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Abstract	The COVID-19 pandemic has impacted not only the health system but also several other sectors of society. Urban mobility patterns have changed due to social distancing and isolation, which have impacted public transport around the world. This paper aims to analyze the effect of the COVID-19 pandemic on the number of passengers transported by public transit buses in the city of São Paulo, Brazil. For this purpose, data were collected from official sources of the municipal government and, subsequently, a quadratic	

regression model was selected and adjusted, considering the number of passengers transported (y) as the dependent variable and confirmed deaths (x_1) and accumulated fully vaccinated population (x_2) as independent variables. The model confirms that COVID-19 has influenced public transport in São Paulo. As expected, the number of confirmed deaths has a negative effect while the advancement of vaccination has a positive effect on the demand for public transport. The results highlight the importance of vaccination and policies of social distancing and isolation to prevent deaths caused by COVID-19, which brought greater health security to the population. Therefore, these policies encourage a brief resumption of public transport services, reducing the risk of losses for stakeholders. We hope this study will contribute to a greater understanding of the effects of the COVID-19 pandemic on public transit buses in São Paulo, helping policymakers during possible future disasters like the COVID-19 pandemic.

Keywords (separated by '-') Public transport - Urban mobility - COVID-19

Implications of COVID-19 on the Use of Public Transport in São Paulo, Brazil

Cecília Aparecida Pereira, Marcela Xavier Tereza de Mello, Pedro Paulo Balestrassi, and Renato da Silva Lima

Abstract The COVID-19 pandemic has impacted not only the health system but also several other sectors of society. Urban mobility patterns have changed due to social distancing and isolation, which have impacted public transport around the world. This paper aims to analyze the effect of the COVID-19 pandemic on the number of passengers transported by public transit buses in the city of São Paulo, Brazil. For this purpose, data were collected from official sources of the municipal government and, subsequently, a quadratic regression model was selected and adjusted, considering the number of passengers transported (y) as the dependent variable and confirmed deaths (x_1) and accumulated fully vaccinated population (x_2) as independent variables. The model confirms that COVID-19 has influenced public transport in São Paulo. As expected, the number of confirmed deaths has a negative effect while the advancement of vaccination has a positive effect on the demand for public transport. The results highlight the importance of vaccination and policies of social distancing and isolation to prevent deaths caused by COVID-19, which brought greater health security to the population. Therefore, these policies encourage a brief resumption of public transport services, reducing the risk of losses for stakeholders. We hope this study will contribute to a greater understanding of the effects of the COVID-19 pandemic on public transit buses in São Paulo, helping policymakers during possible future disasters like the COVID-19 pandemic.

Keywords Public transport · Urban mobility · COVID-19

1 Introduction

The last few years have been marked by the COVID-19 pandemic, a highly transmissible respiratory disease caused by the SARS-CoV-2 virus, the new coronavirus. The disease was first identified in the city of Wuhan, China, in December

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2019, spreading rapidly across the world [1]. In Brazil, the first patient to test positive was diagnosed on February 26th, 2020 and, since then, the country has been considered one of the epicenters of the pandemic [2–4].

Initially, one of the main virus containment policies was social isolation and distancing, causing authorities to restrict people's access to public and private places [5]. However, despite their importance and effectiveness in reducing the spread of COVID-19, such measures have had a significant impact on people's behavior in cities. This created an unprecedented scenario, and the transport sector was one of the most affected [6].

Previous studies have evaluated the impact of COVID-19 on urban mobility around the world. This effort can be explained by the fact that, during a pandemic, time is an important variable for a better understanding and mitigation of events [7]. Since the risk of this type of disaster is increasing, these studies can contribute to a better and faster response to these possibilities [8]. Therefore, it is important to understand the behavior of the variables related to the resilience of urban mobility.

Specifically in Brazil, the urban public transport sector, which previously operated with economic stability and a low degree of uncertainty, faced a sharp drop in the number of passengers due to COVID-19. No benchmarking could provide its return to normality. São Paulo, for example, is the largest and most populous Brazilian city and presented a loss of 51.79% in the number of passengers transported by bus and subway between March and December 2020 when compared to the same period in 2019 [9]. This highlights the serious imbalance that the public transport sector faced during this period.

