QUANTIFICATION OF AGING FLEET IMPACT ON FUEL CONSUMPTION

Área temática: Logística

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Resumo: Railway companies are continually seeking fuel efficiency enhancements. Fuel is responsible for a large percentage of operational costs, and the burning of fuel by diesel-engine locomotives causes significant environmental impacts. In order to improve fuel efficiency, it is very important to understand all aspects that can impact negatively on fuel consumption. This paper's objective is to evaluate and measure one of those impacts – the aging fleet. The influence of this factor on locomotive fuel consumption was studied in a railway company in Brazil in 2010, 2011 and 2012 using the paired-t test. The alternative hypothesis stated that the mean difference of previous-year consumption and subsequent-year consumption was greater than zero. Through analyzing statistical test results, it is possible to conclude that an aging fleet has a significant impact on locomotive fuel consumption in the absence of a robust maintenance program.

Palavras-chaves: .
INTRODUCTION

A significant portion of railway operational costs comes from fuel costs AAR (2015) defines as 22.1% the weight of fuel in the adjustment factor of rail costs in American companies (Table 1) for a period of one year, starting in the last quarter of 2013. Another relevant factor is the constant increase in diesel liter price since 2011. It is noteworthy that from June-August 2012 there was an increase in the order of 5% in the average price. The trend is steadily rising since the tax related to fuel costs became void (ANP, 2013), and with that, any rise in the value of this fuel will affect directly its final value and consequently its end customers through increasing transport costs.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>31.6%</td>
</tr>
<tr>
<td>Fuel</td>
<td>22.1%</td>
</tr>
<tr>
<td>Materials &amp; Suppliers</td>
<td>4.9%</td>
</tr>
<tr>
<td>Equipment Rents</td>
<td>5.4%</td>
</tr>
<tr>
<td>Depreciation</td>
<td>12.0%</td>
</tr>
<tr>
<td>Interest</td>
<td>1.9%</td>
</tr>
<tr>
<td>Other</td>
<td>22.1%</td>
</tr>
</tbody>
</table>

Table 1 – Rail Cost Adjustment Factor
Font: AAR (2015)

Liimatainen and Pöllänen (2010) conclude that energy/fuel efficiency has become an important global objective in recent years. This trend is also observed in cargo transportation and the logistics sector. Energy efficiency and energy use management information is needed both for climate change mitigation and in reaction to price increases. The main impact of the transport sector in this context lies in the fact that it is responsible for more than half of oil consumption. As well, there has been a reduction in the discovery of new reserves (CHAVES; GOMES, 2013). Reflecting the significance of fuel in total railway operational costs, fuel efficiency has been an important factor in the development of locomotives and rail operations (STODOLSKY, 2002).

In general locomotives’ development is associated with innovations in traction motors. Currently these are quite reliable and effective and technologically-based in electric motors of direct current (DC) and alternating current (AC) using power generated by diesel generators. Despite the improvement in fuel efficiency resulting from developments in locomotives,
dependence on the performance and durability of engine fuel consumption can rise. Therefore, the fuel injection system must be in a perfect condition of conservation and operation (STODOLSKY, 2002; PEREIRA, 2009).

The increase in fuel consumption may be related to limits in the engine life cycle. The aging of the locomotive fleet tends to reduce the railway fuel efficiency. The question is whether this impact is significant Does a consumption-increasing profile exist and is it constant over time?

The objective of this study is to evaluate and quantify the impact of the aging fleet on fuel consumption and consequently on fuel efficiency of locomotives with diesel-electric motors (AC and DC) in a Brazilian railway, considering the risks related to equipment reliability.

**NOTATION**

ANTT – Agência Nacional de Transportes Terrestres

FE – Fuel efficiency

TKB – gross tonne-kilometer

TKU – net tonne-kilometer

**MAIN TEXT**

This paper will present a theoretical background in order to support the need for research related to fuel efficiency and its impact in our society. It will also present the statistical approach and tools used to perform fuel consumption comparisons analysis.

1. **Energy efficiency in transportation**

Energy and transportation serve as a basis for the development of any nation's economy. However, the storage capacity of energy is limited and demand grows continuously. With the rapid development of the economy, there was a significant increase in the supply of passenger and cargo movement service and thus an increase in the proportion of energy consumed in transport. The way to resolve conflicts between economic development and energy consumption in transport has become a critical issue to be studied, analyzed and solved (JIA; PENG; LIU and Zhang, 2009; ZHOU; MA; LUO, 2012).

