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The Impact of the COVID-19 Pandemic on the Public Transportation System of Montevideo, Uruguay: A Urban Data Analysis Approach †

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Abstract: Urban mobility and strategies for public transportation play a vital role in promoting a more sustainable, accessible, and livable urban environment in smart cities. Data-driven decision making, multi-modal integration, and innovative means are key elements in developing effective public transportation. The COVID-19 pandemic had a significant impact on public transportation worldwide, including decreased travel, health and security concerns, and a shift in travel patterns. In particular, the use of public transportation reduced by up to 90% in developed countries. This article studies the mobility demands and patterns related to public transportation in Montevideo, Uruguay, amidst the COVID-19 pandemic. The study follows an urban data analysis approach, using open data from various sources, including citizen mobility, the public transportation system, COVID-19 case records, and economic indicators. The urban data methodology allows the deriving of significant findings, encompassing the assessment of trip reductions in Montevideo in March 2020 (71.4%, lower than similar cities in the world), the correlation between trip numbers and COVID-19 cases during the different pandemic waves, the recovery of public transportation usage, and the correlation with socio-economic indicators. These results offer valuable insights for quantifying and comprehending the behavior of citizens concerning public transportation throughout the COVID-19 pandemic, providing valuable understandings for policymakers and researchers to elaborate mobility strategies and policies.

Keywords: public transportation; COVID-19 pandemic; urban data analysis; mobility patterns; socio-economic analysis

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1. Introduction

Urban transportation, i.e., the act of moving something (goods) or someone (people), and urban mobility, i.e., the ability of a person to freely move or be moved, constitute integral elements of the functional dimension of cities nowadays. Alongside other significant factors such as land use and urban planning, urban mobility plays a crucial role in shaping how citizens carry out their daily activities [1].

The advent of data-driven approaches fostered an enhanced paradigm referred to as Intelligent Transportation Systems (ITS). Data-driven approaches refer to methodologies and techniques that rely on the analysis and utilization of large volumes of data to derive insights, make informed decisions, and develop solutions for intelligent mobility. ITS leverage the power of data to uncover patterns, trends, and correlations, enabling administrators, organizations, and individuals to gain valuable insights and improve their decision-making processes. ITS encompasses advanced systems that integrate synergistic technologies to offer services to traffic operators and citizens. The primary objective of ITS is to develop coordinated and integrated mobility solutions that are smarter, safer, more efficient, and provide an enhanced user experience [2].

Urban mobility data play a crucial role in understanding mobility patterns, identifying anomalies and unusual movement behaviors, and conducting simulations of various realistic scenarios to assess the efficiency and quality of different means of transportation. The availability of real and synthesized mobility data has facilitated relevant studies in different domains: to enhance public transportation network designs, develop sustainable mobility initiatives, analyze and enhance the quality of service and user experience, identify stress conditions, predict traffic congestion, analyze public and private vehicle speeds, detect specific incidents, and assist in traffic engineering and traffic operation tasks [3–5]. By leveraging urban mobility data, researchers and practitioners can gain insights into the dynamics of transportation systems, optimize infrastructure and services, and improve the overall efficiency and effectiveness of urban mobility. The combination of real and synthesized mobility data offers a valuable resource for conducting comprehensive analyses and simulations, leading to more informed decision-making and better urban transportation management.

The COVID-19 pandemic had a profound impact on mobility worldwide, with significant disruptions observed across all modes of transportation. However, the impact was particularly prominent on public transportation systems. Among the most important consequences, the pandemic led to decreased ridership, significant operational changes, financial challenges, and an overall shift in travel patterns. All these issues hindered the primary objective of collective transportation (to provide accessible mobility to the public), since the efficiency of public transportation systems relies on the ability to transport large numbers of people and achieve economies of scale. The negative effects of the COVID-19 pandemic prompted a reevaluation of safety measures and future planning to ensure the continued provision of reliable and safe public transportation services.

Despite the implementation of various sanitary measures by governments and local administrations, the COVID-19 pandemic led to a substantial reduction in the number of trips taken on public transportation. This decline can be attributed primarily to the perception among citizens of a high risk of contagion when sharing a mode of transportation with others [6]. The decline in the number of trips on public transportation was significant, with reductions exceeding 90%, particularly in countries that implemented comprehensive lockdowns as a countermeasure. Despite the decrease in contagion levels in several countries, the recovery of public transportation ridership was not complete, i.e., a considerable number of passengers have opted for other means of transportation [7–9].

The analysis of urban mobility data plays a vital role in assisting public administrations and policymakers in enhancing public transportation systems [10]. Particularly during the COVID-19 pandemic, data analysis became even more critical as a tool for studying and understanding mobility patterns. Through a comprehensive analysis using relevant indicators, authorities were able to identify individuals who were compelled to travel despite sanitary measures, gain insights into their behavior, and appropriately size the public transport system to cater to their needs in such unique circumstances.

Following this line of research, this article contributes to the existing body of research by conducting a study that examines the demand and characterizes the mobility patterns of passengers of the public transportation system in Montevideo, Uruguay, during the COVID-19 pandemic. The study employs an urban data analysis approach to process and analyze openly available data pertaining to trips taken in the public transportation system of Montevideo. Furthermore, the study establishes correlations between the number of trips and COVID-19 statistics in the country. In addition to these datasets, other sources of data, such as geographical resources, socioeconomic information, and accessibility data, are also used to analyze several dimensions of the use of the public transportation system.

This article extends the previous conference article "Analysis of public transportation in Montevideo, Uruguay during the COVID-19 pandemic", presented in the V Ibero-American Conference on Smart Cities, Cuenca, Ecuador, 2022 [11]. The new content in this article includes: (i) an extended description of the methodology and the case study, including the description of the processing approach and its implementation; (ii) an evaluation of the performance of the developed computational tool; (iii) an expanded analysis of the mobility patterns for the case study during the COVID-19 pandemic, including the analysis of correlations in five different periods; and (iv) new studies to determine the correlation of mobility patterns with socio-economic information and accessibility characterization for neighborhoods of Montevideo.

The article is structured in the following manner. Section 2 introduces the problem of characterizing the public transportation usage during the COVID-19 pandemic and reviews related works. Section 3 describes the case study, the public transportation system in Montevideo, Uruguay, and the methodology and computational tools developed for the data analysis. The analysis of results obtained applying the proposed methodology is reported in Section 4. Section 5 presents the conclusions and formulates the main lines for future work.

2. Characterization of Public Transportation Usage during the COVID-19 Pandemic

This section focuses on describing the problem at hand and reviewing pertinent related works.

2.1. Description of the Problem

The addressed problem involves performing a characterization of the utilization of public transportation during the COVID-19 pandemic, specifically in a case study in Montevideo, Uruguay. The primary objective is to conduct a quantitative assessment of the reductions in public transportation usage following the declaration of the national sanitary emergency on 14 March 2020. Additionally, the study aims to characterize the mobility patterns of citizens using public transportation during different stages and waves of the pandemic, and understand how citizens resumed using public transportation as the sanitary conditions continually improved. Other relevant points of view are considered to characterize mobility patterns, taking into account different demographic groups, socio-economic information, and accessibility characterization for neighborhoods of Montevideo. The problem under investigation holds significant relevance, primarily due to two distinctive aspects of the case study conducted in Montevideo, Uruguay. These aspects are further elaborated upon in the subsequent paragraphs.

The first distinctive aspect is that in Montevideo, there exists a natural inclination among citizens to transition towards public transportation and other sustainable modes of transportation [12,13]. However, during the COVID-19 pandemic, this inclination experienced a significant reversal as citizens chose to rely on automobiles and other private transportation means for their commuting needs. This shift was driven by concerns regarding the perceived or suspected risk of contracting the virus through shared transportation, given the difficulty of maintaining the recommended social distance. Such a shift imply adverse implications for both sustainability and accessibility [7], leading to setbacks in sustainable mobility and exacerbating issues of equity and social exclusion. This phenomenon is not unprecedented, as safety considerations have long played a crucial role in shaping and influencing the mobility behavior of individuals [14].

The second interesting aspect of the problem and the addressed case study is that the approach taken by the Uruguayan government in managing the COVID-19 pandemic diverged from that of other countries. Instead of implementing strict lockdown measures, Uruguay adopted a model known as ‘responsible freedom’ or ‘libertad responsable’ in Spanish. Under this model, voluntary quarantine was encouraged, but people were not mandated to stay at home and mobility was not limited. The government implemented a meticulous tracking system for infected individuals, along with random COVID-19 testing. Measures such as promoting the use of face masks, public awareness campaigns emphasizing social distancing and social responsibility, and a reasonable reduction in social activities were also implemented. This model proved successful in maintaining control over infections, with several days during the initial months of the pandemic registering zero active cases [15]. The first wave of COVID-19 was thus delayed until mid-2021 when the influence of tourism and the resumption of social activities contributed to the spread of the virus. The situation returned to a state of normalcy in August 2021, only to be disrupted by the onset of the second wave fueled by the Omicron strain in the summer of 2022. However, the vaccination campaign progressed rapidly, with more than 50,000 shots administered per day, and the country ranked among the highest globally in terms of the percentage of vaccinated population [16]. By March 2022, the situation had once again stabilized, leading to the official declaration of the end of the sanitary emergency on 5 April 2022.

An approach applying data analysis to characterize the use of public transportation during the COVID-19 pandemic is valuable to provide relevant insights that can aid public administrations and transportation companies in future planning for incidents in public transportation. Some of the most relevant issues that can contribute to such planning include: (i) demand forecasting, considering the detected patterns and trends, to help optimizing resource allocation, scheduling, and capacity planning to align the service provision with the expected demand and avoid overcrowding or underutilization; (ii) route optimization, considering those most needed origins and destinations for trips, even in hard circumstances such as the pandemic, allowing companies to evaluate existing routes and focus on those that provide a solution to social needs for citizens that cannot afford private transportation; (iii) safety protocols and special allocation of resources for safety measures, by properly analyzing the impact of specific actions and regulations, providing helpful information to improve and refine safety protocols for future incidents or crises; and (iv) communication strategies and public awareness, considering relevant information about passengers behavior, preferences, and concerns during the pandemic, allowing to develop targeted strategies and public awareness campaigns to communicate important information, such as safety guidelines, service updates, and alternative transportation options during incidents or emergencies.

Overall, data analysis provides evidence-based insights that enable informed decision-making and future planning for incidents in public transportation. It helps authorities adapt and optimize services, enhance safety measures, communicate effectively with passengers, and ensure the resilience and sustainability of transportation systems in the face of future challenges.

2.2. Related Work

Several research articles have studied the demand for public transportation during the COVID-19 pandemic across different regions, including Europe, North America, and Asia. All these studies consistently found a significant decrease in the number of trips. However, the behavior of citizens varied depending on factors such as the presence or absence of lockdown measures and cultural influences [17]. For instance, studies reported a 59% reduction in Australian cities [18], a 60% decrease in Stockholm, Sweden [19], and a substantial 80% reduction (peaking at 90%) in Budapest, Hungary [20].

Wielechowski et al. [21] conducted a study in Poland, which confirmed significant variations in the reduction in public transportation usage based on the level of confinement and other policies implemented. Specifically, reductions ranging from 50% to 85% were observed in Warsaw when considering data from subway passengers. These findings were further supported by an online survey questionnaire, which indicated an average reduction of approximately 70% in public transportation usage [22]. In Gdansk, however, the use of public transportation experienced a more substantial decline, reaching up to 90%. Nevertheless, it is noteworthy that 75% of the individuals interviewed expressed their intention to resume using public transportation once the sanitary situation improved [9].

In the Netherlands, a study analyzing data from 2500 Dutch citizens from the Netherlands Mobility Panel revealed reductions in public transportation usage of up to 90% during the COVID-19 pandemic [7]. Among the various modes of transportation, public transportation experienced the largest decrease, surpassing the decline observed in other means of mobility, including private vehicles (both sustainable and non-sustainable options).

