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A STOCHASTIC FRONTIER ANALYSIS OF THE COST EFFICIENCY IN ROAD MAINTENANCE

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Abstract

Road are an integral part of the modern society. Building the new roads require substantial financial resources, which are financed by tax revenues. To retain the value and the acceptable standard of the road, it is important to organize a regular maintenance, and this should be conducted in the most cost efficient way. Therefore, the purpose of this paper is to analyze the cost efficiency in the road maintenance in Sweden. The data on 100 maintenance areas over the period of 2004-2012 is used to estimate the cost efficiency among maintenance areas and over time. Results suggest that there is no persistent maintenance area inefficiency in the data, while a time-varying inefficiency is detected in the data. The policy implications are discussed in the paper.

Keywords: road maintenance, cost efficiency, stochastic frontier analysis
JEL Classification: C23, D24, O18, R42

1. INTRODUCTION

Roads are one of the essential public assets that contribute to socio-economic development and growth by providing its users an access to hospitals, schools and jobs. A road construction requires substantial financial resources where mainly a national government's funds are allocated[1]. The cost of the road over its service life depends on the design, quality of construction and maintenance activities[2] (Karim, 2011). These factors are interrelated in a way that the design of the road and its construction quality may significantly affect its future maintenance costs.

Like other infrastructure assets, roads are subject to deterioration. The intensity of the deterioration process is associated with the passing traffic volume, weather conditions and maintenance activities. Geographical areas with higher traffic volumes and severe weather conditions require a more concentrated maintenance activity. Therefore, an advanced road asset management system is essential to plan the type and the frequency of maintenance activities.

Disregarding a necessity in regular maintenance may lead to enormous social costs which are ultimately paid by the road users and the society. Poorly maintained roads may cause reduced accessibility and may add to congestion resulting in delays, which cost businesses and road users through reduced productivity, vehicle repair, increased fuel consumption and delayed deliveries (Berry, 2014). Besides, badly maintained roads may lead to increased traffic accidents where personal injury and property damage costs can arise. For instance, approximately 32 percent of the traffic fatalities in the US were due to the under-maintained roads in 2003 (Segal et al., 2003).

Road maintenance activities are generally classified as routine, periodic and urgent (Burningham and Stankevich, 2005; Smith, 2012). Routine maintenance includes small-scale cyclic works such as grass cutting, surface patching, cleaning of the roads and drainage systems. Periodic maintenance comprises large-scale works that includes resurfacing and strengthening or reconstruction of the road. Urgent maintenance consists of the unforeseen works which require a reactive response such as collapsed culvert, road damage due to the traffic accident, as well as responding to inspections or complaints regarding the road condition. Moreover, the winter services such as keeping the roads clear of ice and snow is dispensed to the above mentioned class of the maintenance activities.

Forward planning of periodic preventative maintenance is considered to be the most cost effective way of ensuring a good standard of the road, i.e. acceptable condition and reasonable

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[1] There are also different types of public and private collaboration in building roads, Public-Private Partnership (PPP), where financial aspects of a road construction may depend on the agreement between parties. For instance, a private actor engages into a road construction by covering a certain share of the costs with own funds in exchange for charging a fee/toll from road users during a certain period specified in the contract. See Bovaird (2004) and Perkins (2013).

[2] A graphical illustration of the life cycle of the road is provided in Nilsson et al.(201x).

accessibility, while urgent maintenance is the most expensive type of the maintenance to provide the same standard (Berry, 2014; APPGHM, 2013).

In an attempt to increase the efficiency of the road maintenance, governments initiated a competitive tendering to implement road maintenance. While road authorities are still responsible for a diligent execution of road maintenance, its performance might be in-house or contracted out. In-house road maintenance is performed by a work unit under responsible authority. In contracting out road maintenance, a work is tendered under competitive conditions, where both public and private companies may participate. Nowadays, a competitive tendering of a road maintenance contracts is proliferated due to cost efficiency reasons. For instance, competitive tendering reduces road maintenance costs on average by 20-30 percent (Arnek, 2002; Lyon and Dwyer, 2011).

In contracting out road maintenance, mainly two types of the contracting schemes are used, input-based and output-based.

Input-based contracts[3] are heavily regulated by the road authority, i.e. the work method, material and technology choices are specified in details by the contracting agency. The payment to the contractor is on the basis of a unit price per different work items, which may lead to adverse incentives where carrying out the maximum amount of work maximizes contractor profits. Moreover, this type of contracting restricts applying innovative work methods as the whole work process is defined by a road authority (Pinero, 2003; Sultana et al., 2012a).

Output-based contracting[4] is an alternative way to link the client and the agent. This contract is outcome focused where a contracting agency specifies only a final outcome, i.e. a desired standard of the road, while a contractor decides on how to achieve this outcome. In this type of contracting, a contractor optionally decides on a combination of a labor and material inputs as well as different technological solutions which may give rise to the development and implementation of innovative methods (Segal et al., 2003; Bull et al., 2014). Furthermore, output-based contracts may have various forms such as design-build, build-maintain, design-build-maintain with specified warranty periods (Gupta et al., 2011). The contractor is paid a monthly lump-sum payment if a standard of the road specified in the bidding document is complied with.

A contractor bears more risk under output-based scheme than under input-based one, however, a higher risk might be compensated by granting the opportunity to increase company's profits by improving the effectiveness of design, process and technology to meet a road standard stipulated in the contract (Zietlow, 2003). On the other hand, from the contracting agency's perspective, output-based contracts result in lower road maintenance costs with less risk and more predictable financial costs (Hyman, 2009).

[3] Also, denoted as a unit-price and/or a traditional road maintenance contract.
[4] This type of contracting has different designations, e.g. performance contracting, performance-based contract, output-based contract, asset management contracts.

The main argument for an introduction of the output-based contracts is the cost efficiency compared to the input-based alternative (Plummer, 2010), however, on the example of a limited highway section in the US, Fallah-Fini et al.(2012) shows that input-based maintenance contract is turned out to be more efficient that its counterpart. This might be explained by unpreparedness[5] of the road authority and the private sector actors to implement road maintenance under a new contracting approach (Sultana et al., 2012a; Sultana et al., 2012b; Gupta et al., 2011). Nevertheless, output-based contracts are successfully implemented in many countries[6], though in a country specific deviating forms, i.e. the desired final outputs are sometimes specified with the general guidelines regarding a design, a method and a type of the warranty (Hyman, 2009).

Given different initiatives to improve the effectiveness of the road maintenance, the purpose of this paper is to measure the efficiency of the road maintenance among various maintenance areas in Sweden. The data comprises Sweden's national road network with around 100 maintenance areas over the period of 2004-2012.

Results suggests that the there is no persistent maintenance area inefficiency is found, while a time-varying inefficiency is detected in the data. This implies that the efficiency level of the maintenance areas varies over time. One explanation may be that companies operating in maintenance areas are striving to improve their efficiency levels from one period to the other. Another possibility is that a switch from one contractor to another when a contract period is terminated and the contract is up for tender again, brings in new methods. Despite a variation in efficiency levels over time, the average overall inefficiency is rather constant over time being approximately 14 percent. If the work method of the least inefficient area would be in practice, a possibility of the cost reduction might be on average 11 percent, which in monetary terms, on average, translates into MSEK 276 overall savings during the period studied. Therefore, there is a potential to cost reductions for a road authority by improving the efficiency levels of companies operating in maintenance areas.

