^{'} \boldsymbol{lnX}_i + u_{1,i}$$

$$lnM_i^e = \alpha_{2,i} + \delta_{21} lnR_i^e + \theta_{21} lnM_i^e + \beta_{21} lnQ_i + \boldsymbol{\beta}_2^{'} \boldsymbol{lnX}_i + u_{2,i} \tag{4}$$

Hence, from equation (4), we can express the equilibrium renewal cost as

$$lnR_i^e = \frac{\alpha_{1,i}}{1-\delta_{11}} + \frac{\theta_{11}}{1-\delta_{11}} lnM_i^e + \frac{\beta_{11}}{1-\delta_{11}} lnQ_i + \frac{\boldsymbol{\beta}_1^{'}}{1-\delta_{11}} \boldsymbol{lnX}_i + \frac{u_{1,i}}{1-\delta_{11}} \tag{5}$$

and the equilibrium maintenance cost as

$$lnM_i^e = \frac{\alpha_{2,i}}{1-\theta_{21}} + \frac{\delta_{21}}{1-\theta_{21}} lnR_i^e + \frac{\beta_{21}}{1-\theta_{21}} lnQ_i + \frac{\boldsymbol{\beta}_2^{'}}{1-\theta_{21}} \boldsymbol{lnX}_i + \frac{u_{2,i}}{1-\theta_{21}} \tag{6}$$

Note that maintenance cost $\boldsymbol{lnM}_i^e$ is a part of the renewal cost equation (5) and that renewal cost $\boldsymbol{lnR}_i^e$ is a part of the maintenance cost equation (6). If there is interdependence between maintenance and renewals, we will have a secondary effect from a traffic increase; a change in traffic will have an impact on renewal (maintenance) costs, which in turn will have an effect on maintenance (renewal) costs.

With the equilibrium renewal cost in equation (5) and the equilibrium maintenance cost in equation (6), we can derive the equilibrium maintenance cost elasticity with respect to traffic (γ_M^{es}) that includes the secondary effect from the renewal equation:

$$\gamma_M^{es} = \frac{\partial lnM_i^e}{\partial lnQ_i} = \frac{\beta_{21}}{1-\theta_{21}} + \frac{\delta_{21}}{1-\theta_{21}} \frac{\partial lnR_i^e}{\partial lnQ_i} \tag{7}$$

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

$$\gamma_R^{es} = \frac{\partial lnR_i^e}{\partial lnQ_i} = \frac{\beta_{11}}{1-\delta_{11}} + \frac{\theta_{11}}{1-\delta_{11}} \frac{\partial lnM_i^e}{\partial lnQ_i} \tag{8}$$

The last terms in equations (7) and (8) will be zero if there is no interdependence between maintenance and renewals – that is, the equilibrium cost elasticity is then $\frac{\beta_{21}}{1-\theta_{21}}$ for maintenance and $\frac{\beta_{11}}{1-\delta_{11}}$ for renewals. We term these measures "equilibrium elasticities without secondary effects", using the notation γ^e. We report them alongside the estimates from the fuller expressions in (10) and (11) below, which provides information on the influences of the maintenance/renewal interdependence in driving the overall cost response to changes in traffic.

Putting the right-hand side of equation (8) into (7) gives

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

[5] Note that the estimation of these cost elasticities does not include (or require) information on fixed investment costs. Instead, a change in investment costs can be an exogenous shock picked up in the error, which is used to capture the patterns of adjustment for renewals and maintenance, as described in the previous section.

Rearranging, we have

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

We use equations (9) and (10) to get the corresponding renewal cost elasticity

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

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

4. Data

Data has been obtained from the Swedish Transport Administration (the IM), and consists of renewal and maintenance costs, traffic, and characteristics of the railway network such as track length and rail age (a proxy for asset condition). We also consider an input price variable (wages) in this study, which has been obtained from the Swedish Mediation Office (via Statistics Sweden). Moreover, we also make use of a time trend variable, which for example can capture effects from planned traffic changes. 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.[6] The effect 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.[7]

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 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.