In North American countries, comparable reductions in public transportation usage were observed. In the United States, Lui et al. [8] conducted a study examining the impact of the pandemic on public transportation demand across more than 100 cities. They utilized data from a widely used navigation app and conducted statistical analyses, which revealed that communities with higher proportions of essential workers and vulnerable populations exhibited higher levels of demand for public transportation during the COVID-19 pandemic. The most substantial declines in public transportation usage were observed in the US Midwest region. A preliminary analysis indicated a similar trend for public transportation systems in Toronto and Vancouver, Canada. Palm et al. [23] conducted a survey involving 2753 citizens, reporting that 63% of respondents ceased using public transportation during the initial stage of the pandemic. However, when the study was replicated in March 2021 during the second wave of the pandemic, it was found that 70% of citizens who had previously stopped using public transportation had resumed its usage.

In Latin European countries, where there is a certain degree of similarity in citizen behavior compared to Latin American cities, researchers have examined different factors. Carteni et al. [24] conducted a study in Italy during the second wave of COVID-19, prior to widespread vaccination, to analyze the relationship between the spread of the virus and public transportation usage. The study found a high correlation, reaching up to 0.87, between the daily number of confirmed COVID-19 cases and the number of trips taken on public transportation 22 days prior. The authors concluded that the typical two-week quarantine measures, primarily focused on the incubation period, were insufficient as a comprehensive containment strategy. These measures may have led to a potential delay in identifying new cases and subsequently hindered the timely implementation of effective mitigation policies.

A study conducted by Rodríguez et al. [25] in Spain focused on examining the impact of the COVID-19 pandemic on both public and private mobility in Fuenlabrada, a mid-sized city near Madrid. The researchers utilized data from the public transportation smart card system and a Bluetooth traffic monitoring network, covering the period from February to September 2020. The findings revealed a significant reduction in both public and private mobility during the peak of the pandemic, with public mobility decreasing by 95% and private mobility by 86%. Similarly, Aloi et al. [26] conducted a study in the city of Santander, Spain, utilizing data from traffic counters, public transportation ITS, traffic control cameras, and environmental sensors. They observed comparable results, indicating a substantial decline in mobility during the pandemic. To gain initial insights into the extent of the decline in daily mobility and understand any changes in modal distribution and journey purposes, the authors recommended re-estimating the Origin–Destination trip matrices to align with the prevailing conditions during the COVID-19 pandemic. The re-estimation process facilitated an assessment of the reduction in daily mobility and provided valuable insights into shifts in transportation modes and travel purposes. These efforts served as a diagnostic tool to understand the evolving patterns of mobility during the pandemic. Aloi et al. also examined the effects of the pandemic on NO_2 emissions and traffic accidents. They found that the average overall mobility decreased by 76%, with public transportation demand experiencing a reduction of up to 93%. Additionally, there was a significant decrease in NO_2 emissions and traffic accidents, reaching reductions of approximately 60% to 67%.

Awad et al. [27] focused on investigating the behavior of users with regard to public transportation and shared mobility in Spain during the COVID-19 pandemic. A nationwide survey was implemented to gather information about preferences, frequency of trips according to the trip purpose, and willingness for changes, all regarding the COVID-19 pandemic. The main findings indicated a significant decrease in the use of public transportation; however, citizens expressed their willingness to continue using it provided that adequate sanitation measures were in place and without any increase in ticket prices compared to the pre-COVID-19 period.

The impact of the COVID-19 pandemic on public transportation systems in Latin America received relatively less attention in academic literature compared to other regions.

Andara et al. [28] conducted research examining the impact of the COVID-19 pandemic on mobility in eight large Latin American cities: Bogotá (Colombia), Buenos Aires (Argentina), Mexico City (Mexico), Santiago (Chile), Lima (Perú), and Brasilia, São Paulo, and Rio de Janeiro (Brazil). The study utilized mobility data from both public institutions (such as the IDB Invest Dashboard for mobility and traffic congestion) and private organizations (specifically the Moovit platform for public transportation usage), along with COVID-19 contagion data from Johns Hopkins Hospital University. The research developed models based on descriptive statistics to analyze the variations in motorized mobility during the period from March to September 2020. Regression models were employed to study traffic congestion and urban transportation. The main findings indicated that trips using private mobility means recovered at a faster rate compared to public transportation. This fact was attributed to the implementation of specific measures by municipal administrations for public services, as well as the concerns of citizens regarding the risk of infection associated with using public transportation. Additionally, the authors concluded that public transportation did not play a significant role in the spread of the pandemic in the cities under investigation.

Gramsch et al. [29] recently published a comprehensive analysis investigating the impact of a dynamic lockdown strategy on public transportation, specifically buses and metro, in Santiago, Chile. By utilizing a database of smartcard data capturing trips in 2019 and 2020, the authors conducted a comparative analysis to examine various indicators across different administrative divisions (municipalities) of the city. The key findings of the study revealed a significant 72% reduction in public transportation demand during periods of strict lockdown measures, while a 12% reduction was observed when the dynamic lockdown strategy was implemented. The research also highlighted the short-term effectiveness of lockdowns in reducing mobility. Furthermore, through a socio-demographic analysis, the study identified that lockdown measures had a greater impact on public transportation demand in municipalities with a higher proportion of elderly residents and households with higher incomes.

Other articles have focused on global mobility analysis. Puello [30] studied the transportation mode choice during the COVID-19 pandemic, from data surveyed in Santo Domingo, Dominican Republic. Results showed that the limited capacity, reduced safety, and no capacity of guaranteeing social distancing reduced public transportation usage and promoted a strong habit of commuting in private vehicles. Public transportation trips reduced between 40% and 50%. Mode captivity was also studied for public transportation users that had no access to alternative transportation means.

No studies have been published about the use of public transportation during the COVID-19 pandemic in Uruguay. This article contributes to this line of work by applying a data analysis approach to characterize mobility in the public transportation system of Montevideo during the COVID-19 pandemic.

A summary of related works is presented in Table 1. To date, there have been no published studies exploring the utilization of public transportation during the COVID-19 pandemic in Uruguay. However, this article aims to fill this research gap by employing a data analysis methodology to provide insights into the mobility patterns within the public transportation system of Montevideo during the pandemic. Through this study, valuable contributions can be made to enhance our understanding of how public transportation was affected and adapted during the challenging circumstances of the COVID-19 pandemic in Uruguay.

Table 1. Related works about mobility and public transportation reductions due to the COVID-19 pandemic.

Author	Year	Case Study	Contributions
De Vos [17]	2020	The Netherlands	effects of lockdown on mobility patterns
Beck, Hensher [18]	2020	Australian cities	59% reduction
Jenelius, Cebecauer [19]	2020	Stockholm, Sweden	60% reduction
Bucskyr [20]	2020	Budapest, Hungary	60% reduction
Wielechowski et al. [21]	2020	Poland	reductions of 50–85%
Kłos, Gutowski [22]	2022	Warsaw, Poland	reductions up to 90%
Palm et al. [23]	2021	Canada	63% reduction
de Haas [7]	2020	The Netherlands	reductions up to 90%
Liu et al. [8]	2020	USA	essential workers and vulnerable populations continued using public transportation
Carteni et al. [24]	2021	Italy	high correlation between reductions and COVID-19 cases
Rodríguez et al. [25]	2021	Spain	reduction up to 95%
Aloi et al. [26]	2020	Santander, Spain	reduction of 76%
Awad et al. [27]	2021	Spain	significant decrease but willingness to resume if adequate sanitation measures
Andara [28]	2021	Latin American cities	low recovering of public transportation
Gramsch et al. [29]	2022	Santiago, Chile	72% reduction
Puello [30]	2022	Dominican Republic	50% reduction

3. Description of the Case Study and Methodology for Analyzing Mobility and COVID-19 Data

This section describes the addressed case study and the methodology employed to analyze the public transportation system in Montevideo during the COVID-19 pandemic.

3.1. Description of the Addressed Case Study: Public Transportation in Montevideo, Uruguay

The public transportation system in Montevideo, Uruguay, serves as the most important means of commuting for residents and visitors alike. It comprises several modes of transportation, but the most used are buses (taxis and shared transportation are much less used). The Metropolitan Transportation System (STM) initiative is aimed at integrating and unify all public transportation services in Montevideo and its surrounding areas. The STM encompasses an extensive bus network, consisting of 145 primary bus lines that cover a wide range of routes throughout the urban area, over a thousand line variants, and an impressive number of around five thousand bus stops. These numbers are notably substantial for a city of the scale of Montevideo. The network of bus lines within the public transportation system in Montevideo is illustrated in Figure 1.

Buses in Montevideo generally operate on fixed schedules, with specific departure and arrival times for each route. During peak hours, buses tend to run more frequently to accommodate the higher demand. The schedules are accessible to the public and can be obtained from official sources or through online platforms.

As part of a series of efforts to enhance the efficiency, rationality, and safety in public transportation, the STM implemented a significant technological advancement in the last decade: the introduction of contactless electronic smart cards (STM cards) for ticket payment, eliminating the need for physical currency [31]. Commuters can purchase and recharge their STM cards, which are associated with the user identity. The data collected from STM cards play a crucial role in analyzing the performance of the system, understanding citizens' mobility patterns, and identifying specific problems that may impact the quality of service provided to the public. Essential information extracted from data collected by STM includes boarding stop, travel demand, bus line details, date and time of travel, ticket type, and user category, among others. These valuable data enable the computation of performance indicators, the identification of mobility patterns, and the categorization of mobility demands. Other new technologies, such as real-time bus tracking and digital information displays at bus stops, have been implemented to enhance the overall user experience and efficiency of the system.

Our research group has undertaken previous research endeavors [10,12,31–35] that involved the analysis of trip records within the Montevideo public transportation system. These studies also involved the integration of data from other sources, such as geospatial data and line information, to enhance the depth of analysis.

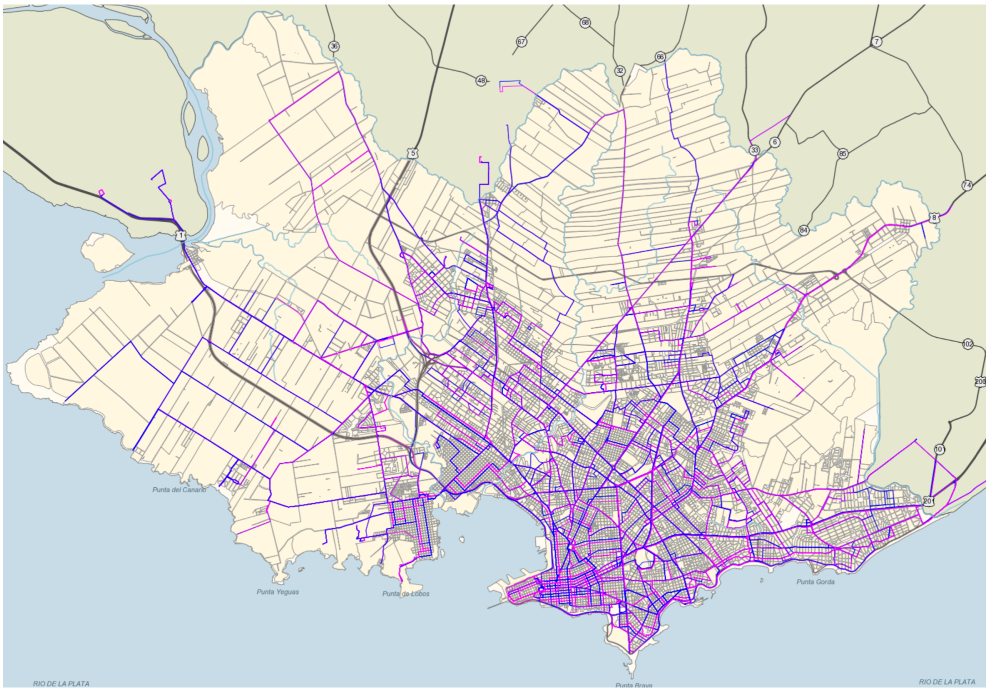


Figure 1. Network of bus lines of the public transportation system in Montevideo (data from sig.montevideo.gub.uy), accessed on 23 September 2023.

