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Understanding the impact of COVID-19 on mobility behavior of public transport passengers: the case of Metropolitan Area of Porto

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Abstract

Public transport systems worldwide experienced significant declines in usage during the COVID-19 pandemic due to lockdowns and work-from-home mandates. While numerous studies have examined these phenomena, there is still a need for empirical evidence that not only documents what occurred but also provides actionable insights for future transport planning. This study aims to enhance understanding of public transport passengers' mobility behaviors during different stages of the pandemic, using the Metropolitan Area of Porto, Portugal, as a case study. Automated Fare Collection data from 2020 were analyzed and compared with data from the pre-pandemic year of 2019. The analysis included temporal, spatial, spatio-temporal, and sociodemographic dimensions. Key patterns and trends identified include a rapid recovery of ridership post-restriction easing, homogenized daily travel patterns, varied impacts on different transport modes, and significant shifts in demographic travel behaviors. These findings highlight the resilience of public transport demand and suggest that adaptive scheduling, enhanced safety measures, targeted support for vulnerable groups, promotion of off-peak travel, investment in bus infrastructure, and encouragement of multi-modal transport are essential strategies. Implementing these strategies can help improve public transport planning and mitigate the adverse effects of future crises.

Keywords Pandemic, AFC, Travel patterns, Spatio-temporal, Sociodemographic

1 Introduction

In December 2019, an increasing number of cases of the new coronavirus (SARS-CoV-2) were identified in the city of Wuhan, China [1]. The contagion rate has happened at unprecedented speed, with the World Health Organization (WHO) declaring a Public Health Emergency of International Concern on 30 January 2020 and a pandemic on 11 March 2020 [2].

Countries around the world have been forced to take urgent and drastic measures to stop the spread of COVID-19 among people, such as lockdowns, work-from-home mandates, school closures, cancellation of public events and mandatory mask wearing. The transport sector, and public transport in particular, was greatly affected, as people were prevented from leaving their homes and when they did, they preferred to use private means of transport [3].

A decrease of 80–90% of public transport use was witnessed in multiple European cities from March 15, 2020

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onwards, roughly the time at which lockdowns were widely imposed in Europe [4]. The city of Santander witnessed an overall decline of 76% in mobility. As for public transport, this decline was up to 93% [4]. In the case of a rural region in northern Thailand, when a nationwide lockdown was enacted, there was a 90% reduction in overall mobility [5]. Reductions of this magnitude are not just limited to rural areas. The authors [6] analyzed nine years of ticketing data at a major transport hub in Paris, highlighting the fact that during the period between March 17, 2020 and May 11, 2020, there was an almost total loss of passengers.

A Stockholm-based study conducted by [7] found that gender affects the likelihood of stopping using public transport and that areas with higher percentages of men were more likely to stop using public transport. This study also noted the existence of connections between age and a reduction in public transport use; however, as the study states, there are conflicting reports from other studies on the relevance of age as a factor, which leads to the belief that it may be different in different locations due to mentality and cultural changes [7].

While [7] found that older people reduced their mobility more than younger people, [8] find the opposite in their analysis of Greece, younger people's mobility, aged between 18 and 25 years old, decreased more than people aged between 26 and 64. Of note is that people over 65 seemed not to decrease their travel even though they are more at risk of suffering severe consequences from the virus; this could be due to a low level of information or due to a low sample size of older people in the study data [8]. Finally, a connection was found between income levels and reductions in mobility; people with higher income were more likely to reduce their travels during the study period. However, there was no connection found between education level and reduction in travel, which is at odds with multiple other studies findings, the authors conclude that due to the impact of these factors, populations should not be considered homogeneous for future studies and research [8].

In contrast [9] found that individuals with higher education were more likely to work from home and, as such, reduced their travel more. In addition to these findings, the authors also found that larger families are more likely to have people working outside the home and, to that end, travel more. Their findings support the claims of [8] regarding women being more likely to work from home, and correlate these findings not only to the impact COVID has had on female-dominated industries, but also to the fact that men tend to be more involved in health-related risks than women during and before the pandemic [9]. This study also found that people over 60 reduced their trips much less than younger people, highlighting once again that, despite being an at-risk population, many elderly people still do not restrict their travel.

In an analysis of the smart card data for metro usage in Taipei, [10] found that the demand for metro services declined sharply and appeared to remain lower after the waves of COVID passed. The reductions were mainly noticed when comparing weekends with weekdays, from Monday to Friday. They noted that the decline in usage was considerably more significant on weekends, and they also noted that on weekdays, declines were smaller during peak hours and more prominent during periods of lower traffic (10am to 4pm and 8pm to 1am) [10]. This leads to the idea that non-essential trips were heavily reduced while work commutes remained imperative; this is also detrimental to overcrowding during peak hours. Another study conducted in Bangkok shows that demand for bus and metro public transport services is more sensitive to changes in restrictions than the demand for boats, and being also influenced by the place of visit [11].

To complement the previous findings [12] analyzed the impacts of COVID-19 on modal shift. The results indicate that 40% of the participants recognized that the pandemic made them change their habits; also, 40% of participants said that they avoided public transport. Finally, the study concludes that the overall modal shift is away from sustainable solutions and towards individual vehicles. This modal shift is corroborated by [13, 14] who identified an increase in the use of private cars, but also by [15] who identified an increase in bicycle sales, indicating a preference for cycling or walking over other means of transport.

The pandemic introduced a high level of uncertainty regarding the recovery of demand for public transport. Previous studies have highlighted the challenges faced by transport systems in predicting and adapting to fluctuating passenger numbers. For instance, [16] discuss the complexities in forecasting demand levels amidst such uncertainties.

In response to the pandemic, various measures have been implemented worldwide to mitigate the spread of the virus and ensure passenger safety. These measures include enhancing sanitation protocols, implementing social distancing, mandating face masks, and utilizing contactless payment systems. However, the effectiveness and acceptance of these measures have varied, influencing their overall impact on public transport systems [17].

Social distancing, a critical measure for controlling the virus's spread, was initially overlooked in many analyses but has since been recognized as a vital component in the strategy to maintain safe public transport operations. Research by [18] provides valuable insights into the effects of social distancing on public transport capacity and operations and [19] show how canceling

non-reserved seats at high speed rail have decreased the number of passengers willing to travel.

Furthermore, the pandemic has necessitated a reevaluation of public transport policies and practices to adapt to the new normal. Studies have documented various measures and their impacts on public transport systems, such as [20] who review the operational adaptations and challenges faced by transit agencies during the COVID-19 crisis.

Based on the above, it is possible to verify that there are several studies on the phenomenon. Some studies are based on surveys [8, 16–18], which introduces a certain bias in relation to the sample [8]. Others study people's mobility during COVID based on cellphone location data [5, 16, 19–21]. This also introduces bias, as mobile phones are not universal and using distances to predict travel behavior can be error-prone [22]. And finally, most of these studies look at the initial impacts of COVID-19, lacking a long-term analysis of the phenomenon [5, 10, 23, 24].

Therefore, this article fills an important gap in the literature by analyzing automated fare collection (AFC) data over an extended period, from January 2019 to December 2020, and spanning two waves of infection, with the first wave of infection occurring from March to May 2020, and the second wave of infection occurring from November to December 2020. In this case, the entire population that uses public transport is analyzed and not just a sample, constituting an important example of what happened in reality. This builds upon existing literature [4, 6] and aims to further enrich the understanding of public transport usage during the pandemic by addressing specific gaps and providing unique contributions, namely by (i) extending the temporal scope, beyond the initial lockdowns; (ii) providing a comprehensive spatial and temporal analysis; (iii) incorporating sociodemographic characteristics of passengers, such as age, gender, and income levels; and (iv) analyzing the impact of COVID-19 on various modes of public transport, including buses, metro, and trains. Furthermore, Portugal in general and the Porto Metropolitan Area (AMP) in particular are an interesting case as Portugal was one of the last countries in Europe to be hit by the pandemic, having had time to react in a timely manner after seeing the devastating effects that were being caused in countries like Italy and Spain. The measures implemented in Portugal have been recognized for having slowed down the spread of the virus and kept the number of deaths among the lowest in Europe.

Thus, this study aims to answer the following research questions:

1. How did COVID-19 affect public transport usage patterns in time, in terms of month, days and hours, compared to the pre-COVID year?
2. How did COVID-19 impact passenger demand for different modes of public transport, namely bus, metro, and train?
3. What was the impact of COVID-19 on the travel behavior of public transport passengers with different sociodemographic characteristics? Did elderly individuals use public transport less due to COVID-19? Did women reduce their use of public transport due to COVID-19? How did income levels affect travel patterns during COVID-19?
4. How did COVID-19 affect public transport usage patterns, both spatially and temporally, compared to the pre-COVID year?

To answer these questions, this work analyses data from the AFC system of the AMP, Portugal, during different stages of the pandemic and pre-pandemic operations. Understanding this phenomenon is crucial to improve public transport planning and avoid the worst effects in similar future situations. The remainder of this paper is structured as follows. The next section introduces the case study and describes the methods used to conduct this study. Section 3 presents the results of the analysis. Section 4 discusses the main findings. Finally, Sect. 5 summarizes the main conclusions.

2 Data and methods

This section describes the data sources that were used in this work as well as the methodological approach.

2.1 Data sources

This work consists of analyzing AFC data from the AMP for the years 2019 and 2020. The main objective was to compare the year before the COVID (2019) and the year of the onset of the COVID pandemic (2020), in order to extract valuable information about the mobility behaviors of urban public transport passengers during the two periods under analysis.

For this purpose, the transaction records of the AMP AFC system were analyzed, which in 2019 registered 175.50 million transaction records [25] and in 2020 registered 106.20 million transaction records [26]. Every time a passenger taps a travel card on a reader, the Andante system generates a transaction record, with various related information. For the analysis carried out, the following are particularly relevant: travel card ID, ticket reader ID, provider code, type of discount, type of travel card, transport operator, time of transaction record, origin AMP zone, origin (stations / bus stops), and estimated alighting zone.

Furthermore, additional data sources were used, such as the geographic locations of stations/stops and the geo-location of AMP points-of-interest, retrieved from Google places API. This last dataset consists of 75.000 places for a rectangular area that covered most of the AMP, with information about the name of the place, category (e.g. restaurant, gym, hospital, school), latitude and longitude.

