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Data-driven analysis of the impact of COVID-19 on Madrid’s public transport during each phase of the pandemic☆

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ABSTRACT

COVID-19 has become a major global issue with large social-economic and health impacts, which led to important changes in people’s behavior. One of these changes affected the way people use public transport. In this work we present a data-driven analysis of the impact of COVID-19 on public transport demand in the Community of Madrid, Spain, using data from ticket validations between February and September 2020. This period of time covers all stages of pandemic in Spain, including de-escalation phases. We find that ridership has dramatically decreased by 95% at the pandemic peak, recovering very slowly and reaching only half its pre-pandemic levels at the end of September. We analyze results for different transport modes, ticket types, and groups of users. Our work corroborates that low-income groups are the most reliant on public transportation, thus observing significantly lower decreases in their ridership during pandemic. This paper also shows different average daily patterns of public transit demand during each phase of the pandemic in Madrid. All these findings provide relevant information for transit agencies to design responses to an emergence situation like this pandemic, contributing to extend the global knowledge about COVID-19 impact on transport comparing results with other cities worldwide.

1. Introduction

COVID-19 is an infectious respiratory disease that appeared at the end of 2019 in Wuhan, China, and was declared a worldwide pandemic by the World Health Organization on 11 March 2020. By the end of September 2020, COVID-19 (SARS-CoV-2 by the International Committee of Taxonomy of Viruses) has infected more than 43 million people globally and caused more than 1.2 million deaths (Johns Hopkins Coronavirus Resource Center, 2020). Within Europe, Spain has been one of the region’s most strongly affected by COVID-19, where a great share of cases and deaths were produced in the Community of Madrid. The virus was first confirmed to have spread to Spain on 31 January 2020, when a German tourist tested positive for SARS-CoV-2 in Canary Islands. By March 13, cases had been confirmed in all 52 provinces of the country resulting in a high degree of hospitalization of patients with this novel disease. On this day, prime Minister of Spain announced a declaration of a nationwide State of Alarm with a national lockdown where residents were mandated to remain in their usual residences except to buy food and medicines, work, or attend emergencies. These orders meant that traveling was restricted only for essential purposes, mass gatherings were prohibited, schools and universities were closed, and people were expected to work from home if possible. This lockdown period of time was divided into several phases with different restriction levels (halting of all non-essential activity, lifting of some restrictions, etc.) until the return to the so called “new normality” stage.

SARS-CoV-2 pandemic has completely transformed mobility behavior worldwide. Public transport has been dramatically affected by these changes, showing a massive drop in ridership (number of passengers/trips). The decline of travelers was due to both government’s safer-at-home policies and people’s reticences, who perceived public

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transportation as riskier than private vehicles. Public transport is a high risk environment for the virus transmission with insufficient social distancing among passengers (Musselwhite et al., 2020). During this time, only essential workers have continued to utilize these services and transit agencies responded by adjusting public transport offer to this new demand, cutting service and hours and redirecting some services to high-need areas such as hospitals. Cleaning activities of transport vehicles were reinforced and the use of a mask on public transport became mandatory from May onwards.

The objective of this paper is to analyze the impact of COVID-19 and stay-at-home orders on daily public transport demand in the Community of Madrid. To this purpose, we use real ticket validations registered by the Smart Card Data (SCD) system operating in every transport mode in the whole region. Related work on the impact of pandemic on public transport is still limited and often uses partial information originating from phone data (with no detailed information on transport mode) or surveys (based on small samples that could be potentially biased). To the best of our knowledge, our research is the first data-driven study that refers to a large region like the Community of Madrid, with an extension of 8,000 km², a population of 6.6 million people, and 10 cities with more than 100,000 inhabitants (including Madrid, Spain’s capital city). Most of previous studies included the analysis of a single city or a limited set of them with no study of the transit interactions among them. SCD collected in real operation on the whole region allow us to infer relevant findings regarding these interactions between a densely populated urban core and its surrounding mid-size cities in pandemic times. In addition, our work addresses a detailed and comprehensive study of COVID-19’s effects on public transport including the next primary contributions:

- We use actual SCD with the aim of correctly reflecting the transport behavior of different passengers as part of their response to the pandemic.
- We provide an extensive analysis of ridership changes due to COVID-19 in one of the most affected regions, the Community of Madrid, in all phases of the pandemic, including demand recovery in de-escalation and ‘new normality’ stages.
- We perform this analysis for different public transport modes (subway, train, bus, etc.), ticket types (single, multi, and travel pass), and traveler groups (youth, senior, tourists, etc.). We address research questions such as: Which traveler groups were the most affected during the pandemic considering their public transport demand? Which type of ticket reduced its use in COVID-19 times? Is there any relationship between the decline in transit demand and the average income of travelers?
- We analyze daily mobility patterns in public transport, finding important differences in the demand for pre and post-COVID-19 phases.
- We perform an investigation on daily validations from active cards and daily trips per card.
- We investigate the specific evolution of the transport demand each district in Madrid showed, illustrating how socioeconomic factors can determine changes in public transport utilization. This study allows us to discuss theoretical arguments such as the hypothetical correlation between public transport decline in pandemic times and average income.