The paper is constructed as follows. Section 2 describes a road maintenance system in Sweden. Section 3 presents a model and its estimation procedure. The data description and the results are presented in Section 4 and 5, respectively. Section 6 draws conclusions.

2. ROAD MAINTENANCE IN SWEDEN

The overall stretch of the Swedish road network is about 580 000 km, of which state roads are 98 000 km (17%), communal roads are 42 000 km (7%) and private, primarily forest roads 436 000 km (76%) (SKL, 2015). The responsibility for road maintenance of the state roads is on the Swedish

[5] Resource and skill constraints, corruption and poor management.
[6] More than 50 countries have adopted output-based road maintenance contracting in year 2006 (Hyman, 2009).

Transport Administration, while the respective communes are in charge of roads within their respective territory. Private roads are the obligation of the different individual road associations. A government subsidizes the maintenance of all state roads and nearly17 percent of the private roads (if these roads are considered to be a complement to the state roads).

The Swedish government enacted a law prescribing the commencement of a gradual procurement of road maintenance activities under competition from 1992. At present, about ten companies participate in road maintenance activities. More than 90 percent of maintenance areas are contracted out to four companies, i.e. NCC, Peab, Skanska and Svevia. The regional shares[7] of these companies indicate that Svevia is an absolute dominant provider of the road maintenance activities across all the regions. Svevia is the commercialized version of the previous in-house maintenance unit.

The whole state road network is divided into 111 maintenance areas.[8] Each area is awarded to a single company, so that the responsibility for the base road maintenance activities is on one company during a contract period. A contract period is between 3-5 years with the option for prolongation from one to three years.

A base road maintenance contract with the specification of the expected output, i.e. an output-based contract, is a common type of contract used in road maintenance[9], though with some elements of detailed requirements as in the input-based contracts (Lingegård et al.,2011). A base maintenance contract includes services of the paved and gravel roads, bridges, side areas and establishments, road equipment as well as the winter services. Winter services include such activities as keeping the roads clear of ice and snow with a predefined urgency of performing these services depending on the class of the road. The roads are classified by the level of a traffic volume, where the roads with higher traffic volume have the highest priority to be served.

The total expenditure on maintenance of the state roads was SEK 2.5 billion in 2012, where on average a 60 percent is spent on the winter services (the size of the winter expenditures may vary depending on the maintenance area and the weather conditions in particular season).

[7] There are six regions, North, Central, South, Stockholm, West and East.

[8] This amount of maintenance areas is valid year 2015, otherwise, historically there were some administrative merges of certain areas, therefore the amount of maintenance areas is not constant.

[9] Reinvestment activities, i.e. the larger resurfacing or reconstruction works, are tendered separately, so that these works are not included in the base road maintenance contracts.

3. MODEL

We estimate the cost efficiencies of maintenance areas in two dimensions, *viz.* among areas and over time, where a four-component model[10] proposed by Kumbhakar et al.(2014) is utilized. The model is specified as:

$$C_{it} = \alpha_0 + X_{it}'\beta + \mu_i + \eta_i + u_{it} + v_{it} \quad (1)$$

where C_{it} is a road maintenance cost at the maintenance area $i=1,\dots,I$ at time t; X_{it} represents the characteristics of the maintenance area. This includes location, road length, vehicle kilometers, a road length with low buoyancy, a road length with a median barrier; winter period specific cost driving factors such as a number of days with slippery roads, snowfall and snowbanks; β is a vector of parameters to be estimated; μ_i is unobserved maintenance area heterogeneity; η_i is the time-invariant inefficiency ($\eta_i > 0$); u_{it} is the time-varying inefficiency ($u_i > 0$); v_{it} is a random noise term.

3.1 Model estimation

The dependent and time-varying explanatory variables are log transformed in the model presented above. However, two variables in the model include zeroes, namely road length with low buoyancy and roads with a median barrier, hence these zero values turn into missing values after the log transformation. Therefore, we need to decompose these two variables. Let's denote them as *Z* variable. Decomposition is as follows: first, a dummy which indicates zero values of Z is created, i.e. *DZ=1* if *Z=0*, 0 otherwise; second, we log transform *Z*, i.e. *Ln(Z)*, replacing missing values (due to zeroes) with the minimum value of *Ln(Z)*. Finally, we include *DZ* and *Ln(Z)* variables into the model, instead of the *Z* variable.

A four component model presented above assumes that unobserved maintenance area heterogeneity, e.g. the quality of the road network and/or the quality of the construction and maintenance or some other unobserved maintenance area specific features, is uncorrelated with the other explanatory variables (including inefficiency terms) in the model. Since this assumption might be restrictive, it is relaxed by allowing a correlation between the unobserved heterogeneity and regressors, then use a Mundlak (1978) transformation to accommodate this flexible model. The idea behind a Mundlak approach is to include the group means of time-varying explanatory variables, which captures unobserved heterogeneity, and estimate with the random effects model.

[10] There are several models in the literature that make different assumptions with respect to the distribution and decomposition of an unobserved heterogeneity and inefficiency effects. A thorough review of these models is presented in Kumbhakar et al.(2015).

Rewriting Eq.1 to estimate in multiple steps, as well as accommodating it to the Mundlak approach results in the following model (Smith et al.(2015)):

$$C_{it} = \bar{X}_i\rho + X'_{it}\beta + \varepsilon_{it} \qquad (2)$$

where $\varepsilon_{it} = \delta_i + \varphi_{it}; \delta_i = \mu_i + \eta_i; \ \varphi_{it} = u_{it} + v_{it}$

$\mu_i \sim N(0, \sigma_\mu^2); \ \eta_i \sim N^+(0, \sigma_\eta^2); \ u_{it} \sim N^+(0, \sigma_u^2); \ v_{it} \sim N(0, \sigma_v^2)$

Let's denote equation (1) and (2) as Model I and Model II, respectively. The choice between these two models is based on the testing the restriction of the Model I, namely unobserved heterogeneity is uncorrelated with the regressors. To test this restriction, Model II is estimated, then a null hypothesis of no correlation between the regressors and unobserved maintenance area heterogeneity is tested, which is equivalent to say that group means of time-varying explanatory variables are jointly zero, i.e. we use a Wald test on the joint hypothesis $H_0: \hat{\rho} = 0 \ \forall \ \hat{X}_i$. If a null hypothesis is rejected, then a model with Mundlak transformation (Model II) should be selected.

Estimation of either model is a multi-stage procedure. In the first stage, both models are estimated with the standard random effects model by Generalized Least Squares (GLS). After the estimation of Model I, we obtain predicted values of maintenance area effects $\hat{\delta}_i$ and residuals $\hat{\varphi}_{it} = \varepsilon_{it} - \hat{\delta}_i$.

In the second stage, the persistent maintenance area inefficiency is estimated. A Stochastic Frontier (SF) model of maintenance area effects $\hat{\delta}_i$ is run on a constant to predict persistent maintenance area inefficiency $\hat{\eta}_i$ (using a Jondrow et al.(1982) estimator). Further, we conduct a hypothesis test on the absence of the persistent inefficiency effects, i.e. a likelihood ratio test is used to test a null hypothesis of no persistent inefficiency effects.

In the third stage, the time-varying maintenance area inefficiency is estimated. A similar SF technique is used as in the second stage, where regressing residuals $\hat{\varphi}_{it}$ on a constant provides a prediction of the time-varying maintenance area inefficiency $\hat{u}_{it}$ (using a Jondrow et al.(1982) estimator). As in the second stage, a likelihood ratio test on the absence of time-varying inefficiency effects is performed, i.e. a null hypothesis of no time-varying inefficiency effects is tested.

