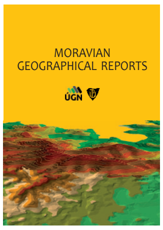

MORAVIAN GEOGRAPHICAL REPORTS

Czech Academy of Sciences, Institute of Geonics
Palacký University Olomouc, Faculty of Science

journal homepage: **www.geonika.cz/mgr.html**

doi: **https://doi.org/10.2478/mgr-2025-0013**

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Are the changes in the functioning of urban transport systems arising from the COVID-19 pandemic just temporary change or a permanent transformation? Examples of Lodz and Bratislava

Marta Borowska-Stefańska [a *], Marcel Horňák [b], Michał Kowalski [a], Edyta Masierek [a], Szymon Wiśniewski [a,c], Pavol Ďurček [b], Richard Hluško [d]

Abstract

This study analysed the impact of the COVID-19 pandemic on the urban transport systems in Lodz and Bratislava, focusing on changes in mobility behaviour, public transport efficiency, and road congestion. To analyse the efficiency of the road network, traffic microsimulations were conducted. For the assessment of public transport efficiency, comparable data on yearly volumes of passengers carried by public transport operators in the two cities were applied. The results confirm that the pandemic triggered significant, though mostly temporary, changes in the use of both personal and public transport. The findings indicate that the pandemic influenced both the organisation and use of urban transport systems. In both cities, public transport ridership declined sharply due to lockdowns and travel restrictions, forcing operators to adjust schedules, reduce service frequencies, and implement additional health measures. Simultaneously, car traffic patterns were also disrupted, with the early stages of the pandemic bringing a reduction in congestion, followed by a return to pre-pandemic levels. The pandemic proved that more emphasis should be placed on developing intelligent transport management systems to better adapt to changing conditions and the preferences of road users.

Keywords: Urban transport system, public transport, spatial mobility, COVID-19, Lodz, Bratislava

Article history: Received 17 December 2024, Accepted 16 June 2025, Published 30 September 2025

1. Introduction

COVID-19 was first detected in Wuhan, China, in the autumn of 2019, and had escalated to a global pandemic by March 2020 (Soetikno et al., 2024). One policy adopted by European governments to curb the spread of the SARS-CoV-2 coronavirus was to reduce mobility, thus leading to major changes in people's daily lives (Barbarossa, 2020). As regards the number of cases and related deaths, the situation was worst in cities, particularly in the largest and most globally connected (Johns Hopkins University, Corona Virus Research Centre, n.d.). The fact that the largest flows of people and goods occur in such cities renders them most vulnerable to all types of crises. Therefore, preventive measures should be implemented at the earliest possible time to mitigate the potential negative effects of future crises in such places.

Research has shown that everyday transport behaviour mostly depends on habit and routine (Schönfelder & Axhausen, 2010). There are, however, circumstances that can trigger changes in this behaviour, and the COVID-19 pandemic was undoubtedly one of them (de Haas et al., 2020). It certainly brought one of the greatest shocks for transportation and mobility worldwide, as reported by numerous studies (Barbieri et al., 2021; Benita, 2021; Borkowski et al., 2021; Das et al., 2021; Karimi et al., 2024; Scorrano & Danielis, 2021; Thombre & Agarwal, 2021). Schäfer et al. (2012) described such emergencies as 'windows of opportunity' to change the everyday transport behaviour of road users, since people are more amenable to interventions after these events, as shown by Verplanken and Roy (2016). The spread of the COVID-19 pandemic, and the resultant restrictions and measures led to unprecedented mobility adaptations amplified by decisions of public transport providers in an attempt to adapt to the increased costs associated with fluctuating numbers of passengers. Therefore, it is extremely important for the development of future urban transport strategies to indicate what changes occurred following the onset of the COVID-19 pandemic and how permanent they are.

The primary aim of this research is to determine whether the impact of the COVID-19 pandemic on the urban transport systems of Lodz and Bratislava resulted in only temporary changes or more permanent transformations in mobility behaviour, public transport efficiency, and road congestion. The study seeks to explain the broader implications of these changes for the future operations

[a] Institute of the Built Environment and Spatial Policy, Faculty of Geographical Sciences, University of Lodz, Lodz, Poland (*corresponding author: M. Borowska-Stefańska, email: *marta.borowska@geo.uni.lodz.pl*)

[b] Department of Economic and Social Geography, Demography and Territorial Development, Faculty of Natural Sciences, Comenius University, Bratislava, Slovakia

[c] Research Center for European Spatial Policy and Local Development, University of Lodz, Lodz, Poland

[d] Department of Spatial Concepts and Analyses, Metropolitan Institute of Bratislava, Bratislava, Slovakia

and planning of transport systems in large urban areas. To this end, the analysis focuses on both public and personal transport performance during key stages of the pandemic.