We believe that these findings can contribute with a greater understanding of how people have changed their habits, providing insights to policy and transit agencies in the design of answers to a pandemic like COVID-19 and the creation of proactive strategies for the future.

The remainder of the paper is structured as follows. Section 2 describes the related work about how SARS-CoV-2 has affected public transport demand worldwide. Section 3 describes the validation data from SCD we used and the methodology we followed for the analysis. Section 4 presents the results and discussion of findings. Section 5 provides the conclusions and future research of the study.

2. Related work

The number of works studying the impact of COVID-19 on public transport use is still limited but quickly increasing since the start of the pandemic. In this regard, research is scarce on the matter prior to SARS-CoV-2 virus. We find only one earlier study (Wang, 2014), where authors explored the public fear of utilizing public transport in Taipei, Taiwan during the peak of the Severe Acute Respiratory Syndrome (SARS) epidemic in 2003.

In times of COVID-19, in (Tirachini & Cats, 2020) we can find an excellent general review for transit policy makers, planners, and researchers to map the state-of-the-art and research needs related to the impacts of the pandemic crisis on public transportation. This study addresses the different responses adopted by authorities and public transportation agencies around the world, and actions that minimized contagion risk in public transportation in the post-lockdown phase. Most of related works that study the effects of the COVID-19 outbreak in public transport have analyzed the problem using two different data sources: phone-based data and surveys. The first category includes research using mobile phone tracking (e.g., Google Mobility Report (Google, 2020)) and the mobility report of Spanish Ministry of Transport, Mobility and Urban Agenda (MITMA, 2020), or mobile application management (e.g., Apple Mobility Trends (Apple, 2020) and Moovit App (Moovit, 2020)). Several authors have utilized these location data to examine the effect of COVID-19 and safer-at-home policies on mobility patterns (Arelhanna et al., 2020; Askitas et al., 2020; Saha et al., 2020; Tamagusko & Ferreira, 2020; Wei et al., 2021; Zhang et al., 2022). Among them, we want to highlight the work in (Liu et al., 2020), a systematic analysis of the decline in ridership demand observed in many public transit systems in the United States. Using data derived from a widely used transit navigation app, the authors employed some analytical methods (fitting logistic functions, regression analysis, distance measures, etc.) to model the decline, providing insights into public transit as an essential service during a pandemic. However, these studies show an important drawback given that the data they use do not represent actual public transport trips and do not include specific information about transport mode. On the other hand, for the second group, mobility surveys have been conducted in several countries like Australia (Beck & Hensher, 2020), (Astroza et al., 2020), Turkey (Shakibaei et al., 2020), and Switzerland (Molley et al., 2020), all of them showing an important reduction in public transit ridership; nevertheless surveys may not be an appropriate approach to generate a comprehensive knowledge about travelers behavior as they just include a small percentage of the whole population.

Among the scientific literature that investigates the relationships between COVID-19 and public transport demand, data-driven approaches are starting to reach great interest. Perhaps the closest comparable reference to our work is (Jenelius & Cebecauer, 2020) where the authors analyze the influence of pandemic on daily public transport ridership in the three most populated regions of Sweden during the spring of 2020. This analysis disaggregates ticket validation data in order to study ridership considering ticket types and transport modes. We can find another relevant data-driven work in (Zhang, Jia, et al., 2021), where the changes in the local travel behavior of various population groups in Hong Kong, between 1 January and 31 March 2020, were analyzed using SCD. Due to the pandemic, local travel volume decreased the most on Sundays and specifically in students and children. Although we have inserted a detailed discussion on the differences between our work and these two closest references in Section 5, let us remark at this point that our analysis includes the complete dataset collected in a large region like the Community of Madrid, where the interactions among different cities can be studied. The other two works limit their analysis to specific cities, without examining connections among them. Next, we describe other interesting data-driven references
for our research. In (Ahangari et al., 2020) the authors investigate the effect of the COVID-19 on public transport ridership, during the first five months of 2020, in 10 cities of the U.S. considering population and service size. The results show that, as expected, ridership decreased in March as the virus spread and stay-at-home orders were issued and reached its lowest level in April in all ten cities. Aloi et al. (2020) combine available data from traffic counters, public transport GPS and bus ticket sales, and pedestrian flows from traffic cameras to provide a preliminary report about how the imposition of quarantine due to the COVID-19 affected the internal mobility in the city of Santander, Spain. Data show an overall decrease of 76%, which reached 93% regarding public transport. The effect of dynamic lockdowns on public transport demand is studied in (Gramsch et al., 2020), by analyzing a 2019–2020 database of smartcard data of trips in Santiago, Chile. We can find other interesting work in (Teixeira & Lopes, 2020), where ridership in the subway and bike sharing system (BSS) in New York City during the COVID-19 outbreak is investigated. The results suggest that BSSs have proven to be more resilient than the subway system, with a less significant ridership drop (71% vs. 90%) and an increase on its trips' average duration (from 13 min. to 19 min. per trip). Moreover, the study found evidence of a modal transfer from some subway users to the BSS. Finally, Park (2020) shows that the number of subway passengers in Seoul notably diminished during late February but slowly increased afterwards, suggesting decreasing levels of risk perception.