2.2 Methodological approach

The primary data used in this study are two years of AFC entries for the AMP Andante system, corresponding to more than 120Gb of data. So the first step is to create a structure to support the data in the form of a PostgreSQL database. The data may have some inconsistent or irrelevant entries as the raw data provided has not been extensively filtered. Once the database was complete, filtering and cleaning the AFC data was the next step. Once the data are properly verified and ready for use, the exploratory analysis of the data was carried out. Through specific queries to the database, results were obtained that can be used for an exploratory analysis, which allows the identification of patterns and conclusions. The outline of the approach is as follows:

i. Creation of the Database environment: through analysis of the datasets provided, an entity-relationship diagram (see Fig. 1) was created and a PostreSQL database was set up using a python script.
ii. Filtering of the datasets: filters were created for each dataset to remove all entries with incorrect values or test entries from the Andante system.
iii. Creation of the main queries: the extraction of information was performed mainly through queries to the database. The queries were created, implemented and run in order to produce statistically relevant data for analyzing behavioral changes over the two years. Figure 2 shows an example of a developed query.
iv. Visual Representation of Google Places and Stops Data: using the Kepler.gl tool [27] to represent the stops data obtained as well as the data from Google Places retrieved.
v. Temporal analysis of the AFC data: analyzing how the AFC entries changed over the two years and correlating this with implemented policies.
vi. Spatial analysis of the AFC data: analysis of how different zones and stops of the public transport network were affected by the pandemic using the

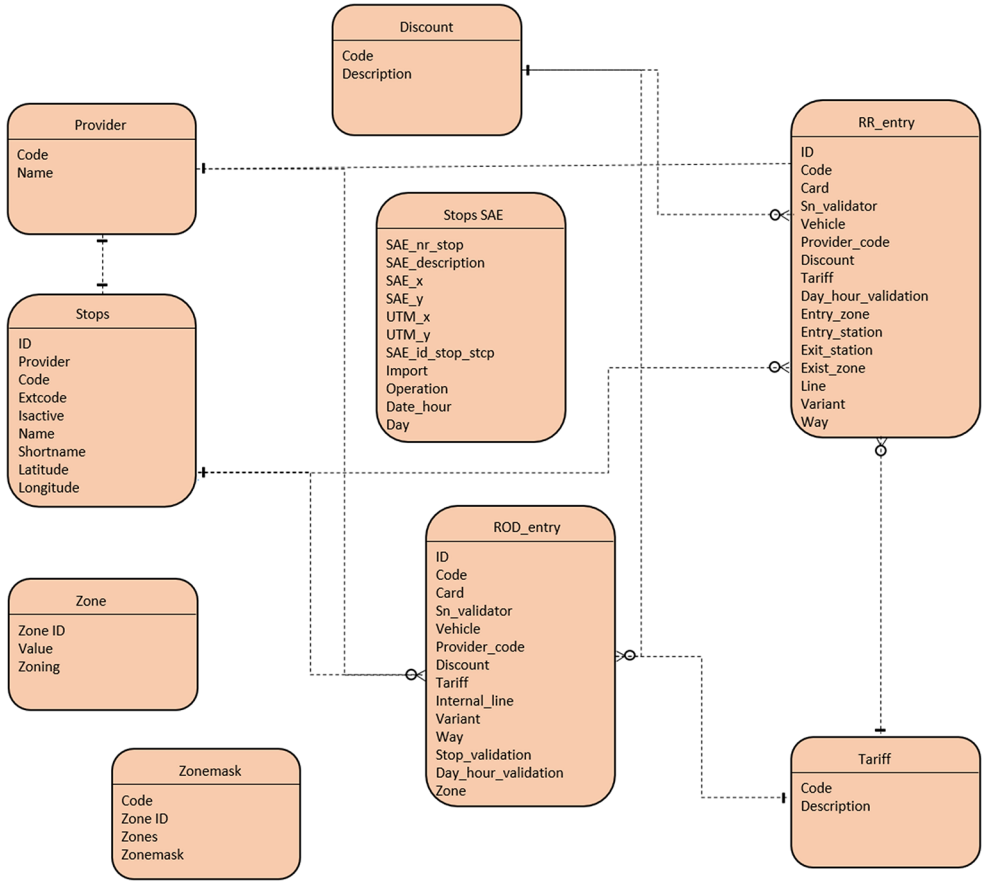

Fig. 1 Entity-relationship diagram for PostgreSQL database

```
sql_rr = '''SELECT COUNT(*)
FROM  rr_entries
WHERE EXTRACT(YEAR FROM data_hora_validacao) = {}
AND EXTRACT(MONTH FROM data_hora_validacao) = {}
AND EXTRACT(HOUR FROM data_hora_validacao) = {};'''
...
def trip_hour(data, y, m):
    record = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
        0]
    i = 0
    while i <= 23:
        if data == 1:
            cursor.execute(sql_rod.format(y, m, str(i)))
        elif data == 2:
            cursor.execute(sql_rr.format(y, m, str(i)))
        result = cursor.fetchone()[0]
        record[i] += result
        ...
```

Fig. 2 SQL query to obtain and store the number of trips for each hour of a day for a month

Kepler.gl tool and Google Places data to look at specific points of interest.

vii. Spatio-temporal analysis of the AFC data: cross-referencing geographic analysis with temporal analysis and draw conclusions about affected global regions for each period using spatial representations created with Kepler.gl. Incorporate the visual analysis of AFC and the Places and Stops data to determine possible impacts of the effects of COVID-19 over time for specific points of interest.

viii. Sociodemographic analysis of the AFC data: analysis and comparison of travel behaviors of different passenger profiles over time.

Finally, with descriptive statistics and visual representations created, conclusions were drawn on what is believed to be some of the impacts of the COVID-19 pandemic, particularly the impact of the lockdowns and public safety measures.

3 Application to the Metropolitan Area of Porto case study

This section presents a brief contextualization of the case of Portugal, regarding the policy measures that were implemented during the COVID-19 pandemic and the public transport services of the AMP. It also presents the main results of the analysis performed. It begins with the results from the temporal analysis of the public transport usage before and during COVID, followed by the passengers' demand for different public transport services. Then it details the socio-demographic analysis and the spatial and temporal analysis of the public transport usage before and during COVID.

3.1 Contextualization of the case of Portugal

3.1.1 Evolution of Portuguese policy measures during COVID-19

Portugal has remained free of COVID-19 longer than most other countries in Europe. The first two cases were detected in Porto on March 2, 2020; the first being a doctor returning from vacation in Italy, and the second being a worker from Spain. After the presentation of the first cases, the country quickly implemented measures to flatten the contagion curve. The main policies implemented in Portugal during 2020 are presented in Table 1. As is it possible to observe, Portugal has been through several waves of infections and had restrictions imposed, withdrawn and imposed again several times.

Portuguese law envisages three possible states to address catastrophes or severe accidents in the law of civil protection bases (law nº 27/2006 [28]), namely: state of alert, state of contingency and state of calamity. An even more severe state can be implemented, called state of emergency, proclaimed in the Portuguese constitution article nº138. During periods where one of these states has been issued, citizens that disobey orders from the authorities can be charged with a crime of disobedience which incurs a maximum sentence of one year and four months of jail time.

3.1.2 Public transport in Metropolitan Area of Porto

The city of Porto is the second largest city in Portugal, with a metropolitan area of more than 2000 km^2, where more than 1.7 million people live. Porto's public transport sector comprises an extensive network of metro, bus, and train services. The metro service alone provides trips for tens of millions of people every year, having reached a record 71 million trips in the year 2019; this number

Table 1 Timeline of the main government policies implemented in Portugal in 2020 to combat the COVID-19 pandemic

Measure	Description	Date
State of Emergency	The government declares its first state of emergency, starting its first lockdown	March 19, 2020
Restrictions lifted	Small stores started to re-open, public transport is back with 2/3 capacity, work from home when possible, prohibition of gatherings over 10 people, libraries and public archives re-open, individual outdoor sports activities allowed	May 4, 2020
Restrictions lifted	The last 2 years of secondary school reopened along with restaurants, cafes, medium-sized stores and nurseries, all these with mandatory mask usage, museums monuments, art galleries allowed to open	May 18, 2020
Restriction for beach overcrowding added	A law went into effect to combat overcrowding in beaches during the summer of 2020	May 25, 2020
Restrictions lifted	Community Religious ceremonies, work-from-home becomes partial, large scale stores open, kindergartens and day-cares re-open, cinemas, theaters, public showrooms re-open, official national football activities re-instated	May 31 and June 1, 2022
Restrictions lifted	The country begins to transition to a state of contingency and alert at more local levels continuing to ease more measures	August 1, 2020
Re-instating restrictions	With a rise in cases the country returns to a country-wide state of contingency, multiple measures are re-instated such as a reduction in maximum number of people allowed in indoor gatherings	September 15, 2020
In-person schooling	Even with an increase in cases the government deemed it necessary that schools returned to in-person classes, while universities mainly resorted to mixed teaching	September 17, 2020
Re-instating restrictions	Reinstating of the state of calamity	October 15, 2020
Re-instating restrictions	Reinstating of the state of emergency	November 24, 2020

is followed closely by the number of trips registered for the leading public bus provider of the region Sociedade de Transportes Coletivos do Porto (STCP) with over 69 million trips recorded, 17 private transport operators that also use the Andante system had over 26 million trips recorded, and lastly, Comboios de Portugal (CP) registered over 8 million train transaction records [25]. Besides the three leading operators, others exist; notably, there are multiple smaller but prominent bus providers in the region, such as Viabus, Transcovizela, Transdev, Mondinense and ETG. Back in the end of 2002 Metro do Porto, STCP and CP joined together to create a business group called Transportes Intermodais do Porto (TIP), which is responsible for the management of the Andante ticketing system.

All transport services mentioned above can be used using the Andante card, an AFC entry-only system. AMP is divided into zones and when users load the Andante travel card they choose the type of ticket they want depending on how many zones they will pass through. For example, to complete a trip that crosses four zones a passenger would need to buy a Z4 ticket. There are several different types of tickets and cards, that are presented in detail in the Appendix.

The AFC system is an entry-only system, which means that passenger has to validate his travel card at the beginning of the journey or when changing vehicles, but do not need to validate it at the end of the journey. This means that there are only transaction records from entry and not to the alighting station, the latter must be estimated. The price to pay for the Andante pass also depends on the characteristics of the passenger, namely age and income. Young and old people have a discount on travel, as well as people with lower incomes.

3.2 Temporal analysis of public transport usage before and during COVID

To carry out a temporal analysis, first the evolution of the public transport usage before and during the pandemic was analyzed over the months, then over the days of the week and finally over the day.

