Determinants of Rolling Stock Maintenance Cost in Metros.

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ABSTRACT

This study examines the economies of scale and the determinants of rolling stock maintenance costs for 24 urban rail transit operators. The estimates reveal significant returns to scale in maintenance for both per car and per car km. The econometric analysis also provides statistically significant cost elasticities for wages and staff hours suggesting substitution effects between factors. Staff outsourcing is found to significantly decrease costs, whereas higher levels of fleet availability at the peak and rolling stock failures increase it. The effect of the age of rolling stock and the network is negligible on rolling stock maintenance costs although the analysis reveals a downward trend in rolling stock costs among the CoMET-Nova metros.

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INTRODUCTION

The process of preserving the condition of the assets has deserved wide and long attention in the industrial literature. The rail industry is very capital intensive, with large infrastructures and valuable mobile assets that require substantial efforts in maintenance. For some assets such as rolling stock, the whole life costs of maintenance is estimated to be significantly larger than the initial acquisition costs [1], which points out the critical importance of understanding the determinants of rolling stock maintenance costs for the rail industry.

Regarding maintenance and costs, there is a relative abundance of academic research on infrastructure maintenance costs whereas the literature on rolling stock maintenance has focused on the technical details of maintenance. The predominance of infrastructure in the economic maintenance literature may have been stimulated by the privatization debate of the infrastructure operators but also by the visibility of infrastructure costs. In the UK, the current infrastructure investment plan to invest £10 billion for the 2014-2019 period has yielded significant media attention [2]. On the contrary, despite rail in the UK is estimated to spend £1.9 billion annually in rolling stock [1], this significant amount of costs has not received much attention either in the media nor the academia.

This paper focus on the rolling stock maintenance costs for high density urban rail operations (hereafter defined as ‘metros’). In comparative terms of social and economic impact, metros have received comparatively less attention in the academic debate than other modes of transport within the rail industry. Nevertheless, metros are fundamental for the development of the most dynamic parts of the countries, metropolitan areas, and the increasing number of metros worldwide [3] is responsible for a large share of the total passengers transported by rail annually in the world.

In order to study the costs in the metros, the help provided by the Railway and Transport Strategy Centre (RTSC) at Imperial College London has been invaluable. The RTSC has been in charge of the CoMET and NOVA metro consortia, a group of more than 30 metros who exchange good practice and operational information in order to improve their performance. This platform of cooperation between metros has been the starting point to develop this econometric analysis presented on this study.
In our research, we put together the relevant KPI’s for rolling stock maintenance costs and we develop an econometric analysis in order to understand and quantify the relative effect of each of the determinants of rolling stock maintenance costs. Thus, despite the previous research on maintenance costs, we believe that this study can make a meaningful contribution to understanding rolling stock maintenance costs and, at the same time, it can provide new insightful evidence about rapid transit operations.

This paper is structured as follows. Section 2 covers the relevant literature and summarises the main conclusions to date. Next, Section 3 describes the econometric techniques and the data used. Section 4 presents and interprets the results on rolling stock maintenance costs determinants. Finally, section 5 concludes the study with the main findings of the research.

LITERATURE REVIEW

Asset maintenance plays a key role in operational standards and has been a popular topic in the industrial academic literature. This is particularly important in the rail industry as it is very capital intensive both in terms of infrastructure and mobile assets. However, much of the literature on rail industry maintenance has focused solely on track and infrastructure maintenance [4-7], largely due to the debates which stemmed from countries such as the US and UK privatizing their infrastructure operators (e.g. Amtrak in the US [8] and Network Rail in the UK [9]).

The academic literature on rolling stock maintenance is also abundant, although the approach to it has been slightly different. Infrastructure maintenance literature has been approached both from an economics and a technical point of view but rolling stock maintenance literature in the rail industry has been almost completely focused on technical dimensions. These include topics such as monitoring asset conditions [10] [11], predicting failures [12], maintaining strategies and schedules [13], optimizing spare provisions and finding best replacement frequencies in the rolling stock assets [14] and other technical areas. This may be due to restrictions on accessing data on rolling stock instead of infrastructure maintenance as infrastructure operators are usually public companies who may be more prone to allowing access to their data for academic research, particularly with the need for

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1 KPI refer to Key Performance Indicators, a large set of indicators collected by the Rail and Transport Strategy Centre in order to compare trends, benchmark performance and identify good practices developed by the metros in the CoMET-Nova consortia.
evidence on costs for the potential privatization of the networks. On the other hand, rolling stock maintenance is usually done in-house by the rail operators or outsourced to the supplier of the rolling stock. In both cases it is most likely to be part of private company operations, which are less likely to share internal data for academic and public research.