Previous research indicates different transit behaviors among socio-economic classes, showing that low income and historically marginalized groups are particularly dependent on public transportation (Wilbur et al., 2020). This work provides a data-driven analysis of bus ridership in Nashville and Chattanooga, observing differences in the temporal variation in the number of passengers depending on their socio-economic group. The authors found the largest drops during the morning and evening commutes, with significantly different decreases between the highest and lowest in- come areas in Nashville (77% vs. 58%). Work in (Almlof et al., 2020) analyzes the propensity to cease traveling by public transport during COVID-19 in Stockholm, Sweden, combined with demographic indicators showing that education level, income, age, and workplace type are strong predictors. Finally, a study compared changes in service frequency of 30 U.S. and 10 Canadian cities by considering average income levels and vulnerability index can be found in (DeWeese et al., 2020).

In the light of these previous works, our paper provides an exhaustive study about the effects of COVID-19 on public transport demand in a large region like the Community of Madrid, one of the most severely affected regions in Europe. As far as we know, this is the first data-driven study that refers to a complete region where the public transport interactions among cities can be analyzed. In any case, our work contributes to extend the global knowledge about COVID-19 impact on public transport, comparing results with other cities and regions worldwide.

3. Dataset and methodology

3.1. Dataset

Public transport data was provided by the Consorcio Regional de Transportes de Madrid (CRTM), a public agency that coordinates and manages the public transport network in the Community of Madrid. It is a wide network (11,000 km) that connects all 179 municipalities, including Madrid, Spain's capital city. In 2017 the traditional magnetic ticket was substituted by a new contactless smart card, registering SCD. Nowadays, this is the only way of payment allowed in the public transport network.¹

The dataset contains validations extending from 01/02/2020 to 30/09/2020 (8 months), thus covering all stages of COVID-19 pandemic in Spain including de-escalation and post-lockdown phases. We can divide this time period into the following specific phases: (1) Pre-pandemic situation (1 February - 8 March); (2) Pre-State of Alarm week (9 March - 14 March); (3) State of Alarm declaration and beginning of national lockdown (15 March - 29 March); (4) Halting of all non-essential activity (30 March - 12 April); (5) End of economic “hibernation” (13 April - 26 April); (6) De-escalation with lifting of some restrictions, State of Alarm still active (27 April - 20 June); and (7) “New normality” phase, State of Alarm was deactivated (21 June - 30 September). These phases are depicted in the timeline in Fig. 1 where different time periods are represented with different colors that we will use later in several following figures.

The smart card is only validated at the entry point of each transport mode. They can integrate up to 3 main different titles of transport (pass, multi-ticket, single ticket... in their various modalities) and can be validated on more than 33.000 stations (pay-points). The public transport network integrates 6 different modes: Subway, Commuter Train, Light Rail and Tram, Intercity Bus, Urban Bus in Madrid City, and Urban Bus in the remaining municipalities. In order to reduce the driver's exposure to the virus, there was no obligation to validate on Intercity and Urban buses (except in Madrid city) during most of the State of Alarm period (from 23 March to 29 June).

Data is recorded with a temporal definition of 2 s. Each validation includes: card ID (anonymized), time stamp, pay-point (the boarding station, coded as a combination of the operator, the line, and the stop), the type of title (pass, multi-ticket, single ticket,... plus tourist ticket, young ticket, senior ticket, children's ticket,...), and the type of discount (large families, disabled persons,...). Data were properly pre-processed to remove invalid entries: duplicates; records with mistakes in some fields; and transactions of people who are not typical transport users (e. g., subway operators, security people, testing tickets,...). After pre-processing we get a dataset with 432.446.293 validations from 6.207.580 different smart cards.