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

	Mean	St.dev.	Min	Max
Hourly wage, SEK[a]	156.7	11.7	128.9	187.4
MaintC (Maintenance costs), million SEK[a]	56.78	44.37	8.03	334.41
RenwC (Renewal costs), million SEK[a]	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

[a] 2014 prices.

5. Model specification

To get a first impression of the main variables of interest, we make a graph of maintenance and renewal costs during years 1999–2014 (see Fig. 1). 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 lumpier 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).

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 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).[8] We include the maximum number of lags in our model checks and consider the lag orders 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), while the model with lag order 2 has the corresponding values −50.55, −234.62 and −208.55. However, we consider the second lag may be informative from an a priori perspective in terms of the expected behaviour of infrastructure managers, i.e. the response in maintenance/renewals from an increase in renewals/maintenance can take longer than one year. Indeed, the esti-

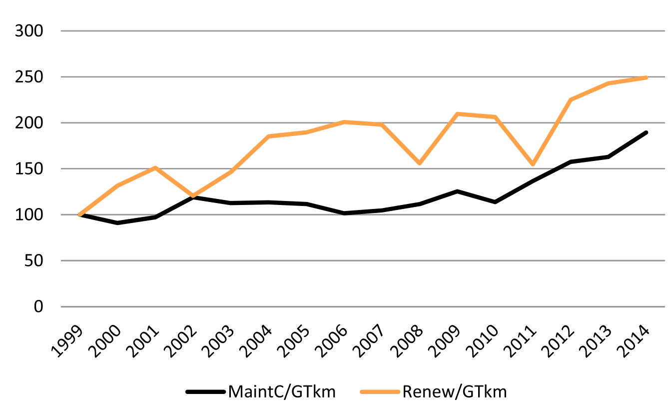

Fig. 1. Indices for maintenance (MaintC) and renewal costs (RenwC) per gross ton-km (GTkm), 1999–2014 (1999 = 100).

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

[7] 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.

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

mation results show that the second order lag is useful. We therefore focus on the model with lag order 2 (Model A) in the next section.

As motivated in section 3.1, we also considered a lagged traffic variable as it could potentially add useful flexibility between traffic and costs in addition to the effect of past traffic being picked up indirectly by lagged costs. However, its coefficient was not statistically significant and other coefficients did not change.

For comparison, we also estimate static counterparts of the models - i.e. dropping the lagged variables and the renewal/maintenance equation - with renewals, maintenance, and the sum of maintenance and renewals as dependent variables (Models B1, B2 and B3, respectively).

6. Results

Estimation results from Model A1 and A2 are presented in Table 2, where the former only includes the endogenous variables, and the latter includes a set of exogenous variables. The static comparison models (Models B1-B3) are presented in Table 3. The models are estimated with robust standard errors, using the iterative GMM estimator. We use the maximum lag length of the instruments (up to 14), which improves the efficiency of the model estimation. However, as noted in section 3, there is a risk of overfitting the endogenous variable if too many instruments are used (see Roodman, 2009). Hence, we test a restriction of the number of instruments (lag length 7), which generates somewhat larger standard errors, but similar estimates. All estimations are carried out with Stata 12 (StataCorp, 2011) using the package provided by Abrigo and Love (2015).

The results for lagged maintenance and renewals are similar in both model A1 and A2 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 A1. We focus on the results from Model A2 which includes 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 0.3193 that is significant at the 1 per cent level. A possible explanation is that budget (or planning) 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 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. 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.

A lagged value of maintenance improves the prediction of current values of renewals compared to only using lagged values of renewals. The estimation results 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. Fig. 2 in section 6.1 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 0.3032 (p-value = 0.000). This estimate is somewhat higher than the coefficient in Odolinski and Nilsson (2017), 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 0.2140. On the contrary, our estimate is low compared to the estimate by Wheat (2015) using British data, which is 0.9585 (however, we note that the same study also had high estimates for the static variants of the model, indicating that the high elasticities were not due to the dynamic model).

Table 2
Estimation results, Models A1 and A2, with order 2 lags (342 obs.).