3.2. Sources of Data

Three main sources of data are applied for the characterization of mobility using public transportation. The first source of data is the open repository from the Uruguayan government, the National Open Data Catalog, available at https://catalogodatos.gub.uy/, accessed on 12 August 2023. The catalog provides access to various collections of data that are freely accessible. Relevant to the reported research, the catalog encompasses a dataset concerning bus trips obtained from the public transportation authorities in Montevideo. This dataset comprises comprehensive information regarding all trips undertaken within the public transportation system in Montevideo. It includes details such as the companies involved, specific bus lines, dates and times of trips, ticket categories, and other pertinent information like the originating bus stop and payment method (either smart card or cash). The dataset utilized for analysis covers a significant timeframe, from November 2019 to June 2022, encompassing the entire duration of the national health emergency caused by the COVID-19 pandemic. This extensive time range allows for a comprehensive analysis of the dynamics of the public transportation system throughout the entire period affected by the sanitary emergency.

The second source of data is the Geographic Information System provided by the Infrastructure for Spatial Data (IDE), from the national government, available at https://www.gub.uy/infraestructura-datos-espaciales/, accessed on 12 August 2023. Geographical information pertaining to the analysis was acquired from shapefiles that contained data on the locations of bus stops in Montevideo, as well as shapefiles containing polygons representing the neighborhoods within Montevideo. These shapefiles provided essential spatial data that facilitated the integration of geographical context into the analysis of the public transportation system in Montevideo during the pandemic.

Additionally, the third source of data is the freely accessible repository from the Uruguayan Interdisciplinary Group for COVID-19 Data Analysis (GUIAD-COVID-19) [36] and the Public Health Ministry. Specifically, the extracted data from this dataset consisted of the daily count of registered COVID-19 cases per department. This data source played a crucial role in incorporating information on the spread of the pandemic and its impact into the analysis.

All the source data and results of the analysis are available at https://github.com/nesmachnow/stm_covid_19, accessed on 30 August 2022.

3.3. Description of the Applied Methodology

The methodology employed in the study consisted of three main stages: data pre-processing, data processing utilizing parallel computing, and analysis of the obtained results. Each stage is described in detail in the following subsections.

3.3.1. Pre-Processing Stage

In this stage, the collected datasets were prepared for analysis. The data pre-processing phase encompassed several tasks, including data cleansing and the association of geographical locations with each recorded ticket sale in the trips dataset.

Geographical data from shapefiles, such as bus stop locations and neighborhood polygons, were processed and linked to the relevant data from the public transportation dataset. This task was accomplished by cross-referencing the shapefile containing the bus stop locations in Montevideo with the shapefile containing the polygons representing the neighborhoods in Montevideo. The cross-referencing process was carried out using the open-source, cross-platform desktop geographic information system application, QGIS. During this stage, a manual classification was conducted for bus stops located outside of Montevideo. These bus stops were categorized as either 'Canelones East' or 'Canelones West', based on their geographical location (Canelones is the department that surrounds Montevideo). By associating each ticket sale with its corresponding neighborhood and categorizing bus stops outside of Montevideo, the data were prepared for subsequent aggregation and analysis of the results.

Additionally, the COVID-19 infection data obtained from GUIAD-COVID-19 were organized and aligned with the corresponding time periods and geographical locations.

3.3.2. Data Processing Using Parallel Computing

The proposed study dealt with a substantial amount of data that required processing. The datasets pertaining to the analyzed period (2019–2022) exceeded 73 GB in size. Moreover, the study involved numerous operations that lent themselves well to parallel computing using the MapReduce paradigm. Several examples of such operations include grouping the data based on the day and neighborhood to analyze daily mobility patterns by neighborhood, transforming each trip into an integer to count the number of trips occurring each day, grouping the data by the day and user category, and grouping the data by the day and bus line. These operations could be effectively parallelized, allowing for efficient processing and analysis of the data. By dividing the data into smaller subsets and processing them using the computational power of multiple processors or computing units concurrently, the computational time for data analysis was significantly reduced.

3.3.3. Statistical Analysis of Data and Results

The concluding stage of the analysis encompassed the computation of pertinent metrics and the application of statistical and time series analysis techniques to the computed results. This stage involved deriving meaningful insights from the processed data by employing data visualization techniques and statistical methods and exploring temporal patterns. By conducting these analyses, the study aimed to uncover significant trends, relationships, significant correlations between variables, and patterns within the data, leading to a comprehensive understanding of impact of the COVID-19 pandemic on the utilization of the public transportation system in Montevideo.

Overall, the applied methodology allowed for the systematic processing and analysis of the collected data, enabling meaningful insights into the relationship between the COVID-19 pandemic and the usage of public transportation in Montevideo.

3.4. Resolution Approach

The development of the parallel algorithm for data processing involved several stages, which are outlined as follows:

1. Computation of daily trip count: A specific algorithmic approach was developed to calculate the number of trips per day. The primary objective was to examine how the onset of the pandemic and the declaration of the sanitary emergency influenced the mobility patterns and public transportation usage reduction. The trip data were partitioned by day to enable parallelization of the computation. A subsequent reduction function was applied in order to group the data by day.
2. Calculation of the correlation between COVID-19 cases and mobility patterns: Another algorithm was developed to determine the correlation between the reported number of COVID-19 cases and the mobility patterns using public transportation. The pandas library was utilized for this task, using the data obtained from the previous stage and the daily COVID-19 cases data. Through the application of statistical computations, the correlation between COVID-19 cases and trip data were calculated.
3. Analysis of mobility patterns: An analysis was conducted to examine the mobility patterns of citizens during the COVID-19 pandemic, considering factors such as neighborhood and socio-economic information, representative sampling of bus lines, and and discrimination by user category. The available data regarding public transportation usage was categorized based on the day and neighborhood, day and line number, and day and user category. Data analysis was conducted using the Pandas library. The objective of this analysis were to determine the mobility patterns during different stages of the COVID-19 pandemic and to identify the user categories that exhibited the highest dependence on public transportation, which was determined by assessing the correlation between COVID-19 cases and trips for each category.
4. Study of the recovery of the usage of public transportation system: The primary focus of this analysis was to study the recovery of the mobility during the COVID-19 pandemic, to pinpoint the periods and specific dates when citizens gradually resumed public transportation usage, reaching levels close to normal. By examining the fluctuations in the monthly average of daily trips over time, valuable insights were obtained regarding the progressive recovery of mobility.

Overall, the proposed stages of the parallel algorithm for data processing aimed to uncover valuable insights into the impact of the pandemic on the mobility patterns of citizens, the correlation between COVID-19 cases and trips, and the recovery of public transportation usage in Montevideo throughout the specified period.

3.5. Implementation Details

The proposed algorithms for data analysis were implemented using Scala [37], a flexible and powerful programming language over the MapReduce framework provided by Hadoop [38]. The choice of Scala was driven by its flexibility, robustness, and excellent interoperability, whereas the MapReduce framework was well-suited for handling the specific characteristics of the data processing problem. Both Scala and the Hadoop MapReduce framework are highly esteemed and widely adopted choices in the field of urban data analysis and big data processing.

For data storage purposes, the Hadoop Distributed File System (HDFS) was utilized. HDFS is specifically designed to be the storage system of Hadoop, employing data replication to ensure fault tolerance. HDFS provides the basis for developing a robust and efficient design for the data processing algorithm. In the event of a processing node failure, the data remains accessible on other configured nodes, guaranteeing availability. HDFS is optimized for storing vast amounts of data while maintaining multiple copies, ensuring both high availability and fault tolerance. Additionally, HDFS facilitates efficient data access, providing a substantial bandwidth. This enables MapReduce applications to effectively process large data volumes. Moreover, HDFS follows a write-once-read-many storage model, where input data are written only once and can subsequently be accessed and read multiple times when required.

The analysis of data and the obtained results was carried out utilizing Python, leveraging the efficiency and widespread usage of the Pandas and Matplotlib libraries. These tools are highly regarded in the field of data analysis, making them suitable choices for the task at hand.

4. Empirical Evaluation of the Case Study: Analysis of Results and Discussion

This section presents the findings from the experimental evaluation conducted to determine the impact of the COVID-19 pandemic and end mobility using the the public transportation system in Montevideo.

4.1. Computational Platform

The experimental evaluation was carried out on HPE Proliant servers with Xeon Gold 6138 processor, 40 cores and 120 GB of RAM memory, from the high performance computing platform of National Supercomputing Center (Cluster-UY), Uruguay [39].

Regarding the distributed implementation, the map processes were allocated 4 GB of physical memory and each one had a dynamic Java Virtual Machine (JVM) size of 3 GB. The reduce processes were assigned 8 GB of physical memory, with a dynamic JVM size of 6 GB. These values were determined in preliminary experiments conducted to determine the best parameters for an efficient use of the computational platform.

4.2. Computational Efficiency of the Parallel Distributed Approach

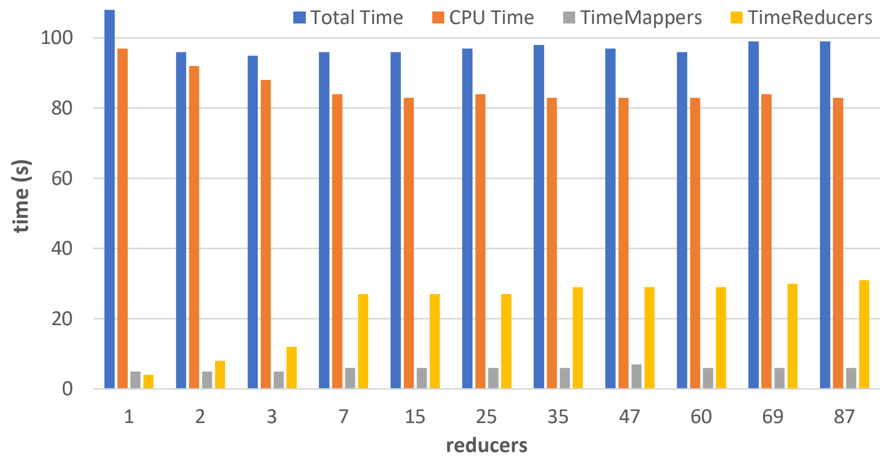
For the analysis of the computational efficiency of the parallel distributed approach, the maximum number of containers per node was set to 50. According to the recommendations and rules-of-thumb for the MapReduce implementation of Hadoop, the number of mappers is set automatically by the framework, according to the size of the input data, and the number of reducers to be used to perform the computations is to be between 1 and 87. Two experiments were carried out, the first with a volume of data of 7 GB (small instance) and the second with 73 GB (large instance). These experiments allow evaluating the computational efficiency and the scalability of the implemented approach for data processing.

Relevant metrics were considered in the analysis, including:

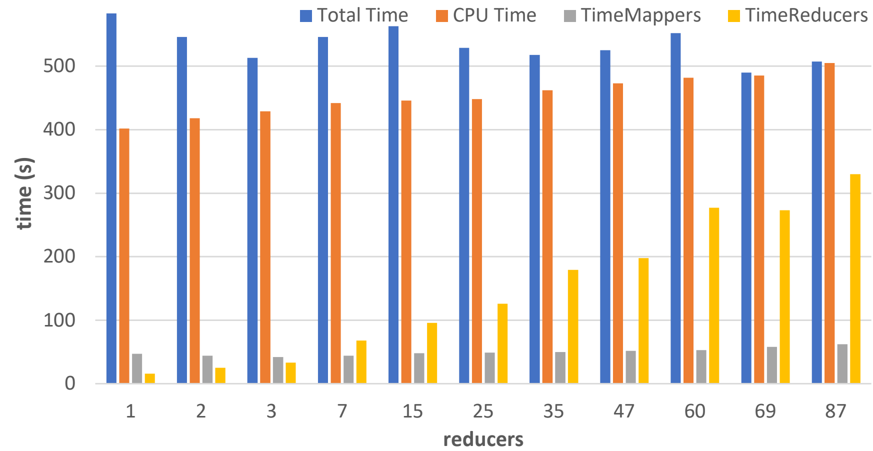
- TotalTime: the total time elapsed from the beginning until the end of the MapReduce job;
- CPUTime: the effective CPU usage time;
- TimeMaps: sum of the execution times of all the Map tasks;
- TimeReducers: sum of the execution times of all Reduce tasks.

Figure 2 presents the results of the computational efficiency evaluation, reporting the four execution time metrics for a different number of reducer processes.

The efficiency results in Figure 2 indicate that the number of reducers do not affect significantly the execution time for when processing 7 GB of data. The lowest overall execution times were computed using two and 60 reduce processes. Overall, the execution time required by mappers and reducers does not vary significantly when using more than three reduce processes. A larger overhead is also noticed when using from 7 to 87 reducers, but without impacting in the overall execution time. A similar result was obtained when processing 73 GB.