The study is guided by two main research hypotheses:

1. Mobility behaviour in Lodz and Bratislava evolved distinctly across the four phases of the COVID-19 pandemic (pre-pandemic, initial lockdown, peak mortality, and post-lockdown) as a result of the pandemic-induced changes in public transport efficiency and road congestion.
2. Operational changes in urban transport systems (such as timetable adjustments, service frequency reductions, and the implementation of health and safety measures) had measurable effects on transport efficiency and contributed to shifts in residents' mobility behaviour.

These hypotheses were verified using traffic microsimulations, data from intelligent transport systems (ITS) and statistical analysis of public transport performance in the two cities. The rationale behind exploring this research topic lies, *inter alia*, in the magnitude and nature of the pandemic, which affected the urban transport systems in Poland and Slovakia beginning in March 2020. The emergence of a global pandemic, that significantly alters how people live, meets the criteria of a black swan event. Additionally, this was the first instance where advanced information technologies, e.g., intelligent transport systems, were available to monitor its impact on transportation. It is also possible to observe the effects stemming from the feeling (or lack of it) of insecurity arising from the information policy concerning the variability of the level of danger and the accompanying formalised policy of restrictions or recommendations on how the population should behave, including those related to mobility. The proposed research topic is also justified by the duration of the stimulus: albeit of variable intensity. It covered a full year at the stage of preparation of this proposal, which allowed the researchers to observe variability against ‘normal’ periods at any temporal resolution, e.g., on a weekly, monthly, seasonal or annual basis. The rationale behind this study also lies in the role of the transport subsystem within the complexity of a large urban centre and from the need to determine whether the observed changes ended, at least locally, when the threat receded or whether the transport behaviour of the population changed permanently enough that it will be necessary to modify transport services on offer.

The results of the study provide a broad diagnostic basis for formulating recommendations, both regarding the management of sustainable mobility among inhabitants and the steps taken by those responsible for providing transport services. The innovative nature of the research lies, first and foremost, in the very factor determining the changes to ‘typical’ transport behaviour of residents of a large urban centre. In addition, as the COVID-19 pandemic was an international threat, it will be possible to compare these data with other urban centres across the world regarding changes in the transport behaviour of inhabitants in different age groups. Another promising field of research was to analyse how transport exclusion evolved due to the pandemic and to identify its new manifestations, resulting, *inter alia*, from the diminished need to make certain trips (as some activities could now be performed online), measures implemented for the sake of the elderly, or the changes in the organisation of public transport, including restrictions on vehicle capacity and the launch of alternative transport services. What also testifies to the innovative nature of the study is the implementation of data derived from an intelligent transport systems (a Big Data resource). The relevance of research into transport behaviour for planning and designing transport systems cannot be overstated either. The COVID-19 pandemic presented a unique opportunity to analyse the impact of simulation modelling on a ‘living organism’, i.e., an urban transport system. The extraordinary circumstances of the epidemic also allow the researchers to predict how urban transport systems will respond to the ongoing depopulation of Poland's metropolitan areas, by which Lodz has been notably affected. Furthermore, the study also delves into the shift of activities related to work, services, and administration online. By employing advanced software for creating digital traffic models, it was possible to identify measurable changes (temporal, financial, etc.) in the operation of the urban transport system.

The remaining sections of the paper have been arranged as follows: section two reviews relevant literature, highlighting major gaps in previous research; section three provides a description of the research areas, detailing the urban contexts of Lodz and Bratislava; section four presents the materials and methods employed, including data collection techniques and the analytical framework; section five presents the results of the study, examining the impacts of the pandemic on the transport systems in question; section six contains the discussion, where the implications of the findings are explored and contextualised within broader urban mobility trends; and the final section, seven, concludes the paper, summarising the main outcomes and making recommendations for future research.

2. COVID-19 and urban mobility adaptations

In many countries worldwide, including those within the European Union, COVID-19 mitigation strategies were implemented to curb the spread of the virus, protect public health, and bolster economies against the financial turmoil caused by lockdowns and restrictions (Filip et al., 2022). Consequently, most governments enforced a number of restrictions on business operations, transport, travel, and daily mobility (Baig et al., 2021; Boot et al., 2020; Brídziková, 2021; Konečný et al., 2023; Przybylowski et al., 2021; Shamshiripour et al., 2020; Smolarski, 2020; Sun et al., 2021; Vickerman, 2021). Italy was the first European country to experience a significant surge in COVID-19 cases, leading to a lockdown on 10 March 2020, with other countries following suit (Latif et al., 2024). Beginning in March/April 2020, approximately 150 countries implemented national lockdowns (Bardosh, 2023).