Energy efficiency in transport appears to be one of the critical points in the global scenario of energy efficiency, somewhat because of the history of competition between different modes of
providing people and cargo transport services. Transport is one of the fundamental conditions for an industrial economy. As a fuel industry it has a vital role in building a healthy economic society. The increase in energy consumption rates has become one of the critical factors in all sectors of the economy (HE; WU; XU, 2010; MORIARTY; HONNERY, 2012). Several authors follow this same line of reasoning: Jia; Mao; Liu and Sun (2010) state that transport is an important component of the national economy, and being a power consumption industry is given great attention globally from all areas of society, especially in regard to oil consumption. For Andrade and Mattei (2011), due to the energy pattern being fossil fuels-based the transportation sector is an important area for study and implementation of actions to reduce greenhouse gas emissions.

Energy efficiency is a key element in the economic development of a country. For the transportation sector, and especially railways, power consumption is high and accounts for a large part of the transport costs. Therefore it is directly related to the earnings of the company. The main objective of companies is to optimize the energy consumption in operation (maintaining at least the same level of service) in order to minimize the total fuel consumption. (FU; GAO LI, 2009; Zhuan; XIA, 2006).

2. Railway fuel efficiency

Due to its financial and environmental importance, fuel efficiency is one of the most critical indexes in a railway company. One of the most used measures of FE is ton-miles per gallon. The units of this indicator follow the American pattern; turning to metric becomes net tonne-kilometer (TKU) per liter. In Brazil it is usual to inverse this relation, thus liter per TKU is the measure used by some companies and presented in the reports of the ANTT. Other companies calculate the TKB instead of the TKU because this index considers the total weight of the train. Regardless of the calculation method, fuel efficiency in a railway company measures the amount of energy (fuel) used to perform cargo transportation to their customers (ALBUQUERQUE, 2006 Stodolsky, 2002).

2.1. Brazilian fuel efficiency evolution

It is possible to note that over the years the FE index has decreased, which indicates that Brazilian railways are becoming more efficient. It means that for the same volume of transportation less fuel is being burned. According to Figure 1, comparing the year 1999 to 2012, there was a reduction of more than one liter of diesel to transport the same amount of TKU, corresponding to a gain of more than 21%. For a comparison basis, in the United States over 24 years gains in fuel efficiency were more than 61% (Tolliver; LU; BENSON, 2013), demonstrating the possibility of
even greater gains for Brazilian railroads. In addition to the financial aspect, there is an environmental gain due to relatively lower carbon dioxide emissions to meet current production.

Figure 1 – Brazilian Fuel Efficiency evolution (L/kTKU)

Font: Vilaça (2013)
3. Factors that impact fuel efficiency

The optimization of energy use has become something that transcends the railways and transport systems. It is an important factor in any industry and for today's society. Regarding railroads, energy efficiency may be influenced by several factors, some more controllable than others. But all of them need to be studied and understood, especially those that generate impacts on fuel consumption directly (REIS; FABIAN MEIER; PACE; PALACIN, 2013).

Several authors have stated factors that influence consumption. For Liu; Mao; Ding; Jia; Lai (2007) the performance of traction and braking system, train weight, track condition and train control methods are points that when adjusted generate energy savings. According to Hoffrichter, Miller, Hillmansen and Roberts (2012) the main points related to consumption on the railroad are the efficiency of the components system and the duty cycle. To Lui.; Golovitcher (2003) the main fuel economy initiatives are related to engine design and locomotives, effective reduction of the moving train resistance and effective maintenance of rolling stock and track.

Another aspect needed to improve the fuel consumption levels is the understanding of the effects of different speed and acceleration profiles. Engineers’ behavior studies are also used to develop training programs focused on driving, promoting a culture of sustainability and reduction in fuel consumption. (LARSSON, ERICSSON, 2009). Murakami; Haga; Nakamura; Maehashi; Yamashita (2009) present some actions that rail operators practice to reduce energy consumption: i) establishment of goals and programs related to energy consumption reduction; ii) implementing an effective train operation; iii) incentive to purchase efficient locomotives; and iv) information regarding real fuel consumption.

3.1. Diesel engine impact

Currently, the diesel engine is the most popular transport power generator because of its efficiency and durability. An ideal diesel engine must have high power, low fuel consumption and low greenhouse gas emissions. Engine components need to be in perfect condition to maintain an efficient combustion process. Furthermore, it would be ideal if components, cylinder or nozzles, for example, were controlled by sensors. The nozzle should be able to spray the fuel in a homogeneous way, at the right time and for the appropriate period of time, without any new injections during the combustion process. A possible efficiency gain may come from the reuse of the gases emitted by the engine. The only problem is the need for investment for development of this technology (AGARWAL;
SRIVASTAVA; DHAR; MAURYA; SHUKLA; SINGH, 2013; LI; CUI; WANG; GUAN, 2009; STODOLSKY, 2002).