3.2. Methodology

In order to analyze the impact of COVID-19 on public transport in the Community of Madrid, we designed a mathematical framework to calculate the relative change in the number of passengers, during each of the phases of the pandemic. Let's consider N(d) the total number of validations registered in a specific day d. We define the relative change in ridership r (in percentage) for the day d as:

\[
  r(d) = 100\% \cdot \left( \frac{N(d)}{R} - 1 \right)
\]

where R is the common reference we use to calculate the overall change defined as:

\[
  R = \frac{1}{28} \sum_{d=1}^{28} N(d)
\]

where d = 1, ..., D corresponds to the reference period from 10/02/2020 to 08/03/2020. This means that we choose as reference the average number of validations recorded in the period immediately preceding the explosion of pandemic in Spain, specifically four complete weeks (from 10 February to 8 March, 2020). On the other hand, relative

¹ Under certain circumstances, it is permitted to use cash as the payment of single-trip tickets in urban buses and commuter trains. For security reasons, in COVID-19 times this form of payment dropped to a negligible percentage of validations, thus becoming irrelevant for this study.
changes in ridership will be compared on a weekly basis with this baseline level in order to avoid the expected weekend effects (as we will see in Fig. 2). This concept of relative change in ridership calculated for different traveler groups or ticket types will be the reference measurement that we use to analyze the impact of COVID-19 on the public transport demand. In addition, this simple metric establishes a straightforward comparative framework with other studies performed in other countries worldwide or even with other transport modes like private mobility.

4. Results

4.1. Analysis of the global ridership change

Fig. 2 shows the daily number of validations in the whole public transport system in the Community of Madrid. The vertical dashed red line marks the declaration of State of Alarm in Spain and the beginning of the national lockdown. In addition, shaded vertical bars represent the different phases of COVID-19 pandemic in Spain shown in Fig. 1. We can see that daily ridership drastically dropped immediately preceding the declaration of the State of Alarm, it continued decreasing during the period of economic “hibernation” (with the lowest number of validations), and it finally began to rebound very slowly. We can also observe the expected weekend effect (less validations in Saturdays and Sundays), the seasonal effect of the holiday period during the months of July and August and how validations started to gradually recover in September, showing values still significantly below those registered before the outbreak of pandemic.

In addition, Fig. 3 shows the relative change in the daily number of validations with respect to the reference period of time calculated using the mathematical framework described in Section 3.2. As we stated above, we present the results on a weekly basis in order to remove the weekend effect. Consequently, this figure summarizes thoroughly the global impact of COVID-19 pandemic and lockdown restrictions on public transit ridership in Madrid. We can observe that the mean daily number of passengers during the week prior to the State of Alarm declaration approximately decreased in 42% (yellow bar). Then it dramatically dropped to almost 90% during the first week of the State of Alarm (first light red bar), reaching its minimum (95% drop) in the second week of period of halting of all non-essential activity (dark red bar). Once the de-escalation stage starts, public transport demand begins slowly to recover; however, it did not reach even half its pre-pandemic level in September.

Finally, we present in Fig. 4 a meaningful visual representation of the actual COVID-19 pandemic’s impact on public transport in the Community of Madrid. In this figure, we present a heatmap of the daily validations at the topmost 50 pay-points (regarding their total ridership) during all phases of the pandemic. The number of travelers in each day

![Timeline](image)

**Fig. 1.** Different phases of COVID-19 timeline in the Community of Madrid, Spain.

**Fig. 2.** Daily number of validations in Madrid.
of the period is represented by colors ranging from dark (black and brown) to light (yellow and white). Consequently, we can observe how the outbreak of pandemic in mid-March produced a total “darkness” and how we notice a slow recovery that is far away from reaching pre-pandemic levels even in late September. This kind of representation also allows to particularize how the different types of stations show distinct behaviors. For example, pay-points like Ciudad Universitaria subway station (row 30 in Fig. 4) that show a much lower number of daily validations (almost a black row) in the post-COVID-19 phase than in pre-COVID-19 phase; Ciudad Universitaria gives access to the main university campus in Madrid, where face to face instruction has not been restarted yet. Chamartín commuter train station (row 47 in Fig. 4) is another example of a relevant decline in the post-COVID-19 ridership. This stop is the closest to the one of the main regional train stations in Spain. Recreational and leisure trips were canceled during the State of Alarm scenario, consequently the number of passengers in Chamartín felt drastically. Generally, stations in business districts (and specially in commercial areas) show more pronounced validation drops than in residential areas.