Vannoni et al. (2020) proved that the severity of a country's response to COVID-19 was strongly correlated with a decrease in mobility. However, these non-pharmaceutical countermeasures affected transport behaviour, especially daily mobility (Hsiehchen et al., 2020; Oszter, 2020; Przybylowski et al., 2021; Tarkowski et al., 2020). A review of recent studies indicates that a majority of research on the effects of the COVID-19 pandemic on travel behaviour shows a significant decline in the willingness to travel during the pandemic (Chen et al., 2022). In Europe, mobility fell by an astounding 90% (Budd & Ison, 2020), which most dramatically affected public transport (Jenelius & Cebecauer, 2020; Zhang et al., 2021). Crowded places, e.g., transport hubs, were considered unsafe due to the risk of infection (De Vos, 2020; Morawska et al., 2020) and using public transport (usually chosen by millions of commuters every day) presented a risk of viral transmission (Musselwhite et al., 2020; Troko et al., 2011). The imposed restrictions combined with the fear of contracting the virus on mass transit made the public more likely to opt for a car when it came to everyday travel (Barbieri et al., 2021; Turoń & Kubik, 2022). Another mode of transport that boasted a noticeable rise in popularity was the bicycle (Molloy et al., 2021). This change in mobility behaviour was particularly evident in urban settings (Shemer et al., 2022). These findings illustrate the immediate impacts of COVID-19 on daily travel but also have implications for the long-term development of transport planning and policies.

The expanding body of literature highlights the significant interest in the impact of the coronavirus pandemic on mobility, facilitating international comparisons of pandemic-related mobility restrictions (Borkowski et al., 2021; Pawar et al., 2020; Przybylowski et al., 2021; Tardivo et al., 2020; Vannoni et al., 2020). Both the anti-Covid measures implemented by different countries and the particular manner in which the virus spread, generated generally similar changes in the transport behaviour of populations across the globe (Echaniz et al., 2021; Ha et al., 2023; Molloy et al., 2021; Tarkowski et al., 2020).

The reaction of populations to the pandemic is also of interest in the context of the implementation of postulates for sustainable urban transport and the development of urban transport policies tailored to passengers' needs (Mogaji et al., 2022). When faced with the pandemic, the said decline in demand for public transport was inevitable, while the threat itself has increased the need for a reappraisal of transport policies (Cho & Park, 2021). Managing the development of urban transport so that it meets actual demand cannot be successful without knowledge of the transport behaviour of road users, and by monitoring the temporal changes caused by the pandemic, one may gain a greater insight into this phenomenon (Jones et al., 2021; Yilmazkuday, 2020). Another compelling research topic is to assess how the pandemic may influence population distribution due to the increasing prevalence of remote working facilitated by e-services, e-administration, etc. (Beckers et al., 2021; Grinin et al., 2022; Mueller-Langer & Gómez-Herrera, 2022).

3. Research area

Two cities were selected for the study – Lodz (Poland) and Bratislava (Slovakia) (Fig. 1). Lodz is the fourth most populous city in Poland and the capital of the Lodz Province (population: 670,642, CSO, National Census 2021). Bratislava is the capital of the country with a population of 475,503 as of 1 January 2021.

Bratislava boasts the largest public transport network in Slovakia, which is operated by a municipal corporation (*Dopravný Podnik Bratislava*), offering buses, trolleybuses and trams, to meet the demands of passenger transport (Galkin et al., 2019). In Lodz, the urban public transport system mainly consists of trams and buses, managed by a municipal transport corporation (*Miejskie Przedsiębiorstwo Komunikacyjne*). The public transport network is well-developed, especially in the central area and within the large housing estates on the eastern and western outskirts of the city.

Both cities suffer from congestion, mostly in their central areas. This is mainly due to the disproportion between the level of car ownership and its alternatives, which significantly reduces speeds and increases travel times. In Lodz, the average daily number of vehicles recorded by the ITS in the central area accounts for almost 76% of the total within the city (Borowska-Stefańska et al., 2022). As for Bratislava, a study of traffic congestion by Galkin et al. (2019) shows that the road network (mainly in the centre) often operates at capacity limits.

According to the 2022 TomTom Traffic Index, Lodz was the most congested city in Poland (ranked 15th among European cities), while Bratislava was placed as low as 165th (https://www.tomtom.com/traffic-index/ranking/).

4. Materials and methods

The methodology consisted of three main phases and several steps, as shown in Figure 2.