The overall efficiency is computed by taking a product of the persistent and time-varying inefficiencies. Furthermore, we make use of the difference in efficiency scores among the maintenance areas to compute a change in cost efficiency which reflects the cost reduction opportunities if the most efficient maintenance area's performance is put into practice by other less efficient counterparts. A change in the cost efficiency (CE) is computed as:

$$CE^{change} = \sum \frac{C_i}{C_{it}} \cdot \frac{(\hat{\pi}_{it}^{best} - \hat{\pi}_{it})}{\hat{\pi}_{it}} \quad (3)$$

where

$$\hat{\pi}_{it} = \left(\hat{\eta}_i + \frac{\sum C_{it} \cdot \hat{u}_{it}}{\sum C_{it}} \right)$$

where $\hat{\pi}_{it}$ is a cost weighted overall efficiency, $\hat{\pi}_{it}^{best}$ is a cost weighted overall efficiency of the maintenance area with the best performance, i.e. the most efficient maintenance area.

Moreover, the overall saving (OS) estimates in monetary terms are computed as follows:

$$OS = \sum C_{it} \cdot (\hat{\pi}_{it}^{best} - \hat{\pi}_{it}) \quad (4)$$

Note that the difference in efficiency scores is zero for the most efficient maintenance area, implying that this maintenance area is on the frontier, i.e. the performance of this area is the best compared to the other maintenance areas in the sample.

4. DATA

A study uses the unbalanced panel of the road maintenance data on the Swedish state roads comprising nearly 100 maintenance areas over the period 2004-2012, where the level of observation is maintenance area and a unit of time is a year. Maintenance area is an aggregate of a number of road sections within a certain administratively defined maintenance area, hence all data on a road section level is aggregated to the maintenance area level.

The dependent variable is the road maintenance cost which is the sum of the costs of operation, maintenance and winter services. The quality of the cost data is rather modest, because it is difficult to separate the costs for additional orders from initial work items specified in the base contract. Moreover, these additional orders might include work items related to the reinvestment activities, which are not a part of the maintenance work. Another possible issue with the cost data is that there is a risk of double registration of the costs in year 2010, which is a subject of further investigation later in the paper.

The explanatory variables are the road characteristics, traffic, weather and geographical data. Road characteristics include the length of the road, the length of the road with low buoyancy, the length of the road with a median barrier. The traffic data consists of vehicle-kilometers for light and heavy vehicles, which is a multiplication of the road length travelled with the number of passages[11]

[11] The number of passages is an estimated value rather than an actual measured number of passages, i.e. the data is based on the measurements of the vehicle passages at certain times (not a year-round measurement) which are then used to forecast an annual daily traffic. Moreover, there is a potential risk for overestimating the effect of passage (traffic

of a respective vehicle type, however, due to the high correlation between them the vehicle-kilometers for light vehicles is used to describe a traffic volume in a certain maintenance area[12]. Weather data includes the number of days with slippery roads, snowfall and snowbanks. Geographical data describes a regional belonging of maintenance areas.

The maintenance cost, weather and geographical data have been provided directly by the Swedish Transport Administration, while the road characteristics and traffic data are from the National Road Data Base (NVDB).

4.1 Descriptive statistics

The descriptive statistics is based on the unbalanced panel on 96 maintenance areas over the period 2004-2012, which amounts to 695 observations.

A Table 4.1 suggests that a large amount of resources are allocated to the road maintenance activities with an average cost are about SEK 25 million. The traffic is overwhelmingly dominated by light vehicles compared to the heavy ones, i.e. the traffic volume of the light vehicles is eight times greater than the heavy vehicles.

A road length among the maintenance areas ranges from 44 to 3000 km, with an average length being 1000 km. The length of the roads with lower buoyance ranges from zero to 323 km, which implies that in certain maintenance areas there are no roads with lower buoyance. A dummy for the road buoyance suggests that almost two percent of the maintenance areas do not include the roads with lower buoyance. Similarly, the length of the median road barriers varies between zero and 183 km, implying that not all the roads within a maintenance area are equipped with a median barrier. A following dummy variable for median barrier elucidates that 43 percent of the maintenance areas contain no roads with median barriers.

Due to a northern location of Sweden, the average duration of winter season is characterized by: a slippery road is almost six months, snowfall is nearly four months and snowbanks is a half month.

The regional categorical variable shows that the northern region is represented with the highest share in the dataset (27 percent) compared to the lowest share in the sample Stockholm (0.28 percent). Due to the lowest representative share of the regions Stockholm and West, the data is considered to be unrepresentative for these regions, thus omitted from the analysis.

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volume), because a measure of a passage in a particular maintenance area is a sum of passages on all road sections within this maintenance area. The problem is that it is not possible to observe whether the same vehicle has passed the whole road section or just a part of it. At the time being, we are not able to overcome this issue with the available data.

[12] It might also be possible that the wear and tear of the road is caused more by heavy vehicles than by light ones. Therefore, we conduct a sensitivity analysis on the choice of the vehicle kilometers for heavy vehicles.

Table 4.1 Descriptive statistics, maintenance area average for 2004-2012

	Mean	SD	Min	Max
Maintenance costs, m SEK	25979.53	11440.53	1193.256	95121.12
Light vehicle kilometers	439991.7	299713.9	30508.75	1353765
Heavy vehicle kilometers	51986.12	38050.36	4067.929	207719.3
Road length, kilometers	1046.252	352.4578	44.8814	2958.094
Road buoyance, kilometers	53.2949	68.8739	0	323.1171
Dummy road buoyance	0.0172	0.1303	0	1
Median barrier, kilometers	25.3498	46.4483	0	183.3325
Dummy median barrier	0.4316	0.4956	0	1
Slippery road, number of days	169.2295	65.5026	67.869	315.431
Snowfall, number of days	106.0446	43.5567	36.5745	178.215
Snowbanks, number of days	18.7905	12.5930	5.6	54.457
Regions:				
North	0.2676	0.4430	0	1
Central	0.2561	0.4368	0	1
Stockholm	0.0028	0.0536	0	1
South	0.2057	0.4045	0	1
West	0.0877	0.2831	0	1
East	0.1798	0.3843	0	1
Years:				
2004	0.1050	0.3068	0	1
2005	0.1050	0.3068	0	1
2006	0.1050	0.3068	0	1
2007	0.1035	0.3049	0	1
2008	0.1035	0.3049	0	1
2009	0.1050	0.3068	0	1
2010	0.1237	0.3295	0	1
2011	0.1179	0.3228	0	1
2012	0.1309	0.3375	0	1

Note: Maintenance cost is defined in thousands, while light and heavy vehicle kilometers are defined in millions.

The categorical variable for period variable, i.e. year, indicates that up to year 2009 a sample includes almost the same number of observations, while there are a slightly higher number of observations from that year forth. We possess information that a data for year 2010 may contain the duplication of the cost data, this issue is analyzed later in the paper.

After excluding the regional categories Stockholm and West, a remaining number of observations for the analysis are 632, which comprises 73 maintenance areas over the period 2004-2012.

5. RESULTS

In this section, we present the estimation results as well as the specification and hypotheses tests in a sequence described in Section 3.1. After a brief result presentation, a relevant discussion of the results is provided in the following subsection.