Equation	Variable	*Model A1* Coef.	Std. Err.	*Model A2* Coef.	Std. Err.
RenwC	RenwC_t-1	0.3361***	0.0655	0.3193***	0.0678
	RenwC_t-2	−0.0718	0.0521	−0.0848	0.0544
	MaintC_t-1	−0.3918	0.2645	−0.1671	0.2729
	MaintC_t-2	0.2535	0.2829	0.5776**	0.2436
	Ton density	–	–	0.2633	0.3885
	Track length	–	–	2.2840	1.6545
	Rail age	–	–	−0.0591	0.6446
	Switch length	–	–	−0.6738	0.9885
	Length of struct.	–	–	0.6425	0.6824
	Trend	–	–	0.0263	0.2142
	Trend2	–	–	−0.0104	0.0199
	Mixtend	–	–	0.3549	0.3445
	Ctend	–	–	0.0734	0.3759
MaintC	RenwC_t-1	−0.0107	0.0099	0.0044	0.0106
	RenwC_t-2	−0.0021	0.0094	0.0091	0.0093
	MaintC_t-1	0.4665***	0.0570	0.3032***	0.0560
	MaintC_t-2	0.1530***	0.0522	0.0065	0.0503
	Ton density	–	–	0.2330***	0.0901
	Track length	–	–	0.2181	0.2151
	Rail age	–	–	0.1617	0.1109
	Switch length	–	–	0.3765***	0.1331
	Length of struct.	–	–	0.3852***	0.1323
	Trend	–	–	−0.1339***	0.0325
	Trend2	–	–	0.0157***	0.0030
	Mixtend	–	–	−0.0694	0.0639
	Ctend	–	–	−0.1145*	0.0695
Moduli of eigenvalues		0.69, 0.26, 0.26 and 0.22		0.42, 0.35, 0.35 and 0.11	

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

Table 3
Estimation results, Models B1-B3 (342 obs.).

Dependent variable	*Model B1* RenwC		*Model B2* MaintC		*Model B3* RenwC + MaintC	
	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
Ton density	−0.1189	0.4612	0.2431***	0.0769	0.2506**	0.1197
Track length	3.2393**	1.5187	0.5908***	0.2232	0.6333**	0.3236
Rail age	−0.2836	0.4919	0.1754	0.1139	0.2027	0.1658
Switch length	−1.4351**	0.6651	0.4559***	0.1532	0.2406	0.2149
Length of structures	0.2130	0.6583	0.3610***	0.1191	0.3627*	0.1953
Trend	0.2501	0.2382	−0.1588***	0.0367	−0.0994	0.0709
Trend2	−0.0323	0.0219	0.0190***	0.0033	0.0117*	0.0064
Mixtend	0.2823	0.4257	0.1019	0.0775	0.1264	0.1456
Ctend	0.1988	0.4526	−0.0051	0.0818	0.0518	0.1502

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

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. The parameter estimate for ton density in the maintenance equation is 0.2330 (p-value = 0.010), which is in line with previous results on Swedish data (see for example Odolinski and Nilsson, 2017 or Andersson, 2008) and results from other European countries, where estimates are in the interval 0.18–0.35 (Link et al., 2008) or 0.2–0.45 (Wheat et al., 2009). In the renewal equation, the coefficient for ton density is 0.2633 (yet, not significantly different from zero, p-value = 0.498), which is similar to the estimate by Wheat (2015) on British data (0.2774). However, it is lower than previous estimates on Swedish data; 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.

For comparison, we estimate the static counterparts of the models, including a model with the sum of maintenance and renewal costs as the dependent variable (see Table 3). The renewal model (B1) generates non-satisfactory results due to a negative and insignificant traffic elasticity estimate, which is not surprising given the lumpy nature of renewals. The results in models B2 and B3 are more in line with the maintenance equation results in model A2, with similar cost elasticities with respect to ton density even though renewals are included in model B3. However, adding renewals to maintenance in this model is not the preferable approach given the results in Model B1.