(**a**) small instance (7 GB)



(**b**) large instance (73 GB)

Figure 2. Computational efficiency of the proposed MapReduce implementation for data processing using different number of reducer processes.

The execution time values also demonstrate an excellent scalability of the implemented approach, since the average overall executions times only increased by a factor of five when increasing the size of the processed dataset in a factor of ten. This result indicates that the implemented MapReduce algorithm is able to properly adapt the data processing to take full advantage of the parallel capabilities offered by the high performance computing platform used.

Another interesting evaluation is the utilization of overlapping in the data processing workflow. This approach involves initiating the reducer tasks while the mapper tasks are still in progress, rather than waiting for the mappers to complete before starting the reducers. The analysis focused on observing the behavior and evaluate the overall execution time when the reducers start their work at different completion percentages of the mappers, specifically at 12%, 26%, 55%, and 89% of their progress. Additionally, a comparison is performed against the execution time without employing the overlapping technique. Figure 3 presents the execution time results for the considered overlapping percentages.

Based on the data obtained from Figure 3, the best performance was achieved when the reducers begins processing when the mappers have completed 87% of their tasks. Initiating the reducers earlier prolongs the execution time, since they lack sufficient data to process, resulting in idle time. However, without the implementation of overlapping, the overall execution time is also affected. As the mappers reach a significant completion percentage of their work, they start releasing resources, which are wasted if the reducers do not begin their tasks at that particular moment.

The configuration that obtained the best execution time results was used to perform the computation for all the analyses reported next.

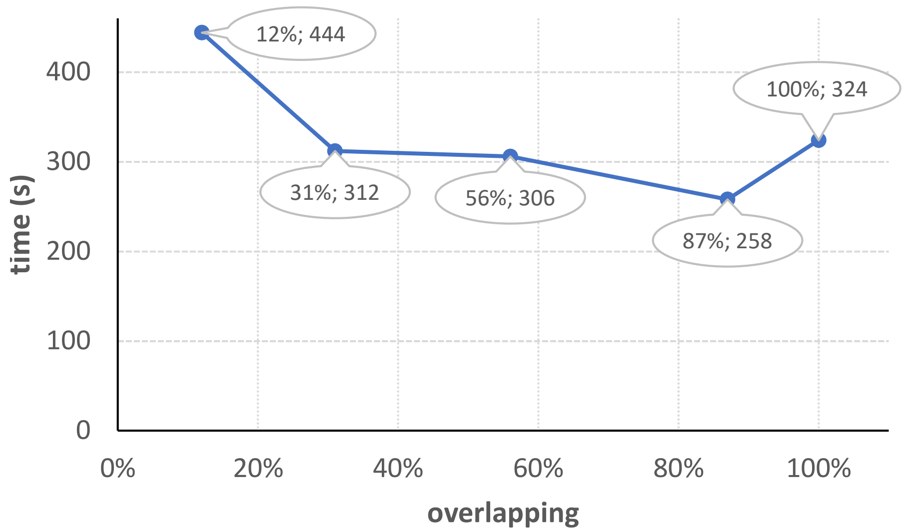


Figure 3. Execution time of the developed parallel MapReduce algorithm for different overlapping percentages.

4.3. Analysis 1: Impact of Declaring a State of Sanitary Emergency

The state of sanitary emergency was declared in 14 March 2020. This subsection analyzes the average number of trips for the public transportation system of Montevideo before and after that date. The baselines for the comparison are the month of November, 2019, and the period 1 March to 13 March 2020. The months between December and February are not fully representative of the mobility using public transportation in the city. The second term of public and private education ends in early December, significantly reducing the number of trips. In turn, the last week of December is Family Day (i.e., Christian Christmas) and New Year's Eve, and most activity in the city is reduced. January and February are the holiday months, and the number of people in Montevideo reduce significantly, since many people move to the Eastern seaside houses and resorts. The majority of educational activities, including schools, high schools, and universities, commenced on 2 March 2020. Under normal circumstances, bus trips experience a peak in March, with an average comparable to that of November.

A comparison of the average number of trips taken on the STM before and after the declaration of the sanitary emergency in Uruguay is depicted in Figure 4.

To account for the substantial difference in the number of trips between working days and weekends, Figure 5 illustrates a comparison of the average number of trips taken on the STM before and after the declaration of the sanitary emergency. The comparison is further differentiated to specifically examine the variations on working days and weekends.

Regarding the values reported in Figures 4 and 5, the dip observed at the beginning of the year is attributed to the seasonal nature of the data. As explained, January and February are typically holiday months, which results in a lower number of bus trips. However, the trend changes when most educational activities commenced on March.

Figure 4 provides a clear illustration of the decline in bus trips following the declaration of the sanitary emergency on 13 March 2020. The overall trips reduction amounted to 71.4%, compared to the daily trip count recorded from 1 March to 13 March. The same reduction was observed considering the trips performed in November, 2019 as a reference baseline. A contrasting situation is observed when analyzing weekdays and weekends separately. On weekends, Figure 5 shows that the reduction in weekend trips was more than a half (54.1%), which is partly attributed to the inherently lower number of bus trips typically taken during weekends. Consequently, the impact of the COVID-19 pandemic resulted in a relatively less significant reduction in weekend trips.

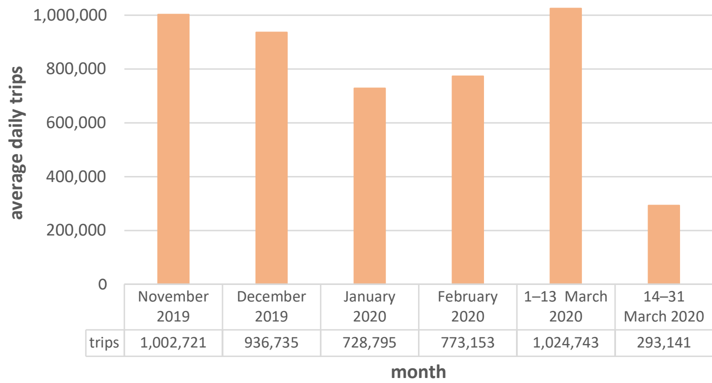


Figure 4. Time series of average daily trips before and after the sanitary emergency declaration (13 March 2020) in Montevideo, Uruguay (data from the period November 2019–March 2020).

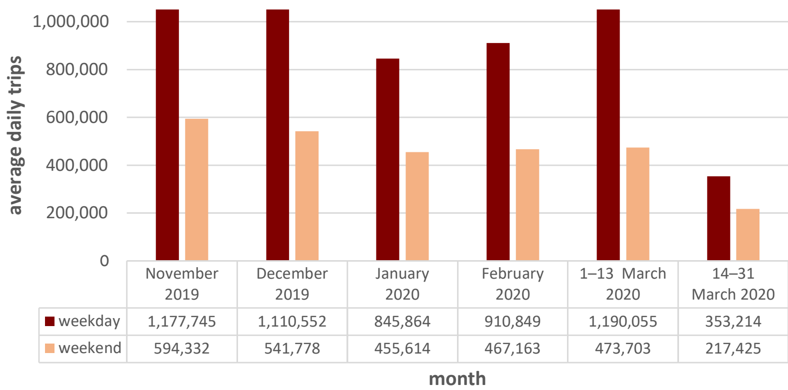


Figure 5. Time series of average daily trips in weekdays and weekends before and after the sanitary emergency declaration (13 March 2020) in Montevideo, Uruguay (data from the period November 2019–March 2020).

The documented reductions in public transportation trips in Montevideo are comparatively lower than those reported in similar cities across Europe and America. This outcome indicates that the responsible freedom model implemented in Montevideo effectively mitigated the perceived risk associated with public transportation trips, resulting in a lesser reduction when compared to other countries.

In the case study of Montevideo, the dependence on public transportation holds particular significance, as there are no alternative commuting options that are perceived as safer by passengers. In 2018, a shared bicycle public system was proposed for a limited area in Montevideo, but its operation was short-lived, and the service was discontinued in 2019. Despite some efforts to revive this system, none have succeeded in achieving their objectives. Therefore, the shared bicycle public system was not a viable commuting option during the COVID-19 pandemic. In 2019, a new form of mobility was introduced in Montevideo: shared e-scooters. Initially, the system gained popularity due to its novelty. However, users soon discovered several drawbacks associated with e-scooters, including a limited operational area, high costs, the risk of sharing roads with automobiles, a lack of available charged vehicles, and operational failures such as the use of non-sustainable methods (trucks) for arranging vehicles during the day. Unfortunately, the business model for e-scooters proved unsuccessful in Montevideo [12]. Private bicycles emerged as the only viable option for personal and safe transportation during the COVID-19 pandemic. However, they are not the preferred means of mobility in Montevideo, accounting for less than 15% of the modal share, mainly due to the lack of adequate cycling infrastructure in the city.

Since the declaration of the sanitary emergency, the utilization of public transportation exhibited a consistent upward trend, except in specific outbreak periods. A detailed analysis of the evolution is presented in the next subsection.

4.4. Analysis 2: Evolution of Public Transportation Usage during the COVID-19 Pandemic

Figure 6 illustrates the progression of the number of trips within the public transportation system in Montevideo from April 2020 to May 2022 (blue series), alongside the reported count of confirmed COVID-19 cases, as provided by GUIAD-COVID-19 and the Public Health Ministry (orange series).

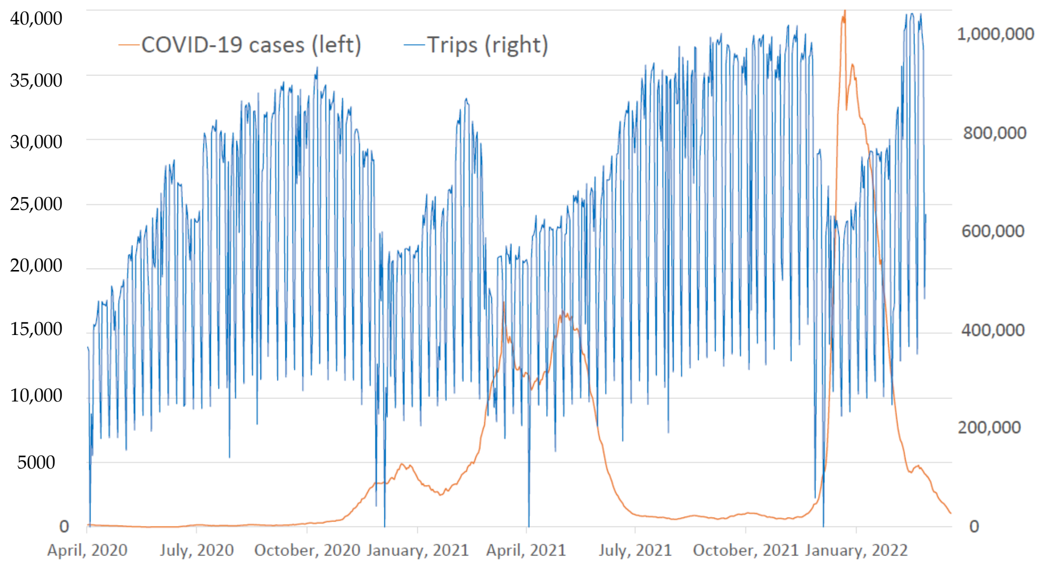
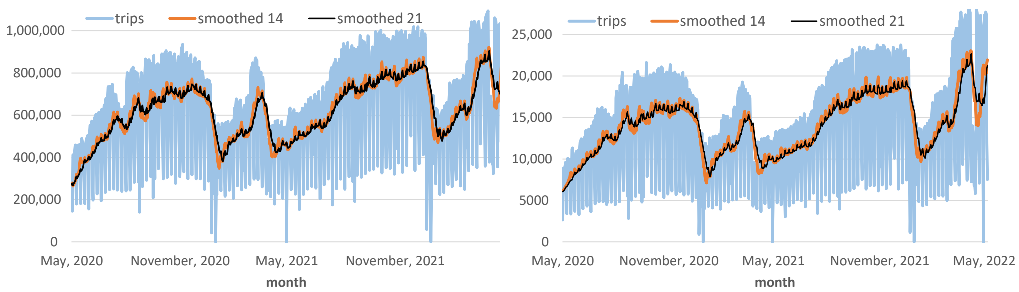


Figure 6. Number of confirmed COVID-19 cases and trips performed in the public transportation of Montevideo during the sanitary emergency period (April 2020–May 2022).