5.1 The estimation results

The first stage estimation

The estimation results of the initial four component random effects model (Model I) and its Mundlak (1978) transformed version (Model II) is presented in Table A.1 (Appendix A). The selection between Model I and II hinges on the Wald test results, where the null hypothesis of no correlation between the regressors and unobserved heterogeneity is rejected at 1 percent significance level (Appendix A, Table A.1, row 36). This implies that there is a correlation between regressors and unobserved maintenance area heterogeneity, which invalidates the assumption of the Model I, therefore a model with Mundlak transformation (Model II) should be selected.

In efficiency analyses, the coefficient estimates of the first stage estimation are usually of limited importance, therefore a brief interpretation (*ceteris paribus*) of the statistically significant results of Model II is provided.

The coefficient estimate for indicator variable for low buoyance road (Appendix A, Table A.1, column 3, row 5) suggests that the maintenance costs are lower by 21 percent[13] for roads with no lower buoyance than compared to the roads with lower buoyance.

The coefficient estimates for the number of days with slippery road and snowbanks suggests that, on average, a 1 percent increase in the occurrence of these days leads to a 0.19 percent increase in the maintenance costs (Appendix A, Table A.1, column 3, rows 8, 10).

Compared to the northern regions of Sweden, the maintenance cost are significantly higher in southern and eastern regions (Appendix A, Table A.1, column 3, rows 13, 14). The figures for the region indicators are unreasonably high (on average 12 000 percent), which might depend on the

[13] (exp(-0.2424)-1)*100=21.52

quality and representativeness of the data (note that regions Stockholm and West are excluded from the sample).

In years 2009 and 2010, there was a significant increase in the maintenance costs, i.e. 11 and 18 percent, respectively, compared to the year 2004 (Appendix A, Table A.1, column 3, rows 20, 21).

The group means of the time-varying explanatory variables are not interpreted usually, thus we skip commenting them.

The second stage estimation

The estimation results show that OLS residuals are skewed in the wrong direction, i.e. residuals are negatively skewed while a positive skew is expected in the cost functions, which implies that there are no persistent inefficiency effects detected. Moreover, the LR test suggests that we cannot reject the null hypothesis of no inefficiency effects (Appendix A, Table A.1, row 39)[14]. This implies that there are no persistent maintenance area inefficiency effects, or at least we are unable to distinguish inefficiency from unobserved heterogeneity.

The third stage estimation

The LR test suggests a rejection of the null hypothesis of no inefficiency at 1% significance level (Appendix, Table A.1, row 43), which implies that a time-varying inefficiency effects are present in the data[15].

The overall efficiency estimation

According to the results of the second stage estimation, no persistent maintenance area inefficiency effects are detected, which implies that the value of the efficiency score is equal to one. Therefore, as the overall efficiency is a product of the persistent and time-varying efficiencies, the overall efficiency is equal to the time-varying efficiency.

5.2 Result discussion

In accordance with the results from the first stage, it seems that there is a correlation between regressors and unobserved maintenance area heterogeneity, which implies that an initial four component model inappropriately models the cost function along with its explanatory variables.

[14] The result of the wrong skew is also revealed in Model I (we present the results for Model I for comparison reasons, though, in the previous stage it was shown that Model II should be chosen). Besides, the LR test suggests that we cannot reject the null hypothesis of no inefficiency in the case of Model I as well (Appendix A, Table A.1, row 39).

[15] We arrive at the same conclusion for Model I (the results for Model I are presented for comparison reasons).

Therefore, a four component model with Mundlak transformation is found to be a better model specification.

We are unable to detect any persistent maintenance area inefficiency effects in the second stage estimation, which might imply that (1) we are not capable to separate unobserved maintenance area effects from inefficiency effects, although we can control for the unobserved maintenance area effects that are correlated with the regressors (through Mundlak transformation), (2) companies performing maintenance activities are working on a constant improvement of their efficiency or (3) there is a company switch after each contract period, i.e. a new company takes over a certain maintenance area after the current contract period ends (different companies may have various efficiency levels in performing the maintenance activities).

In contrast to the second stage results, a time-varying maintenance area inefficiency effects is found in the data. This suggests that (based on the argument above), a company operating in a certain maintenance area might be inefficient in this period, and due to the learning effects may change its work strategy in the next period to improve its efficiency. Similarly, as we are unable to distinguish which companies are operating in the particular maintenance area, our other conjecture to the detection of the time-varying efficiency is that not the same companies are in charge of the maintenance work in a given maintenance area, thus the varying efficiency scores are observed over time.

Having obtained the results from the second and the third stages, an overall efficiency estimate is computed. The overall efficiency varies between 45.1 and 97.3 percent, with the mean efficiency being 85.7 percent. Figure 5.1 demonstrates the evolution of the yearly average overall efficiency scores across all maintenance areas. In general, the overall efficiency estimates are fairly constant over time, with the exception of year 2010 where a slight decrease is seen on the figure.

In Table A.2 and Table A.3 (Appendix A), a list of the *annual* top three the most and the least efficient maintenance areas, respectively, is provided based on the overall efficiency scores. As one may note in the table, among the maintenance areas ranked first, the maintenance area with the highest overall efficiency estimates[16] over the four year period (2004-2007) is Umeå Norra, while at the same time having the lowest overall efficiency over the three year period (2009, 2010, 2012). This implies that the efficiency levels of maintenance areas may change over time. We plot the development of the efficiency of this maintenance area over time in Figure A.1 (Appendix A). As it can be seen on the figure, a sharp decrease in the overall efficiency is observed after year 2007, which is probably explained by a switch of the company performing maintenance activities in this area.

[16] The highest efficiency score might also be reinterpreted as the lowest inefficiency score. For instance, an efficiency score of 97 percent is as equivalent as an inefficiency score of 3 percent.

Moreover, it is also found that over the *entire period* studied, on average, the most efficient maintenance area is Norsjö, while the least efficient area is Umeå Norra (the last rows, Table A.2

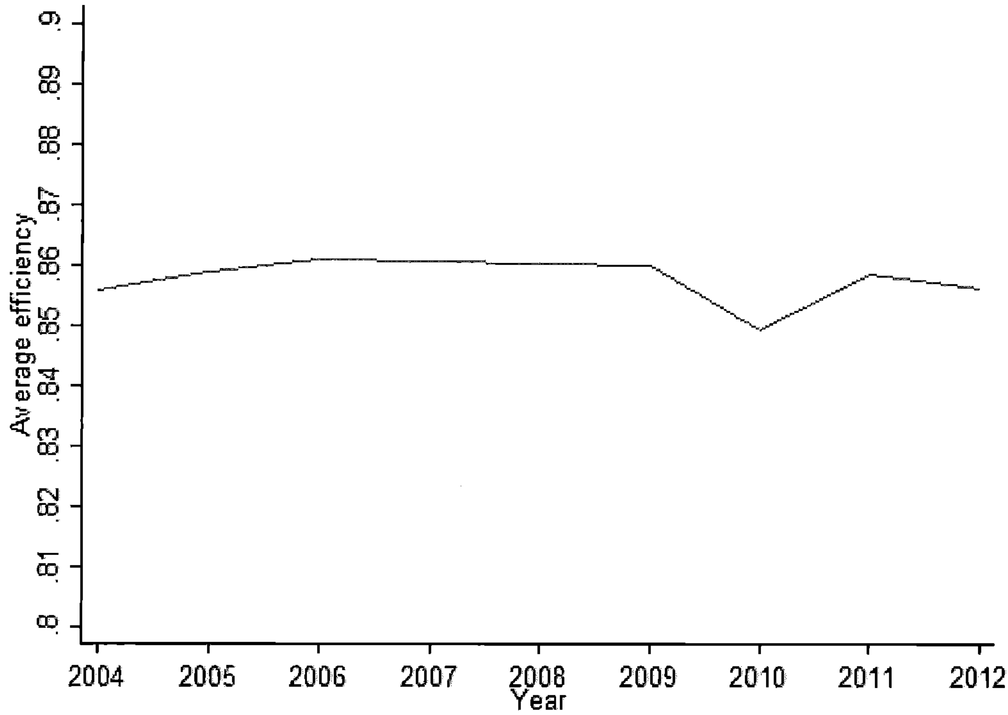

Figure 5.1 Overall efficiency over time

and Table A.3, Appendix A)[17]. The case of Umeå Norra evidences that being the most efficient area during a four year period (2004-2007), a drastic decrease in efficiency may occur, so that this frequently efficient area turns out to be the least efficient one if an average efficiency is computed over the entire period studied.