Most organizations in Brazil and several other countries, whether public or private, are not prepared to respond quickly and effectively to disturbances caused by external factors. Many of them take years to recover or do not survive after a disaster [10]. Thus, when these disturbances occur, the structural failures of organizations are exposed, which highlights the need to restructure their risk management approaches [8]. Passenger transport companies, mainly public ones, need to change both their operational and financial structure, aiming to overcome the reduction in the number of users of their services and provide a better use of their resources, while still providing good service.

Even with the advancement of vaccination, essential for containing the coronavirus, the impacts on the urban public transport sector remain in a challenging situation in Brazil, even with the accumulation of experience and perspectives. This can be explained by the persistence of habits that have grown during the pandemic until today, such as remote work and teaching, e-commerce, and the use of active transport, such as cycling or even walking. Therefore, these new habits also impact urban mobility, including the use of public transport, which has not reached the same number of passengers as before the pandemic yet.

Given the above, studies related to the impact of the COVID-19 pandemic on people's behavior and urban mobility play a key role in truly effective decision-making. Therefore, this paper aims to evaluate the effect of the COVID-19 pandemic on the number of passengers transported by public transport in the city of São Paulo, Brazil. The application in São Paulo was due to its significant national importance.

Public transit buses were used as a delimitation, considering that they are the most used mode of public transport in the city. In addition, they cover a larger number of regions, unlike trains and subways, which only operate in a few specific areas. In the meantime, this study contributes to decision-makers in this sector, assisting them with investments and/or restructuring of public transport, as well as in the elaboration of strategies for future perspectives.

2 Background

The COVID-19 pandemic caused several changes in the world, even affecting urban mobility. Since the beginning of preventive measures to contain the spread of the virus, there have been changes in travel patterns, transport demands, and preferences related to mobility [11]. Since then, several studies have analyzed the impacts of the COVID-19 pandemic on urban mobility around the world.

Fatmi [6] conducted a survey on the immediate change in the behavior of individuals as a result of the COVID-19 pandemic in their daily activities in Canada. The author concluded that outdoor activities decreased by approximately 50% during the pandemic. Cui et al. [12] used real-time data to measure the performance of traffic conditions before and during the COVID-19 pandemic to verify how urban mobility patterns changed in the Geater Seattle region, in the United States. They found that the demand for transportation declined during the COVID-19 pandemic, as well as a significant reduction in the overall average speed rate on major freeways.

The study by [13] analyzed the impact of the confinement measures imposed due to the COVID-19 pandemic on urban mobility in the city of Santander, Spain. The results showed that travel flows were reduced by 76% in this region during the COVID-19 pandemic when compared to previous periods. This reduction reached 93% for public transport. Grassi et al. [14] carried out a similar study in a medium-sized city in Argentina. They found a decrease not only in vehicular flow (~23%) but also in pollutant and greenhouse gas concentrations (~70%) when assessing data from before and during the pandemic. In addition, the study also identified changes in the population's mobility habits, with a decrease of about 66% and an increase of approximately 53% in the use of buses and bicycles, respectively, which is unusual in the city.

Orro et al. [15] investigated the mobility behavioral changes induced by COVID-19 by analyzing the travel patterns of Berlin residents over 20 months and comparing them to the pre-pandemic situation. Based on an analysis of nearly 800,000 recorded trips, the study revealed that public transport has continually declined, with trip frequencies and distances traveled decreasing by approximately 50% and 43% respectively. In contrast, cycling was the mode that increased the most, with an increase of approximately 53% in trip frequency and 117% in travel distance.

The study carried out in Spain by [16] analyzed the impact of COVID-19 on urban mobility through the number of passengers per bus line, the use of stops, and

the main origin-destination flows in the city. The authors identified a reduction in the supply of buses and the number of passengers. On the other hand, there was an improvement in the reliability of this service, due to reduced travel times. It is also interesting to highlight the findings of the study by [17] in India. The results revealed Indians' willingness to pay more for a transport service that is safer, faster, cleaner, more comfortable, and less exposed to contamination risks when compared to existing public transport.