We calculate the equilibrium cost elasticities with respect to ton-density for both renewals and maintenance, using the results from model A2. These are presented in Table 4, where γ^e denotes equilibrium cost elasticity without secondary effects and γ^{es} denotes the equilibrium cost elasticity including secondary effects, as discussed in section 3.3. The elasticities for renewals are not significant at the 10 per cent level, while the estimates for maintenance are significant at the 5 per cent level. Including the secondary effect does not have a large impact on the maintenance elasticity, while the elasticity becomes larger for renewals – from 0.3439 with p-value = 0.506, to 0.5324 with p-value = 0.350 – due to the positive coefficient for lagged maintenance costs in the renewal equation. All in all, the elasticities are larger than their static counterparts.

The dummy variable for tendering of maintenance contracts shows that maintenance costs decreased with about 11 per cent,[9] similar to the results in Odolinski and Smith (2016). 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.

Table 4
Equilibrium cost elasticities with respect to ton density, Model A2.

Cost elasticity	Coef.	Std. Err.
$\gamma^e_{Maintenance}$	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

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

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. It should also be noted that a difference-in-differences approach would be a more accurate way of estimating the effect of tendering, an approach used in Odolinski and Smith (2016).

Finally, we note that the estimates for track length, average rail age, and length of structures have the expected signs in the maintenance equation. The estimate for average rail age is close to zero in the renewal equation, and not statistically significant, as is the coefficient for switch length.[10] It is only the coefficients for switches and structures in the maintenance equation that is statistically significant. Using lag order 1 does not change these coefficients in the maintenance equation significantly.

6.1. 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 Fig. 2 below. We use one standard deviation shocks and trace its effects in each of the two equations in Model A2 (similar results are generated by Model C2). The horizontal axis in both figures represent years. The dashed lines are 90 per cent confidence intervals based on 200 Monte Carlo draws using Gaussian approximation.

The top left graph in Fig. 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 Fig. 2 show how a shock in renewal cost affects the different cost categories. As noted in Section 3, 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 influence 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 Fig. 3 in

[9] exp(-0.1145)-1 = −0.1082.

[10] We also estimated the model without switch length, which did not affect the results significantly.