To analyse the efficiency of the road network, traffic microsimulations were conducted. For this purpose, the Car Following Model was employed – a solution based on differential equations which describe the movement of vehicles and enable the researcher to calculate the position and speed of each vehicle, as well as the distance from the preceding car and its speed. The study employed the Wiedemann model implemented in the VISSIM software. A given vehicle was deemed to be held up if it slowed down to a speed of up to 5 km/h when approaching the vehicles in front, and it was assumed to leave 'the queue' when its speed exceeded 10 km/h. For each vehicle, the travel time in undisturbed driving conditions was calculated, which became the benchmark for calculating delay time. Data from inductive loop detectors were employed to reflect the traffic conditions during the periods under study. These detectors are installed within each entry lane of the junctions selected for the study. Data was collected for Wednesdays during the pre-COVID-19 period, the first COVID-19 pandemic-related lockdown, the peak of COVID-19 related mortality, and the post-COVID-19 period. It was also necessary to faithfully reproduce the infrastructure and traffic management in order to perform the traffic microsimulations. To this end, a road network model was built based on satellite measurements and field research (Fig. 3). The traffic management and the parameters of the traffic light control system were obtained from the transport authority.

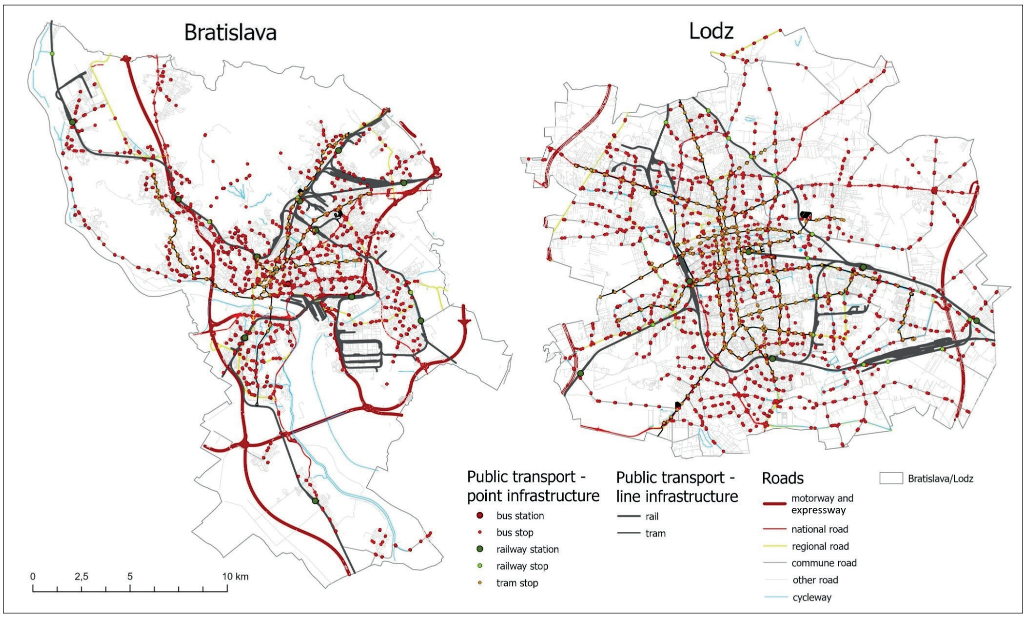

Fig. 1: Point and linear elements of the transport system in Bratislava and Lodz
Source: Authors' elaboration based on data from OpenStreetMap

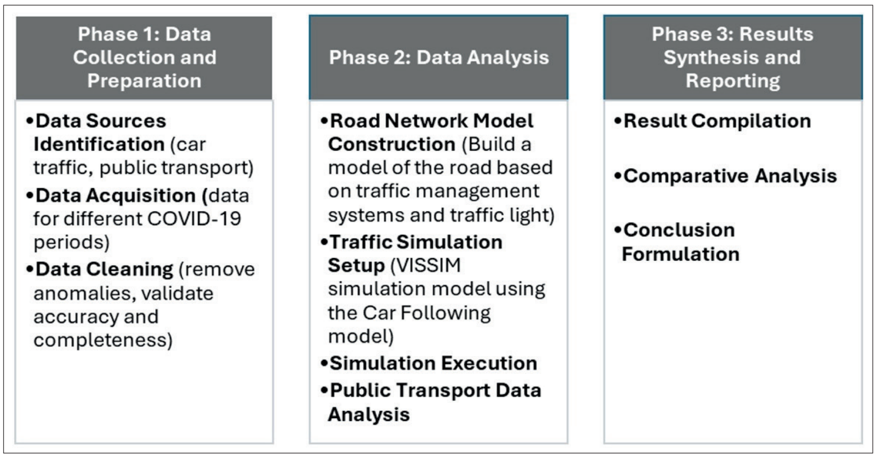

Fig. 2: An overview of data collection, analysis, and simulation for urban transport research
Source: Authors' conceptualisation