In order to measure the impact of a diesel engine on FE, the calculation of the specific fuel consumption is one of the most common measurements of motor efficiency in transforming the chemical energy of the fuel into useful work. In general, the most favorable points in the specific fuel consumption curves have approximately 80% load of the rated engine power and where the highest torque values are measured.

4. **Statistical inference**

Statistical inference is defined as an interval estimation process or hypothesis testing that considers data from a sample to draw conclusions about characteristics of a population, since the sample is a representative subset of the population (ANDERSON; SWEENEY; WILLIMAS, 2007; WALPOE; MYERS; MYERS; YE, 2012).

Even the best estimator is not able to estimate the population parameter exactly. Through confidence intervals it is possible to add more information to the estimator of the unknown parameter. It is expected to find the parameter value in this range, despite being probabilistic information (WALPOE; MYERS; MYERS; YE, 2012; DEGROOT; SCHERVISH, 2012).

To determine confidence interval calculation it is necessary to define the accuracy of the estimation. The higher the degree of confidence, the greater the accuracy and range values are (MONTGOMERY; RUNGER, 2012).

5. **Hypothesis testing**

Procedure used to test hypotheses about the statistical values of parameters of a probability distribution (MONTGOMERY, 2004):

The structure of the hypothesis testing is formulated using the null hypothesis term (H0) and the alternative hypothesis (H1). The rejection of the null hypothesis indicates acceptance of the alternative hypothesis. In general, H0 is the question to be answered or the theory to be tested. H1 usually is the complement of the tested hypothesis and therefore it is not possible make a conclusion about
alternative hypothesis statement. Thus, the answers related to hypothesis testing are: to reject or fail to reject H0 (WALPOE; MYERS; MYERS; YE, 2012).

Decision procedures can lead to two wrong conclusions. Rejecting the null hypothesis when it is true is defined as a type I error. Failing to reject the null hypothesis when it is false is defined as a type II error. A usual procedure in hypothesis testing is to define the significance level (type I error probability) of $\alpha = 0.05$ (MONTGOMERY; RUNGER, 2012).

According to Montgomery (2004) an evaluation approach to hypothesis testing widely adopted in practice is the calculation of p-value. This is the lowest level of significance which would lead to rejection of the null hypothesis H0. Therefore, the determination of the result will be a comparison of the significance level ($\alpha$) and the p-value, following these conditions:

If p-value > $\alpha$, fail to reject H0
If p-value ≤ $\alpha$, reject H0

6. Paired t-test (dependent population)

Hypothesis testing is commonly used to perform comparison between means. A particular case of a test of two samples occurs when the observations are collected in pairs which are under homogeneous conditions (MONTGOMERY; RUNGER, 2012).

As an example, the weight of 15 subjects can be compared before and after a diet. To determine if the diet has been effective, the study compares the difference in the paired observations. The estimator of the population mean $\mu_D$ is the mean of the differences, usually denoted as $\bar{D}$ (WALPOE; MYERS; MYERS; YE, 2012). Hypothesis definition is similar to those ones stated when samples are independent. For paired-t test, hypotheses are:

6.1. Two-sided paired-t test

H0: $\mu_D = \mu_0$
H1: $\mu_D \neq \mu_0
6.2. One-sided paired-t test

\[ H_0: \mu D \geq \mu 0 \]
\[ H_0: \mu D \leq \mu 0 \]
\[ H_1: \mu D < \mu 0 \]
\[ H_1: \mu D > \mu 0 \]

7. Study Methodology

Commonly in research it is not possible to work with the entire population, rather it is necessary to select a sample (that is, a part of the population). The sample must be representative, so that it may be inferred for the rest of the population. Sampling cannot be probabilistic or probabilistic, the former being chosen without presenting any random selection and the latter based on the principle that all members of the population have the same probability of being chosen (MARCONI E LAKATOS, 2010).

The population basis for this study is the locomotive fleet of a cargo transportation railway company operating in southeastern Brazil. It was decided that the study would be carried out with two models of locomotives: AC and DC, both with 4400 HP of power and from the same manufacturer. The company had during the duration of this study a fleet of 195 locomotives AC and 84 locomotives DC. Statistical tests were used to evaluate the results of those which had measurements of specific consumption in the years 2010, 2011 and 2012. Some locomotives had 2010 and 2011 measures, for example, but in order to work with a fixed sample size it was decided that all locomotives for this study should have this measure in those three years. The specific consumption was chosen instead of fuel efficiency because it is a measurement without any other impact other than engine life cycle and its components.

Despite the existence of other locomotive models in the company's fleet, the study sample had an intentional stratification on selection. This was done because the automatic data measurement method reduces a possible variability that could be caused by different people measuring, even with the existence of a formal procedure.