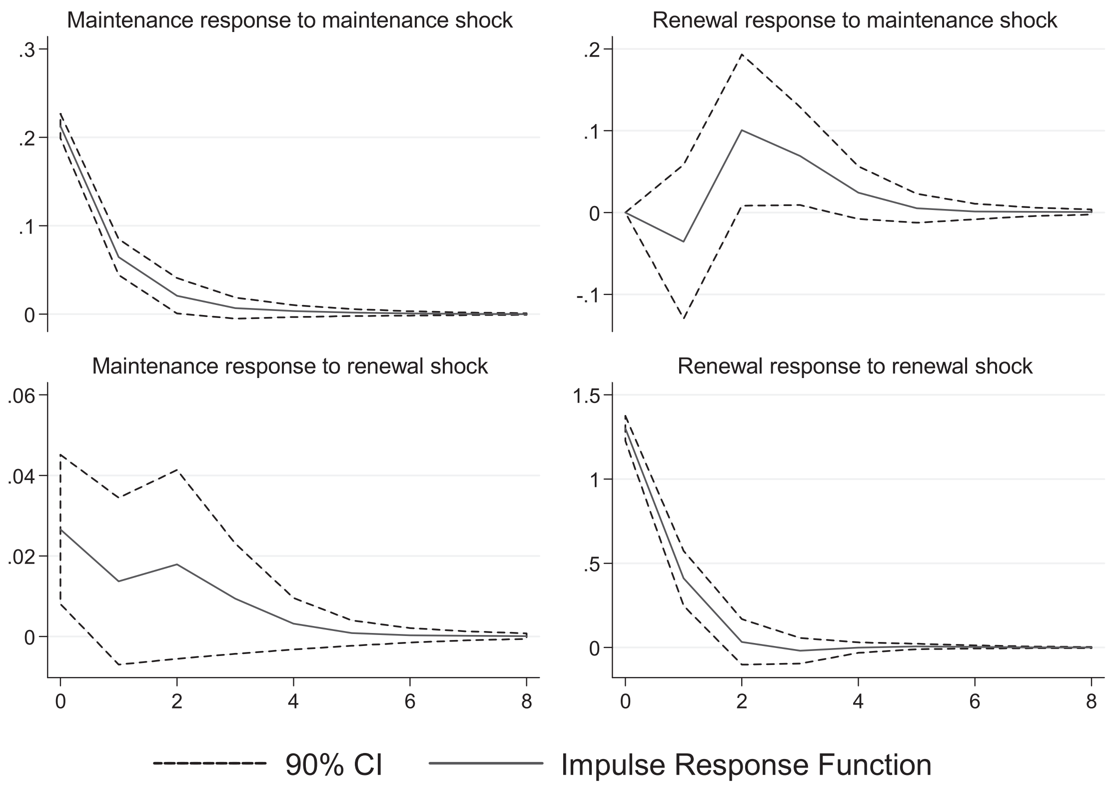

Fig. 2. Impulse response functions.

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 Fig. 2. As expected, the IRFs for maintenance vs. maintenance and renewals vs. renewals do not change with the ordering in the identification method.

As noted earlier, we found 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 and/or planning 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 Fig. 2, we can see that a shock in maintenance costs has a direct impact on maintenance cost within a year, with a recovery within two or three years. This suggests that the IM adjusts rather quickly to a sudden increase in traffic, without making an over-investment in preventive maintenance. 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.

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

7. Conclusions

This paper is the first paper in the literature to have estimated a panel vector autoregressive model for rail infrastructure costs, using data for Sweden. We provide estimates on dynamic effects in infrastructure provision that can be important to consider when pricing infrastructure use. Specifically, we provide empirical evidence on the relationship between maintenance and renewals, as well as evidence on intertemporal effects for each of these activities.

As well as insights into the interplay between maintenance and renewals cost over time, our results highlight that analysing costs within such a holistic dynamic model can result in different elasticities of cost and thus marginal cost, with respect to traffic. In particular, we find that once we take into account both the contemporaneous change in cost and future changes in cost from increasing traffic, the ‘equilibrium’ maintenance cost elasticity, and thus marginal cost of traffic, is substantially higher than that found for static models (both the estimate in this dataset and in comparison to those in the literature on Swedish data). We do acknowledge the uncertainty around our estimates (particularly with respect to renewals cost). However, our finding could have important implications subject to further research, since econometric analysis of railway maintenance and renewals costs is accepted by the European Commission as an appropriate methodology to set track access charges across EU member states (European Commission, 2015). Thus, there could be substantial charging implications for adopting this methodology in the future. Moreover, we have contributed to the literature on renewal costs, showing that modelling this cost category in a dynamic setting can be a fruitful approach for future research.

Our 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 an exogenous shock. 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.

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.

There are opportunities for more methodological research in this area over and above collecting more data and undertaking more empirical applications with a view of providing more robust estimates. For example, the analysis in this paper is not able to answer if 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.

Acknowledgements

The authors are grateful to the Swedish Transport Administration, European Commission Horizon2020 project NeTIRail-INFRA (Grant number 636237) and the Engineering and Physical Sciences Research Council (Grant number EP/M023109/1) for funding this research. Special thanks to Vivianne Karlsson and Anders Nilsson for providing data. Daniel Wikström and Mattias Haraldsson have provided helpful comments on an earlier version of this paper. All remaining errors are the responsibility of the authors.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ecotra.2018.01.001.