Based on the estimation sample[18] and overall efficiency estimates, the cost reduction opportunities are estimated according to the Eq.3 and Eq.4. As stated above, we do not control for the switch of the companies within the same maintenance area during the period studied, therefore a cost reduction possibility is examined on aggregated data. A possibility of the cost reduction is estimated to be on average 18.1 percent ($CE^{change} = 18.1\%$), while in monetary terms the overall saving estimates are on average MSEK 276 ($OS_{overall} = 276\ million$) if the work method of the maintenance area Västbo would have been in practice for other maintenance areas[19].

[17] In terms of the *cost weighted* average overall efficiency, Västbo (nowadays merged with Gislaved and Värnamo) is the most efficient area (86.4 percent efficient), while Umeå Norra is the least efficient area (55.5 percent efficient).

[18] Note that the estimation sample excludes regions West and Stockholm due to the data limitations, but still comprises about 75 percent of all maintenance areas in Sweden.

[19] Over the *entire period* studied (2004-2012), a maintenance area Norsjö, on average, is the most efficient area (Table A.3, Appendix A). However, in terms of the *cost weighted* average overall efficiency Västbo is the most efficient maintenance area. As discussed above, maintenance area Umeå Norra was among both the most and the least efficient areas during the period studied. Therefore, a caution is necessary in interpreting the results when data is aggregated,

Taking into account the aggregated nature of the data in previous calculation of a potential cost reduction possibility, we compute a change in cost efficiency and an overall saving estimate on the example of the last year of the observation period, i.e. year 2012. The results suggest that the costs might be reduced by 11.3 percent ($CE_{2012}^{change} = 11.3\%$) which in monetary terms is MSEK 151 ($OS_{2012} = 151\ million$) if less efficient maintenance areas would have put into practice the work method of the maintenance area Kiruna[20] in year 2012.

5.3 Sensitivity analysis

In this section, we check whether the results obtained above are robust to the exclusion and the replacement of the variables, i.e. a sensitivity analysis is conducted in terms of a period and a measure of the traffic data (replacement).

5.3.2 Sensitivity analysis: A period

The analysis of the average annual maintenance costs demonstrates a significant increase (approximately 38 percent) in the costs in year 2010 compared to the other years (Figure A.2, Appendix). A possible explanation to this issue provided by data supplier is that a fault in the accounting software which was changed in year 2010, i.e. there is a vague suspicion that some cost data is double registered in the system during a transition period from one software to the other. Therefore, a data on year 2010 is excluded and the estimation procedure is performed as above.

As in the main analysis (results presented in section 5.1), in the first stage estimation a Wald test suggests (Appendix B, Table B.1, row 35) the presence of unobserved maintenance area effects, thus a four component model with Mundlak transformation (Modell II) is preferred.

The second stage estimation results show that there is no persistent maintenance area inefficiency effects, while the third stage estimation results suggests that we cannot reject the null hypothesis of no inefficiency effects hence conclude the presence of time-varying inefficiency effects.

The overall efficiency estimates range from 46.96 to 97.63 percent, with a mean efficiency being 87.29 percent. Figure B.1 (Appendix B) shows the development of the average overall efficiency across all maintenance areas over the period studied (excluding year 2010).

A general conclusion from the sensitivity analysis suggests that exclusion of the data on year 2010 do not significantly affect the model choice in the first stage and the efficiency estimates in the second and the third stages compared to the main results.

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especially, the fact that the efficiency level of this area was declining during the last years of the observation (2009, 2010, 2012).

[20] Kiruna is the most efficient maintenance area in 2012 (Table A.3, Appendix A).

5.3.2 Sensitivity analysis: A measure of the traffic volume

It is possible that the road condition is affected more by a heavy vehicles compared to the light ones. Therefore, we replace a current measure of the traffic volume, i.e. light vehicle kilometers, with the heavy vehicle kilometers and check whether the obtained results are robust to the measure of the traffic volume.

Compared to the main analysis, the estimation results from the first stage estimation are not significantly different. The results of the Wald test (Appendix B, Table B.1, row 35) provide similar outcome, i.e. we reject the null hypothesis of no correlation between unobserved maintenance area heterogeneity and regressors at 1 percent significance level, hence Model II is chosen.

The second stage estimation results also indicate that there are no persistent maintenance area inefficiency effects (Appendix B, Table B.1, row 38). The third stage estimation results suggest that the time-varying maintenance area inefficiency effects are found, as in the main analysis.

The overall efficiency estimates vary between 45.21 and 97.28 percent, with an average efficiency being 85.83 percent. A graphical illustration of an average overall efficiency over time is presented in Figure B.2 (Appendix B). As we may see, some substantially distinct result is not attained in comparison with the main result.

The conclusion from this sensitivity analysis is that the results obtained in the main analysis are robust to the choice of a measure of the traffic volume.

6. CONCLUSION

One of the prerequisites of the sustainable socio-economic growth of a country is a road infrastructure. Roads expand the mobility of goods and individuals, which facilitate a growth of a national and an international trade, as well as a well-functioning labor market. Moreover, an unimpeded access to the hospitals of people living in both rural and urban areas is an important benefit of the road to the society.

Building a road requires a large amount of financial resources, therefore in many cases the governmental funds, which are formed by taxes, are allocated to the road projects. After accomplishing a road construction project, further expenses should be allocated to the annual road maintenance activities to retain an acceptable standard of the road, because as any other infrastructure, roads are subject to deterioration.

From a political perspective, building the new roads may deliver larger political benefits than maintaining the existing roads. However, disregarding the regular maintenance activities may intensify the road deterioration, which in turn may result in reduced accessibility and congestion, hence delays. Therefore, the potential costs to the businesses and road users are reduced productivity, impaired vehicle, increased fuel consumption, retarded labor mobility and delayed deliveries. Moreover, poor condition roads may contribute to an increase in road accidents resulting in further costs for personal injuries and property damages.

As the costs of the road maintenance activities are huge enough and require an annual allocation from the road funds, it is necessary to realize maintenance activities in a cost efficient way. There are a number of insights indicated in the literature and in practice to accomplish this goal. First, a preventative maintenance is considered to be the most cost effective way of preserving the value of the road asset, than some urgent and ad hoc maintenance which could have been avoided if maintenance was conducted regularly. Second, a competitive tendering of the implementation of maintenance work is also found to increase the efficiency of the road maintenance. Third, in contracting out road maintenance, the output-based contracts, where a road authority specifies the expected outcome, while contractor decides on how to achieve this outcome, are considered as a further step in improving the cost efficiency.

