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The influence of trains control system modernization on the energy consumption in the Sao Paulo subway

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ABSTRACT

The aim of this research is to study the potential association between the reduction in electricity consumption in Line 2 – Green of the São Paulo Subway and the change of the Train Control System from the "fixed block" type to the "moving block" type. Most of the previous studies published on energy efficiency at subways and trains are simulation studies and only a few based on empirical data. The statistical approach was chosen because there is no installed equipment to directly measure this influence, since the energy consumption is measured at the entrances of the System and there is no individual measurement of each train. The study of the relationships among the variables that potentially influence energy efficiency was performed by means of a multivariate regression. The results of the regression generated an equation model with significance for the variables: type of system, proportion of use of the fleets (particularly the proportion of more modern trains) and the number of trips made. In the regression process, the stepwise method was used and some variables were withdrawn when verifying that they had multicollinearity. The data extracted from the communication protocol were not used in the regression, but they did allow verifying an evidence of improvement in the speed profiles and also a reduction in the number of stops that the train made in the route, indicating a smaller interference between the train movements with the new system. The calculated savings obtained by the new system was around 2.8%, achieving 7.8% on average when the new fleet was included, which only uses the "moving block" system.

Introduction

This study was conducted at the Companhia do Metropolitano de São Paulo (São Paulo Metro), the company responsible for the subway and monorail system in the city of São Paulo.

The city of São Paulo has a population of twelve million people, an area of 1521 km^2. In this sense is one of the largest cities in the world. However, São Paulo's subway network is significantly smaller than other cities that are among the largest in the world, Mexico City, with 8,9 million people and 1485 km^2, for example, has a subway network with around 180 km (Vaz et al., 2014). The São Paulo subway network has a total of 75.1 km of railway (not including 2.3 monorail, which runs separately and not a subway system).

The São Paulo Metro was founded in 1968 and its works began soon afterwards. The first test journey took place in 1972 and commercial operation started in 1974 (Metrô São Paulo, 2016).

The São Paulo Metro currently has four operational lines (Line 1 – "blue line", Line 2 – "green line", Line 3 – "red line" and Line 5 – "purple line"), with a network of 66.2 km, 59 stations and 150 trains, and one monorail line (Line 15), with 2.3 km, two stations and four trains. The metropolitan rail system in the city of São Paulo also has a fifth line (Line 4 – "yellow line"), operated as a public-private partnership, with 8.9 km of tracks, 7 stations and 14 trains. The entire system transports approximately 4,700,000 passengers per day and operates daily from 4:40 h to 24:00 h (Metrô São Paulo, 2016).

In 2017, the new train control system, responsible for the movement of trains, on Line 2 became operational with changes on route management, control of trains and communication system. This new control system includes several changes in concept, being based on communication between the trains and centralized control. The main objectives were to reduce the time between trains and offer passengers more space. As the trains would be closer more trains are allowed to operate in the same region, providing more seats. The aim was to reduce the time between trains without affecting travel time, increasing the capacity to transport passengers. Other benefits like lower maintenance costs through the replacement of an obsolete system and greater control of trains, with improved communication and information exchanges with the control center, were expected.

Sao Paulo Metro operates currently with several train models, as it is shown in Fig. 1. After the system change, all trains running on Line 2 operate under CTBC control.

Following the implementation of the new system, a secondary effect was noticed: the total lower energy consumption on the line, without any changes to the systems responsible for powering the line or tracking the trains.

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Feature	Fleet "E"	Fleet "G"	Fleet "N"	
			Model I	Model J
Operation history	Started in 1999	Started in 2009	1972 - Original operation in 2011 - total retrofitting – control, engine, passenger comfort	1972 - Original operation in 2011 - total retrofitting – control, engine, passenger comfort
Producer	Alstom	Alstom	Alstom/Siemens	Bombardier
Number of available trains	11	16	25	26
Passenger termal comfort	Ventilation	Air conditioning	Air conditioning	Air conditioning
Traction system	DC Engine	AC Engine	AC Engine	AC Engine
Control System ATC	Yes, original from factory	Yes, original from factory	Some units, which do not run on Line.	Some units, which do not run on Line 2
Control System CBTC	Yes, later addition	Yes, later addition	Yes, original from complete retrofitting in 2011	Yes, original from complete retrofitting in 2011

Fig. 1. Types of trains available for operation at São Paulo Metro.
(Source: Prepared by the authors.)

The characteristics of the electrical system and the way energy consumption was measured meant that it was not possible to state that the decrease of electricity consumption had been caused by changing the system, or even if this could mean that energy efficiency had been improved. There was potential interference of other variables like the propulsion system, number of users, topography of the line, the occurrence of technical faults and unscheduled train stoppage.

The main purpose of this study is to analyze whether the control system of the São Paulo Metro influenced the energy efficiency on Line 2 by lowering energy consumption and determine the intensity of this variation in consumption.

Material and methods

In this study, several types of software were used:

- LibreOffice (The Document Foundation, 2016) to create spreadsheets, figures, graphs and in the text.
- Wireshark (Wireshark Foundation, 2016) to extract communication data.
- GIMP (The GIMP Team, 2016) to edit images,
- Zotero (CHNM, 2016) to organize references,
- R (R Core Team, 2015) for statistics,
- Python (Python software Foundation, 2016) as development language to extract data from the protocol.
- With the tools defined, data collection is described in the following section.

Data collection

The data were obtained from historical records in operational databases (electronic base) of the control system, from files with the capture of the communication protocol of trains and from records of electricity consumption from the power distribution company. Some data were obtained directly by the researchers, consulting electronic files available at the company and its information service, as shown in Fig. 2.

Data analysis procedures

Based on Spiegel and Stephens (2009), the basic steps for the statistical analysis of the data were defined, as shown in Fig. 3.

The following tools have been used:

a) Descriptive statistics: medians, standard deviations, proportions, normality test. In the normality tests, the null hypothesis (H0) is that the distributions adhere to normality, and as a significance level of 5% is desired, a *p*-value greater than 0.05 is expected in order not to reject the H0. For samples with more than 50 items, the Kolmogorov-Smirnov test with Lilliefors correction is suggested (Spiegel & Stephens, 2009). The tests were performed with the complete sample and only for working days, as at the time in question, there were no weekends, with the system operating in ATC mode.
b) Test of averages: to confirm the difference between energy consumption before and after the implementation of the new control system (Spiegel & Stephens, 2009).
c) Multivariate regression (Navidi, 2006; Hair, Black, Babin, Anderson, & Tatham, 2009; Devore, 2011), with consumption as the dependent variable and journeys made, number of passengers and the use of different fleets of trains as independent variables. The qualitative variables were included as dummies, such as the type of system, if there were occurrences of maintenance and whether it was a working day.
d) Verification of normality of errors to evaluate the adequacy of the regression (Navidi, 2006; Hair et al., 2009; Devore, 2011) and the inflation of variance to gauge whether the recommended level of 5.0 was not overtaken.

Data	Origin
Energy consumption	Direct measurement at primary substations
Fleets of circulating trains (types of train)	Operational Reports
Number of Passengers (**P**)	Operational Reports
Number of Journeys (**V**)	Operational Reports
Occurrences of Significant Failures (**FM**)	Maintenance Report
Day of the week (**D**)	Operational Reports
Control System in Operation (**S**)	Operational Reports
Consumption per Journey	Calculated dividing the energy consumption of the day by the number of journeys
Speed Profile	Communication Analysis

Fig. 2. Variables studied.
(Source: Prepared by the authors.)