Appendix

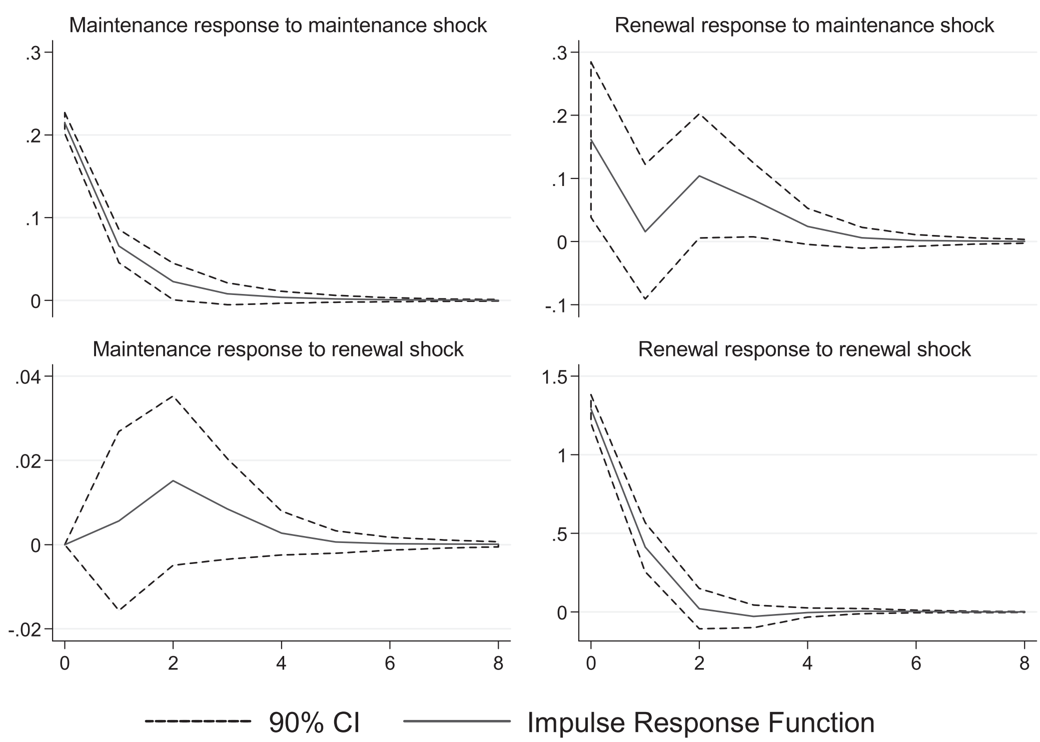

Fig. 3. IRFs with wrong ordering in the recursive identification, Model A2.

Statement of contribution

Transport infrastructure needs to be maintained and renewed to obtain a required performance level, where a proper balance between and within these activities can minimize costs. An increase in traffic levels will have an impact on this cost minimizing balance. There is an extensive research on the impact of traffic on maintenance costs, while the empirical evidence on the renewal cost element is scarcer and less robust, and even more so is the evidence on the dynamics within and between these cost categories. This type of research has high policy relevance given that econometric analysis of infrastructure costs is accepted as an appropriate method for setting track access charges in EU member states.

In this paper, we estimate a panel vector autoregressive (VAR) model, taking the interdependence between renewals and maintenance into account, as well as their intertemporal effects. In doing so, we contribute to the literature by providing insights into the dynamics in infrastructure provision. We also show that modelling renewal costs in a dynamic setting can be a useful approach in future research on infrastructure costs, in view of the difficulties in providing a robust estimate in the existing literature. Moreover, the comparison of our results with estimates in static models, indicate that dynamic modelling of maintenance and renewals can have significant track access charging implications across EU member states.

References

Abrigo, M.R.M., Love, I., 2015. Estimation of Panel Vector Autoregression in Stata: a Package of Programs. Working paper, May 2015.

Ahlfeldt, G.M., Moeller, K., Wendland, N., 2014. Chicken or Egg? The PVAR Econometrics of Transportation. Spatial Economics Research Centre. SERC Discussion Paper 158.

Andersson, M., 2006. Marginal cost pricing of railway infrastructure operation, maintenance, and renewal in Sweden - from policy to practice through existing data. Transport. Res. Rec. 1943, 1–11.

Andersson, M., 2008. Marginal railway infrastructure costs in a dynamic context. EJTIR 8, 268–286.

Andersson, M., Smith, A.S.J., Wikberg, Å., Wheat, P., 2012. Estimating the marginal cost of railway track renewals using corner solution models. Transport. Res. Pol. Pract. 46, 954–964.