Given the different insights on improving the cost efficiency of road maintenance, the purpose of this paper is to measure the cost efficiency among the road maintenance areas and over time on the example of Sweden. The data comprises a state road network on 100 road maintenance areas over the period of 2004-2012. We use a four component model with Mundlak transformation to account for unobserved maintenance area heterogenety, where the results suggest that there is no persistent maintenance area inefficiency present in the data. However, a time-varying inefficiency is detected, which we conjecture due to (1) companies performing maintenance activities learn their efficiency level from the previous period and improve their efficiency in the next period; (2) there is a company switch after each contract period in a certain maintenance area, which is difficult to observe due to the data limitations.

The results also suggest that the overall inefficiency varies between 2.7 to 54.9 percent, with an average inefficiency being 14.3 percent. In general, an average overall inefficiency is almost constant over the whole studied period. Based on the overall inefficiency scores, a ranking of the maintenance areas is done on an annual and entire period basis. In terms of the annual ranking, Umeå Norra area is frequently the least inefficient area, while at the same time is found to be frequently the most inefficient area as well. This suggest that inefficiency level of the maintenance areas may vary over time, which in turn may depend on the switch of the companies after each contract period as the efficiency level may vary both among companies and over time within the same company. In terms of the ranking over the entire period studied, Norsjö is found to be the least inefficient area, while Umeå Norra is the most inefficient area.

A potential for a cost reduction on road maintenance is found to be on average 11 percent, based on the entire period studied, if all maintenance areas would have followed the work method of the least inefficient area, which in monetary terms amounts to MSEK 276 overall savings.

The implications ensuing from this study suggest that from a road authority's perspective it is worth to study the best practices of the road maintenance and encourage implementing these work methods in practice to ensure the most cost efficient provision of the road maintenance.

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REFERENCES

APPGHM (All Party Parliamentary Group on Highway Maintenance), 2013. *Managing a valuable asset: improving local road condition.*

Arnek, M. 2002. Empirical essays on procurement and regulation. Uppsala University, *Doctoral Thesis*

Berry, S. 2014. Gearing up for efficient highway delivery and funding. Department for Transport. *Report*

Bovaird, T. 2004. Public–private partnerships: from contested concepts to prevalent practice. *International Review of Administrative Sciences, 70 (2)*

Bull, M., Brekelmans, R.,and Wilson, L. 2014. Lessons learned in output and performance-based road maintenance contracts. *Issue Brief October 2014*

Burningham, S. and Stankevich, N. 2005. Why road maintenance is important and how to get it done? The World Bank, *Transport Note No. TRN-4*

Fallah-Fini, S., Triantis, K., de la Garza, J.M., Seaver, W.L. 2012. Measuring the efficiency of highway maintenance contracting strategies: A bootstrapped non-parametric meta-frontier approach, *European Journal of Operational Research,* 219 (1)

Gupta, D., Vedantam, A. and Azadivar, J. 2011. Optimal contract mechanism design for performance-based contracts. Minnesota Department of Transportation, *Report*

Hyman, W.A. 2009. Performance-based contracting for maintenance. National cooperative highway research program, *Synthesis 389*

Jondrow, J., Lovell, C.A.K., Materov, I.S. and Schmidt, P. 1982. On the estimation of technical inefficiency in the stochastic frontier production function model. *Journal of Econometrics, 19*

Karim, H. 2011. Road design for future maintenance- Life-cycle cost analyses for road barriers. *Royal institute of technology, Doctoral thesis*

Kumbhakar, S.C., Lien, G. and Hardaker, J.B. 2014. Technical efficiency in competing panel data models: A study of Norwegian grain farming. Journal of Productivity Analysis, 41

Kumbhakar, S.C., Wang, H-J. and Horncastle, A.P. 2015. *A practitioner's guide to Stochastic frontier analysis using STATA*. Cambridge University Press

Lingegård, S., Lindahl, M. and Svensson, N. 2011. PSS contracts for rail and road infrastructure. *Functional thinking for value creation:* Proceedings of the 3rd CIRP international conference on industrial product service systems, Technische Universität Braunschweig, Braunschweig, Germany

Lyon, B. and Dwyer, A. 2011.Road maintenance: Options for reform. Infrastructure Partnerships Australia, *Report*

Mundlak, Y. 1978. On the pooling of time series and cross sectional data. *Econometrica, 46(1)*

Perkins, S. 2013. Better regulation of public-private partnerships for transport infrastructure. International transport forum, *Discussion paper 2013-6*

Pinero, J.C. 2003. A framework for monitoring performance-based road maintenance. Virginia Polytechnic Institute, *Doctoral thesis*

Plummer, J. 2010. Efficiency ratings in performance-based road maintenance contracts. Virginia Tech, *Master thesis*

Segal, G.F., Moore, A.T., McCarthy, S. 2003. Contracting for road and highway maintenance. Reason Public Policy Institute. *How to Guide No.21*

SKL (Sveriges Kommuner och Landsting) 2015. Drift, Underhåll. Retrieved from: http://skl.se/samhallsplaneringinfrastruktur/trafikinfrastruktur/driftunderhall.291.html. Accessed: July 7, 2015

Smith, M. 2012. Sixty years of highway maintenance. The chartered institution of highways and transportation. *Report*

Smith, A.S.J, Buckell, J., Wheat, P.E., and Longo, R. 2015 (forthcoming), Hierarchical performance and unobservable heterogeneity in health: A dual-level efficiency approach applied to NHS pathology in England, in Greene, W.H., Sickles. R., Khalaf, L., Veall, M., and Voia, M.C.. eds., *Productivity and Efficiency Analysis*, Springer Proceedings in Business and Economics.

Sultana, M., Rahman, A. and Chowdhury, S. 2012a. An overview of issues to consider before introducing performance-based road maintenance contracting. *World Academy of Science, Engineering and Technology 62*

Sultana, M., Rahman, A. and Chowdhury, S. 2012b. Performance based maintenance of road infrastructure by contracting- A challenge for developing countries. *Journal of Service Science and Management, 5*

Zietlow, G. 2003. Cutting Costs and Improving Quality through Performance-Based Road Management and Maintenance Contracts. The Latin American and OECD Experiences. Paper presented at the Senior Road Executives Programme, Restructuring Road Management, Birmingham, UK

APPENDICES

Appendix A

Table A.1 Regression results

		Model I		Model II	
		Coef.	SE	Coef.	SE
Col / Row		1	2	3	4
1	***The first stage estimation***				
2	Ln (Light vehicle kilometers)	0.1055	0.0717	-0.0107	0.1019
3	Ln (Road length)	0.1825**	0.0817	0.0324	0.0993
4	Ln (Road buoyance)	0.0040	0.0142	0.0023	0.0163
5	Dummy road buoyance	-0.0731	0.1367	-0.2424*	0.1458
6	Ln (Median barrier)	-0.0029	0.0201	0.0141	0.0235
7	Dummy median barrier	0.1058	0.1043	0.1179	0.1086
8	Ln (Slippery road)	0.2031**	0.0802	0.2089***	0.0808
9	Ln (Snowfall)	0.1169	0.1010	0.1044	0.1016
10	Ln (Snowbanks)	0.1746***	0.0432	0.1820***	0.0435
11	Regions:				
12	Central	0.3395***	0.1011	0.9559	1.1047
13	South	0.5972***	0.1503	5.5661***	1.0835
14	East	0.5233***	0.1407	3.6475***	0.5442
15	Years:				
16	2005	-0.0445	0.0489	-0.0397	0.0493
17	2006	-0.0922**	0.0465	-0.0771	0.0473
18	2007	-0.0514	0.0477	-0.0295	0.0487
19	2008	-0.0540	0.0525	-0.0324	0.0535
20	2009	0.0815	0.0521	0.1063**	0.0532
21	2010	0.1426*	0.0789	0.1648**	0.0801
22	2011	-0.0134	0.0501	0.0054	0.0515
23	2012	-0.0325	0.0575	-0.0091	0.0589

***, **, * Significant at 1%, 5% and 10%, respectively.

Note: Region north and year 2004 are reference categories.