Nevertheless, there is some literature on the economic’s and cost’s implications, which includes rolling stock maintenance for the rail industry. Wang and Liao [15] have developed a multi-product cost structure and analysed productivity growth of the Taiwan railway for the period 1991-2000. In this analysis they consider variable costs under four categories, which includes a rolling stock maintenance category. This maintenance category is a price index calculated by dividing the total maintenance expenses by the total hours of repair and maintenance spent on rolling stock. The results found small elasticities for all the input factors including rolling stock labour prices. This implies that changes in price of the input factors, among these the changes in rolling stock maintenance labour, have little impact on labour utilization. Moreover, Wang and Liao [15] also found that there is a substitution effect between labour, maintenance and materials and supplies, and a complementary relationship between maintenance and intermediate inputs (e.g. supplies materials).

Despite the academic contributions stated above, the knowledge gap in understanding rolling stock cost determinants has been partially covered by reports issued or commissioned by public institutions needing a deeper understanding of rolling stock maintenance costs. For instance, the Department for Transport and the Office of Rail Regulation, both in the UK, commissioned a report on rolling stock whole life costs [1], analysing the evolution of costs in the rolling stock maintenance along the life cycle of the asset. According to their estimates, rolling stock maintenance is the largest cost related to rolling stock whole life costs (44%), even greater than the acquisition of the rolling stock itself. Besides this, Jan and Phillips [1] describe how some practices, such as number of vehicle types in the fleet, may lead to 15-20% higher rolling stock maintenance costs due to increasing complexity of the rolling stock maintenance. However, the report reviews other factors that may increase rolling stock maintenance costs without quantifying by how much these factors affect maintenance costs. Clearly there is scope for providing additional insight beyond these reports as quantifying the relative importance of the factors is key to making better informed optimizing decisions.

The Association of Train Operating Companies (ATOC) in the UK has also developed a study on rolling stock costs and value [16], which reviews practices and cost drivers. ATOC
estimated that internalizing responsibility for maintenance may reduce maintenance costs by 10%. However, the remaining factors mentioned in the report are seldom quantified and the study focused on the impact of maintenance franchise and schemes while neglecting the drivers that define rolling stock maintenance productivity. Thus, despite some general evidence on the rail industry overall maintenance costs, the scarce academic literature focused on particular rolling stock maintenance costs and, lastly, the imprecise review of factors provided by commissioned reports, the understanding of the determinants of rolling stock maintenance costs and the quantification of these factors remain unclear. Therefore, filling the gap on understanding the determinants of rolling stock maintenance costs and quantifying their effect is the main contribution of this study.

METHODOLOGY AND DATA

Methodology
The aim of this study is to quantify the relative weight of the explanatory factors of rolling stock maintenance costs. In order to do that, we use econometric regression analysis on an unbalanced panel of 24 metros over 8 years. A regression using this double dimension, cross sectional and time series, will look similar to EQUATION 1:

\[ y_{it} = \alpha + \beta X'_{it} + u_{it} \quad where \quad u_{it} = \mu_i + \nu_{it} \]

Where the \( i \) sub index, \( i = 1, \ldots, N \), refers to the metros, or cross-sectional units in the panel. The \( t \) sub index, \( t = 1, \ldots, T \), represents the time dimension where each unit equals a year. In EQUATION 1, \( \alpha \) is a scalar, \( \beta \) the set of coefficients for each respective variable, \( X'_{it} \) describes the explanatory variables included in the econometric model\(^2\). The \( u_{it} = \mu_i + \nu_{it} \) in EQUATION 1 refers to the error component for the disturbances. The unobserved time-invariant individual-specific effect is represented by \( \mu_i \), which is interpreted for this model as the metro-specific effect not included

in the regression. The $v_{it}$ is the random disturbance, which can change from metro to metro and also over time, as a simple disturbance term in a simple Ordinary Least Squares (OLS) regression.

In the type of panel modelling applied in our case, an essential consideration is the specification of $\mu_i$, the unobservable individual-specific effect. One approach includes fixed effects (FE) modelling, allowing for correlation between the explanatory variables and the unobserved individual effects. Alternatively, if we consider that there is a random variation across the cross-sectional units, and uncorrelated with the explanatory variables in the econometric model, then the most pertinent model is the random effects (RE) model.