Andersson, M., Björklund, G., Haraldsson, M., 2016. Marginal railway track renewal costs: a survival data approach. Transport. Res. Pol. Pract. 87, 68–77.

Andrade, A.R., Teixeira, P.F., 2011. Biobjective optimization model for maintenance and renewal decisions related to rail track geometry. Transport. Res. Rec.: J. of the Transportation Res. Board 2261, 163–170.

Andrews, D.W.K., Lu, B., 2001. Consistent model and moment selection procedures for GMM estimation with application to dynamic panel data models. J. Econom. 101, 123–164.

Arellano, M., Bover, O., 1995. Another look at the instrumental variable estimation of error-components models. J. Econom. 68, 29–51.

Baltagi, B.H., 2011. Econometrics. Springer-Verlag Berlin and Heidelberg.

Baltagi, B.H., 2013. Econometric Analysis of Panel Data, fifth ed. Wiley.

De la Garza, J.M., Akyildiz, S., Bish, D.R., Krueger, D.A., 2011. Network-level optimization of pavement maintenance renewal strategies. Adv. Eng. Inf. 25, 699–712.

Doran, H.E., 1989. Applied Regression Analysis in Econometrics. Marcel Dekker, Inc, New York and Basel.

European Commission, 2015. Commission Implementing Regulation (EU) 2015/909 of 12 June 2015 on the Modalities for the Calculation of the Cost that Is Directly Incurred as a Result of Operating the Train Service.

Gaudry, M., Quinet, E., 2009. Track wear-and-tear cost by traffic class: functional form, zero output levels and marginal cost pricing recovery on the French rail network. In: Working Paper No. 2009-32, Paris-Jourdan Sciences Économiques.

Gaudry, M., Lapeyre, B., Quinet, E., 2016. Infrastructure maintenance, regeneration and service quality economics: a rail example. Transp. Res. Part B Methodol. 86, 181–210.

Góes, C., 2016. Institutions and growth: a GMM/IV Panel VAR approach. Econ. Lett. 138, 85–91.

Granger, C.W.J., 1969. Investigating causal relations by econometric models and cross-spectral methods. Econometrica 37 (3), 424–438.

Grimes, G.A., Barkan, C.P.L., 2006. Cost-effectiveness of railway infrastructure renewal maintenance. J. Transport. Eng. 132 (8), 601–608.

Gu, W., Ouyang, Y., Madanat, S., 2012. Joint optimization of pavement maintenance and resurfacing planning. Transp. Res. Part B Methodol. 46, 511–519.

Holtz-Eakin, D., Newey, W., Rosen, H.S., 1988. Estimating vector autoregressions with panel data. Econometrica 56 (6), 1371–1395.

Johansson, P., Nilsson, J.-E., 2004. An economic analysis of track maintenance costs. Transport Pol. 11, 277–286.

KVA, 2011. Empirical macroeconomics. In: Scientific Background on the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2011 Compiled by the Economic Sciences Price Committee of the Royal Swedish Academy of Sciences. Kungliga Vetenskapsakademien, 10 October 2011.

Lee, L.-F., Yu, J., 2014. Efficient GMM estimation of spatial dynamic panel data models with fixed effects. J. Econom. 180 (2), 174–197.

Link, H., Stuhlehemmer, A., Haraldsson, M., Abrantes, P., Wheat, P., Iwnicki, S., Nash, C., Smith, A.S.J., 2008. CATRIN (Cost Allocation of TRansport INfrastructure Cost). Deliverable D 1, Cost Allocation Practices in European Transport Sector. VTI, Stockholm. March 2008.

Love, I., Zicchino, L., 2006. Financial development and dynamic investment behavior: evidence from panel VAR. Q. Rev. Econ. Finance 46, 190–210.

Lütkepohl, H., 2005. New Introduction to Multiple Time Series Analysis. Springer-Verlag Berlin, Heidelberg, 2005.