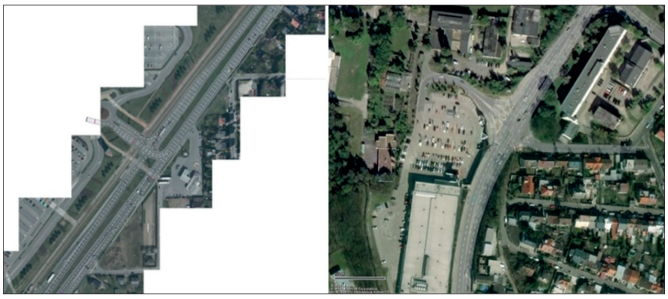

Fig. 3: Models of the road network in Lodz (left) and Bratislava (right) used in the microscopic simulations against the background of a satellite image (Google Maps)
Source: Authors' elaboration based on Google Maps

To gain comparable results for the two cities, a thorough selection of junctions (one in each city) was carried out with functional similarity of both junctions and full availability of traffic data in mind. To cover the main COVID-19 pandemic stages, the authors decided to cover the following four key periods:

- Pre-COVID-19 period (autumn 2019);
- First COVID-19 pandemic-related lockdown (spring 2020);
- Peak of COVID-19 related mortality (early spring 2021);
- Post-COVID-19 period (autumn 2022).

For each of the periods above, a single, nondescript, Wednesday (excluding holidays or other peculiarities) was selected for each junction. The traffic data gained via induction loops on the selected days (full 24-hour datasets) was provided by the relevant local authorities (*Urząd Miasta Łodzi* and by *Magistrát hlavného mesta SR Bratislavy*).

The data on the volume of public transport services in Lodz were derived from the official website of the transport operator (*Miejskie Przedsiębiorstwo Komunikacyjne Łódź*). Similarly, General Transit Feed Specification (GTFS) data from the Public Transport System (PTS) in Bratislava was the main source of data on the volume of public transport services there. In addition, comparable data on yearly volumes of passengers using public transport in both cities were also applied.

To ensure the robustness of our findings and to validate the significance of the changes observed in public transport service levels during the COVID-19 pandemic, the authors supplemented their descriptive analysis with statistical hypothesis testing. Specifically, they applied a paired t-test to assess whether the mean number of daily journeys by public transport during the pandemic significantly differed from pre-pandemic levels. This approach allowed the authors to determine whether service reductions had been systematic responses to changing demand rather than incidental fluctuations. Additionally, the authors conducted ANOVA (Analysis of Variance) to assess whether the fluctuations of public transport services within the different peak hours followed a structured pattern over time. This test helped assess whether public transport service adjustments had been uniformly distributed throughout the day or whether certain time periods had been prioritised based on travel demand and operational constraints.

These statistical analyses were performed separately for Lodz and Bratislava, enabling a comparative assessment of transport policy responses in both cities. The results confirm that service reductions were statistically significant, reinforcing the interpretation that transport authorities had implemented structured, data-driven adjustments in response to pandemic-related mobility shifts. By integrating inferential statistics, the authors have enhanced the methodological rigour of their study, ensuring that the reported trends reflect meaningful operational changes rather than random variations.

4.1 Scope of empirical evidence and data sample for car traffic analysis

The study utilises a dataset obtained from the inductive loop detectors installed at the selected junctions in Lodz and Bratislava. These sensors provide continuous traffic flow measurements, enabling the analysis of vehicle movement patterns before, during, and after the COVID-19 pandemic. Although the dataset is limited to the junctions in question, the selection focused on urban locations that are particularly significant within the transport networks of the two cities due to high traffic volumes, functional complexity, and central location.

Rather than aiming for statistical representativeness, the junctions were purposefully selected as exceptional cases. Namely, these were major mobility hubs where pandemic-induced fluctuations in traffic were expected to be most noticeable. Their unique positioning within the dense urban fabrics and proximity to commercial areas (e.g., shopping centres) allowed for the identification of highly dynamic changes in traffic patterns. These extraordinary sites offered a meaningful lens through which to observe stress responses within the urban mobility systems under study. To enhance the robustness of the findings, the authors supplemented the inductive loop data with additional sources, including publicly available traffic reports and datasets provided by the local transport authorities (*Urząd Miasta Łodzi* and *Magistrát hlavného mesta SR Bratislavy*). This multi-source approach helped validate observed trends and mitigate potential biases resulting from the spatial limitations of the sensor coverage.

While the study does not include a city-wide traffic analysis, it aims to capture key shifts in transport behaviour caused by the pandemic, particularly regarding demand variation and network efficiency. The methodological approach employed follows previous research on transport adaptation to external disruptions, where strategically chosen high-impact locations have served as valuable indicators of broader trends. Given the constraints imposed by the pandemic, the selection applied reflects a balance between empirical feasibility and analytical insight. In Lodz, the analysed junction is in the central part of the city, where commuting traffic converges, several public transport routes intersect, and peak-hour congestion is exceptionally high. In Bratislava, the chosen junction links residential areas with the central business district and includes access roads to a major shopping centre which remained open during lockdowns due to its essential retail functions. Both junctions are monitored by intelligent transport systems (ITS), enabling a continuous, high-resolution traffic flow analysis throughout the different pandemic phases.