In order to decide whether FE or RE is more suitable for the panel data being modelled, we apply the Hausman test. The Hausman test essentially compares the RE and the FE models and estimates if the differences are more than what it is expected given a certain sample error, or what is the same, and if the differences in the coefficients on explanatory variables that change over time are statistically significant. If the Hausman test null hypothesis is rejected, then either the differences in the estimates are negligible or the variation in the FE sample is too large to conclude that the differences are statistically significant. In any case, the null hypothesis was not discarded in our study so RE modelling is preferred.

The choice of RE instead of FE has also an important consequence on the extension of the application of the results. In the FE modelling, the explanatory variables are correlated to the unobserved individual effects, so the coefficients of those estimations may not apply so accurately to other cross sectional units, in our case metros, beyond the sample of individuals included in the analysis.

The RE model can be explained as having an independent and identically distributed individual effect, $\mu_i \sim IID(0, \sigma^2_\mu)$ where $\mu_i$ is assumed independent from both the predictor variables, and also $v_i \sim IID(0, \sigma^2_v)$ as random disturbance. In the case where we know the variance structure, then the RE model is estimated applying Generalized Least Squares (GLS) and it is said to be BLUE [Best Linear Unbiased Estimator]. In this case the variance matrix is shown in EQUATION 2.

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According to the GLS method, the matrix, $\Omega_{T \times T}$, serves for the calculation of $\theta$ and the rest of the variables as in EQUATION 3. EQUATION 3 also demonstrates how to calculate $\hat{x}_{it}$ and $\hat{y}_{it}$, which will be estimated using an OLS model in order to obtain the random effect model coefficients.

$$\begin{bmatrix} \sigma^2_{\mu} + \sigma^2_{\nu} & \sigma^2_{\mu} & \cdots & \sigma^2_{\mu} \\ \sigma^2_{\mu} & \sigma^2_{\mu} + \sigma^2_{\nu} & \cdots & \sigma^2_{\mu} \\ \cdots & \cdots & \cdots & \cdots \\ \sigma^2_{\mu} & \sigma^2_{\mu} & \cdots & \sigma^2_{\mu} + \sigma^2_{\nu} \end{bmatrix}$$

EQUATION 3

$$\theta = 1 - \frac{\sigma^2_{\nu}}{\sqrt{T\sigma^2_{\mu} + \sigma^2_{\nu}}}$$

$$\hat{y}_{it} = y_{it} - \theta \bar{y}_{it}$$

$$\hat{x}_{it} = x_{it} - \theta \bar{x}_{it} \text{ for all } X'_{it}$$

As for any econometric modelling output, it is convenient to assess the extent to which the observed data matches the values expected by the model. The most common measure of goodness of fit is the R-square which in the case of panel data has three potential equivalents; within, between and overall R-squared, all of them computed in a slightly different fashion to the usual R-squared. The R-squared within reports the R-squared from the mean-deviated regression and it is the closest one to the common OLS. The R-squared between uses fixed effects fitted values and the within-individual averages for the explanatory variables in order to calculate the correlation between these two. Finally, the R-squared overall also computes the fixed effects fitted values so it can correlate them with the original independent variables.

Data
The CoMET-Nova consortia was established more than 20 years ago and it comprises more than 30 of the largest metros in the world. The CoMET-Nova consortia are managed by the Railway and
Transport Strategy Centre (RTSC), an autonomous organization within the Imperial College London. The RTSC collects data for a wide range of metro operational dimensions clearly defined in the CoMET-Nova Handbook of KPI definitions, which ensure data quality and comparability among the members. This data from the consortia are the source of the data used in this study. However, due to the RTSC existing confidentiality agreement with its members, any data or results presented in this study must be presented in an anonymised form.

The panel of metros used in this study comprises of 24 metros over an 8 year period (2005-2012). However, the sample includes some missing years for some cross sectional units so it is an unbalanced panel data with 104 observations. Despite the missing observations for some of the years, panel data increases the variability of the variables, allows controlling for heterogeneity, tends to have less collinearity between the variables and more degrees of freedom [17].