Table A.1 Regression results (cont.)

		Model I		Model II	
		Coef.	SE	Coef.	SE
Row \ Col		1	2	3	4
24	Group means of:				
25	Light vehicle kilometers			0.0000	0.0000
26	Road length			0.0005***	0.0001
27	Road buoyance			0.0006	0.0005
28	Median barrier			-0.0010	0.0012
29	Slippery road			0.0234**	0.0117
30	Snowfall			0.0247	0.0317
31	Snowbanks			-0.0933	0.0679
32	Constant	5.0434***	0.8758		
33					
34	Number of observations	632		632	
35	R-squared	0.3221		0.4593	
36	Wald test			79.76***	
37					
38	***The second stage estimation***				
39	Likelihood ratio test: Persistent inefficiency	0		0	
40	Number of observations	73		73	
41					
42	***The third stage estimation***				
43	Likelihood ratio test: Time-varying inefficiency	6.834***		6.692***	
44	Number of observations	632		632	

***, **, * Significant at 1%, 5% and 10%, respectively.

Note: Region north and year 2004 are reference categories.

Table A.2 The most efficient maintenance areas

	Maintenance area		
Rank / Year	1	2	3
2004	Umeå Norra [0.9727]	Kalix [0.9268]	Storuman/Vä/Ö/Sorsele [0.9218]
2005	Umeå Norra [0.9595]	Västervik/Valdemarsvik/Söderköping [0.9184]	Kalix [0.9112]
2006	Umeå Norra [0.9446]	Linderödsåsen [0.9222]	Göinge [0.9050]
2007	Umeå Norra [0.9450]	Storuman/Vä/Ö/Sorsele [0.9180]	Lycksele [0.9141]
2008	Söderslätt [0.9291]	Storuman/Vä/Ö/Sorsele [0.9175]	Helsingborg [0.9164]
2009	UmeåSödra/Umeå/Norsjö [0.9285]	Eslöv [0.9218]	Bjäre – Åsbo [0.9119]
2010	Gävle [0.9521]	Växjö/Lenhovda [0.9423]	Ånge [0.9303]
2011	Österlen [0.9439]	Gävle [0.9403]	Malung [0.9180]
2012	Kiruna [0.9341]	Österlen [0.9292]	Västerås [0.9290]
	Entire period		
2004-2012	Norsjö [0.8642]	Bräcke [0.8639]	Västbo/Gislaved/ Värnamo [0.8638]

Note: Efficiency scores are in brackets. The presence of the several area names separated with a slash symbol implies that these areas are administratively merged during the period studied.

Table A.3 The least efficient maintenance areas

	Maintenance area		
Rank / Year	1	2	3
2004	Göinge [0 .6693]	Linderödsåsen [0.7329]	Bjäre - Åsbo [0.7372]
2005	Sollefteå [0.7690]	Göinge [0.7694]	Söderslätt [0.7694]
2006	Gävle [0.7895]	Umeå Södra/Umeå/Norsjö [0.7914]	Örnsköldsvik [0.7999]
2007	Gävle [0.7681]	Umeå Södra/Umeå/Norsjö [0.7816]	Gällivare [0.7899]
2008	Österlen [0.7356]	Linderödsåsen [0.7641]	Uppsala [0.7740]
2009	Umeå Norra [0.6176]	Lit [0.7860]	Uppsala [0.7906]
2010	Umeå Norra [0.4511]	Storuman/Vä/Ö/Sorsele [0.5428]	Pajala [0.6836]
2011	Hudiksvall [0.7504]	Boden [0.7619]	Söderslätt [0.7881]
2012	Umeå Norra [0.4768]	Västervik/Valdemarsvik/Söderköping [0.6943]	Storuman/Vä/Ö/Sorsele [0.7230]
	Entire period		
2004-2012	Umeå Norra [0.7706]	Storuman/Vä/Ö/Sorsele [0.8388]	Gävle [0.8396]

Note: Efficiency scores are in brackets. The presence of the several area names separated with a slash symbol implies that these areas are administratively merged during the period studied.