The final sample size for this study was limited to 46 locomotives (25 AC and 21 DC) which were those with valid measurements in the three years of analysis (2010, 2011 and 2012).
8. Results

Due to sample characteristic and test objective a paired-t test was performed to evaluate if the specific consumption mean of the sampled locomotives is the same in different and consecutive years. This means that each measure of a specific locomotive is dependent. For all hypothesis tests performed the significance level defined was $\alpha = 0.05$. Normality test (Figure 2) and test for equal variances (Table 2) were also performed. For both assumptions tests p-value was greater than $\alpha = 0.05$, so mean comparison could be performed with no restrictions.

![Probability Plot of 2010](image)

<table>
<thead>
<tr>
<th>Locomotive</th>
<th>Year</th>
<th>Levene’s test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>2010</td>
<td>0.37</td>
<td>0.692</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The hypotheses to be tested were defined as follow:

H0: \( \mu(year - (year - 1)) \leq \mu_0 \)

H1: \( \mu(year - (year - 1)) > \mu_0 \)

Being \( \mu_0 = 0 \), it means that there was no statistically significant alteration between the specific consumption difference among two consecutive years. It was expected that there would be an increase between one year and another, so the test was set so that if the null hypothesis was rejected, this proposition would be true. The results for the tests are summarized in Table 3.

<table>
<thead>
<tr>
<th>Comparison (years)</th>
<th>Difference</th>
<th>t test</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 - 2010</td>
<td>5.57</td>
<td>4.81</td>
<td>&gt; 0.000</td>
</tr>
<tr>
<td>2012 - 2011</td>
<td>0.71</td>
<td>0.55</td>
<td>0.292</td>
</tr>
</tbody>
</table>

Table 3 – Summarized results for Paired t-test
The results obtained has showed that there was a statistically significant increase from 2010 to 2011 (p-value <0.05, rejecting the null hypothesis). However, from 2011 to 2012 the same behavior was not observed. With the non-rejection of the null hypothesis for the comparison of this period, it became necessary to determine whether there was an increase in the specific consumption or if it remained constant between the years. From this result, the following hypothesis was tested comparing 2011 and 2012:

H0: \( \mu(2012 - 2011) = \mu_0 \)

H1: \( \mu(2012 - 2011) \neq \mu_0 \)
<table>
<thead>
<tr>
<th>Comparison (years)</th>
<th>Difference</th>
<th>t test</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012 - 2011</td>
<td>0.71</td>
<td>0.55</td>
<td>0.584</td>
</tr>
</tbody>
</table>

Table 4 – Summarized results for Paired t-test (second test)

Paired T-Test and CI: 2012; 2011

Paired T for 2012 - 2011

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>46</td>
<td>158.34</td>
<td>8.89</td>
<td>1.31</td>
</tr>
<tr>
<td>2011</td>
<td>46</td>
<td>157.63</td>
<td>6.87</td>
<td>1.01</td>
</tr>
<tr>
<td>Difference</td>
<td>46</td>
<td>0.71</td>
<td>8.71</td>
<td>1.28</td>
</tr>
</tbody>
</table>

95% CI for mean difference: (-1.88; 3.30)
T-Test of mean difference = 0 (vs not = 0):

T-Value = 0.55  P-Value = 0.584

Figure 4 – Pared t-test comparing 2012 and 2011 – second test

As the p-value > 0.05 (Table 4), does not reject the null hypothesis, so the average differences between the years 2012 and 2011 are statistically equal for a 95% confidence level.

Comparing the specific consumption difference between years, it was possible to estimate a raise of 3.7% from 2010 to 2011 (as the hypothesis test indicated). From 2011 to 2012, despite a raise of 0.5%, this difference is not statistically significant.

<table>
<thead>
<tr>
<th>Comparison (years)</th>
<th>Average difference (specific consumption)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 - 2010</td>
<td>5.57</td>
<td>3.7</td>
</tr>
<tr>
<td>2012 - 2011</td>
<td>0.71</td>
<td>0.5</td>
</tr>
</tbody>
</table>
CONCLUSION

The two tests conducted have presented different results. Since these measurements are independent of other variables such as driving performance, train weight and others, the root cause should be related to the machine or maintenance performed on it.

The change in the result was investigated and the root cause was determined. There was a procedure change in 2012, Diesel engine components related directly to fuel consumption had been exchanged more frequently, meaning this part of the locomotive was being constantly renewed.

By the results assessed it is possible to conclude that if there are no ongoing maintenance interventions, the specific consumption value will increase. Thus, as a result, locomotive consumption and the Fuel Efficiency index of the company will also rise. Statistical tests indicated an average increase of 3.7%, which means an increase in operational costs in the order of tens of millions of dollars in the studied company.

REFERENCES