The moving average of the number of trips was studied to provide a clearer representation. This approach smooths the curve, filtering out the peaks caused by weekends and holidays, and provides a refined characterization of public transportation usage. Two periods were studied for defining the moving average: 14 and 21 days, according to the most generally accepted number of days for the contagious period for a person infected with COVID-19 (from two to four days before they develop symptoms, and for a period of two weeks afterward). The analysis showed a correct smoothness of the time series of trips, as shown in Figure 7 for the overall number of trips and for a representative neighborhood (Aguada). The curves showed almost no differences between the moving average values computed for 14 and 21 days. Thus, the moving average computed using the previous 14 data points in the series were considered in the following analysis.

Figure 8 presents a cleaner version of the number of trips in the public transportation system of Montevideo (moving average, blue curve) and the confirmed COVID-19 cases (orange series) from April 2020 to May 2002. Four special events (E1 to E4) are marked in the graphic, which are commented on next.

The relationship between public transportation mobility and the number of COVID-19 cases is clearly depicted in Figures 8 and 9. During periods of COVID-19 outbreaks, there was a noticeable decrease in the number of trips, which was subsequently followed by a gradual recovery as the number of cases declined. After an initial reduction of 70% in the first month and a half following the declaration of the sanitary emergency, the number of trips steadily rose until the end of 2020. Uruguay experienced a relatively milder initial phase of the pandemic compared to other countries, with several days even reporting no new cases. Consequently, citizens gradually resumed their use of public transportation. A slight increase in COVID-19 cases was observed in August 2020, resulting in a 10% reduction in public transportation usage (this situation is marked as event 'E1' in Figures 8 and 9). However, the first wave of the pandemic hit Uruguay in December 2020, with cases peaking at 5000. The outbreak led to a significant reduction of over 20% in public transportation usage (event 'E2' in Figures 8 and 9). In March 2021, cases decreased, and public transportation usage began to recover. However, a new outbreak happened in May 2021: the second wave, with over 15,000 COVID-19 cases. It caused a reduction of more than 40% in the number of trips (the valley marked as event 'E3'). Between August and December 2021, the number of COVID-19 cases significantly dropped, and public transportation usage returned to almost normal levels, over 800,000 daily trips on average. However, the third wave of the pandemic, caused by the highly contagious Omicron strain, started in January 2022. The third wave led to an exponential increase in infected individuals, reaching almost 40,000 confirmed cases by the end of January 2022. As a result, public transportation usage decreased significantly, dropping to approximately 50% of its usual level (event 'E4'). As COVID-19 cases declined, citizens quickly resumed their regular mobility patterns, leading to over 900,000 tickets sold in May 2022.



(**a**) Montevideo (**b**) Aguada neighborhood

Figure 7. Moving average analysis for trips in Montevideo and a representative neighborhood (Aguada). Light blue: trips, orange curve: average over 14 days, black curve: average over 21 days.

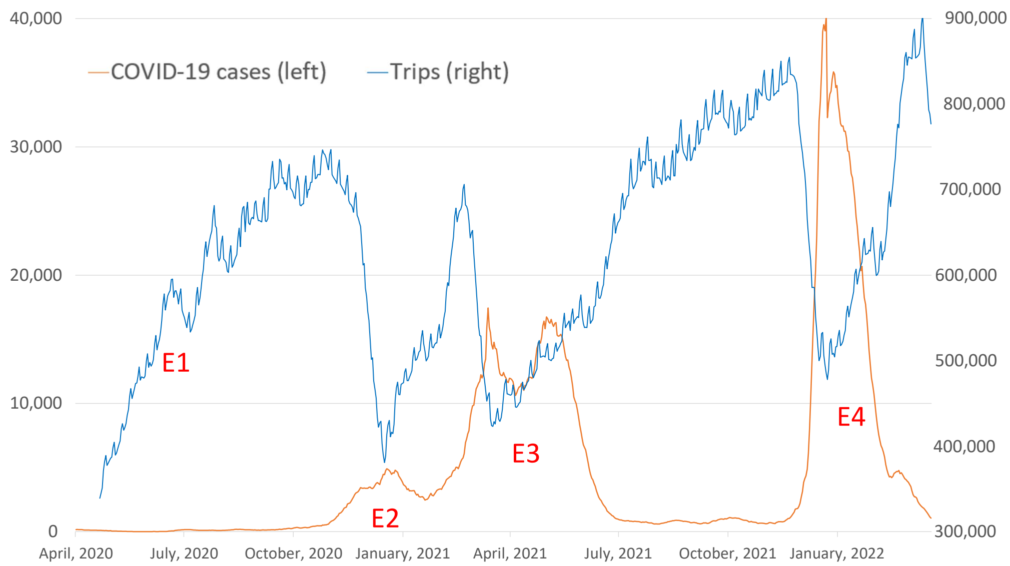


Figure 8. Number of trips and COVID-19 cases (smoothed, moving average).

Based on the reported results, five periods are identified in Figure 9 regarding the behavior of both COVID-19 cases and trips: a first period with few infections (gray background), the first wave (blue background), the second wave (green background), a second period with few infections (red background), and the third wave (yellow background). These periods are relevant to compute the statistical correlation between the studied time series.

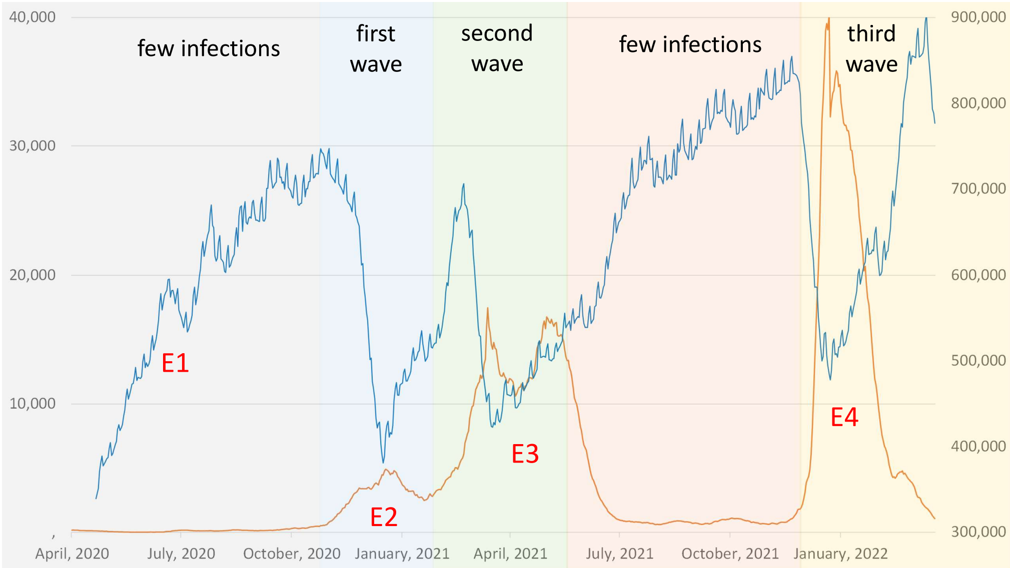


Figure 9. COVID-19 cases and trips performed in the public transportation of Montevideo during the sanitary emergency period (April 2020–May 2022)

Table 2 reports the Pearson correlation coefficient between the number of trips in the public transportation of Montevideo and the number of COVID-19 cases reported in the city for each of the five periods. The three COVID-19 waves are marked in gray and the higher values of the Pearson correlation coefficient are marked in bold font.

The Pearson correlation coefficient indicates a strong negative correlation between the two studied time series during the three COVID-19 waves (values up to −0.89378 for the first wave). As the number of COVID-19 cases experiences an upward trend, the use of public transportation exhibited a downward trend, and vice versa. The magnitude of −0.89378 suggests a high degree of linear relationship between the two variables. As the Pearson correlation coefficient evaluates linear relationships, the correlation coefficient closer to −1 indicate an inverse linear relationship. In the other periods, no correlation was detected, mainly because very few cases of COVID-19 occurred.

Table 2. Correlation between the number of trips in the public transportation system of Montevideo and the number of COVID-19 cases.

Period	Time	Pearson Coefficient
few infections 1	April–November 2020	0.67132
first wave	December 2020–February 2021	−0.89378
second wave	March–May 2021	−0.81794
few infections 2	June–November 2021	−0.43036
third wave	November 2021–February 2022	−0.85285

4.5. Analysis 3: Recovery of Public Transportation Usage

In Montevideo, Uruguay, the recovery of public transportation usage outpaced that of other capital cities worldwide. Table 3 presents the average number of daily trips for each month during the period when the public health emergency was in effect (from April 2020 to April 2022). It also includes the percentage compared to the average pre-COVID-19 pandemic trips (November 2019 and 1–13 March 2020).

Table 3. Recovery of the public transportation system in Montevideo.

2020								
pre-COVID-19 1,024,743 100.0%	April 262,008 25.6%	May 357,921 34.9%	June 585,612 57.1%	July 860,123 83.9%	Aug. 620,732 60.6%	Sept. 805,118 78.6%	Oct. 915,852 89.4%	Nov. 925,801 90.3%
2020	2021							
Dec. 880,519 85.9%	Jan. 650,070 63.4%	Feb. 575,294 56.1%	March 720,518 70.3%	April 572,381 55.9%	May 590,163 57.6%	June 701,371 68.4%	July 738,023 72.0%	Aug. 835,182 81.5%
2021				2022				
Sept. 925,830 90.3%	Oct. 996,702 97.3%	Nov. 992,601 96.9%	Dec. 990,924 96.7%	Jan. 602,185 58.8%	Feb. 712,046 69.5%	March 1,050,306 102.5%	April 1,082,415 105.6%	

The results presented in Table 3 demonstrate that following an initial sluggish period of two months after the declaration of the public health emergency, the number of trips in the public transportation of Montevideo experienced a rapid recovery. Within just four months (by July 2020), the system had regained 84% of its pre-COVID-19 reference value. Despite a slight decline in August 2020, the number of trips nearly reached pre-pandemic levels by November 2020, with a 90% recovery rate. However, the onset of the first major wave of COVID-19 cases in February 2021 led to a significant reduction of up to 56% in trip numbers. Once again, users gradually regained confidence in public transportation, resulting in a steady recovery until the second wave hit between April and June 2021, causing a decline in trips to 56% of pre-COVID-19 levels.

Following the first wave, the recovery of trip numbers was notably faster, reaching over 90% within just three months (by September 2021), and achieving a complete recovery in the latter months of 2021. The emergence of the third wave, specifically with the Omicron strain, led to a reduction in trip numbers to 59% in January 2022. However, the recovery was remarkably swift, surpassing the pre-COVID-19 value within only two months, by March 2022.

The presented results indicate that despite the initial decline in public transportation trips due to the rise in COVID-19 cases, citizens quickly regained their trust in the system. The recovery periods for trip numbers became progressively shorter with each wave and, in 2022, it took only around a month and a half to fully recover. This pace of recovery is notably faster compared to similar case studies reported worldwide [9,27,29]. These findings lead to the conclusion that the responsible freedom model implemented in Montevideo not only effectively mitigated the impact of the pandemic but also ensured a swift restoration of mobility patterns and the utilization of public transportation.