Although the chosen junctions do not represent the full diversity of road network typologies across either city, they provide a detailed insight into how critical nodes within the urban systems were impacted by the crisis. The authors acknowledge the limitations of this approach and recommend that future studies incorporate a broader array of locations, including peripheral and residential areas, as well as apply spatial modelling techniques. The authors have carefully framed their conclusions as context-specific observations rather than universal claims. The findings should be interpreted within the spatial and functional characteristics of the selected locations, while future research may build upon these results with broader and more diversified data sources.

5. Results

5.1 Individual car transport

Delays observed at the junctions in question were mainly due to the method of traffic management (i.e., traffic lights). For the junction in Lodz, traffic lights serve all directions, while in Bratislava they apply for all directions except for when turning right. Although both of these systems led to queues that effectively prevented free-flowing travel (Fig. 4), quite distinct differences between the junctions under study were observed.

In Poland, the initial pandemic restrictions resulted in a significant decrease in urban vehicle traffic, especially in the areas where shopping centres are located. In consequence, the lower volume on the main road within the analysed area and the negligible volume on the subordinate roads (exits and entrances to the shopping centres) significantly improved traffic conditions. Observations from Slovakia, however, give a different picture of the early pandemic. On average, longer delays were observed for traffic at the junction under study.

A closer look at the roads where delays were noted gives a precise insight into the mechanism behind this seemingly paradoxical phenomenon. Although the traffic volume on the main road was significantly lower than before the pandemic, a dramatic rise in the percentage of cars heading to the shopping centre was observed within the total volume. This, rather than a different distribution of traffic, contributed to a deterioration in the efficiency of the junction under study (increased travel time), as the routes to and from the shopping centre are by a network of roads with no right of way. The centre located close to the analysed