4.2. Analysis of ridership change per transport mode

In this section we analyze the impact of COVID-19 pandemic in public transport demand per transport mode. We recall that public transport network in the Community of Madrid integrates 6 different modes: Subway, Commuter Train, Light Rail and Tram, Intercity Buses, Urban Buses in Madrid city, and Urban Buses in the remaining municipalities. We exclude from this analysis Intercity and Urban buses (except in Madrid city) from 23 March to 29 June given that there was no obligation to validate in these buses. Fig. 5 illustrates the relative change
in the daily number of validations per transport mode relative to the baseline level. We observe that all transport modes show a similar decrease, but with some relevant peculiarities. First, the commuter train (yellow) exhibits the greatest demand during the State of Alarm stage, which may be due to the fact that long-distance passengers had fewer alternatives to public transport. During the “new normality” phase, and particularly during the last weeks of September when the second wave of pandemic started, subway and light rail modes present the largest declines compared to the reference, since travelers saw them as a potential risk due to their limited ventilation, specially in the case of the subway (darker blue). These results match the findings of the study in (Jenelius & Cebecauer, 2020). Only urban buses in other cities and intercity buses have recovered more than half the pre-pandemic demand at the end of September.

4.3. Analysis of ridership change per ticket type

Fig. 6 shows how COVID-19 changed public transport ridership depending on the ticket type. The smart cards in the Community of Madrid combine 3 different ticket types (travel pass, multi-ticket, and single ticket). During the first days of the State of Alarm, the ticket type travelers used the most was the travel pass (blue); this is the ticket type that is commonly used by workers, who were the only users of public transport during this period, while leisure trips (frequently related to more flexible tickets) stopped. Since mid-April, this trend changes and single tickets (yellow) and multi-tickets (red) take the lead given that travelers decide not to renew their 30-day travel pass as they are forced to stay home. Finally, during the “new normality” phase, we can observe that travel pass slowly grows while single and multi-ticket decay as people progressively get back to their usual activities.

4.4. Analysis of ridership change per user type

Analysis of the specific ridership shown by each user type provides us with meaningful information about the distinct response of different population groups to the COVID-19 outbreak. In this respect, we identify different temporal variations in ridership change and observe that the reduction of public transport demand was not uniform among this set of groups.

In the Community of Madrid, CRTM offers reduced fare tickets for youth, children, senior people, and low-income and disadvantaged groups. In addition short period cards can be purchased by national and international tourists. Fig. 7 illustrates the relative change in the daily number of validations relative to the baseline level per user type. As we can observe, international travel restrictions and local mobility limitations caused that tourist short period cards (purple) dropped to almost...
zero during the State of Alarm, with only a slight increase in summer holidays. Tourist and business travel abruptly stopped during COVID-19 pandemic and showed a very limited increase during July and August. For its part, senior ticket type (red) experienced the second largest decline since the elderly constitute the highest risk group, which affected their use of public transport. In late September, the relative decrease for this specific group is almost 70%, while the average drop is 50%. In addition, youth (blue) and children (yellow) tickets also significantly dropped with the outbreak of COVID-19. However, they both reached values above 50% with the reopening of schools and universities in September, showing a continuous growing trend. Finally, one the most interesting findings of this analysis is that reduced fare tickets for low-income and vulnerable groups (green) have suffered the lowest drop during the toughest months of pandemic (March and April) and the de-escalation phase. This result is in line with previous works, which state that low-income and historically marginalized groups are particularly dependent on public transportation. We will further analyze this issue in Section 4.7.

4.5. Active travelers and trips per active card

Fig. 8 performs a similar analysis to that presented in (Jenelius & Cebecauer, 2020) showing the daily total number of smart cards with validations (in blue) and the daily average number of trips per active card (in red), compared with the reference period of time. The daily number of active cards drastically declined with the outbreak of COVID-19 pandemic (around 95% in the phase of halting of all non-essential activity). On the contrary, the daily average number of trips per active card only dropped as much as 15%. This result make sense: the only passengers that continued using public transport during pandemic were commuters, who needed to continue traveling both to and from working location; in addition, the slight reduction in the mean daily number of trips may be due to the fact that leisure trips disappeared during this period.