In this study we gathered data for rolling stock maintenance costs, our dependent variable, and several explanatory factors. According to the CoMET-Nova handbook, the rolling stock maintenance cost comprises of the following:

- All maintenance of rolling stock (e.g. change in lighting of the cars, routine checks of key parts, etc.) and maintenance of workshops.
- All rolling stock cleaning, both regular and in-depth cleaning operations.
- All management and support staff costs associated with the rolling stock maintenance and the workshops.
- Salaries, training, overtime and employment-related fringe costs for metro staff and any contract labour cost in cases where they exist.

Within this category, there are certain rolling stock maintenance operations that are excluded such as mid-life rolling stock refurbishment and renewal of time expired assets. New investment in rolling stock is also excluded from this cost category.

The dependent variable for each of the models has been rationalized per output (car kilometres) and per scale (fleet units or number of cars) and their summary statistics are shown in TABLE 1. Regarding rolling stock maintenance costs per car km, the panel average is 0.685 US$ in Parity

\[ 4 \] Car kilometres include all car kilometres which were actually operated in revenue service, and excludes empty stock movements, movements from depots, engineering trains, driver training runs, cancellations of scheduled runs, and rail replacement bus services.
Purchasing Power (PPP) units, with values ranging from 1.467 to 0.280 US$ in PPP. Median values are close to the mean, and the standard distribution is 0.198 US$ in PPP, so there are some values above 1 US$ in PPP but these are rare.

Regarding rolling stock maintenance per car, on average the annual maintenance of a car costs 73,455 US$ in PPP across the CoMET-Nova members that were included in this research. The standard deviation is also a moderate 19,838 US$ in PPP, although the range of values within the consortia is significant with a maximum of 136,994 US$ and a minimum of 34,487 US$ in PPP.

**TABLE 1** Dependent variable summary statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Obs.</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS maintenance costs per car km (PPP US$)</td>
<td>104</td>
<td>0.685</td>
<td>0.653</td>
<td>0.198</td>
<td>0.280</td>
<td>1.467</td>
</tr>
<tr>
<td>RS maintenance costs per car (PPP US$)</td>
<td>104</td>
<td>73455</td>
<td>73612</td>
<td>19838</td>
<td>34487</td>
<td>136994</td>
</tr>
</tbody>
</table>

Legend: Obs.: Observations, SD: Standard Deviation.

Regarding the explanatory variables, we present the summary statistics in TABLE 2. We consider one output and one scale variable, each of which rationalize the dependent variable rolling stock maintenance cost: car km as total actual operated revenue car km and total number of cars, which refers to the total number of cars owned/leased by the metro which are suitable for operation in normal passenger service (average over the year).

The addition of the car km and fleet size variables enable us to compare the economies of density and the economies of scale in the evaluation of the rolling stock maintenance costs. In case there are economies of density, the increase in output (car kilometres) would be associated with a decrease in rolling stock maintenance costs per car kilometre. With respect to the economies of scale, the change in the size of the fleet may be associated with a change in the rolling stock maintenance costs per car. If a larger fleet shows lower rolling stock maintenance costs per car, a metro exhibits a positive economy of scale.
Besides this analysis on the economies of density and scale, the car kilometres and fleet size measures demonstrate the variability in the size of the CoMET-Nova members. The maximum car kilometres delivered by any member in the panel is 724 million kilometres, whereas the minimum is a much lower 5 million car kilometres. Likewise, the member with the smallest fleet included in this study has 76 cars while the member with the largest fleet adds up to 6,417 cars for a given year.