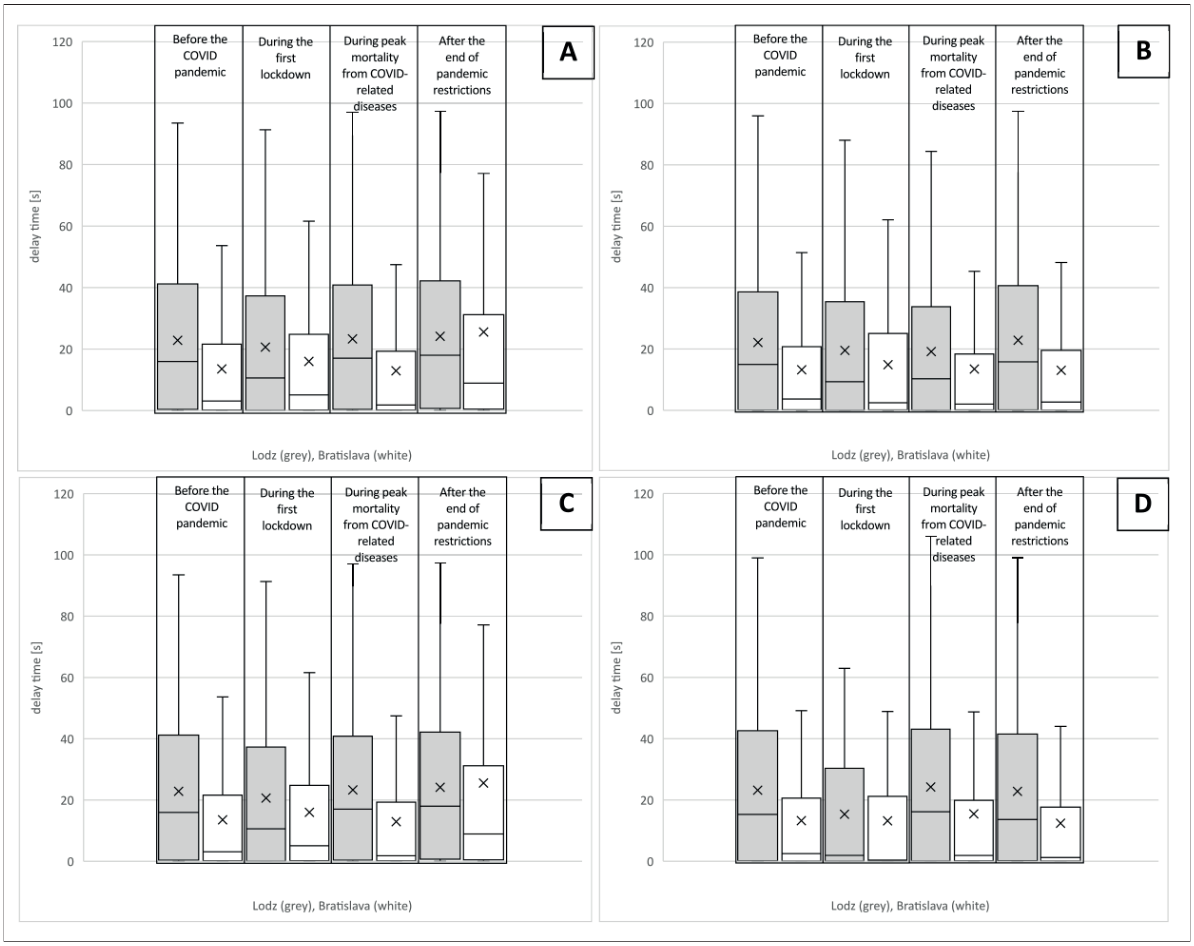

Fig. 4: Delayed travel time at the selected junctions in Lodz and Bratislava during: A – morning rush hours (7 to 9 a.m.); B – around noon (11 a.m. to 1 p.m.); C – afternoon peak (3 to 5 p.m.); and D – evening (8 to 10 p.m.)
Source: Authors' elaboration based on data provided by the local authorities of Lodz and Bratislava

junction in Bratislava was a branch of a food retail chain that remained open to secure food availability in Slovakia during all COVID-19 pandemic lockdowns (Brídziková, 2021). The traffic flow at the junctions under study during the peak mortality of the pandemic also showed a change. In Lodz, the traffic volume and the magnitude of delays rose almost to pre-pandemic levels, while in Slovakia the most efficient (throughout the whole study) state of transport equilibrium was observed. After the pandemic, the efficiency of the junctions in question deteriorated compared to pre-pandemic observations. However, while this change is hardly noticeable in Lodz, the magnitude of the delays observed in Bratislava increased sharply.

The pandemic-induced fluctuations in urban mobility were particularly evident in commercial areas, where shopping centres played a pivotal role in shaping traffic patterns. In Bratislava, the traffic volume around major shopping hubs experienced two distinct phases: an initial sharp decline due to lockdown restrictions, followed by a rapid surge as retail activity resumed. During the lockdown, car traffic around shopping centres dropped by up to 60% compared to pre-pandemic levels, reflecting the strict limitations on in-person shopping. However, once restrictions were lifted, shopping-related traffic rebounded rapidly, exceeding pre-pandemic levels during peak shopping hours. This trend implies that consumer behaviour, influenced by temporary e-commerce reliance during the lockdown, quickly reverted to physical store visits once permitted.

This post-lockdown rebound effect is consistent with mobility trends observed in other European cities, where pent-up demand for retail experiences and social outings contributed to short-term spikes in vehicle traffic. Notably, the rebound was more pronounced during weekends, indicating a shift in shopping patterns, with consumers opting for fewer but more concentrated trips. This behavioural shift had operational implications for both public and personal transport networks, affecting public transport demand and congestion levels.

5.2 Urban public transport

In both Bratislava and Lodz urban public transport experienced a decline in ridership as residents were urged to stay at home and practice social distancing during the COVID-19 pandemic. Notably, pandemic-related lockdowns impacted public transport in Lodz earlier than in Bratislava. In Lodz, the early signs of a decline in daily journeys were observed on March 20, 2020, coinciding with the initial lockdown measures in Poland. This aligns with the first confirmed cases of SARS-CoV-2 reported on March 4, 2020 in Poland, compared to March 3, 2020 in Slovakia. However, the decrease in ridership in Lodz during the period was relatively modest. In contrast, Bratislava experienced a more pronounced impact during the first wave of the pandemic. A sharp decline in daily journeys was recorded starting April 20, 2020, with approximately 1,800 fewer journeys compared to earlier in the month. This reduced transport activity persisted until May 18, 2020 (see Tabs. 1 and 2). The Bratislava Public Transport Company responded to the crisis by reducing the frequency of services, deploying vehicles with lower capacities, and suspending selected routes, including special university-related lines and all Volkswagen-specific services. Additionally, most daily services operated under modified timetables typical of school holidays, weekends, or public holidays (DPB Bratislava, 2022; Raport o stanie miasta, 2020).