In turn, the study by [11] sought to identify the impacts of the pandemic on the profile of travel behavior and mobility preferences in Brazil, using a case study of cities located in Rio Grande do Sul. The authors identified that the use of private vehicles grew as the main mode of transport during the pandemic. On the other hand, the use of public transport drastically reduced by approximately 73%. There was also greater adoption of active mobility measures, especially regarding cycling.

In general, changes in mobility affected demands for public transport mainly due to the reduction in the number of passengers during the period in which social isolation and distancing measures were imposed [11, 12, 15, 18, 19]. However, with the availability of vaccines (even if unevenly distributed worldwide), the pandemic appears to be more manageable, and economies appear to be recovering nowadays [15].

However, the transport sector has not recovered the same number of users as before the pandemic. Even after the return of activities, this sector still faces uncertainties about the long-term effects of the pandemic on the choice of mode of transport and on individual travel behavior [15]. In this context, [12] predicted that urban mobility will hardly return to pre-pandemic standards, mainly due to the expansion of remote work and teaching, e-commerce, and active and sustainable mobility, which has gained more encouragement around the world.

3 Methodology

The methodology follows an adaptation of a framework for modeling time series proposed by [20], as shown in Fig. 1. The first step of the methodology consists of the problem and objective definition [21, 22]. For this study, we aim to evaluate the effect of the COVID-19 pandemic on the number of passengers transported by the public transport service of the city of São Paulo, as detailed in Sect. 1.

Data were collected based on official sources from the municipal government of São Paulo. In this way, the monthly number of passengers transported by public

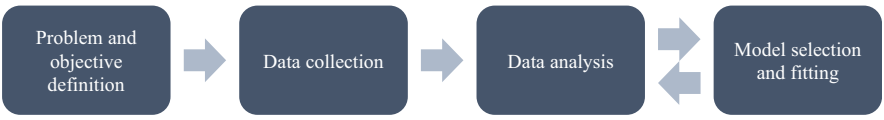

Fig. 1 Steps for the modeling process of time series

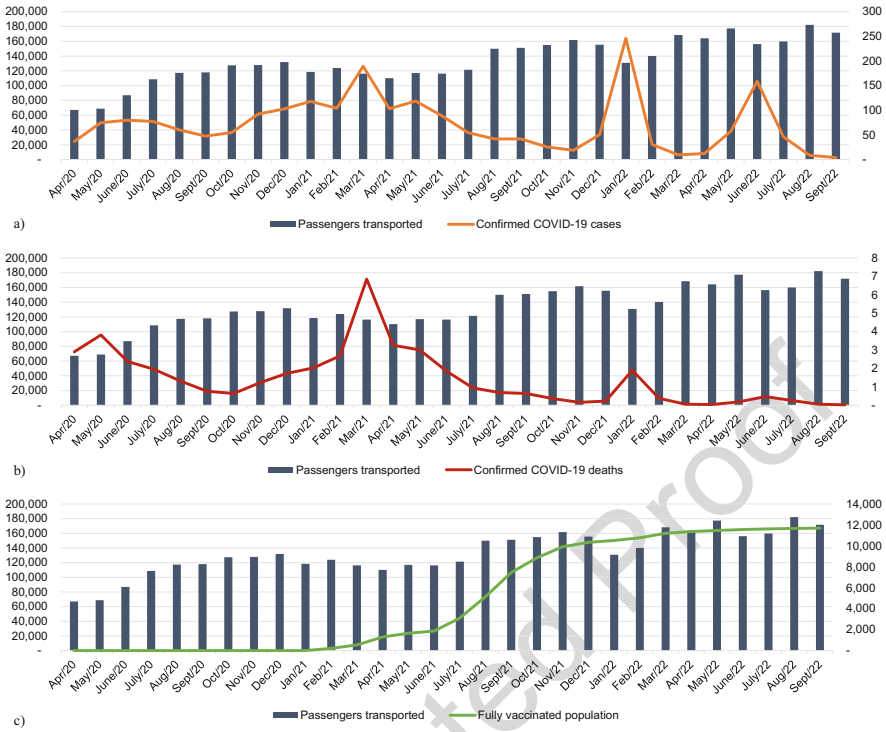

Fig. 2 Number, in thousands, of passengers transported and (**a**) confirmed cases of COVID-19, (**b**) confirmed deaths from COVID-19, and (**c**) accumulated fully vaccinated population. (Source: Prefeitura Municipal de São Paulo [9, 23])

transit buses between April 2020 and September 2022 was obtained [9]. In addition, the monthly number of cases and deaths caused by the coronavirus was collected, as well as the accumulated monthly number of fully vaccinated population (first and second dose) [23]. Figure 2 presents the data that compose the time series of this study.