### TABLE 2 Explanatory variables summary statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Obs.</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car km (m)</td>
<td>104</td>
<td>164.726</td>
<td>100.505</td>
<td>167.782</td>
<td>5.22</td>
<td>724.300</td>
</tr>
<tr>
<td>Fleet (number of cars)</td>
<td>104</td>
<td>1545.290</td>
<td>816</td>
<td>1684.420</td>
<td>76</td>
<td>6417</td>
</tr>
<tr>
<td>Wages (PPP US$)</td>
<td>104</td>
<td>37.861</td>
<td>39.745</td>
<td>14.797</td>
<td>11.20</td>
<td>78.270</td>
</tr>
<tr>
<td>RS maintenance staff hours (m)</td>
<td>104</td>
<td>2.384</td>
<td>1.627</td>
<td>2.363</td>
<td>0.064</td>
<td>13.300</td>
</tr>
<tr>
<td>Fleet availability at peak (%)</td>
<td>104</td>
<td>0.880</td>
<td>0.865</td>
<td>0.075</td>
<td>0.654</td>
<td>1</td>
</tr>
<tr>
<td>% RS maintenance staff hours contracted out</td>
<td>104</td>
<td>0.265</td>
<td>0.234</td>
<td>0.248</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>104</td>
<td>33.583</td>
<td>33.00</td>
<td>6.190</td>
<td>12</td>
<td>45</td>
</tr>
<tr>
<td>RS Mean distance between failure (m of km)</td>
<td>104</td>
<td>1.087</td>
<td>0.259</td>
<td>1.907</td>
<td>0.019</td>
<td>9.900</td>
</tr>
<tr>
<td>% of rolling stock with AC</td>
<td>104</td>
<td>48.952</td>
<td>40.500</td>
<td>45.466</td>
<td>0.000</td>
<td>100</td>
</tr>
<tr>
<td>Rolling stock age (years)</td>
<td>104</td>
<td>18.884</td>
<td>19.552</td>
<td>8.547</td>
<td>3.406</td>
<td>40.427</td>
</tr>
<tr>
<td>Age of the network (years)</td>
<td>104</td>
<td>53.144</td>
<td>37.500</td>
<td>38.901</td>
<td>10</td>
<td>149</td>
</tr>
<tr>
<td>Year</td>
<td>104</td>
<td>2005</td>
<td>2005</td>
<td>2012</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


There are other explanatory variables related to labour, rolling stock units and operational dimensions. Regarding labour, labour wages considered in our econometric model show values between 11.2 US$ to 78.27 US$ per hour. The analysis also includes variables on the total number of rolling stock staff hours employed by the metros, in order to take into account how labour intensive the processes are, and also to account for rolling stock maintenance hours contracted out. In this latter case, some metros do not contract out any staff related to rolling stock maintenance whereas others completely outsourced this function. Thus, minimum and maximum values for this variable are 0 and 1 respectively, with an average of 0.265. In other words, 26.5% of the rolling stock maintenance hours are outsourced on average across the members of the CoMET-Nova consortia.

This study on the determinants of rolling stock maintenance costs for metros also takes into account the condition and characteristics of the rolling stock of the metro. There is a variable to take
into account the actual size of the fleet, as described above, and also a further variable which captures
the percentage of rolling stock with air conditioning. Regarding this percentage, on average 48.95%
of the fleet has air conditioning across the CoMET-Nova consortia metros included in this research.
However, there is a large variability in these figures, with some members having no air conditioning
at all in their fleets while some members provide air conditioning in all their cars. Furthermore, this
study also considers the rolling stock age, which corresponds to the average age of the fleet over a
year. In our panel of metros, the average age of the fleet is 18.88 years with a maximum value of
40.42 years and a minimum of 3.4 years, with the young age being attributed to a metro that has
started operations recently. On average, the usual life cycle of rolling stock is generally around 30
years. However, this can be extended with mid-life refurbishments.

We also take into account operational variables that may influence the rolling stock
maintenance costs. First, the percentage of fleet available at the peak shows an average value of 88%,
which is different to the actual fleet utilisation at the peak, and it ranges between 65% and 100% for
some metros in a given year. Next, we also consider the average commercial speed of the service. In
this case, the average is 33 km/h with a standard deviation of 6.19 km/h. Despite the record low of
12 km/h demonstrated by one of the metros, the metros are found to operate at speeds ranging mostly
between 27 km/h and 40km/h. Another interesting indicator is the rolling stock mean distance
between failures (MDBF), which indicates the number of millions of car kilometres travelled between
each incident or service disruption caused by a rolling stock failure. In this case, an incident is
considered when it causes a delay of 5 minutes or longer to the service. On average, metros deliver
1.08 million car kilometres before having an incident caused by a rolling stock failure. However, this
average is heavily influenced by some metros with very high reliability. The median value shows an
incident caused by rolling stock failures every quarter of a million kilometres (0.259). This divergence
between the average and the median is also shown by the standard deviation of 1.907 million
kilometres.

Lastly, the age of the network measured since the beginning of operations is also considered.
This variable is included to take the operational circumstances of the metro into account. This variable
shows a maximum of 149 years, which corresponds to the London Underground. On average, the
panel of metros from the CoMET-Nova consortia included in this study are 53.14 years old, despite
a relatively large standard deviation of 37 years. Overall, this corresponds with the demographics of
metros across the world; with some early starters in the 19th century while most of the metros starting operations in the 1960s and 1970s.