4.6. Average daily ridership patterns

In addition to the overall weekly trends previously shown, in this section we investigate on the temporal changes in public transport ridership within a day. The aim is to identify the different mobility patterns of public transit demand according to the COVID-19 pandemic evolution in Spain. Specifically, for this analysis we have divided the time period (see Fig. 9) in three specific phases: (1) Pre-State of Alarm: pre-COVID-19 situation (1 February - 8 March); (2) State of Alarm:
national lockdown (15 March - 20 June); and (3) Post-State of Alarm: “new normality” (21 June - 30 September).

Fig. 10 illustrates the average daily ridership patterns calculated using validations aggregated every 15 min. Upper to lower rows respectively correspond to the pre-State of Alarm, the State of Alarm and lockdown, and the post-State of Alarm periods. Columns represent the type of day analyzed: Mondays, Tuesdays, Wednesdays, and Thursdays (left); Fridays (center); and weekends and public holidays (right). The number in red at the top left corner indicates the average of number of daily validations in the specific period of time; in addition, the time when validations reached their maximum is shown on the curve.

Focusing on the left column (Monday to Thursday) we can derive two relevant findings. First, we confirm the drastic drop in the mean daily number of validations since the declaration of the State of Alarm, from 5.4 M (top) to 0.8 M (center), which recovered to 2.3 M (bottom) during the “new normality” phase. Second, we notice that the shape of the patterns is also different. In the State of Alarm scenario shown in Fig. 10 (d), the morning peak (related to commuting) not only is notably reduced, but also it appears an hour before its usual time. In addition, the mid-day peak still exists but showing two distinct local maximums; in fact, the peak at 15:15 becomes the maximum ridership throughout the day. The third peak in afternoon almost disappears. On the other hand, the shape of the mobility pattern for the post-State of Alarm stage in Fig. 10 (g) is quite similar to that of the previous phase. It seems that the first peak in the morning returns to its original position and the afternoon peak reappears, but it is evident that this pattern is different from the one in the pre-COVID-19 situation.

We can extract similar conclusions for the average daily pattern on Fridays (central column). During the State of Alarm phase in Fig. 10(e), the maximum ridership is reached on the mid-day peak (again showing two local maximums) instead of on the morning peak. This peak is reduced and appears an hour before it did during the pre-State of Alarm, and recovers its original position during the “new normality” phase in Fig. 10(h), although its ridership does not recover to its pre-pandemic value. Finally, we observe that the shape of weekend and holiday daily public transport patterns in pre (Fig. 10(c)) and post- COVID-19 (Fig. 10(f)) are quite similar, with their maximum at 19:30. On the contrary, these models are substantially different from the one corresponding to the State of Alarm stage in Fig. 10(f), in which we can observe morning and mid-day peaks that resemble a typical working day behavior. This makes sense since essential workers were the only travelers forced to use public transport in weekends and holidays.

As complementary information to that presented in Fig. 10, we show the average daily ridership patterns for the three most important transport modes in the Community of Madrid in Fig. 11: subway (blue), Madrid urban bus (red), and commuter train (yellow). Let us focus our analysis on weekdays. First, we can observe in Fig. 11(d) that subway ridership includes a mid-day peak (now split into two local maximums) that almost reaches the morning peak values, which appears an hour before its usual time in the pre-State of Alarm period. This subway morning peak returns to its usual time (08:30) during the post-State of Alarm phase (blue curve in Fig. 11(g)) and gains importance although not yet reaching pre-pandemic levels. In addition, afternoon peak also grows. Second, we notice that the Madrid Urban Bus pattern substantially changes during the State of Alarm phase (red curve in Fig. 11(d)), keeping a relatively flat ridership until the afternoon. Furthermore, the usual urban bus pattern is recovered during the “new normality” phase (Fig. 11(g)). Third, the commuter train patterns experience only slight changes in workdays (left and central columns in Fig. 10) during the course of the pandemic. This could be due to the fact that long-distance travelers, who typically use the commuter train, have fewer alternatives, thus being forced to continue using public transport even in an extreme situation.

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Fig. 9. Different phases of COVID-19 timeline according to the State of Alarm.

Fig. 10. Average daily ridership patterns in the Community of Madrid (15-min validations).
situation. Furthermore, the commuter train pattern in weekends and holidays during the State of Alarm phase (Fig. 11(e)) replicates those found in weekdays as traveling was limited to essential workers.

Finally, we conclude this section with a review of the main findings we identified. We observe that the shape of daily public transport patterns is different in pre-, during, and post-State of Alarm scenarios, showing much lower afternoon peaks and shifting morning peaks an hour before its usual time (also notably reduced) in the most difficult periods of pandemic.

4.7. Socioeconomic analysis per zone

Finally, we analyze how socioeconomic factors affected travelers’ predisposition to use public transport in COVID-19 times in the Community of Madrid. Previous literature already stated that low-income and vulnerable groups are the most reliant on public transportation as they may be least likely to own a private car.