The third step of the methodology consists of data analysis. Given the context of the pandemic and although the first case of COVID-19 was confirmed in February 2020 in São Paulo, data were collected from April 2020 onwards due to the more severe adoption of social isolation and distancing measures, such as the suspension of face-to-face teaching, work, and commerce activities, among others [5]. The intensity of these measures was influenced by the number of cases, deaths, and subsequent vaccination against COVID-19, influencing the use of public transport by the population. Therefore, these were the independent variables considered in this study.

Finally, a mathematical model was selected and adjusted for the time series. For this purpose, a regression analysis was performed, one of the most widely used statistical tools to establish useful relationships between variables. This relationship

is expressed as an equation or model that connects the response variable (dependent) to the predictor variables (independent or explanatory) [20]. The regression analysis results can be found in the next section, as well as the analysis of the data obtained from these results, according to the proposed methodology.

4 Results

The results were analyzed using the Minitab® and RStudio®. First, we measured the degree of relationship between the dependent variable (number of passengers transported) and the independent variables (cases, deaths, and full vaccination) using a correlation matrix, as shown in Table 1.

On the one hand, both death and vaccination variables show a strong statistically significant correlation with the number of passengers transported ($r > |0.700|$; p-value < 0.050). On the other hand, the confirmed cases variable does not have a statistically significant correlation with the dependent variable (p-value > 0.050). This maybe implies that the number of confirmed COVID-19 cases does not provide any information about the number of passengers transported by buses in São Paulo. In addition, Table 1 shows a possible absence of multicollinearity ($r < |0.700|$ or p-value > 0.050), that is, there is no strong statistically significant correlation between the independent variables, which is good for the model interpretation.

From this, we developed regression models according to the aim of this paper. Through the significance values of the coefficients (β) of the terms, it was possible to discard, in fact, the confirmed cases variable from the model, as expected due to the correlation analysis performed. Thus, Table 2 presents the regression model that best fits our study. The model is quadratic and composed of the variables of passengers transported (y) as a dependent variable and confirmed deaths (x_1) and full vaccination (x_2) as independent variables.

In addition to the significance of the coefficients, as already mentioned, the regression model was also selected based on the R^2 and adjusted R^2 values. Selecting a model that maximizes these values is equivalent to selecting a model that minimizes the residual sum of squares, i.e., a model that has a good fit with the time series [20]. Therefore, the model presented in Table 2 explains 80.1% of the variation in the number of passengers transported by public transit buses in São Paulo.

Table 1 Correlation matrix and their respective p-values

	Passengers transported	Confirmed cases	Confirmed deaths
Confirmed cases	−0.342		
	0.064		
Confirmed deaths	−0.707	0.615	
	0.000	0.000	
Full vaccination	0.832	−0.286	−0.646
	0.000	0.126	0.000

Table 2 Summary of the regression model selected

Terms	β	β standardized	T-value	P-value
Constant	146,115.000	9.200,000	15.880	0.000
x_1	−24,877.000	6.010,000	−4.140	0.000
x_2	2.065	0,788	2.620	0.014
x_1^2	2895.000	848,000	3.410	0.002
			R^2	0.822
			Adjusted R^2	0.801