Next, we present our hypothesis about why these independent variables may have a relevant role in explaining the rolling stock maintenance costs:

1) Car kilometres may not show a significant elasticity with rolling stock maintenance costs, as many of the rolling stock maintenance routines are scheduled on mileage, therefore, an increase in car kilometres may yield a more or less proportional increase in maintenance costs for the rolling stock.

2) Fleet size: we anticipate some economies of scale with respect to the fleet size variable. We suppose that larger fleets may enable higher productivity as the metros will be able to introduce specialization and automatization functions, thus, leading to lower rolling stock maintenance costs. However, all rolling stock maintenance may not be carried at one single depot. Large metros may have multiple depots distributed across the network which optimizes reallocation of fleet for service. Therefore, we expect some gains from the economies of scale but these may be moderate.

3) Wages and rolling stock staff hours: we assume that both higher prices or larger quantities of labour employed to be directly correlated with higher costs of maintenance. However, this effect may be mutually modulated as metros with very high wages may tend to use less labour whereas places with low wages may employ more people. Therefore, the final effect on the rolling stock maintenance costs may be balanced between the two.

4) Regarding availability at the peak, we expect that this should increase costs, as having the fleet available sets an additional constraint on the hours and times when maintenance can be conducted.

5) Outsourcing of staff hours is believed to decrease wages and, therefore, reduce maintenance costs. However, often in-house staff has a more detailed knowledge of the rolling stock and contractors can be more expensive than in-house workers.

6) Higher average commercial speed may increase the maintenance costs per car but it also helps to produce more car kilometres. As such, rolling stock maintenance per car kilometre may decrease as speed increases.

7) Rolling stock mean distance between failures caused by rolling stock faults is ambiguous; on one hand higher incidents due to poor rolling stock condition may point out the need for higher
maintenance. However, metros with insufficient rolling stock maintenance may also present higher rates of incidents so the expected effect is unclear.  

8) Rolling stock with air conditioning may tend to be more expensive to maintain and, even on newer fleets, the effect attributed to fleet age should be captured by the rolling stock age variable.  

9) The effect of rolling stock age itself is hard to predict. According to bathtub theory, we expect a new fleet to exhibit higher initial maintenance costs to slightly more mature fleets. We also expect the maintenance costs to increase again progressively as the fleet becomes older and approaches the end of its design life towards being rendered obsolete. Therefore, both new and old fleets may be expensive, leading to non-significant coefficients.  

10) Age of the network may influence increasing maintenance due to structure design, although how relevant the effect may be is unclear.  

RESULTS  
TABLE 3 reports the results for the modelling of rolling stock maintenance costs per car kilometre and per car. The variables described in the data section appear in natural logarithms so we can estimate cost elasticities with respect to these factors. Only rolling stock age and the age of the network appear without logarithms in order to describe the results more intelligibly.  

The first output variable, car kilometres, shows statistically significant cost elasticities of -0.24 for rolling stock maintenance per car kilometre. This suggests an increase of 10% in car kilometres leads to a decrease of 2.4% in maintenance costs per car kilometre. Likewise, car kilometres presents a positive 0.66 cost elasticity for rolling stock maintenance costs per car which implies that an intensive use of the assets leads to a less than proportional increase in costs. In the case of costs per fleet, it seems that an increase in the fleet size decreases the rolling stock maintenance costs with a cost elasticity of -0.88. This estimate seems to be larger than expected but at the same time also controls for the car kilometres produced by that fleet. Therefore, there seems to be strong evidence of economies of scale in the rolling stock maintenance per car, most likely due to labour specialization and automatization of maintenance routines. It is important to note that these coefficients represent the average cost elasticities for the CoMET-Nova metros participating in the study.
The next variable considered refers to both labour prices and quantities. The effect of the wages and the rolling stock maintenance staff hours are similar, probably due to a substitution effect between these two variables. As labour prices increase, rolling stock maintenance may become less labour intensive and vice versa. The cost elasticities for both labour wages and quantities range between 0.2568 to 0.2895, suggesting that an increase in labour costs leads to a less than proportional increase in rolling stock maintenance costs. On one hand, we have to bear in mind that there are other inputs comprised in the rolling stock maintenance costs. Besides this, an increase in labour prices may also lead to a substitution effect between factors, such as substituting labour for capital, thus, decreasing the effect of the cost elasticity. This is in line with the previous academic literature on input costs and substitution effects in rolling stock maintenance [15].