3.2.1 Analysis per month

The evolution of the pandemic over the months is shown in Table 2 and in Fig. 3. A careful analysis of Table 2 shows that there was an initial drop in total trips in February, which is consistent with the behavior of the previous year. However, from February to March, there is a substantial drop of 54.4% in the number of trips compared to February. This was due to the start of the lockdown in mid-March. Initially, March was on track to see an increase from February's 15.7 million transaction records.

Table 2 Number of travel card records per month during 2020 and corresponding variation between months

Month	Number of trip records per month during 2020	Variation between month *n* and month *n*-1
January	16.153.955	
February	15.720.016	-2.7%
March	7.168.270	-54.4%
April	30.052	-99.6%
May	4.321.219	+14,279%
June	6.863.744	+58.8%
July	9.021.687	+31.4%
August	8.360.529	-7.3%
September	10.315.576	+23.4%
October	11.024.597	+6.4%
November	9.338.894	-15.3%
December	8.261.252	-11.5%

The full impact of the lockdown is evident in April, with an extreme 99.6% decrease from March, highlighting not only the minimal public transport usage due to strict lockdown measures but also the fact that no public transport entries were recorded during this month. The beginning of easing restrictions led to a 14,279% increase from April, though this still represents a 39.7% drop from March. This marks the start of the recovery phase as small stores reopened and public transport resumed at reduced capacity.

Starting with May, the recovery process is initiated, with May registering under a third of the number of trips from February, the last whole month of trip records. However, from May to June, a significant increase of 58.8% was registered, due to a continued easing, including the reopening of larger stores and cultural venues; this would, however, be the most significant single increase in trip numbers. After the massive increase to June, proceeding to July, the recovery slowed down to a total increase of 31.4% total trips, still a considerable increase but significantly lower than the previous.

From July to August, the first decrease in trip numbers since the end of lockdown was registered, a small decrease of only 7.3% but a decrease nonetheless. This is a common pattern in previous years as people tend to travel less during the holiday period. For this reason, it is thought that this decrease is not directly related to COVID. Also, after the small setback of August, the number of trips increased again by 23.4%.

Resuming in-person schooling and the state of contingency led to a 23.4% increase in trips in September as people returned to routine activities. During October the stated of calamity was reinstating, and despite rising cases, the number of trips increased by 6.4%, though the smallest increase since the recovery phase began. After October, the number of COVID cases in the country started to rise, and during November, the public safety measures started to return and led to a 15.3% decrease in trip totals, followed by an 11.5% decrease in December due to the continued restrictions and numerous public holidays.

Figure 3 shows the monthly public transport trips for 2019 and 2020, highlighting key policy changes during the pandemic and its correlation with variations in trip numbers. Through the analysis of Fig. 3, and as mentioned earlier, assuming that the pattern present in the year 2019 is a normal pattern of trip fluctuation for a regular year, the year 2020 was on track to achieve higher

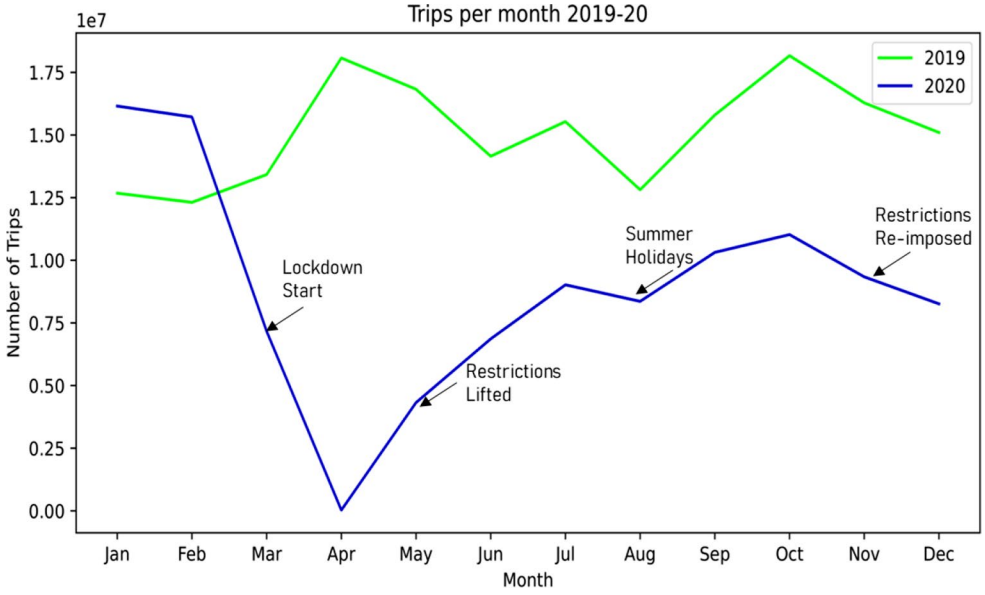

Fig. 3 Comparative plot of the number of trips for each month for 2019 and 2020 and different policies imposed

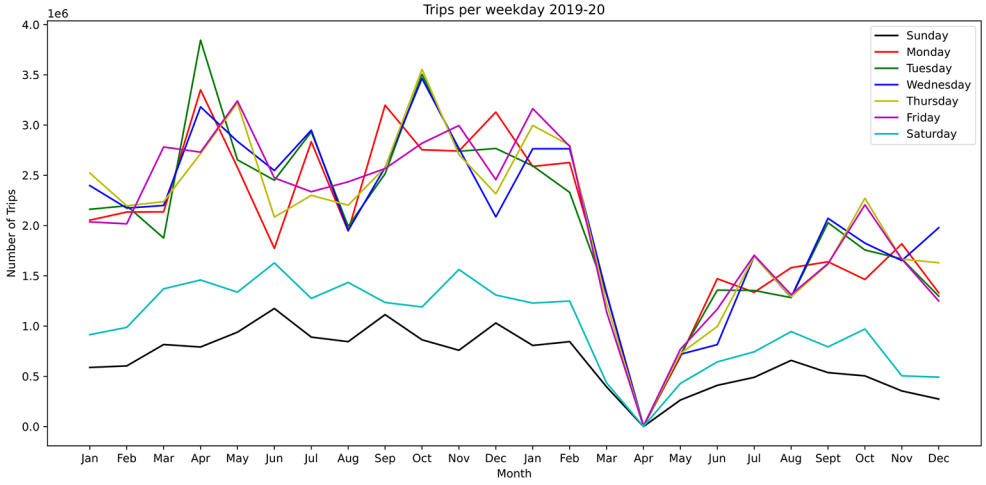

Fig. 4 Evolution of travel records by day of the week from January 2019 to December 2020

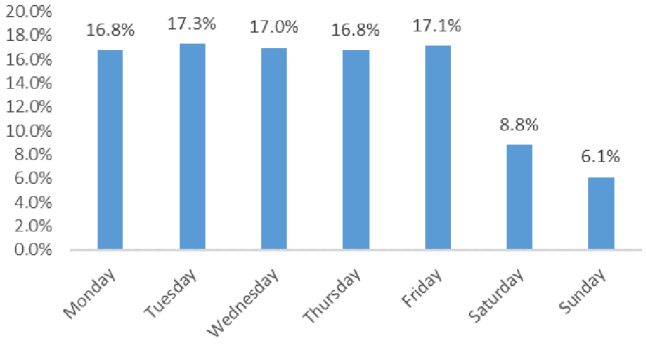

Fig. 5 Percentage of trips by day of the week for the 8-month period from May to December 2019

totals than 2019. Second, the fluctuation pattern presents in 2019 is also reflected in 2020 after the month of May. In particular, looking at the months from the second half of the year, a more homogenized version of the same pattern seems to be manifesting itself, which also corroborates the assertion that the August drop was not related to the COVID-19 pandemic. In short, after May, the same trends are observed, but with less amplitude in 2020.

In short, through data analysis it is possible to identify three important phases. The first is related with the initial significant impact triggered by the onset of the pandemic and subsequent lockdowns that drastically reduced public transport usage, with April 2020 being an extreme outlier. This phase is followed by recovery phases, with a gradual recovery beginning in May and characterized by substantial month-on-month increases, though with some seasonal fluctuations. Then, the resurgence of COVID-19 cases in late 2020 led to renewed declines in public transport usage.

3.2.2 Analysis by days of the week

An analysis was carried out by day of the week over the two years under analysis, which is summarized in Fig. 4. In general, it is possible to verify that during the week more trips are made in public transport than at the weekend. This trend continued during the COVID period, but with lower travel numbers on all days of the week.

Comparing the 8 last months of 2019 with the 8 last months of 2020 (see Figs. 5 and 6), during 2019 the trip records on Saturdays represented 8.8% and on Sundays 6.1% of the total trip records, while during 2020 the trip records on Saturdays represented 8.2% and on Sundays 5.2% of the total week trip records. This shows a reduction in weekend travel, which could indicate a decrease in leisure and non-essential trips, but further studies would be needed to corroborate this.

In short, public transport usage remained higher on weekdays compared to weekends throughout the pandemic period, albeit with reduced total numbers. This reflects the continued necessity of weekday travel for essential activities.