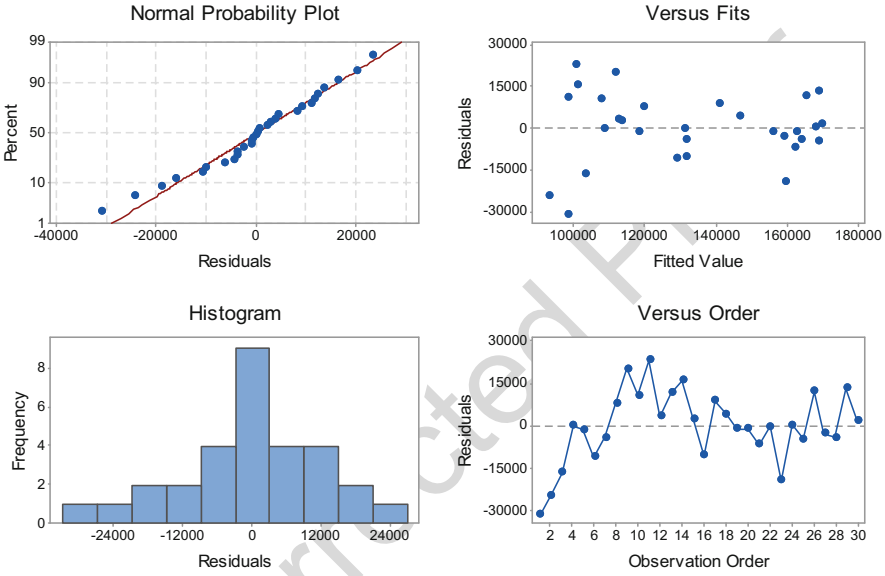

Fig. 3 Residuals plots for passengers transported

In addition to model selection, a residual analysis is performed to compare actual and fitted values. Figure 3 presents the residual graphs for the number of passengers transported. The first assumption of a reliable model was homoscedasticity, i.e., ensuring that the error variance is constant over time. For this, the residual plots were analyzed, identifying randomly arranged points, a result that meets this assumption.

Finally, another assumption evaluated was the normality of residuals, which also reaffirms the homogeneity of the error variance. The Ryan-Joiner test, similar to the Shapiro-Wilk test, was performed for the residual data. This test was chosen due to its indicated application for small samples. Thus, the normality test presented a p-value greater than 0.100, accepting the null hypothesis (H_0) and concluding that the residuals are normally distributed.

With the assumptions properly tested, we concluded that the selected model is reliable and proves that the conditions of the COVID-19 pandemic influence the number of users of public transport in São Paulo. Therefore, Eq. (1) mathematically

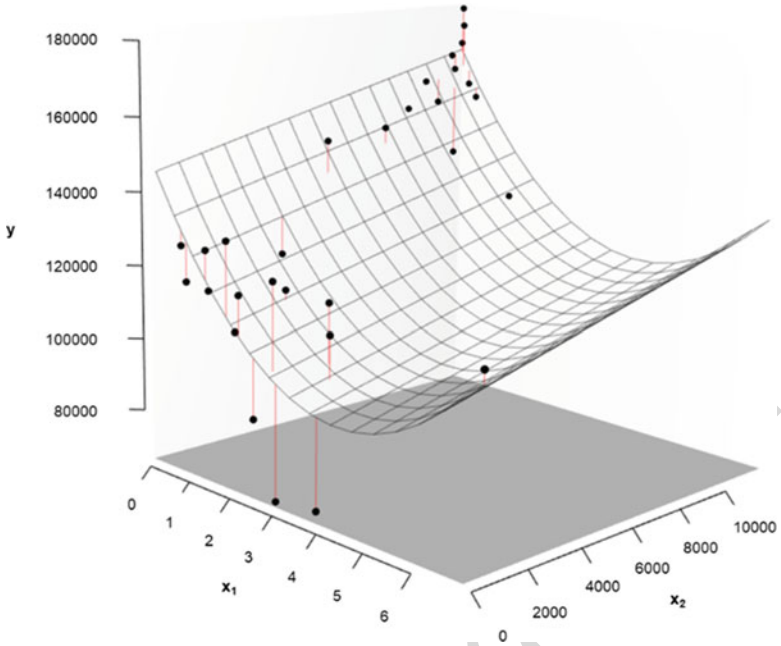

Fig. 4 Actual data scatter plot with the model surface

represents this statement, in thousands, according to the selected model. Graphically, Fig. 4 presents Eq. (1), represented by the grid, compared with the actual number of passengers transported, represented by the black balls. The red lines represent the difference between the actual value and the model-fitted value.

$$y = 146{,}115 - 24{,}877x_1 + 2.065x_2 + 2{,}895x_1^2 + \varepsilon \tag{1}$$

5 Discussion

Figure 5 shows the effects of the COVID-19 pandemic on the number of passengers transported by public transit buses in São Paulo before and during the pandemic, as well as the fit model selected in this study. Despite the gradual increase during the pandemic, the demand for public transport has not returned to previous numbers yet.