### TABLE 3 Rolling stock maintenance costs results

<table>
<thead>
<tr>
<th>Variables</th>
<th>Rolling Stock Maintenance Costs Models</th>
<th>Car km t-value</th>
<th>Car t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car km (m)</td>
<td>-0.2419 ** -2.1</td>
<td>0.6696 ***</td>
<td>3.59</td>
</tr>
<tr>
<td>Fleet (number of cars)</td>
<td>-0.8881 ***</td>
<td>-4.9</td>
<td></td>
</tr>
<tr>
<td>Wages (PPP US$)</td>
<td>0.262 ** 2.24</td>
<td>0.2568 ** 2.16</td>
<td></td>
</tr>
<tr>
<td>RS maintenance staff hours (m)</td>
<td>0.2895 *** 3.14</td>
<td>0.2792 *** 2.99</td>
<td></td>
</tr>
<tr>
<td>Fleet availability at peak (%)</td>
<td>0.506 1.61</td>
<td>0.5746 * 1.73</td>
<td></td>
</tr>
<tr>
<td>% RS maintenance staff hours contracted out</td>
<td>-0.5694 ** -2.4</td>
<td>-0.556 ** -2.31</td>
<td></td>
</tr>
<tr>
<td>Avg speed (km/h)</td>
<td>-0.0215 -0.1</td>
<td>-0.0057 -0.03</td>
<td></td>
</tr>
<tr>
<td>RS Mean distance between failure</td>
<td>-0.1073 *** -2.97</td>
<td>-0.1062 *** -2.91</td>
<td></td>
</tr>
<tr>
<td>% of rolling stock with AC</td>
<td>0.1869 1.35</td>
<td>0.1859 1.33</td>
<td></td>
</tr>
<tr>
<td>Rolling stock age (years)</td>
<td>-0.001 -0.18</td>
<td>-0.0005 -0.08</td>
<td></td>
</tr>
<tr>
<td>Age of the network (years)</td>
<td>0.0004 0.14</td>
<td>-0.0001 -0.01</td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>-0.0175 ** -2.38</td>
<td>-0.0163 ** -2.16</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>34.7195 ** 2.37</td>
<td>45.8256 *** 3</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>112</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>R² Within</td>
<td>0.5014</td>
<td>0.5426</td>
<td></td>
</tr>
<tr>
<td>R² - Between</td>
<td>0.5969</td>
<td>0.7115</td>
<td></td>
</tr>
<tr>
<td>R² - Overall</td>
<td>0.6001</td>
<td>0.6524</td>
<td></td>
</tr>
<tr>
<td>Estimator</td>
<td>GLS</td>
<td>GLS</td>
<td></td>
</tr>
</tbody>
</table>

Note: Significance at 10%, 5% and 1% levels is indicated by *, **, and ***, respectively

The next variables are those under managerial control of the metro operator in the short to medium term. First, fleet availability at the peak shows positive and statistically significant coefficients at around a 10% confidence level. The cost elasticity of fleet availability is 0.506 for
maintenance per car kilometre and 0.5746 for the model per car, indicating that a 10% increase in
fleet availability would lead to a 5.06% - 5.746% increase in rolling stock maintenance costs per car
km and per car respectively. As stated above, this in line with our expectations as increasing the
availability of fleet at the peak sets an additional constraint on the hours and times when maintenance
can be conducted.

The second variable under relative control of the management of the metro is the percentage
of rolling stock staff hours contracted out. The cost elasticities estimated for this variable are
statistically significant for both models, per car kilometre and per car, and equal to -0.5694 and -0.556
respectively. Consequently, it seems that outsourcing of maintenance activities decreases
maintenance costs for rolling stock, probably by means of introducing competition and alternatives
for the operator. In any case, this gives rise to potential future research to determine whether
outsourcing savings are concentrated in certain maintenance tasks or routines.

Lastly, the remaining variable which can be influenced directly by the management of the
metro is the average commercial speed of the service. In our case, the effect seems negligible, which
may also be due to the fact that the effect is also captured in the production of car kilometres itself.

There is a second group of explanatory variables reflecting the state of the assets. For starters,
rolling stock mean distance between failures (MDBF) caused by rolling stock accounts for the state
of maintenance of the rolling stock. In our case, the cost elasticity of rolling stock MDBF is moderate
and negative, -0.1073 and -0.1062 for the models of per car kilometre and per car respectively, which
implies that less frequent failures caused by rolling stock is linked to lower costs. In other words,
rolling stock in better condition seems to be associated with lower rolling stock maintenance costs.