Fig. 12 shows the relative change in the total daily ridership for two important municipalities in the Community of Madrid: Pozuelo (in blue) and Fuenlabrada (in red), which respectively show one the highest (25,902 €) and lowest (10,061 €) average per capita incomes in 2017 within the region. During the State of Alarm, we observe a significantly pronounced decrease in ridership in Pozuelo, with a minimum of almost 99% drop in the second week of economic “hibernation”, while Fuenlabrada shows a 92% decrease in the same week. Additionally during de-escalation phase both cities show similar ascending and descending trends in ridership until the end of September when Pozuelo overtakes the relative change in Fuenlabrada (around 50%). These results confirm that low-income groups had a lower possibility of avoiding using public transport in COVID-19 times.

In order to corroborate this finding, we complete the analysis studying the relationship between average per capita income and

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Fig. 11. Average daily ridership patterns per transport mode in Community of Madrid (15-min validations).

Fig. 12. Weekly relative change of daily number of validations in Pozuelo (high-income municipality) and Fuenlabrada (low-income municipality) compared to reference.
average change in transport public during the State of Alarm phase for the 21 districts of Madrid City. We represent this information through the scatter plot in Fig. 13. By simple visual inspection, we can easily identify a strong correlation between higher incomes and steeper decreases in public transport demand. To confirm this issue, we have fitted a linear model to this set of data points, showing the regression line plotted in the same figure (including an estimation of a 95% prediction interval). On one hand, we see low-income districts (e.g. Villaverde, Puente de Vallecas, and Usera) with relative changes in ridership around 20%. On the other hand, high-income zones (e.g. Chamartín, Salamanca, and Chamberí) show a relative change around 12%. Prediction interval includes almost all districts, except for two that fall just outside the interval: Centro and Barajas, two mid-income areas that show a significant drop in ridership. We can find a plausible explanation for both districts. Centro is the most important commercial and leisure area in Madrid, so the closure of non-essential activity resulted on a huge decrease in the public transport use in this district. On the other hand, the municipality of Barajas includes Madrid’s main airport, so passengers in this area drastically dropped due to the international travel restrictions that were imposed on tourism and business during the COVID-19 pandemic.

Apart from the fact that low-income families are less likely to own a car, there are specific causes related to COVID-19 pandemic that can support this observation. Essential activities like grocery stores, logistics, and cleaning commonly employ low-income workers that need to take the public transport to commute. In addition, these workers cannot work remotely as their jobs are physically bound to their workplace. On the contrary, high-paid employees are more likely to be able to perform their jobs remotely, thus avoiding using the public transport during the pandemic.

5. Conclusions, discussion and future research

COVID-19 is changing the travel behavior and disrupting the public transport demand throughout the world. In this work we have presented a data-driven analysis of the impact of this pandemic and safer-at-home policies on public transportation in the Community of Madrid, using ticket validation data. We have found that ridership dropped by almost 95% at the pandemic peak in the period of economic “hibernation”, beginning to increase very slowly from that moment and reaching roughly only half of the pre-pandemic levels in September.

In addition, we have particularized this analysis to the different transport modes, ticket types, and groups of users. Next, we describe the most important findings of our research, some of which constitute a novelty in the existing international literature. Among the different public transport modes, commuter trains showed the greatest demand in COVID-19 times, due to the fewer transport alternatives that long-distance travelers have. This result can only be obtained if we analyze data from the whole region (as we have done in our work). In addition, during the post-lockdown phase, subway and light rail modes presented the largest decline because of the higher potential risk that passengers perceive in them. We also show that those people who were forced to continue using public transport to reach their workplaces during the pandemic, tended to switch to more flexible ticket types (single and multi-ticket) because of the scenario of uncertainty due to COVID-19. Regarding different user groups, results show lower demands in young (closed school/universities and no leisure trips) and senior people (most susceptible group to pandemic). Maybe the most relevant conclusion is that reduced fare tickets for low-income and vulnerable groups have suffered lower decreases, providing evidence that groups with lower socioeconomic status are particularly dependent on public transportation. This finding is supported by an additional spatial analysis of the 21 districts of Madrid City, which shows a high correlation between income levels and drop in ridership. Finally, the obtained results also display distinct average daily patterns of public transit demand during the different phases of COVID-19 pandemic in the Community of Madrid. For example, it is worth mentioning that during the State of Alarm period, the morning peak related to commuting time was notably reduced and appeared an hour before its usual pre-pandemic time, the mid-day peak was still present but split into two local maximums, and the afternoon peak was almost non-existent. Thus, our study contributes to bring together experiences from different regions throughout the world.