As an example, Figs. 7 and 8 show the evolution of travel records for the months of March 2020, when the first cases of COVID were detected, and May 2020, when confinement measures began to be lifted. Although being one of the last European nations to start having COVID-19 cases, Portugal quickly transitioned from detecting the

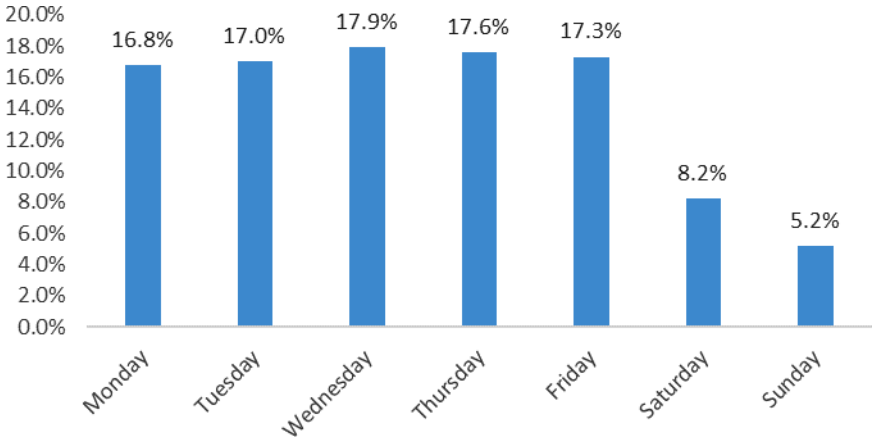

Fig. 6 Percentage of trips by day of the week for the 8-month period from May to December 2020

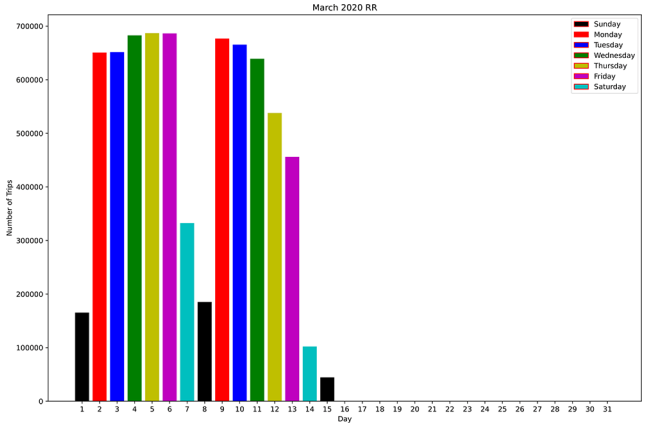

Fig. 7 Number of trips made per day during the month of March 2020

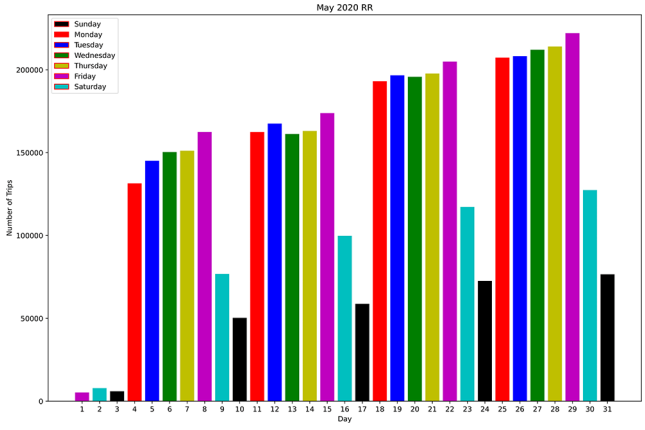

Fig. 8 Number of trips made per day during the month of May 2020

first cases inside the borders to a nationwide lockdown, and all this was in the month of March 2020.

In Fig. 7 it can be seen that the detection of the first cases had no impact on usage in the days immediately after the news broke. This is followed by a drastic drop in usage as of Tuesday, March 10, 2020; that is when the lockdown was announced for the next week. In May 2020, the nationwide lockdown was lifted and the public transport service recovery began. Looking at Fig. 8, the pattern of growth is clear over the month, apparently indicating a steady overall recovery.

Although being one of the last European nations to start having COVID-19 cases, Portugal quickly transitioned from detecting the first cases inside the borders to

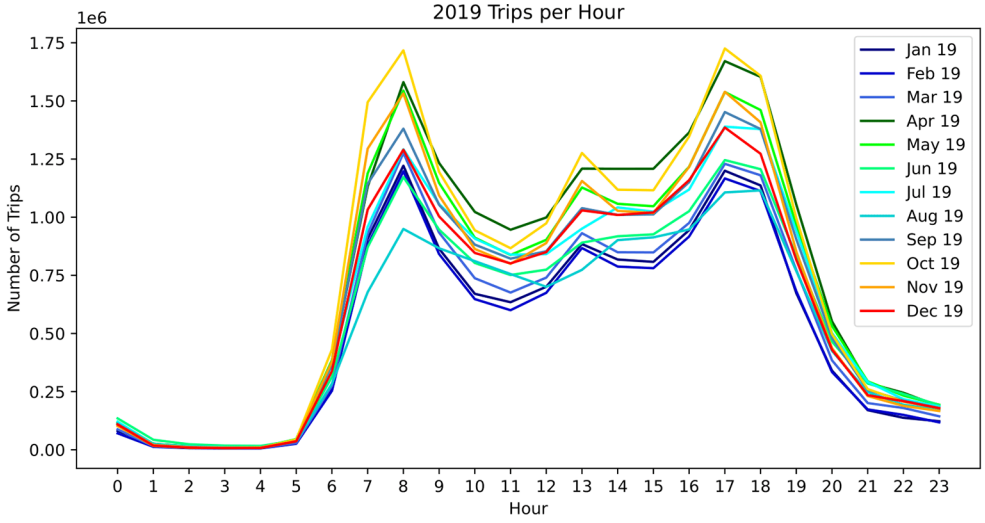

Fig. 9 Trips per hour for each month of 2019

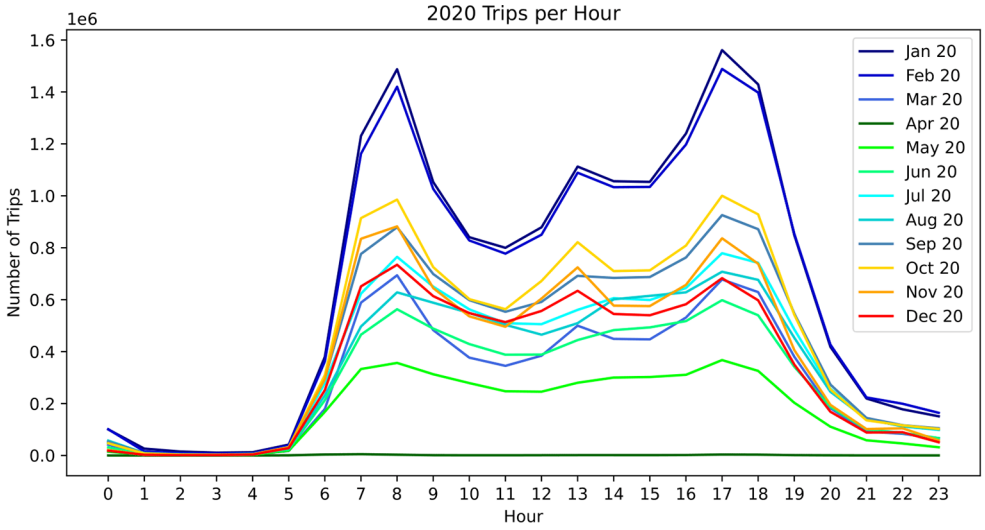

Fig. 10 Trips per hour for each month of 2020

a nationwide lockdown, and all this was in the month of March 2020.

3.2.3 Analysis by hours of the day

Observing Fig. 9, which represents the total number of trips per hour per month in 2019, a clear trend can be identified. The data shows a minimal number of trips in the early hours and as the morning starts, the number of trips starts to grow exponentially, peaking around 8:00 am, then decreasing progressively. The second rise begins to manifest around 12:00 and 13:00, followed by another drop. Depending on the month, this decrease changes in magnitude more than in the morning. At the end of the afternoon, the number of trips increases again, around 17:00 to 18:00, the peak is reached, followed by a decrease for the night. The two most prominent peaks of the day can be observed in the morning around 8:00 am and in the afternoon around 5:00 pm, with a smaller one occurring at 12:00 pm.

When looking at Fig. 10 the first two months of the year 2020 stand out, whose presence in the graph shows the impact of the lockdown. January and February 2020 have very similar lines to the months of 2019 from Fig. 9, and to a lesser extent, March as well, although with a reduced number of total trips. The graph clearly shows that the distribution of trips throughout the day has been highly homogenized. The two prominent peaks from 2019 are not that far off the numbers during other times of day, although still clearly present.

To complement the analysis carried out and understand the full impact of the phenomenon, Fig. 11 was created, which shows the total trips per hour for each of the years. The graph clearly shows that the distribution of trips throughout the day was highly homogenized. The

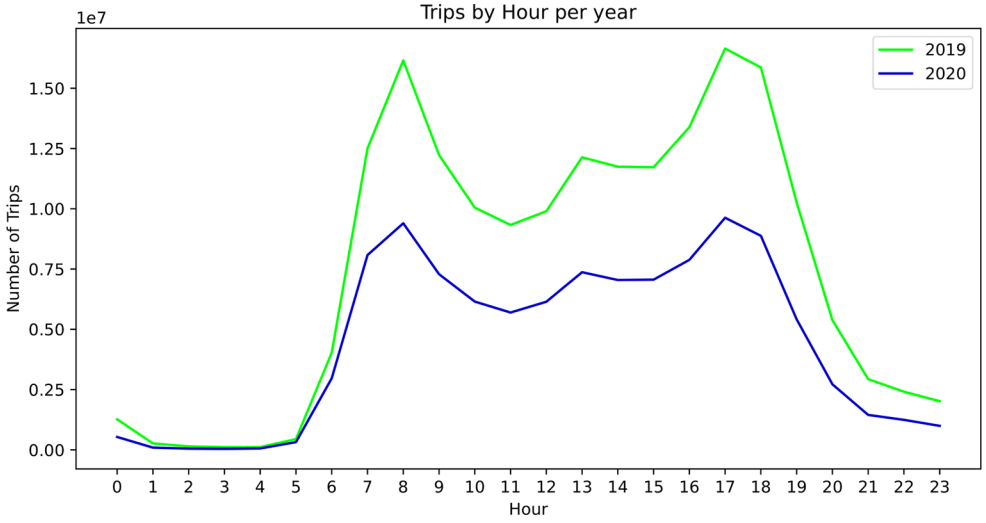

Fig. 11 Total trips per hour for years 2019 and 2020

Table 3 Percentage and number of registered trips between May 2019 and December 2020 by public transport operator

	Metro do porto		STCP		CP		Private bus operators
	%	Nr	%	Nr	%	Nr	%
May-Dec 2019	39.9%	49,705,973	38.6%	48,075,066	5.3%	6,545,409	21.5%
Jan-Mar 2020	39.2%	15,310,309	37.7%	14,725,939	5.8%	2,247,545	23.1%
May-Dec 2020	35.8%	24,173,077	42.9%	28,946,927	5.5%	3,719,434	21.3%

two prominent peaks of 2019 are not that far off the numbers during other times of the day, although they are still clearly present. Even with January and February included in the 2020 line numbers, it is clear that the distribution is much less uneven and skewed towards the peak hours of 8am and 5pm.

In short, pre-pandemic patterns showed clear morning and afternoon peaks. During the pandemic, these peaks became less pronounced, indicating a more even distribution of trips throughout the day. This suggests changes in commuting patterns, likely due to altered work and school schedules and increased remote activities.