4.6. Analysis 4: Socioeconomic Characterization of Public Transportation Usage

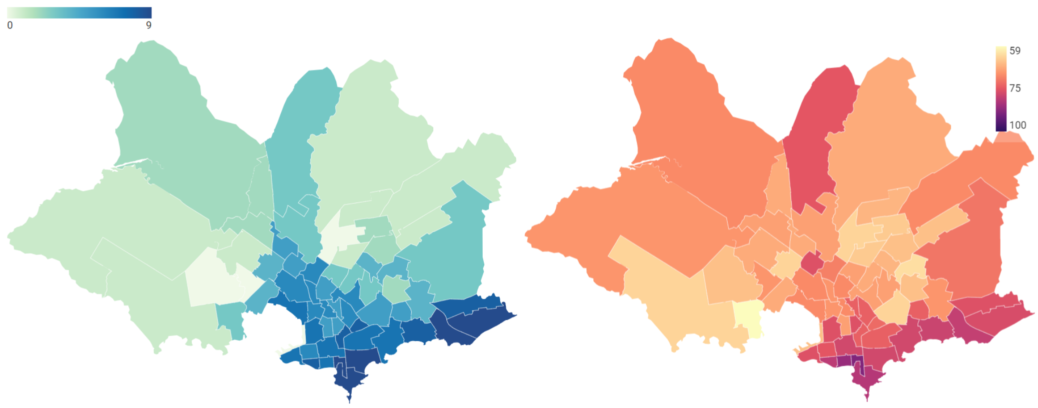
The socio-economic context in Montevideo gave rise to diverse residential neighborhoods, each one with distinct characteristics. A relevant analysis to effectively characterize and understand the mobility patterns within the city is studying the correlation between trips originating from the different neighborhoods and their socio-economical level. This analysis provides valuable insights into the dynamics of movement between different locations in Montevideo.

For the analysis, the repository of trips was processed as follows. Given the absence of neighborhood information in the trips dataset, shapefiles containing bus stop locations and neighborhood polygons in Montevideo were processed. By determining the intersection between these shapefiles, the neighborhood corresponding to each bus stop was identified. This task was performed using the QGIS software. Subsequently, the trip dataset was grouped based on the neighborhood of each bus stop, and the Pearson correlation was calculated to assess the relationship between the number of trips originating from each neighborhood and the reported COVID-19 cases in the city.

The assessment of the socio-economic conditions in neighborhoods was conducted using the Socioeconomic Level Index (INSE) developed by Llambí and Piñeyro [40], and later updated by Perera and Cazulo [41] and Perera [42]. The INSE is a methodological tool used to assess the purchasing power or income of households. It relies on a set of indirect questions as a means to capture the information, considering the challenges associated with directly measuring or asking people about their income. By utilizing the INSE, households can be classified and segmented based on their consumption capacity, enabling a practical means to characterize the population according to their various income levels. The INSE defines 10 values for different geographical and administrative divisions, from 0 (lowest socio-economic level) to 9 (highest socio-economic level).

4.6.1. Reduction in the Number of Trips after the Declaration of the Sanitary Emergency

The reduction in the use of the public transportation system in Montevideo after the declaration of the sanitary emergency had a great dispersion. The minimum reduction was 63% for neighborhoods Casavalle and Casabó–Pajas Blancas. In turn, the maximum reduction was 89% for Parque Rodó neighborhood. The reduction is correlated with the INSE values. Neighborhoods exhibiting a weak correlation between the number of trips and COVID-19 cases are characterized by consistently low INSE values (2 or lower), with the exception of one neighborhood (La Blanqueada, with an INSE value of 6). Conversely, neighborhoods demonstrating a strong correlation between trips and COVID-19 cases tend to have higher INSE values (7 to 9). The Pearson correlation between the reduction in trips on public transportation and the INSE values is 0.7764, suggesting a reasonably high linear correlation between both variables. Figure 10 graphically presents the INSE values for the 63 neighborhoods in Montevideo (values between 0 and 9) and the reductions.



(**a**) Socioeconomic index (INSE) (**b**) Reduction in trips

Figure 10. Socioeconomic index and reduction in trips in the public transportation of Montevideo.

The choropleth maps in Figure 10 have a very similar structure, both with largest values of the reported indicators located along the southern seaside (in those neighborhoods where the wealthiest people live), and smaller values in peripheral neighborhoods of the city. The findings consistently indicate that residents in low-income neighborhoods had limited commuting options and were forced to rely heavily on public transportation, even in the hard circumstances of the COVID-19 pandemic. Individuals with low incomes often face limited mobility options and are more likely to rely on on-site manual labor jobs that are not compatible with the remote work paradigm. In contrast, individuals with higher incomes and greater purchasing power, living in neighborhoods with larger INSE values, significantly reduced their usage of public transportation, probably because they can afford other means of (private) transportation and/or they can perform their work from home.

The boxplots in Figure 11 clearly show the relationship between the socioeconomic level and the percentage of reductions. The observed reductions were significantly larger for neighborhoods with higher values of INSE, i.e., higher socio-economic conditions.

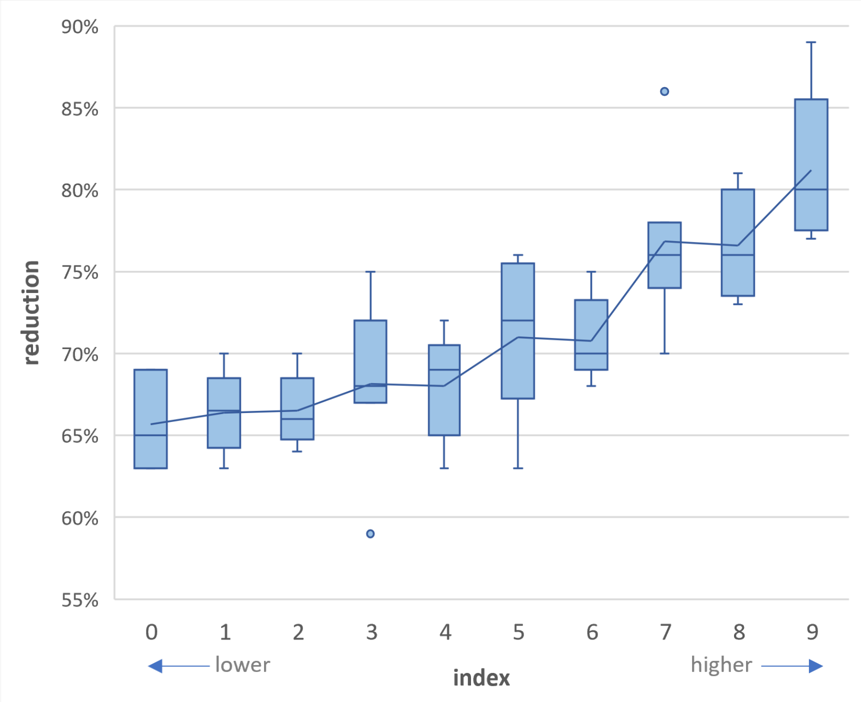


Figure 11. Boxplots summarizing the information of the results distributions for the reduction in trips on public transportation by neighborhood, grouped by socio-economic index.

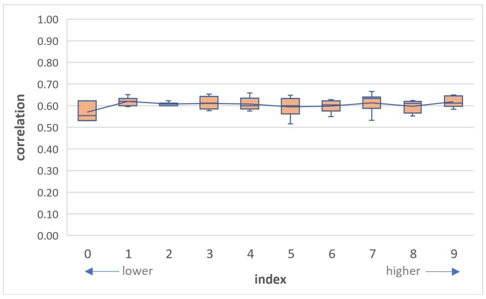
4.6.2. Evolution and Recovery of the Use of Public Transportation System during the COVID-19 Pandemic

The analysis studies the correlation between the use of public transportation in Montevideo during the different stages of the COVID-19 pandemic and the socio-economic characterization provided by INSE values. The study is performed for the five periods identified in Section 4.4.

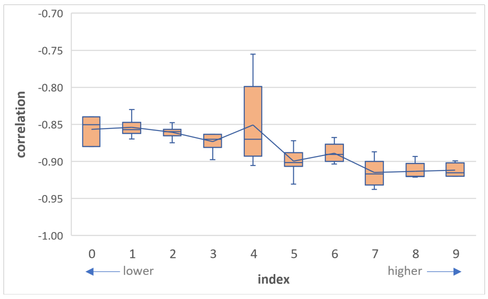
Figure 12 reports the Pearson correlation coefficient between the number of trips and the socioeconomic level of neighborhoods in Montevideo for the five periods studied. A consistent trend is detected for the three outbreak periods (waves), where the Pearson correlation coefficient was closer to -1 (linear inverse relationship) for neighborhoods with the highest INSE values, whereas the correlation for neighborhoods with lower INSE values had smaller coefficients (between -0.80 and -0.85). In the two periods with few infections, no relationship was detected.

An example of the different behavior of citizens regarding the use of public transportation system is shown in Figure 13. Trips for two representative neighborhoods in Montevideo are presented: Pocitos, a high-income neighborhood having the maximum INSE value (9) and a high negative correlation with the number of COVID-19 cases; and Casabó, a low-income neighborhood having the minimum INSE value (0) and a low correlation. The poverty index is almost 30% in Casabó, whereas a negligible value is reported for Pocitos (2%) [43]. Accessibility indexes are also significantly higher for Pocitos than for Casabó [44].

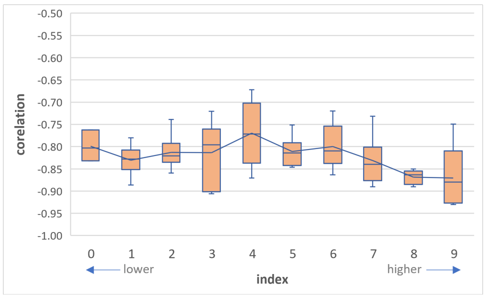
Results presented in presented in Figure 13 clearly show a noteworthy reduction in trips from the Pocitos neighborhood, associated with the special events and waves of the pandemic. The reduction in trips from Casabó neighborhood are not as significant. In the first wave, trips from Pocitos reduced up to 57.8%, while from Casabó only reduced 35.4%. A similar situation happened during the third wave of the COVID-19 pandemic: trips from Pocitos reduced by 55.3%, while from Casabó only reduced by 37.3%. The recovery rates were higher for Pocitos in both cases. Similar figures were obtained for other neighborhoods in each of the ten levels defined by the INSE indicator.



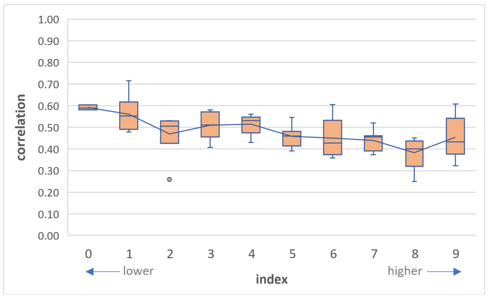
(**a**) Few infections 1 (April–November 2020)



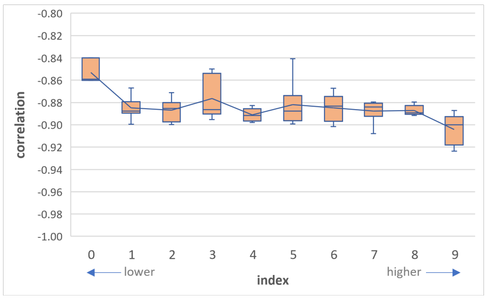
(**b**) First wave (December 2020–February 2021)



(**c**) Second wave (March–May 2021)



(**d**) Few infections 2 (April–November 2020)



(**e**) Third wave (November 2021–February 2022)

Figure 12. Correlation between socio-economic index and the number of trips by neighborhood in the public transportation of Montevideo, for the five identified periods of the COVID-19 pandemic.

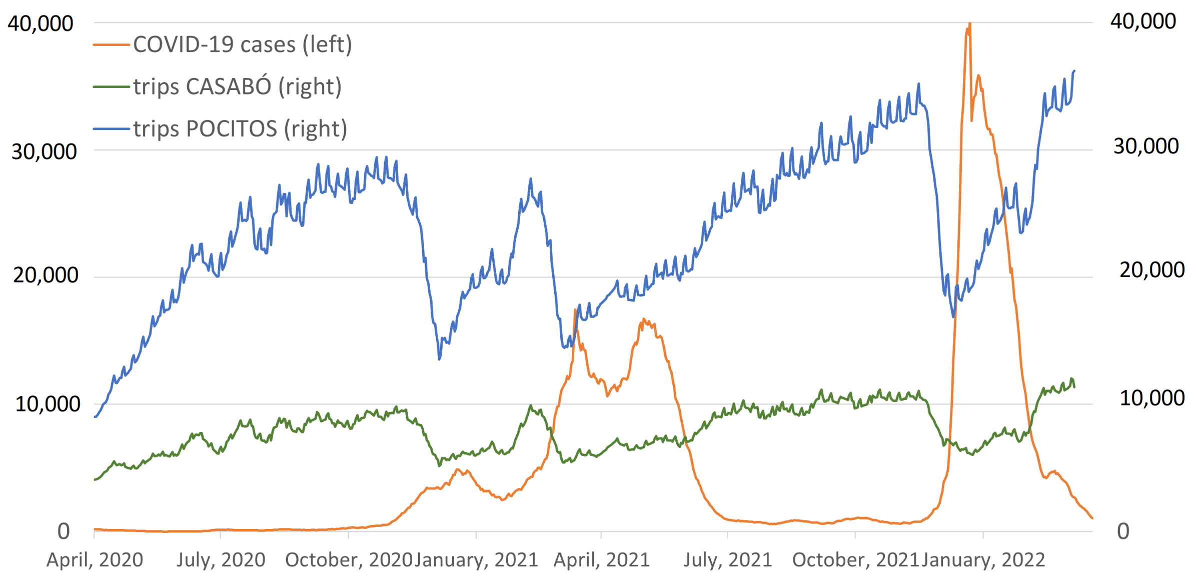


Figure 13. Comparison of trips from Pocitos (high INSE, high negative correlation) and Casabó (low INSE, low correlation) and COVID-19 cases.