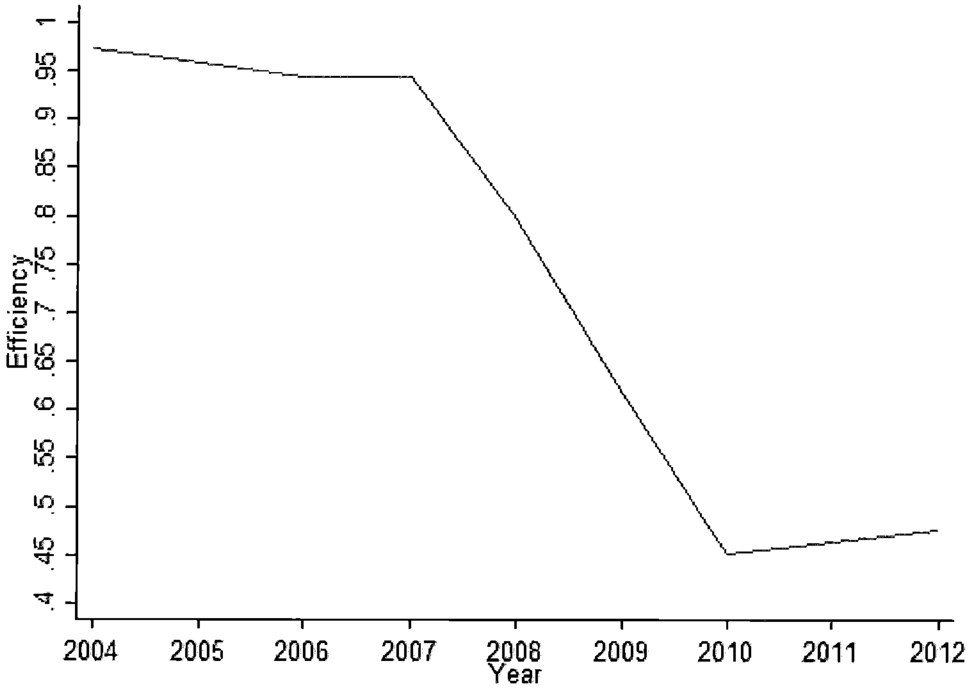

Figure A.1 Overall efficiency over time: Maintenance area Umeå Norra

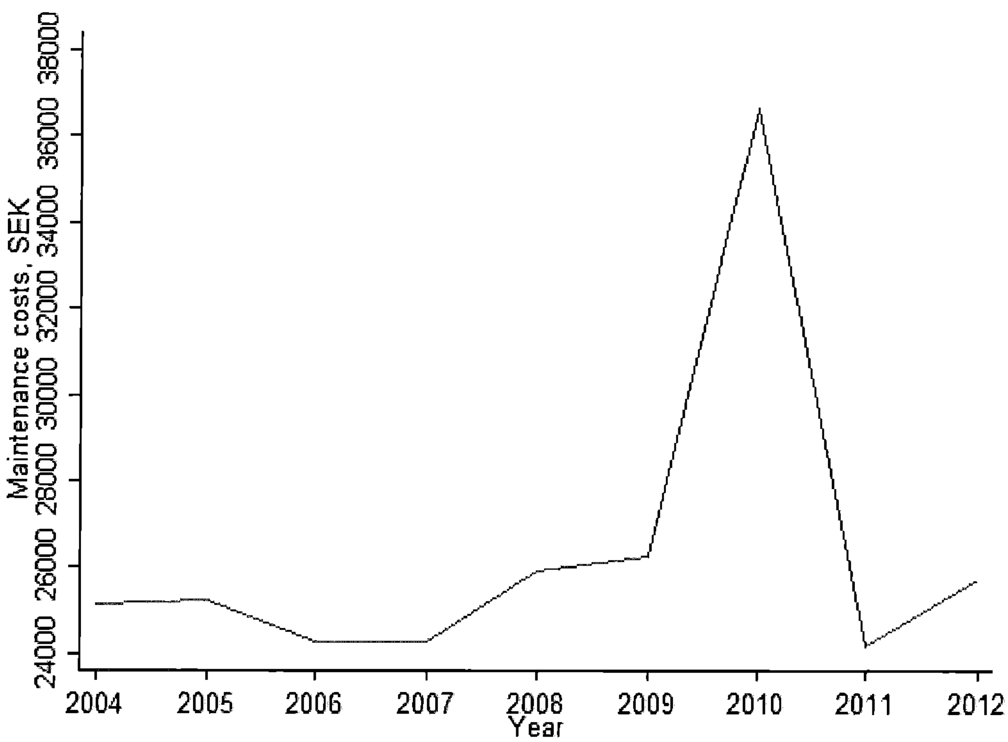

Figure A.2 Average maintenance costs

Appendix B

Table B.1 Regression results

		SA: Period Model II		SA: Traffic volume Model II	
		Coef.	SE	Coef.	SE
Col / Row		1	2	3	4
1	***The first stage estimation***				
2	Ln (Light vehicle kilometers)	-0.0039	0.1062	0.0367	0.0916
3	Ln (Road length)	0.0408	0.0960	0.0193	0.0967
4	Ln (Road buoyance)	-0.0047	0.0159	-0.0019	0.0163
5	Dummy road buoyance	-0.02656*	0.1372	-0.2616*	0.1452
6	Ln (Median barrier)	0.0012	0.0255	0.0157	0.0236
7	Dummy median barrier	0.0172	0.1179	0.1347	0.1083
8	Ln (Slippery road)	-0.0822	0.0868	0.2093***	0.0808
9	Ln (Snowfall)	0.5440***	0.1696	0.1076	0.1016
10	Ln (Snowbanks)	0.1573***	0.0382	0.1810***	0.0435
11	Regions:				
12	Central	-0.2732	1.6001	1.0041	1.1117
13	South	6.2356***	1.4494	5.2645***	0.9573
14	East	3.4376***	0.6371	3.5202***	0.4807
15	Years:				
16	2005	-0.1186**	0.0471	-0.0423	0.0493
17	2006	-0.1259***	0.0463	-0.0856*	0.0487
18	2007	-0.0818*	0.0437	-0.0384	0.0500
19	2008	-0.1123**	0.0508	-0.0418	0.0548
20	2009	-0.0136	0.0526	0.0959*	0.0548
21	2010			0.1502*	0.0827
22	2011	0.0419	0.0492	-0.0082	0.0549
23	2012	-0.1621**	0.0652	-0.0236	0.0623

***, **, * Significant at 1%, 5% and 10%, respectively.

Note: Region north and year 2004 are reference categories. In row 2, in the column "SA: Traffic volume" there should be the heavy vehicle kilometers instead of the light vehicle kilometers.

Table B.1 Regression results (cont.)

			SA: Period Model II		SA: Traffic volume Model II	
			Coef.	SE	Coef.	SE
Row \ Col			1	2	3	4
24	Group means of:					
25		Light vehicle kilometers	0.0000	0.0000	0.0000	0.0000
26		Road length	0.0005***	0.0001	0.0005***	0.0001
27		Road buoyance	0.0008	0.0005	0.0006	0.0005
28		Median barrier	-0.0008	0.0012	-0.0010	0.0013
29		Slippery road	0.0114	0.0146	0.0261**	0.0116
30		Snowfall	0.0552	0.0454	0.0169	0.0308
31		Snowbanks	-0.1757	0.1225	-0.0896	0.0677
32						
33	Number of observations		565		632	
34	R-squared		0.4479		0.4561	
35	Wald test		65.93***		85.21***	
36						
37	***The second stage estimation***					
38	Likelihood ratio test: Persistent inefficiency		0		0	
39	Number of observations		73		73	
40						
41	***The third stage estimation***					
42	Likelihood ratio test: Time-varying inefficiency		7.823***		6.636***	
43	Number of observations		565		632	

***, **, * Significant at 1%, 5% and 10%, respectively.

Note: Region north and year 2004 are reference categories. In row 25, in the column "SA: Traffic volume" there should be the heavy vehicle kilometers instead of the light vehicle kilometers.

Figure B.1 Sensitivity analysis: Overall efficiency over time in terms of period

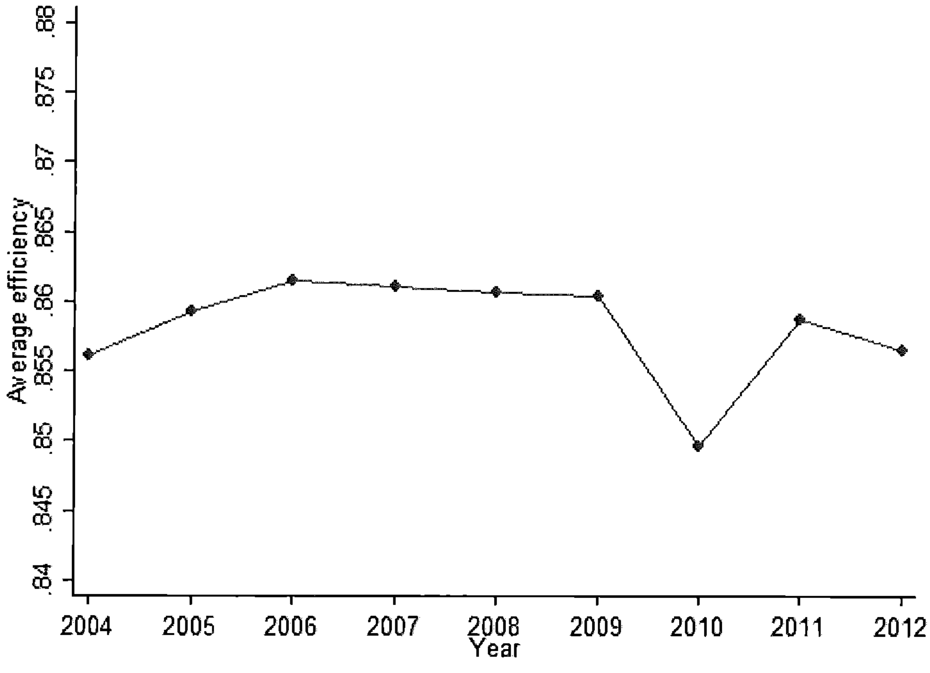

Figure B.2 Sensitivity analysis: Overall efficiency over time in terms of a measure of the traffic volume