3.3 Passengers demand for different public transport operators before and during COVID

Passenger demand was analyzed in relation to public transport operators during the years 2019 and 2020 and is summarized in Table 3. The data from January to March 2019 are not presented for two reasons: firstly, because for the comparison period in question they were not at all necessary, secondly because in April 2019 the Tariff Reduction Plan (PART) came into force in AMP, which drastically reduced the prices of public transport having considerably changed the demand for public transport. Introducing the data before PART into the analysis would cause additional entropy resulting from the tariff change that occurred. Therefore, analysis of Table 3 show that from May to December 2019, the light rail, Metro do Porto, recorded the highest number of trips (39.9%), followed by the public bus operator, STCP, with a market share of 38.6%. The trains operator, CP, represent a residual demand of 5.3%, followed by the 17 private bus operators which together represent 21.5% of total demand.

At the beginning of 2020, Metro do Porto reinforced its prominent position, being the preferred means of public transport for AMP passengers, with a 39.2% market share against 37.7% for STCP, which lost market to trains and private bus operators. However, in the period of COVID, there was a reversal of the trend, with people starting to prefer public buses (42.9%) instead of lightrail (35.8%). Variations for private trains and buses before and during COVID are minimal.

This analysis indicates a shift in preferences during COVID-19, in which we move from a state of pre-pandemic stability, where Metro do Porto and STCP were the dominant public transport operators, with relatively stable and significant market shares, to a state of pandemic-induced shifts. During the pandemic, a clear shift occurred with passengers favoring public buses (STCP) over the metro (Metro do Porto), possibly due to changes in travel patterns, safety perceptions, or service adjustments.

Table 4 Percentage and number of registered trips between May 2019 and December 2020 by passenger age group

	Children and youth (under 25y)		Adults (24-64y)		Elderly (+65y)	
	%	Nr	%	Nr	%	Nr
May-Dec 2019	16.0%	19,753,797	69.1%	86,249,059	14.9%	18,576,500
Jan-Mar 2020	17.7%	6,922,697	68.2%	26,626,473	14.0%	5,472,477
May-Dec 2020	11.8%	7,872,596	73.4%	49,137,393	14.8%	9,928,084

Table 5 Percentage and number of registered trips between May 2019 and December 2020 by passenger income level

	Normal income		Low income	
	%	Nr	%	Nr
May-Dec 2019	81.1%	101.021.621	18.9%	23.557.732
Jan-Mar 2020	81.4%	31.745.158	18.6%	72.64.267
May-Dec 2020	82.0%	55.343.795	18.0%	12.115.031

3.4 Socio-demographic analysis of public transport usage before and during COVID

As mentioned earlier, the analyzed AFC data has anonymous information about user profiles in terms of age and income levels useful for the analysis. Hence, an analysis was carried out for three age groups: children and young people up to 25 years old, adults between 26 and 64 years old and elderly people over 65 years old. An income-based analysis was also carried out, comparing people with lower incomes, entitled to a discount on the price of public transport tickets, with people with normal average incomes. Finally, an analysis was carried out that crosses the two types of user profiles based on age and income.

Table 4 shows the trips registered between May 2019 and December 2020 by passenger age group. In general terms, it appears that the age group of adults is the one that uses public transport the most, although it should be noted that it is also the one that covers the most ages.

From May to December 2019, adults represented around 69.1% of the demand, children and young people around 16.0% and the elderly around 14.9%. At the beginning of 2020, there were some slight fluctuations, but the values remained close to the previous ones.

During the COVID-19 period, there was a decrease in the use of public transport by children and young people (11.8%). As expected, the lockdown and online classes significantly impacted this group, particularly in their use of public transport for education. What was not expected, however, was that the group containing the elderly population would increase. The age group of adults returned to the percentages of 2019, but obviously lower in absolute number of total trips. This corroborates the hypothesis that elderly individuals maintained or increased their use of public transport during the pandemic due to the necessity of accessing essential services and the lack of alternative transportation options.

When analyzing the mobility of public transport passengers according to income level, few differences are observed in the analyzed period (see Table 5). The majority of public transport users, around 80%, are of a normal profile, not being entitled to discounts on the price of public transport. More specifically, there is a slight increase in normal profile users from 81.1% from May to December 2019 to 81.4% from January to March 2020. In the analyzed COVID period, from May to December 2020, this value rises to 82%, with low-income passengers accounting for 18% of total transaction records. This corroborates the hypothesis that individuals with lower income, who likely have less availability of private cars, did not increase their public transport travel significantly during the pandemic compared to individuals with normal income levels.

After an individual analysis of the sociodemographic characteristics, age and income, of public transport passengers, an analysis was carried out that crossed the two characteristics. This proved to be a challenge, especially in the case of low-income elderly people, as it was difficult to identify this group in the data. As an example, the Social+A type of discount can be attributed to Seniors through the government fund Complemento Solidário de Idosos (CSI), but these are not identified as such, therefore Elderly Low Income group is seriously under-represented.

Despite this, when analyzing the two user profiles together, age and income, it is possible to draw interesting conclusions (see Table 6). When comparing May-Dec 2019 with Jan-Mar 2020 it is possible to obverse a considerable increase in the number of children and youth normal income trips of more than 4% points, as well as a decrease in the adult normal income group of 2.3% points

Table 6 Percentage of registered trips between May 2019 and December 2020 by passenger age and income level

	Children and youth (under 25y)		Adults (24-64y)		Elderly (+65y)	
	Low income	Normal income	Low income	Normal income	Low income	Normal income
May-Dec 2019	5.7%	7.3%	13.8%	57.8%	0.0%	15.4%
Jan-Mar 2020	5.9%	11.9%	12.8%	55.5%	0.0%	14.0%
May-Dec 2020	3.7%	8.0%	14.4%	59.1%	0.0%	14.8%

and decreases of 1.4 and 1% points in the elderly normal and adult low-income groups, respectively.

When analyzing the period during COVID, May-Dec 2020, considerable decreases are seen in both the low and normal income children and youth groups, of 2.2 and 3.9% points respectively, and these are coupled with increases in both adult income groups. The adult low income group saw an increase of 1.6% points and the normal group saw the most significant increase of all increasing by 3.6% points. Lastly an increase was also seen in the elderly normal income group of 0.8% points. The number of elderly low-income entries increased through all the periods, although their relevance is diminished.

The evidence is consistent with the decrease in use by young people, also showing that this was common for both low and normal income groups with a more considerable impact on the normal income group. The COVID-19 lockdown and public safety measures appear to have reversed the trends of slowly decreasing the number of adult ridership for low-income and normal-income individuals.

In summary, it can be concluded that adults remained the primary users of public transport before and during the pandemic, with their share remaining stable. On the other hand, the pandemic led to a decrease in youth usage and an increase in elderly usage, indicating differing impacts on these age groups. With regard to income, some stability can be seen, as the proportion of normal income users remained high and stable, while low-income users saw a slight decrease. These results, namely the increase in elderly travel and the stable usage among adults, highlight the role of public transport in providing essential services, even during a crisis.

3.5 Spatial and spatio-temporal analysis of public transport usage before and during COVID

In terms of spatial analysis, the evolution of the total number of validations per zone of the AMP was analyzed. As an example, the month of January 2020 (pre-COVID) and the month of September 2020 (period between waves of COVID infection) were selected. Comparing Figs. 12 and 13, it is possible to verify that there was no significant change in the busiest areas before and after COVID. Essentially, the greatest demand is concentrated in the city centers of Porto, Gaia, Matosinhos, with the more peri-urban areas registering the lowest records of trips in public transport.

In order to understand the impact of COVID in spatio-temporal, some stations/stops were selected for the analysis and their geographic location is represented in Fig. 14. These stations/stops were classified according to the characteristics of the predominant land use nearby, namely hospital, university, restaurants and shops and beachside. From the analysis of Table 7, it is possible to verify that the use of stations classified as universities, restaurants and shops and beachside decreased during the COVID period when compared to the pre-COVID period. On the other hand, the use of stations/stops classified as hospitals increased during the COVID period.

It can be concluded that central business districts and high-density ones experienced the most significant declines in public transport usage due to remote work, business closures, and reduced commercial activity. While, suburban and residential areas showed a more stable demand for public transport. This might be due to the necessity for essential travel within local communities and a lower adoption of remote work in these areas compared to central urban zones.

4 Discussion

This section analyzes and discusses some of the most relevant results presented in the previous section. First, it discusses the effects of public safety measures on the total ridership. It then discusses the trajectory and overall recovery in the post-lockdown period. Next, the impacts of COVID-19 on the use of public transport throughout the day, on different modes of public transport and on the travel behavior of different demographics are assessed.

4.1 Effects of the public safety measures on total ridership

After the COVID outbreak in Portugal, the first restrictions were implemented in the second week of March. However, these would soon be overshadowed by the implementation of the first lockdown. The lockdown lasted until May 4, when restrictions began to be eased and daily use of public transport restarted, but passenger limits per bus were capped at two-thirds of the total standard capacity.

The lifting of restrictions was done gradually throughout the month of May, as shown in Sect. 2.1. Comparing May and June numbers, the results seem to indicate a significant impact. June 2020 saw an increase of more than 58% in the use of public transport, it being essential to take into account that the growth trends presented in May throughout the month are of constant increases and that in the month of May itself the number of trips per day went from less than 150 thousand to close to 250 thousand. On the other hand, there is no doubt that the constant removal of restrictions contributed to a linear recovery in May and early June. After the third easing of restrictions, no more would be lifted during June and July. From the third survey until August, there was a steady growth in trips per day.