4.7. Analysis 5: Mobility Patterns of the Elderly

Several articles has stated that the COVID-19 pandemics significantly changed the mobility patterns of the elderly, since restrictions excluded them from using public transportation [45–47]. Other factors were also relevant for the diminished number of trips of older adults using public transportation during the pandemic [48].

A specific analysis was conducted to examine the usage of public transportation by elders in Montevideo. The study utilized the information from the automated ticket sales system of the STM in Montevideo, which includes records for retired individuals (i.e., over 60/65 years old). Within this group, two types of tickets are sold: 'retired A' for those with the lowest economic income and 'retired B' those with a standard economic income. Table 4 presents the observed reduction in trips for both the 'retired A' and 'retired B' categories following the declaration of the sanitary emergency on 14 March 2020. Additionally, the reduction in trips for normal users tickets sold, corresponding to adults between 20 and 60 years old, is also provided to serve as a comparative baseline.

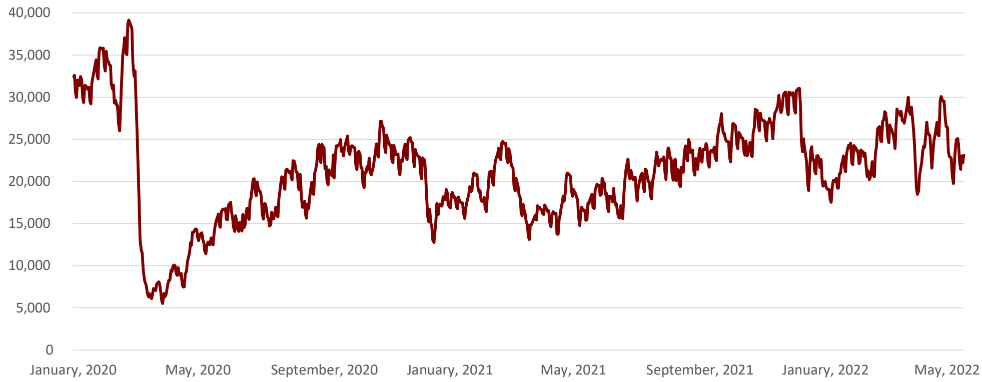
Table 4. Reduction in trips using public transportation in Montevideo for 'retired A', 'retired B', and normal users categories, following the declaration of the sanitary emergency on 14 March 2020.

Category	1–13 March	13–31 March	Reduction
retired A	40,041	9365	76.6%
retired B	14,383	3203	77.7%
normal users	541,259	181,378	66.5%

Results in Table 4 show that the reduction in public transportation usage by older individuals was 10% larger than for normal users. Despite that, the number of trips show that a significant share of the elder population (about one quarter) still relied on public transportation for commuting during the early days of the COVID-19 pandemics. This result is different to other reported reductions for countries like China [46], Iran [47], Italy [49], Korea [50], and the United Kingdom [51], where the mobility of older people using public transportation reduced to almost zero in the early stages of the COVID-19 pandemic, as a consequence of the very high perceived risk and the applied lockdown measures. No significant variations were detected in the reduction between the two studied 'retired' categories, suggesting that the economic factor did not play a significant role in that regard. The observed results can be reasonably attributed to the implementation of the 'responsible freedom' strategy by the Uruguayan government, as well as the remarkably low infection rates experienced in the initial days and months following the declaration of the sanitary emergency. As occurred for middle age adults, the perceived risk of using public transportation among older adults was not as high as in other countries. This is an important result, since maintaining mobility and social interactions have been recognized as crucial for older adults' health during the COVID-19 pandemic. This finding holds great significance as the preservation of mobility and social interactions has been acknowledged as critical for the health and well-being of older adults during the COVID-19 pandemic [48].

Figure 14 presents the evolution of public transportation usage for the three studied categories: retired A, retired B, and normal users (smoothed average values are reported).

The same trends are observed for the three categories regarding the initial reduction following the declaration of the sanitary emergency and the detected events related to the three waves of the COVID-19 pandemics. Furthermore, the recovery patterns follow a similar distribution too, with a less smooth recovery than for normal users, due to the larger number of tickets sold and the reduced mobility of the elderly in days with bad weather conditions. A sustained increment on public transportation usage is observed in the few infection periods identified in Figure 9 regarding the behavior of both COVID-19 cases and trips. The analysis suggests that the behavior of older people followed the same trend observed for normal users and other categories, without significant changes in the patterns of tickets sold. Overall, the number of trips recovered in May 2022 to up to 80% of the reference pre-pandemic value (March 2020), a similar value than for normal users.



(**a**) Category: retired A

(**b**) Category: retired B

(**c**) Category: normal

Figure 14. Evolution of public transportation usage in Montevideo during the COVID-19 pandemic for retired and normal categories of users.

4.8. Summary of Results

The analysis allowed to determine several relevant results about public transportation usage in Montevideo during the COVID-19 pandemics. The main results are summarized next.

Regarding the impact of declaring a state of sanitary emergency, the analysis confirmed that the overall reduction on public transportation trips in Montevideo was 71.4%. The reduction was higher on working days (73.2%) than on weekends (54.1%). These reduction values were lower than for case studies in similar cities, e.g., 80–90% reduction in Budapest, Hungary [20], up to 85% in Warsaw, Poland [22], 90% in Gdansk, Poland [9], 90%

in cities in the Netherlands [7], 95% in Fuenlabrada, Spain [25], up to 93% in Santander, Spain [26], and more than 80% in major Latin American cities [28],

Regarding the evolution of public transportation usage during the COVID-19 pandemic, a negative correlation was found with the number of COVID-19 cases. The analysis identified four special events characterized by an increase in reported COVID-19 cases, as well as five distinct periods in the studied period, between April 20202 and May 2022. The negative correlation was particularly pronounced during the wave periods, namely the first wave (December 2020–February 2021) with a Pearson correlation coefficient of -0.89378, the second wave (March–May 2021) with a Pearson correlation coefficient of -0.81794, and the third wave (November 2021–February 2022) with a Pearson correlation coefficient of -0.85285. These coefficients indicate that as the number of COVID-19 cases increased, there was a corresponding decrease in public transportation usage, and vice versa.

Regarding the recovery of public transportation usage, Montevideo surpassed other similar capital cities worldwide. The number of trips in public transportation experienced a rapid rebound, with an impressive recovery rate. Within just four months after the declaration of the sanitary emergency in July 2020, the system had already regained 84% of its pre-COVID-19 trips. Although there was a slight decline in August 2020, the number of trips nearly reached pre-pandemic levels by November 2020, achieving a 90% recovery rate. Notably, the recovery of trip numbers after the first wave was significantly faster, surpassing 90% within three months and fully recovering in the latter months of 2021. A similar trend was detected after the second wave. Following the third wave, the recovery was remarkably swift, surpassing the pre-COVID-19 value within just two months, by March 2022. The recovery results indicate that despite the initial decline in public transportation trips due to the rise in COVID-19 cases, citizens swiftly regained their trust in the system. The recovery periods for trip numbers became progressively shorter after each new wave and, in 2022, only a month and a half was required to achieve full recovery. This recovery pace is significantly faster than the ones observed in similar case studies reported worldwide.

Finally, regarding the socioeconomic characterization of public transportation usage, different results were obtained for diverse neighborhoods of Montevideo. The reduction in trips after the declaration of the sanitary emergency was significantly lower in low-income neighborhoods (e.g., 63% in Casavalle and Casabó–Pajas Blancas) than in the wealthiest neighborhoods (e.g., 89% Pocitos and Parque Rodó). These results show that lower-income populations were more forced to continue using public transportation, due to limited alternative options for commuting.

The main findings obtained from this study provide valuable insights into the mobility patterns and public transportation usage in Montevideo during the COVID-19 pandemic. These findings offer important understanding for policymakers and researchers, enabling them to make informed decisions and develop effective strategies in response to similar challenges in the future.

5. Conclusions and Future Work

This article reported a study devoted to examine and characterize the utilization of the public transportation system in Montevideo, Uruguay, throughout the COVID-19 pandemic. The study adopts an urban data analysis approach, leveraging accessible open data on trips and relevant statistics related to the COVID-19 situation in Uruguay.

Several data sources were processed and studied applying a data analysis approach, to compute relevant indicators to characterize the public transportation usage. Trips data were correlated with the number of COVID-19 cases and socio-economic information to determine and analyze the different behavior of citizens.

The primary findings of the study reveal that the decrease in public transportation trips in Montevideo was 71.4%, which is noticeably lower compared to similar case studies. Additionally, a negative correlation was observed between the utilization of the public transportation system in Montevideo and the confirmed COVID-19 cases in Uruguay. Notably, the analysis of the correlation suggests that neighborhoods with a lower socio-economic index, indicating lower-income populations were more reliant on the use of public transportation due to the lack of alternatives. Furthermore, the analysis of the recovery of public transportation trips indicates a swift rebound, surpassing the pace observed in other capital cities.

The obtained collective insights and results shed light on the mobility patterns and the usage of public transportation in Montevideo during the COVID-19 pandemic, providing valuable understanding for policymakers and researchers. The analysis made a concerted effort to address and mitigate the impact of various limitations. These included the heavy reliance on data availability and accuracy, the avoidance of bias by considering diverse population subsets and multiple geographical areas, and the consideration of external factors such as government regulations, work pattern changes, alternative transportation options, and individual preferences. However, establishing definitive causal relationships between the COVID-19 pandemic and the reduction in public transportation usage remains challenging due to subjective factors like the fear of infection and perceived risk associated with different modes of transportation, as well as specific economic factors. In terms of temporality, the study not only focused on the short-term effects of the pandemic on public transportation usage, but also considered potential long-term impacts and whether the observed changes in behavior persist beyond each immediate crisis or wave. It is crucial to recognize and address these limitations when interpreting the findings of the study to ensure the accuracy, validity, and the generalization of the results to other regions.

The main lines for future research include broadening the analysis to encompass additional categories such as age and tariff type. This expansion would provide a more comprehensive understanding of how different demographic factors influence public transportation usage during the COVID-19 pandemic. Another important direction for future work is to conduct a comprehensive analysis of the normalized post-COVID-19 situation, taking into account more recent trip data. These analyses would enable a more accurate assessment of the recovery and changes in public transportation patterns as the pandemic situation evolved and the everlasting impact on the behavior of citizens and their mobility habits. By considering these factors and incorporating updated data, further research can enhance the understanding of the long-term effects of the COVID-19 pandemic on public transportation and elaborate future mobility strategies and policies.