Next, the percentage of rolling stock with air conditioning seems to have moderate and
positive cost elasticities. This implies that a larger percentage of fleet with air conditioning leads to
higher maintenance costs, which is intuitive since having new equipment on board is likely to add
extra maintenance routines and procedures. However, both coefficients fail to be statistically
significant at a 10% level perhaps due to low variability of the variable over time, as the percentage
of fleet with air conditioning is a relatively stable variable.

Last in the group of asset condition explanatory factors, the age of the rolling stock and the
age of the network seem to have no effect on the rolling stock maintenance costs once all the factors
stated above have been controlled for. In the case of rolling stock age, this may reflect the concern
described in hypothesis 9) above. The rolling stock maintenance costs are non-linear and usually
show high but rapidly decreasing maintenance costs for newer fleets, with a low and almost flat
profile during the maturity of the assets. That is until the assets become significantly obsolete, the
rolling maintenance costs start increasing significantly. If this is the case, the variable rolling stock
age may have a neutral or zero estimate when modelling for rolling stock maintenance costs because
newer and older fleets will both show higher costs than mature but not obsolete units.

Finally, the time trend variable, year, is significant at a 5% confidence level for both models.
This entails that, given certain conditions for all the explanatory variables described above, every
additional year is correlated to a decrease of 1.7%-1.63% in rolling stock maintenance costs per car
kilometre and per car respectively. Despite this percentage being moderate, it indicates a steady
improvement in the rolling stock maintenance costs for most of the metros in the sample. The cause
for this may be the increase in productivity due to new technologies but it may also be an exception
due to a selection bias of the sample. The sample is formed by RTSC members who routinely
exchange good practices and cost saving recommendations, which may lead to a decreasing trend in
costs not necessarily common in the rest of the industry sector.

Lastly, regarding the extent to which the model fits the data, the R-squared values shown in
the table present relatively high values, implying that much of the variation of the data from the
sample average is explained by the models. The values range between 0.5014 and 0.7115, which
imply that the model was able to explain at least 50% of the variation in the rolling stock maintenance
costs. The remaining variation can be attributed to dimensions not included in the models (such as
number of doors per car), data inaccuracy and, particularly, the various good practices metros carry
out that allow them to perform beyond expectations given their conditions.

CONCLUSION
The study reviewed several variables that help to explain the rolling stock maintenance costs using a
panel of 24 metros worldwide over a period of 8 years. There are two econometric models that
quantify the effect of these variables by means of cost elasticities or the effect of an additional year
in the asset age.
The results of the study present strong evidence concerning the existence of economies of scale in the rolling stock maintenance costs (e.g. -0.88 cost elasticity for fleet size and maintenance cost per car). Besides this, there are also clear returns to the intensity of use in the assets, lowering maintenance per car kilometre as more car kilometres are produced and with rolling stock maintenance costs per car increasing less than proportionally to the increase in car kilometres.

Labour related factors such as wages and total rolling stock maintenance staff hours present positive and statistically significant cost elasticities. These cost elasticities range between 0.2586 and 0.2895, suggesting less than proportional increases in maintenance costs when labour costs increase. This complements previous findings in the literature on substitution effects between inputs in rolling stock maintenance. Likewise, outsourcing of rolling stock maintenance staff also presents a clear negative cost elasticities (-0.55) as predicted by economic theory.

The condition of the assets has shown to present relevant variables to understand maintenance. The mean distance between failures caused by rolling stock is linked to higher maintenance costs, both per car kilometre and per car, with cost elasticities of 0.1073 and 0.1062. Rolling stock with air conditioning seems to increase maintenance costs but the cost elasticity estimates failed to be statistically significant at a 10% confidence level. The age of the rolling stock and the age of the network system appear to have a negligible effect on rolling stock maintenance costs once the other factors explained above have been considered. Finally, there is a negative time trend for the sample of CoMET-Nova members suggesting an improvement in rolling stock maintenance costs over time. However, because all the metros considered in the sample are part of the CoMET-Nova consortia, we do not know if this decrease in rolling stock maintenance costs is a rail industry wide trend or caused by the benchmarking and good practices shared in the consortia. Thus, further research incorporating other modes of rail transport and other metros not included in the CoMET-Nova consortia could offer further evidence to compare against the results found in this study.

REFERENCES