In early August, there is a final relaxation of restrictions, moving the country into contingency and alert states depending on the region and lifting low-level restrictions. Despite the lifting of restrictions, for the first time since the lockdown, the total number of trips

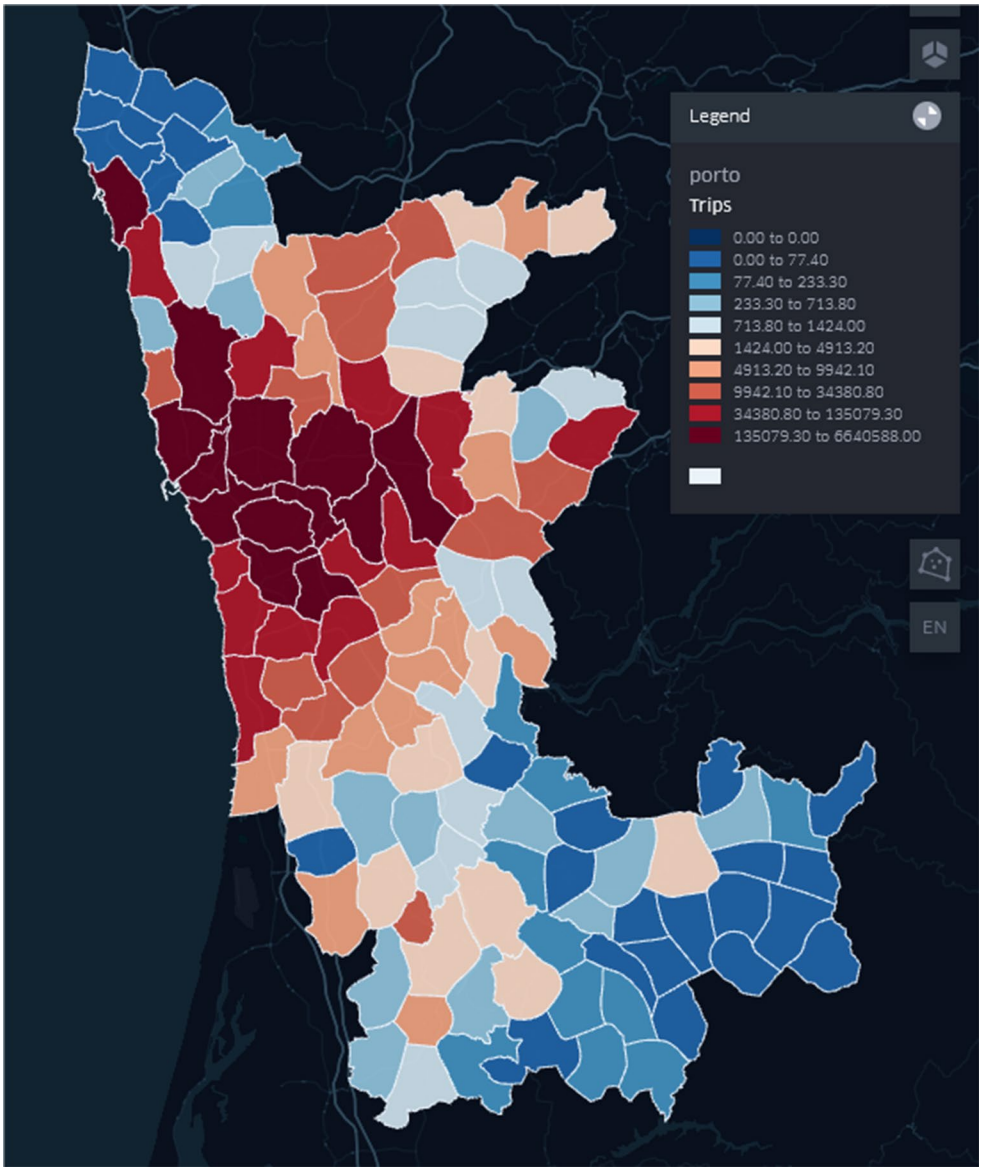

Fig. 12 2D color coded map representing the average number of trips per AMP zone during January 2020

decreased slightly in August. However, this decrease is believed to be unrelated to any specific public health and safety measure or pandemic.

With a slight increase in cases with the approach of the autumn season and the start of face-to-face teaching for all schools, the Government decided to place the country in a state of contingency on September 15th, re-establishing multiple restrictions, for example, public meetings again being limited to just six people.

On September 17, face-to-face schooling was immediately reflected in the data. There was a general increase in the use of transport, particularly by students. However, the government's fears of a second wave during autumn and winter began to materialize in mid-October, when the number of cases began to rise more rapidly. The state of the country went from a contingency instituted in September to a calamity. However, some restrictions were not reflected in the October data as it still showed increases in total numbers.

By the end of November, the second wave was undeniable, so the state of emergency was re-established and restrictions increased once more as the number of cases reached record numbers at the time. This would be the last increase in restrictions for the year 2020. The month of November had already seen a drop in total travel due to what is believed to be a mix of the increase in restrictions in October and the worsening number of cases. In December 2020, there was again a decrease in the number of trips on public transport, reflecting the measures implemented in November.

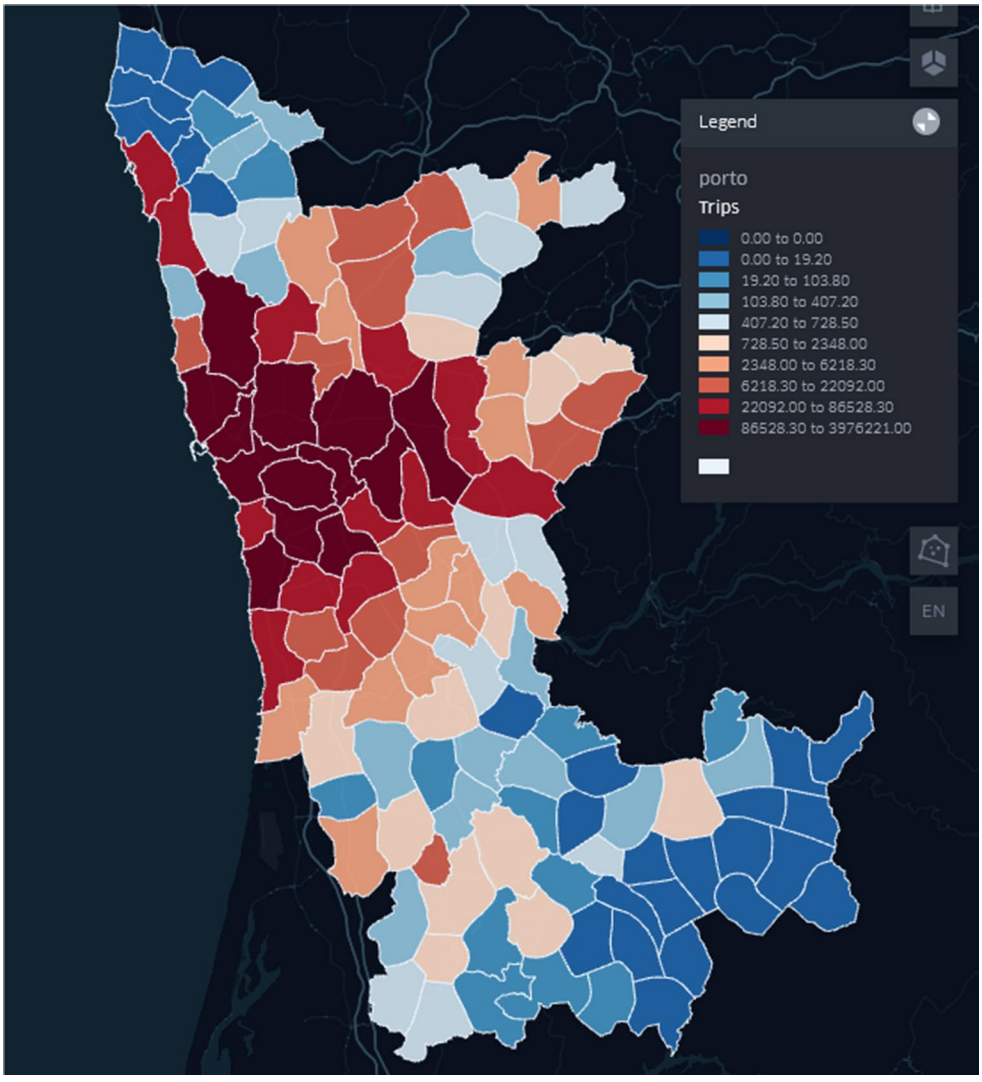

Fig. 13 2D color coded map representing the average number of trips per AMP zone during September 2020

In summary, the observed recovery periods suggest that public transport usage can rebound quickly as restrictions ease, highlighting its resilience. However, transport authorities should consider adaptive strategies to manage sudden drops in usage and facilitate rapid recovery, including flexible scheduling and enhanced safety measures.

4.2 Impact on public transport usage throughout the day

When analyzing pre-COVID data, in this case 2019, it appears that there are two significant peaks in the use of public transport during the day. The first corresponds to the morning rush hour, typically caused by most jobs and schools starting at 8am or 9am. After the first significant peak in congestion, there is a smaller peak around 1 pm, coinciding with lunchtime. The second major peak coincides with the time interval between 5 pm and 6 pm, which corresponds to the return home after a day at work.

When analyzing the period during COVID, the same three peaks of congestion are observed. However, the magnitude of these is substantially reduced, with the representation of trips during the day being much more homogeneous. The observation of these peaks is in line with previous studies [10].

Multiple factors are believed to be a significant influence on the reduction of these peaks. The widespread adoption of virtual classes and work from home effectively eliminated the most prominent reasons why the two most significant congestion spikes existed. This effect is particularly visible in the months immediately following the lockdown, such as May, June and July, when most schools were closed and people continued to work from home. With the return to face-to-face classes in September, and the return of some to face-to-face work,