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References

1. Cervero, R.; Guerra, E.; Al, S. *Beyond Mobility*; Island Press/Center for Resource Economics: Washington, DC, USA, 2017. [CrossRef]
2. Sussman, J. *Perspectives on Intelligent Transportation Systems (ITS)*; Springer Science + Business Media: Berlin/Heidelberg, Germany, 2005.
3. Hu, T.; Wang, S.; She, B.; Zhang, M.; Huang, X.; Cui, Y.; Khuri, J.; Hu, Y.; Fu, X.; Wang, X.; et al. Human mobility data in the COVID-19 pandemic: Characteristics, applications, and challenges. *Int. J. Digit. Earth* **2021**, *14*, 1126–1147. [CrossRef]
4. Huang, X.; Li, Z.; Jiang, Y.; Ye, X.; Deng, C.; Zhang, J.; Li, X. The characteristics of multi-source mobility datasets and how they reveal the luxury nature of social distancing in the U.S. during the COVID-19 pandemic. *Int. J. Digit. Earth* **2021**, *14*, 424–442. [CrossRef]
5. Nesmachnow, S.; Baña, S.; Massobrio, R. A distributed platform for big data analysis in smart cities: Combining Intelligent Transportation Systems and socioeconomic data for Montevideo, Uruguay. *EAI Endorsed Trans. Smart Cities* **2017**, *2*, 153478. [CrossRef]

6. Tirachini, A.; Cats, O. COVID-19 and Public Transportation: Current Assessment, Prospects, and Research Needs. *J. Public Transp.* **2020**, *22*, 1–21. [CrossRef] [PubMed]
7. de Haas, M.; Faber, R.; Hamersma, M. How COVID-19 and the Dutch 'intelligent lockdown' change activities, work and travel behaviour: Evidence from longitudinal data in the Netherlands. *Transp. Res. Interdiscip. Perspect.* **2020**, *6*, 100150. [CrossRef] [PubMed]
8. Liu, L.; Miller, H.J.; Scheff, J. The impacts of COVID-19 pandemic on public transit demand in the United States. *PLoS ONE* **2020**, *15*, e0242476. [CrossRef] [PubMed]
9. Przybylowski, A.; Stelmak, S.; Suchanek, M. Mobility Behaviour in View of the Impact of the COVID-19 Pandemic—Public Transport Users in Gdansk Case Study. *Sustainability* **2021**, *13*, 364. [CrossRef]
10. Massobrio, R.; Nesmachnow, S. Travel Time Estimation in Public Transportation Using Bus Location Data. In *Smart Cities*; Springer International Publishing: Berlin/Heidelberg, Germany, 2022; pp. 192–206. [CrossRef]
11. Collares, A.; Helal, D.; Nesmachnow, S.; Tchernykh, A. Analysis of Public Transportation in Montevideo, Uruguay During the COVID-19 Pandemic. In *Smart Cities*; Springer Nature: Cham, Switzerland, 2023; pp. 200–214. [CrossRef]
12. Hipogrosso, S.; Nesmachnow, S. Analysis of Sustainable Public Transportation and Mobility Recommendations for Montevideo and Parque Rodó Neighborhood. *Smart Cities* **2020**, *3*, 479–510. [CrossRef]
13. Hipogrosso, S.; Nesmachnow, S. A Practical Approach for Sustainable Transit Oriented Development in Montevideo, Uruguay. In *Smart Cities*; Springer International Publishing: Berlin/Heidelberg, Germany, 2022; pp. 256–270. [CrossRef]
14. Bohte, W.; Maat, K.; van Wee, B. Measuring Attitudes in Research on Residential Self-Selection and Travel Behaviour: A Review of Theories and Empirical Research. *Transp. Rev.* **2009**, *29*, 325–357. [CrossRef]
15. Taylor, L. Uruguay is winning against COVID-19. This is how [corrected]. *BMJ* **2020**, *370*, m3693. [CrossRef]
16. Costabel, M. Uruguay Emerges as a Rare Pandemic Winner in Latin America, 2021. *Foregn Policy* **2020**. Available online: https://foreignpolicy.com/2020/07/21/uruguay-coronavirus-pandemic-success-latin-america/ (accessed on 12 August 2023).
17. De Vos, J. The effect of COVID-19 and subsequent social distancing on travel behavior. *Transp. Res. Interdiscip. Perspect.* **2020**, *5*, 100121. [CrossRef]
18. Beck, M.; Hensher, D. Insights into the impact of COVID-19 on household travel and activities in Australia. *Transp. Policy* **2020**, *99*, 95–119. [CrossRef]
19. Jenelius, E.; Cebecauer, M. Impacts of COVID-19 on public transport ridership in Sweden: Analysis of ticket validations, sales and passenger counts. *Transp. Res. Interdiscip. Perspect.* **2020**, *8*, 100242. [CrossRef] [PubMed]
20. Bucsky, P. Modal share changes due to COVID-19: The case of Budapest. *Transp. Res. Interdiscip. Perspect.* **2020**, *8*, 100141. [CrossRef]
21. Wielechowski, M.; Czech, K.; Grzeda, Ł. Decline in Mobility: Public Transport in Poland in the time of the COVID-19 Pandemic. *Economies* **2020**, *8*, 78. [CrossRef]
22. Kłos, Z.; Gutowski, P. The Outbreak of COVID-19 Pandemic in Relation to Sense of Safety and Mobility Changes in Public Transport Using the Example of Warsaw. *Sustainability* **2022**, *14*, 1780. [CrossRef]
23. Palm, M.; Allen, J.; Liu, B.; Zhang, Y.; Widener, M.; Farber, S. Riders Who Avoided Public Transit During COVID-19. *J. Am. Plan. Assoc.* **2021**, *87*, 455–469. [CrossRef]
24. Cartenì, A.; Di Francesco, L.; Henke, I.; Marino, T.; Falanga, A. The Role of Public Transport during the Second COVID-19 Wave in Italy. *Sustainability* **2021**, *13*, 11905. [CrossRef]
25. Rodríguez, A.; Wilby, M.; Vinagre, J.; Fernández, R. Characterization of COVID-19's Impact on Mobility and Short-Term Prediction of Public Transport Demand in a Mid-Size City in Spain. *Sensors* **2021**, *21*, 6574. [CrossRef]
26. Aloi, A.; Alonso, B.; Benavente, J.; Cordera, R.; Echániz, E.; González, F.; Ladisa, C.; Lezama, R.; López, Á.; Mazzei, V.; et al. Effects of the COVID-19 Lockdown on Urban Mobility: Empirical Evidence from the City of Santander (Spain). *Sustainability* **2020**, *12*, 3870. [CrossRef]
27. Awad, S.; Julio, R.; Gomez, J.; Moya, B.; Sastre, J. Post-COVID-19 travel behavior patterns: Impact on the willingness to pay of users of public transport and shared mobility services in Spain. *Eur. Transp. Res. Rev.* **2021**, *13*, 20. [CrossRef]
28. Andara, R.; Ortego, J.; Gómez, M.; Ramírez, R.; Navas, L.; Vásquez, C.; Gaitán, M. Behavior of Traffic Congestion and Public Transport in Eight Large Cities in Latin America during the COVID-19 Pandemic. *Appl. Sci.* **2021**, *11*, 4703. [CrossRef]
29. Gramsch, B.; Guevara, C.A.; Munizaga, M.; Schwartz, D.; Tirachini, A. The effect of dynamic lockdowns on public transport demand in times of COVID-19: Evidence from smartcard data. *Transp. Policy* **2022**, *126*, 136–150. [CrossRef]
30. Puello, L. Impact of COVID-19 restrictions on mode use and mode captivity the city of Santo Domingo in Latin America. *Transp. Res. Interdiscip. Perspect.* **2022**, *13*, 100515. [CrossRef] [PubMed]
31. Massobrio, R.; Nesmachnow, S. Urban Mobility Data Analysis for Public Transportation Systems: A Case Study in Montevideo, Uruguay. *Appl. Sci.* **2020**, *10*, 5400. [CrossRef]
32. Denis, J.; Massobrio, R.; Nesmachnow, S.; Cristóbal, A.; Tchernykh, A.; Meneses, E. Parallel computing for processing data from Intelligent Transportation Systems. In Proceedings of the 10th International Supercomputing Conference in Mexico, Monterrey, Mexico, 25–29 March 2019; pp. 1–15.
33. Fabbiani, E.; Nesmachnow, S.; Toutouh, J.; Tchernykh, A.; Avetisyan, A.; Radchenko, G.I. Analysis of Mobility Patterns for Public Transportation and Bus Stops Relocation. *Program. Comput. Softw.* **2018**, *44*, 508–525. [CrossRef]

34. Massobrio, R.; Nesmachnow, S.; Tchernykh, A.; Avetisyan, A.; Radchenko, G. Towards a Cloud Computing Paradigm for Big Data Analysis in Smart Cities. *Program. Comput. Softw.* **2018**, *44*, 181–189. [CrossRef]
35. Massobrio, R.; Pías, A.; Vázquez, N.; Nesmachnow, S. Map-Reduce for Processing GPS Data from Public Transport in Montevideo, Uruguay. In Proceedings of the Simposio Argentino de Grandes Datos, 45 Jornadas Argentinas de Informática, La Plata, Argentina, 5–9 September 2016; pp. 41–54.
36. Grupo Uruguayo Interdisciplinario de Análisis de Datos. COVID Stats per Department. Available online: https://github.com/3dgiordano/covid-19-uy-vacc-data (accessed on 21 July 2022).
37. Odersky, M.; Spoon, L.; Venners, B. *Programming in Scala: [A Comprehensive Step-by-Step Guide]*; Artima Inc.: Walnut Creek, CA, USA, 2008.
38. White, T. *Hadoop: The Definitive Guide*, 4th ed.; O'Reilly: Beijing, China, 2015.
39. Nesmachnow, S.; Iturriaga, S. Cluster-UY: Collaborative Scientific High Performance Computing in Uruguay. In *Supercomputing*; Communications in Computer and Information Science; Springer: Berlin/Heidelberg, Germany, 2019; Volume 1151, pp. 188–202. [CrossRef]
40. Llambí, C.; Piñeyro, L. Índice de Nivel Socioeconómico. 2012. Available online: https://cinve.org.uy/wp-content/uploads/2012/12/Indice-de-nivel-socioecon%C3%B3mico.pdf (accessed on 30 August 2022).
41. Perera, M.; Cazulo, P. Índice de Nivel Socioeconómico: Propuesta de Actualización. 2016. Available online: http://ceismu.org/site/wp-content/uploads/inse-informe-final-28032016.pdf (accessed on 30 August 2022).
42. Perera, M. Índice de Nivel Socioeconómico. 2018. Available online: https://ceismu.org/site/wp-content/uploads/INSE-2018-documento-final.pdf (accessed on 30 August 2022).
43. CERES. La Delgada Línea de la Pobreza, 2020. Text in Spanish. Available online: https://ceres.uy/admin/uploads/slides/archivo_1667994302.pdf (accessed on 30 August 2022).
44. Perera, S.; Massobrio, R. Walking Accessibility to the Public Transport Network in Montevideo, Uruguay. In *Proceedings of the Smart Cities*; Communications in Computer and Information Science; Springer: Berlin/Heidelberg, Germany, 2023; pp. 17–30.
45. Lättman, K.; Olsson, L.E.; Waygood, E.O.D.; Friman, M. Nowhere to go–Effects on elderly's travel during Covid-19. *Travel Behav. Soc.* **2023**, *32*, 100574. [CrossRef]
46. Liu, Q.; Liu, Y.; Zhang, C.; An, Z.; Zhao, P. Elderly mobility during the COVID-19 pandemic: A qualitative exploration in Kunming, China. *J. Transp. Geogr.* **2021**, *96*, 103176. [CrossRef]
47. Shaer, A.; Haghshenas, H. Evaluating the effects of the COVID-19 outbreak on the older adults' travel mode choices. *Transp. Policy* **2021**, *112*, 162–172. [CrossRef]
48. Choe, E.Y.; Du, Y.; Sun, G. Decline in older adults' daily mobility during the COVID-19 pandemic: The role of individual and built environment factors. *BMC Public Health* **2022**, *22*, 2317. [CrossRef] [PubMed]
49. Guida, C.; Carpentieri, G. Quality of life in the urban environment and primary health services for the elderly during the Covid-19 pandemic: An application to the city of Milan (Italy). *Cities* **2021**, *110*, 103038. [CrossRef] [PubMed]
50. Park, B.; Cho, J. Older Adults' Avoidance of Public Transportation after the Outbreak of COVID-19: Korean Subway Evidence. *Healthcare* **2021**, *9*, 448. [CrossRef] [PubMed]
51. Reinhard, E.; Carrino, L.; Courtin, E.; van Lenthe, F.J.; Avendano, M. Public Transportation Use and Cognitive Function in Older Age: A Quasiexperimental Evaluation of the Free Bus Pass Policy in the United Kingdom. *Am. J. Epidemiol.* **2019**, *188*, 1774–1783. [CrossRef]