This behavior can be explained by several factors resulting from COVID-19. First, we mention the social distancing and isolation measures that, consequently, led to a reduction in the number of people attending public and private places. This had a direct impact on urban mobility, as the population was prevented from generating trips to carry out their basic and leisure activities during periods of strict restrictions.

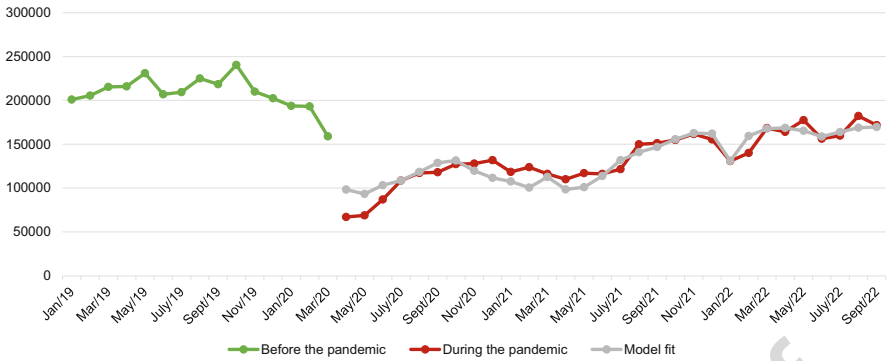

Fig. 5 Number of passengers transported, in thousands, before and during the COVID-19 pandemic

However, it is important to emphasize that, in many cases, some of these measures became routine and were extended until today, such as remote work. This may be one of the reasons that explain the lower numbers of passengers currently transported when compared to those reported in periods before the pandemic.

Another factor that impacted the population's behavior regarding the use of public transport is related to their constant concern to preserve their own safety and health during the pandemic, as well as that of people close to them. This can be explained by the high mortality rate of the new coronavirus, which was confirmed by the negative effect that the number of deaths has on the model selected in this study. In this sense, part of the population opted to stay in their houses during these periods and, when necessary, use individual vehicles for transportation. Consequently, this reduced the demand for public transport, as shown in Fig. 4.

Finally, Fig. 4 and the regression model of this study show us the positive effect of the vaccination rate on the number of passengers transported by public transit buses in São Paulo. This reflects the importance of the vaccine not only for containing the virus but also for the normality of economic and leisure activities of the population.

6 Conclusion

This paper aimed to analyze the effect of the COVID-19 pandemic on the number of passengers transported by public transit buses in the city of São Paulo, Brazil. For this purpose, a quadratic regression model was selected and adjusted, considering the number of passengers transported (y) as a dependent variable and confirmed deaths (x_1) and accumulated population fully vaccinated (x_2) as independent variables. The selected model presented high R^2 values and distributionally normalized residuals, which is reliable for the purpose of this study.

The finding results confirm that COVID-19 influences public transportation in São Paulo. As expected, the number of confirmed deaths has a negative effect on the demand for public transport. However, this demand has increased with the arrival and advancement of vaccination in the country, consequently contributing to economic and leisure activities. Therefore, these conclusions highlight the importance of social distancing and isolation measures in order to prevent deaths caused by COVID-19, in addition to the importance of vaccination, which brought greater health security to the population. Consequently, these policies encourage a brief resumption of public transport service during a pandemic.

This study has limitations that can be explored in future work. As previously discussed, the study was limited to the city of São Paulo and its generalization to another region must be accompanied by new data collection. Furthermore, as the pandemic occurred recently, it was not possible to collect a large amount of data, which could further improve the model fit. Therefore, a suggestion would be to update this data over time and monitor the model's adjustment, always updating it whenever necessary.

Despite these limitations, this paper contributes to a greater understanding of the effect that the COVID-19 pandemic has had on public transport in São Paulo. In addition, this study also benefits a better use of public transport, since, as it is a service, its underuse can bring losses to stakeholders. Therefore, we expect that the findings results can benefit decision and policymakers during possible future disasters like the COVID-19 pandemic.

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