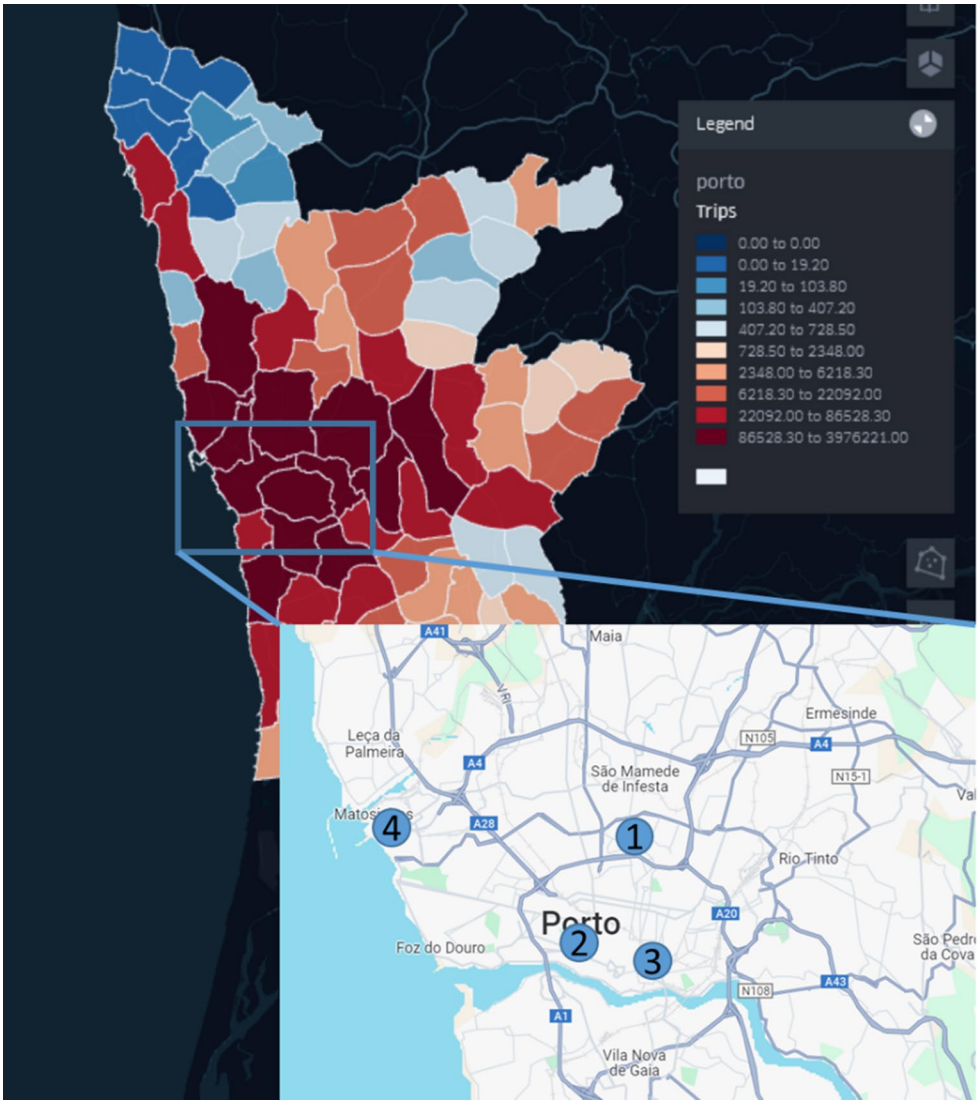

Fig. 14 Geographic location of stations/stops selected for analysis

Table 7 Number of trip records carried out during September 2019 and September 2020 in different stations/stops and land use types

Station/stop (location in map)	Land use type	No of trip records during Sep 2019	No of trip records during Sep 2020	Variation between Sep 2020 and Sep2019
Bus stop - Hospital São João (1)	Hospital	62.244	74.083	+ 19.02%
Metro station – IPO (1)	Hospital	32.641	40.412	+ 23.81%
Metro station - Polo Universitário (1)	University	82.445	38.479	-53.33%
Bus stop – Junta Massarelos 1 (2)	University	23.961	16.136	-32.66%
Bus stop – Junta Massarelos 2 (2)	University	25.010	12.842	-48.65%
Train station - São Bento (3)	Restaurants and stores	124.558	87.411	-29.82%
Metro station - São Bento (3)	Restaurants and stores	265.662	140.467	-47.13%
Metro station - Matosinhos sul (4)	Beachside	93.339	55.782	-40.24%
Bus stop - Matosinhos praia (4)	Beachside	18.577	13.150	-29.21%

the peaks are again more pronounced, but with a smaller amplitude than in 2019.

It is clear that the distribution of trips throughout the day during the pandemic has become more homogenized, indicating significant changes in commuting behaviors. However, changes in daily travel patterns underscore the importance of understanding and adapting to new travel behaviors, possibly incorporating flexible travel options to accommodate remote work and school trends.

4.3 Impact on different public transport modes

Due to the specific characteristics of each means of transport, it was expected that different impacts would affect each of the three: bus, lightrail and train.

The rail services provided by CP in the AMP were the least affected, in percentage of the three, in the eight months following the confinement, showing only a minimum drop of 0.3% points compared to the first three months of 2020 and reinforcing numbers higher than those in the same period eight-month period of 2019, where the percentage was 0.2% points lower. It is believed that the low fluctuation of these percentages is due to the fact that a significant percentage of trips made by train are trips to destinations outside the AMP or to and from regions for which the only other alternative is the car, in short, trips made by train are less likely to be replaced or completely removed as superfluous.

Lightrail has seen substantial reductions in the percentage of trips over the last eight months of 2020, with a reduction of more than 4% points in total share. With work from home being widely used during the post-lockdown period, the lightrail service, heavily centralized in downtown Porto and focused on providing connections from peripheral locations to the city center, has lost relevance because these offices spaces are not needed employees to commute to work in person.

Bus services were the biggest gainers in market share. As expected, STCP stands out from the other providers, increasing its total share by more than 5% points. Other bus service providers had mixed results, Gondomarense had a slight drop, but Espírito Santo had small increases. Bus service providers were expected to benefit from the loss of percentage points for the metro and train. Due to the nature of the bus as a means of transport, its level of adaptation is much higher than the lightrail and the train, not requiring as much infrastructure and having the possibility of changing routes to adapt to circumstances, which is one of the reasons that it is believed have helped this mode to increase their percentages. However, it is believed that the biggest reason is the negative impact suffered by the lightrail. With downtown Porto not being such a relevant destination, the increase in metro travel speed is starting to be worth less than the greater adaptability of using bus lines. In the literature analysis, [11] demonstrate that the demand for public transport services via buses and subways is more sensitive to changes in restrictions than the demand for boats, for example.

This pandemic-induced shifts requires public transport operators to adapt to changing passenger preferences, especially during crises. This includes enhancing bus services and ensuring safety and convenience to retain and attract passengers. Furthermore, understanding the reasons behind these shifts can help in strategic planning for future disruptions, ensuring that transport services remain resilient and responsive to passenger needs. Lastly, emphasizing safety measures and improving accessibility for all types of public transport can help regain and stabilize passenger demand during and after a crisis.

4.4 Impact on the travel behavior of different demographics

The impacts of a pandemic on different demographics are expected to differ considerably, keeping the overall negative impact overall. No demographic groups saw growth in the total number of trips, but the analysis showed changes in the percentage distribution for different subgroups.

Following the previously identified impact of the return to school, data from the eight months after confinement showed that the number of children and young people using public transport decreased considerably compared to the first three months of the year, with the drop being almost 6% points. This reversed previous trends. From the last eight months of 2019 to the first three of 2020, the percentage of trips taken by those under 25 years old has increased by precisely 4% points. These results are in line with the study carried out in Greece, in which younger people significantly reduced their use of transport compared to other ages during the pandemic [8].

The then lost percentage of those under 25 years old was mainly won by adults with an increase of more than 5% points and by the elderly with a slight increase of 0.8% points. The pandemic was expected to negatively impact the percentages of adults due to the widespread implementation of work from home, and the elderly, considered at risk, were expected to decrease their use of public transport. However, these factors were less relevant than the lack of face-to-face school activities.

In addition, an analysis was carried out to verify how the passengers' income influenced the impacts experienced. Low-income people were expected to have an increase in percentages because they have no other alternative to public transport, since people with medium or high incomes should abandon public transport at least temporarily. However, the results show that low-income

people were the ones who saw their percentages decrease, but only slightly, around 0.6% points, unlike [8] study, in which people with higher incomes were more likely to reduce their travel.

Finally, when cross-referencing income and age analyses, the data revealed that the effects were particularly devastating for the under-25 normal-income subgroup, with a drop of nearly 3% points. However, low-income under-25s were also negatively affected, with reductions of more than 2% points. As a result, the percentage of adults increased, specifically the subgroup of normal-income adults increased by 3.6% points, followed by the group of low-income adults with a 1.6% point increase in trip percentages.

This analysis indicate that public transport policies should consider targeted support for vulnerable groups, such as youth and low-income passengers, during disruptions. Furthermore, ensuring the safety and availability of public transport for essential travel is crucial, particularly for adults and elderly passengers. Lastly, transport operators need to adapt to changing travel patterns, possibly by increasing services during off-peak hours or ensuring better safety measures to encourage ridership among hesitant groups.

5 Conclusions

The main objective of this work was to identify the behaviors of public transport passengers induced by the context of the COVID-19 pandemic, lockdowns and restrictions through the analysis of AFC data of the AMP for the years 2019 and 2020. An analysis of the data was carried out from a temporal and spatial point of view and taking into account the sociodemographic characteristics of the passengers.

The analysis revealed that there was a generalized decrease in the use of public transport in the Porto Metropolitan Area after the recognition of the pandemic, in March 2020. After the confinement of April 2020, public transport resumed its activity, but always with very lower values than those recorded in 2019. It appears that the peaks between months of the year and between peak and off-peak hours are less pronounced, with a reduction in the use of all stations/stops in general. Those stations/stops that recorded values higher than 2019 are essentially those located next to large hospital units.

In the analysis carried out, a preference of passengers for the bus to the detriment of the light rail during COVID was also observed. In the pre-COVID period, the trend was reversed. This fact can be explained by several reasons, such as greater flexibility in adapting the buses to the routes and demand, greater control of the number of passengers inside the buses and higher travel speed due to the low number of vehicles circulating on the roads.

Additionally, when analyzing the socio-demographic data of public transport passengers, there is a marked reduction in the number of children and young people, largely due to the closure of schools during the pandemic. The drop is greater among young people from higher-income families, quite possibly because they have the possibility of adopting alternative means of transport. Surprisingly, the elderly maintained their percentage of using public transport, despite all the risk of suffering serious consequences from the virus.

The comprehensive analysis carried out suggests several strategic directions for improving public transport planning and ensuring resilience in future crises. First, given the quick rebound in usage post-restriction, transport authorities should implement flexible scheduling to accommodate sudden changes in demand. For instance, dynamic bus routing systems can adjust routes and frequencies based on real-time demand data. Maintaining high standards of cleanliness and safety is also crucial to regain and stabilize passenger demand, especially during crises. Regular disinfection of vehicles, mandatory mask policies, and providing hand sanitizers in stations and on transport modes are essential measures.

Policies should also target support for demographics most affected by travel disruptions, such as youth, low-income individuals, and the elderly. This support can include subsidized or free travel passes for essential workers and vulnerable populations during emergencies. Encouraging travel during off-peak hours can help distribute demand more evenly throughout the day, which can be achieved by offering discounted fares for travel during non-peak times.

Investing in bus infrastructure is another critical component in crisis response due to the adaptability of bus services. Developing dedicated bus lanes and priority signals can ensure reliability and speed, even during disruptions. Additionally, facilitating seamless connections between different modes of transport can enhance overall system resilience, with integrated ticketing systems and synchronized schedules between buses, trains, and lightrail being prime examples.