Marti, M., Neuenschwander, R., Walker, P., 2009. CATRIN (Cost Allocation of TRansport INfrastructure Cost), Deliverable 8 – Rail Cost Allocation for Europe – Annex 1B – Track Maintenance and Renewal Costs in Switzerland. VTI, Stockholm.

Munduch, G., Pfister, A., Sögner, L., Siassny, A., 2002. Estimating Marginal Costs for the Austrian Railway System. Vienna University of Economics & B.A. Working Paper No. 78, February 2002.

Odolinski, K., Nilsson, J.-E., 2017. Estimating the marginal maintenance cost of rail infrastructure usage in Sweden; does more data make a difference? Econ. Transit. 10, 8–17.

Odolinski, K., Smith, A.S.J., 2016. Assessing the cost impact of competitive tendering in rail infrastructure maintenance services: evidence from the Swedish reforms (1999 to 2011). J. Transport Econ. Pol. 50 (1), 93–112.

Roodman, D., 2009. A note on the theme of too many instruments. Oxf. Bull. Econ. Stat. 71 (1), 135–158.

Sathaye, N., Madanat, S., 2011. A bottom-up solution for the multi-facility optimal pavement resurfacing problem. Transp. Res. Part B Methodol. 45, 1004–1017.

Sharma, A., Yadava, G.S., 2011. A literature review and future perspectives on maintenance optimization. J. Qual. Mainten. Eng. 17 (1), 5–25.

Sims, C.A., 1980. Macroeconomics and reality. Econometrica 48, 1–48.

Small, K.A., Winston, C., Evans, C.A., 1989. Road Work – a New Highway Pricing & Investment Policy. The Brookings Institution, Washington, D.C.

Smith, A.S.J., Wheat, P., 2012. Estimation of cost inefficiency in panel data models with firm specific and sub-company specific effects. J. Prod. Anal. 37 (1), 27–40.

Smith, A.S.J., Wheat, P.E., Smith, G., 2010. The role of international benchmarking in developing rail infrastructure efficiency estimates. Util. Pol. 18, 86–93.

StataCorp, 2011. Stata Statistical Software: Release 12. StataCorp LP, College Station, TX.

Tervonen, J., Pekkarinen, S., 2007. Marginal Rail Infrastructure Costs in Finland 1997-2005. Finnish Rail Administration. Publications of the Finnish Rail Administration A3/2007.

Tiwari, A.K., 2011. Comparative performance of renewable and nonrenewable energy source on economic growth and CO2 emissions of Europe and Eurasian countries: a PVAR approach. Econ. Bull. 31 (1), 2356–2372.

Trafikverket, 2012. Organiseringen Av Underhåll Av Den Svenska Järnvägsinfrastrukturen. Trafikverket Rapport, Dnr 2012/63556. (In Swedish).

Trafikverket, 2016. The Swedish Transport Administration - Annual Report 2015. Trafikverket, Swedish Transport Administration, 2016:054.

Wheat, P., Smith, A.S.J., 2008. Assessing the marginal infrastructure maintenance wear and tear costs for Britain's railway network. J. of transp. Econ. Pol. 42 (2), 189–224.

Wheat, P., Smith, A.S.J., 2009. CATRIN (Cost Allocation of TRansport INfrastructure Cost). Deliverable 8 – Rail Cost Allocation for Europe – Annex 1E – Renewals Costs in Great Britain. VTI, Stockholm.

Wheat, P., Smith, A.S.J., Nash, C., 2009. CATRIN (Cost Allocation of TRansport INfrastructure Cost). Deliverable 8 – Rail Cost Allocation for Europe. VTI, Stockholm.

Wheat, P., 2015. The Sustainable Freight Railway: Designing the Freight Vehicle–track System for Higher Delivered Tonnage with Improved Availability at Reduced Cost SUSTRAIL', Deliverable 5.3: Access Charge Final Report Annex 4, British Case Study.

Yarmukhamedov, S., Nilsson, J.-E., Odolinski, K., 2016. The Marginal Cost of Reinvestments in Sweden's Railway Network. VTI. Notat 23A-2016.