Let us now contrast our results to those from previous works that employ other data sources and to those from researches performed in other countries. First, we compare our findings with other data sources that do not represent actual trips based on mobile phone tracking or applications. Fig. 14 shows the evolution of public transport demand relative to the typical usage before COVID-19’s outbreak in the Community of Madrid, based on data from Moovit’s app usage (Moovit, 2020). These results resemble those in Fig. 3, showing a similar overall shape with a dramatic drop during the eruption of pandemic and the sequence of increasing and decreasing trends. However both results do not match in absolute terms, particularly during the post-State of Alarm phase, when Moovit’s data seem to overestimate the real ridership values. For example, data from Moovit app shows a relative drop of approximately 5% at the end of September, whereas our data from actual validations show a decrease of more than 50%. Both approaches use different time periods to construct their references; nevertheless, the observed deviation is too high for this to be its fundamental cause. In
fact, this conclusion about app-based data is in line with the results in (Jenelius & Cebecauer, 2020), where the authors suggest that indicators based on human proximity to public transport stations or travel planner queries (as with Moovit) could overestimate the recovery of public transport ridership in the months succeeding the outbreak.

On the other hand, we compare our results with those reflected by other data-driven works like (Jenelius & Cebecauer, 2020) and (Zhang, Jia, et al., 2021) using data from Sweden and Hong Kong, respectively. All results show that, as expected, ridership decreased when the virus spread and stay-at-home orders were issued, showing highest declines for specific traveler groups (elderly, students, etc.) and for specific ticket types (e.g., touristic). However we can identify relevant differences of our approach with respect to these two previous works. First of all, our analysis includes a complete set of SCD collected in a large region like the Community of Madrid, where the transit interactions among different cities can be investigated. This interesting aspect allowed us to infer relevant findings that cannot be derived from the data employed in the other references. If we focus in the work in (Jenelius & Cebecauer, 2020), we can find additional differences: public transport demand recovery is not analyzed in the post-lockdown phase; it does not perform a deep study about the changes in daily travel patterns; and its results are not linked to socioeconomic data, which has a direct impact on users’ decision to travel. Furthermore, our paper focuses on the Community of Madrid, where severe restrictions were imposed, thus providing a significantly different scenario to that in Sweden, where more flexible political strategies were applied. As regards the second work in (Zhang, Jia, et al., 2021), data is analyzed only until 31 March 2020, thus excluding any investigation on how demand recovered during the “new normality” phase. In addition, only data from mass transit railway was used because data from other types of public transport (e.g., bus) were not available. In any case, as mentioned in (Jenelius & Cebecauer, 2020), collaborative effort is required to put the results about this issue in the international context.

World in general and mobility in particular are confronting an unprecedented transformation in a very short period of time due to COVID-19. For this reason, the findings of our work are relevant from a policy perspective in the design of responses to an exceptional situation like this pandemic and the creation of proactive strategies for the future. First, our results show that preventive policies of the governments, including stay-at-home lockdowns, have been effective in reducing human mobility. Second, our analysis allows transit agencies to identify those trips and routes that are expected to significantly drop due to the pandemic, and reallocate the corresponding resources to provide service to travelers that are highly dependent on public transport. Third, results shed light on the effect of new hybrid work models and new alternatives as e-commerce that reduce unnecessary trips, as well as the influence of travelers’ perception of public transport that the pandemic has brought, which must to become key points to address by policy agencies in their new strategies for the future. The number of public transport users and their mobility patterns may never be the same again, forcing public transport systems to become more innovative, efficient, flexible, and sustainable. With the outbreak of the pandemic, we are witnessing a time of change that we can take advantage to introduce transforming achievements to create sustainable and resilient cities, based on technology and knowledge.

As the pandemic continues to spread, future work includes the extension in time of the analysis of how people adjust their mobility behavior in public transport, contributing to understand its post COVID-19 outbreak evolution. Furthermore, a comparison with other transport modes is needed to complete the study. We are currently analyzing the results we have obtained from a pilot deployed in the city of Fuenlabrada (Madrid), which monitors private vehicle mobility using a Bluetooth Monitoring System. The idea is to compare the COVID-19 impact on both modes, private vehicle and public transport, in order to address how travelers moved from the latter to the former given the potential risk they perceive in public transportation. This flow of travelers from public to private transport modes (cars, bikes...) is in agreement with previous literature (Molloy et al., 2020). Whether this pattern is provisional or implies a definitive change is an important opened issue to answer.

CRediT authorship contribution statement

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