Finally, supporting remote work and learning can reduce pressure on transport systems during crises. Partnering with businesses and educational institutions to develop remote work and learning infrastructure and policies can significantly contribute to this effort. These strategies collectively ensure a more resilient and adaptive public transport system, capable of handling future crises effectively.

The limitations of this work are in themselves opportunities for future work, namely a deeper study on the impacts of COVID-19 on mobility habits in public transport, for example, through the correlation of the progression of recovery in an area with a certain type of land

use or through further study of socio-demographic data coupled with other data sources such as surveys. It would also be interesting if this analysis could be extended to subsequent years, 2021 and 2022, in order to be able to analyze the evolution and adaptation of the use of public transport to the different phases of the COVID pandemic.

Finally, with the possibility of analyzing more years of the pandemic, it is suggested to produce forecasting algorithms for recovery. Using further analysis of the effects of each type of restriction on passenger numbers, more travel data possibly from 2021 and beyond, and perhaps even data from other similar urban environments in Europe, a machine learning and artificial intelligence approach can be used to create algorithms that could predict how a city's public transport would recover from a disease outbreak. This may be relevant in the future should an epidemic or pandemic-level health crisis occur and would reduce the unpredictability of the situation, allowing for better allocation of resources during the crisis.

Appendix

In the AMP public transport network, there are several different types of tickets and cards available:

- Occasional Ticket: individual paper ticket purchased directly from the bus driver that is only valid for that particular bus and does not allow for changing vehicle.
- Blue Andante Card: a non-personalized rechargeable contactless paper card that allows passengers to purchase and charge several individual travel tickets for a type of zone, for example, a passenger can have 10 Z4 tickets in a card, but not 5 Z4 and 5 Z3 tickets. These cards are on sale at a large number of ticket stores and vending machines. Each ticket has a useful life of at least 1 h (varies according to the Z number). During this time, the passenger can use as many transport services as they wish without exceeding the limit of the zone where the first transaction was recorded.
- Andante 24: a 24-hour ticket that allows passengers to validate it as many times as they want for 24 h, similar to a daily ticket.
- Andante Pass: a personalized subscription-based card, paid monthly and non-transferable. It can include all zones of the AMP area or just a combination of 3 zones for a lower price. It is necessary to go to ticket stores to obtain this card.

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References

1. Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., Ren, R., Leung, K. S. M., Lau, E. H. Y., Wong, J. Y., Xing, X., Xiang, N., Wu, Y., Li, C., Chen, Q., Li, D., Liu, T., Zhao, J., Liu, M., Tu, W., Chen, C., Jin, L., Yang, R., Wang, Q., Zhou, S., Wang, R., Liu, H., Luo, Y., Liu, Y., Shao, G., Li, H., Tao, Z., Yang, Y., Deng, Z., Liu, B., Ma, Z., Zhang, Y., Shi, G., Lam, T. T. Y., Wu, J. T., Gao, G. F., Cowling, B. J., Yang, B., Leung, G. M., & Feng, Z. (2020). Early Transmission Dynamics in Wuhan, China, of Novel coronavirus–infected pneumonia. *New England Journal of Medicine*, *382*, 1199–1207. https://doi.org/10.1056/nejmoa2001316
2. WHO (2020). WHO Director-General's opening remarks at the media briefing on COVID-19–11 March 2020. *WHO Dir Gen Speeches* 4.
3. Fulgêncio, R., Ferreira, M. C., Abrantes, D., & Coimbra, M. (2022). Restart: A Route Planner to encourage the Use of Public Transport Services in a pandemic context. *Transp Res Procedia*, *62*, 123–130. https://doi.org/10.1016/j.trpro.2022.02.016
4. Aloi, A., Alonso, B., Benavente, J., Cordera, R., Echániz, E., González, F., Ladisa, C., Lezama-Romanelli, R., López-Parra, Mazzei, V., Perrucci, L., Prieto-Quintana, D., Rodríguez, A., & Sañudo, R. (2020). Effects of the COVID-19 lockdown on urban mobility: Empirical evidence from the city of Santander (Spain). *Sustain*, *12*. https://doi.org/10.3390/su12093870
5. Haddawy, P., Lawpoolsri, S., Sa-Ngamuang, C., Yin, M. S., Barkowsky, T., Wiratsudakul, A., Kaewkungwal, J., Khamsiriwatchara, A., Sa-Angchai, P., Sattabongkot, J., & Cui, L. (2021). Effects of COVID-19 government travel restrictions on mobility in a rural border area of Northern Thailand: A mobile phone tracking study. *PLoS One*, *16*, 1–13. https://doi.org/10.1371/journal.pone.0245842
6. de Nailly, P., Côme, E., Samé, A., Oukhellou, L., Ferriere, J., & Merad-Boudia, Y. (2021). What can we learn from 9 years of ticketing data at a major transport hub? A structural time series decomposition. *Transp A Transp Sci*. https://doi.org/10.1080/23249935.2021.1948626
7. Almlöf, E., Rubensson, I., Cebecauer, M., & Jenelius, E. (2021). Who continued travelling by public transport during COVID-19? Socioeconomic factors explaining travel behaviour in Stockholm 2020 based on smart card data. *Eur Transp Res Rev*, *13*. https://doi.org/10.1186/s12544-021-00488-0
8. Politis, I., Georgiadis, G., Nikolaidou, A., Kopsacheilis, A., Fyrogenis, I., Sdoukopoulos, A., Verani, E., & Papadopoulos, E. (2021). Mapping travel behavior changes during the COVID-19 lock-down: A socioeconomic analysis in Greece. *Eur Transp Res Rev*, *13*. https://doi.org/10.1186/s12544-021-00481-7
9. Astroza, S., Tirachini, A., Hurtubia, R., Carrasco, J. A., Guevara, A., Munizaga, M., Figueroa, M., & Torres, V. (2020). Mobility changes, Teleworking, and Remote Communication during the COVID-19 pandemic in Chile. *Findings*, *1*, 1–8. https://doi.org/10.32866/001c.13489
10. Mützel, C. M., & Scheiner, J. (2022). Investigating spatio-temporal mobility patterns and changes in Metro usage under the impact of COVID-19 using Taipei Metro smart card data. *Public Transp*, *14*, 343–366. https://doi.org/10.1007/s12469-021-00280-2
11. Siewwuttanagul, S., & Jittrapirom, P. (2023). Transportation Research Interdisciplinary perspectives the impact of COVID-19 and related containment

measures on Bangkok ' s public transport ridership. *Transp Res Interdiscip Perspect*, *17*, 100737. https://doi.org/10.1016/j.trip.2022.100737
12. Šinko, S., Prah, K., & Kramberger, T. (2021). Spatial modelling of modal shift due to COVID-19. *Sustain*, *13*. https://doi.org/10.3390/su13137116
13. Christidis, P., Navajas Cawood, E., & Fiorello, D. (2022). Challenges for urban transport policy after the COVID-19 pandemic: Main findings from a survey in 20 European cities. *Transport Policy*, *129*, 105–116. https://doi.org/10.1016/j.tranpol.2022.10.007
14. Vega-Gonzalo, M., Gomez, J., & Christidis, P. (2023). How has COVID-19 changed private car use in European urban areas? An analysis of the effect of socio-economic characteristics and mobility habits. *Transp Res Part A Policy Pract*, *172*, 103679. https://doi.org/10.1016/j.tra.2023.103679
15. Habib, M. A., & Anik, M. A. H. (2023). Impacts of COVID-19 on Transport modes and mobility behavior: Analysis of Public Discourse in Twitter. *Transportation Research Record*, *2677*, 65–78. https://doi.org/10.1177/03611981211029926
16. Coppola, P., Fabiis, F., & De (2020). Evolution of mobility sector during and beyond COVID-19 emergency: A viewpoint of industry consultancies and public transport companies. *TeMA - J L Use Mobil Environ*. https://doi.org/10.6092/1970-9870/6900
17. Gkiotsalitis, K., & Cats, O. (2021). Public transport planning adaption under the COVID-19 pandemic crisis: Literature review of research needs and directions. *Transp Rev*, *41*, 374–392. https://doi.org/10.1080/01441647.2020.1857886
18. Tirachini, A., & Cats, O. (2020). COVID-19 and public transportation: Current assessment, prospects, and research needs. *J Public Transp*, *22*, 1–34. https://doi.org/10.5038/2375-0901.22.1.1
19. Chang, N., Tsai, Y. C., Chen, W. J., Lo, C. C., & Chang, H. H. (2024). COVID-19 control measures unexpectedly increased the duration of stay at high speed rail stations during the first community outbreak in Taiwan. *Bmc Public Health*, *24*, 1–7. https://doi.org/10.1186/s12889-024-17964-6
20. Coppola, P., & De Fabiis, F. (2021). Impacts of interpersonal distancing on-board trains during the COVID-19 emergency. *Eur Transp Res Rev*, *13*. https://doi.org/10.1186/s12544-021-00474-6
21. Campisi, T., Basbas, S., Skoufas, A., Akgün, N., Ticali, D., & Tesoriere, G. (2020). The impact of COVID-19 pandemic on the resilience of sustainable mobility in sicily. *Sustain*, *12*, 1–25. https://doi.org/10.3390/su12218829
22. Zhang, N., Jia, W., Wang, P., Dung, C. H., Zhao, P., Leung, K., Su, B., Cheng, R., & Li, Y. (2021). Changes in local travel behaviour before and during the COVID-19 pandemic in Hong Kong. *Cities*, *112*, 103139. https://doi.org/10.1016/j.cities.2021.103139
23. Aparicio, J. T., Arsenio, E., & Henriques, R. (2021). Understanding the impacts of the COVID-19 pandemic on public transportation travel patterns in the city of Lisbon. *Sustain*, *13*, 1–18. https://doi.org/10.3390/su13158342
24. González, A. B. R., Wilby, M. R., Díaz, J. J. V., & Pozo, R. F. (2021). Characterization of COVID-19's impact on mobility and short-term prediction of public transport demand in a mid-size city in Spain. *Sensors (Basel, Switzerland)*, *21*. https://doi.org/10.3390/s21196574
25. Transportes Intermodais do Porto (2019). Relatório e Contas.
26. Transportes Intermodais do Porto (2020). Relatório e Contas.
27. kepler.gl, https://kepler.gl/
28. Portugal (2006). Decreto-Lei n^{o} 27, de 10 de fevereiro de 2006. *Diário Da República 1 Serie A*, 1095–1099.

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