Date	Number of lines	Daily number of journeys by public transport vehicles	Relative change in daily number of journeys by public transport vehicles (27.01.2020 – 100%)	Number of journeys by public transport vehicles from 6:00 a.m. to 8:00 a.m.	Relative change in number of journeys by public transport vehicles from 6:00 a.m. to 8:00 a.m. (27.01.2020 – 100%)	Number of journeys by public transport vehicles from 10:00 a.m. to 12:00 a.m.	Relative change in number of journeys by public transport vehicles from 10:00 a.m. to 12:00 a.m. (27.01.2020 – 100%)	Number of journeys by public transport vehicles from 3:00 p.m. to 5:00 p.m.	Relative change in number of journeys by public transport vehicles from 3:00 p.m. to 5:00 p.m. (27.01.2020 – 100%)
27.01.2020	104	4,351	100.0%	501	100.0%	427	100.0%	504	100.0%
11.03.2020	106	4,399	101.1%	513	102.4%	441	103.3%	523	103.8%
20.03.2020	106	4,314	99.1%	510	101.8%	431	100.9%	516	102.4%
25.03.2020	106	4,395	101.0%	528	105.4%	450	105.4%	532	105.6%
20.04.2020	108	4,449	102.3%	531	106.0%	458	107.3%	534	106.0%
04.05.2020	107	4,447	102.2%	522	104.2%	435	101.9%	523	103.8%
18.05.2020	107	4,437	102.0%	526	105.0%	449	105.2%	527	104.6%
01.06.2020	106	4,441	102.1%	523	104.4%	446	104.4%	521	103.4%
10.08.2020	106	4,423	101.7%	533	106.4%	451	105.6%	535	106.2%
12.10.2020	106	4,393	101.0%	527	105.2%	448	104.9%	523	103.8%
19.10.2020	106	4,402	101.2%	530	105.8%	454	106.3%	527	104.6%
26.10.2020	106	4,412	101.4%	529	105.6%	451	105.6%	522	103.6%
09.11.2020	106	4,433	101.9%	518	103.4%	447	104.7%	515	102.2%
30.11.2020	106	4,416	101.5%	531	106.0%	452	105.9%	529	105.0%
28.12.2020	106	4,399	101.1%	527	105.2%	442	103.5%	523	103.8%
01.02.2021	106	4,403	101.2%	529	105.6%	446	104.4%	522	103.6%
01.03.2021	106	4,398	101.1%	535	106.8%	449	105.2%	524	104.0%
22.03.2021	106	4,399	101.1%	525	104.8%	443	103.7%	519	103.0%
29.03.2021	106	4,418	101.5%	522	104.2%	447	104.7%	517	102.6%
04.05.2021	106	4,379	100.6%	522	104.2%	467	109.4%	515	102.2%
07.06.2021	106	4,401	101.1%	521	104.0%	435	101.9%	517	102.6%
30.08.2021	106	4,399	101.1%	528	105.4%	457	107.0%	519	103.0%
01.09.2021	106	4,391	100.9%	531	106.0%	471	110.3%	524	104.0%
12.10.2021	106	4,401	101.1%	533	106.4%	467	109.4%	516	102.4%
23.11.2021	106	4,409	101.3%	536	107.0%	449	105.2%	514	102.0%
20.12.2021	106	4,412	101.4%	522	104.2%	456	106.8%	511	101.4%
21.02.2022	106	4,403	101.2%	527	105.2%	464	108.7%	521	103.4%

Tab. 1: Variation in the number of journeys by public transport on weekdays in Lodz between January 27, 2020 and February 21, 2021
Source: Authors' calculations based on data from ITS in Lodz

Date	Number of lines	Daily number of journeys by public transport vehicles	Relative change in daily number of journeys by public transport vehicles (05.02.2020 – 100%)	Number of journeys by public transport vehicles from 6:00 a.m. to 8:00 a.m.	Relative change in number of journeys by public transport vehicles from 6:00 a.m. to 8:00 a.m. (05.02.2020 – 100%)	Number of journeys by public transport vehicles from 3:00 p.m. to 5:00 p.m.	Relative change in number of journeys by public transport vehicles from 3:00 p.m. to 5:00 p.m. (05.02.2020 – 100%)	Number of journeys by public transport vehicles from 10:00 a.m. to 12:00 a.m.	Relative change in number of journeys by public transport vehicles from 10:00 a.m. to 12:00 a.m. (05.02.2020 – 100%)
05.02.2020	107	6,442	100.0%	999	100.0%	631	100.0%	938	100.0%
18.03.2020	105	6,173	95.8%	960	96.1%	608	96.4%	887	94.6%
20.04.2020	99	4,331	67.2%	507	50.8%	509	80.7%	530	56.5%
04.05.2020	101	4,338	67.3%	449	44.9%	462	73.2%	492	52.5%
18.05.2020	101	4,352	67.6%	437	43.7%	462	73.2%	488	52.0%
08.06.2020	102	5,448	84.6%	804	80.5%	562	89.1%	750	80.0%
10.08.2020	103	5,704	88.5%	839	84.0%	593	94.0%	765	81.6%
07.10.2020	100	6,007	93.2%	905	90.6%	611	96.8%	839	89.4%
26.10.2020	99	5,884	91.3%	913	91.4%	588	93.2%	826	88.1%
16.11.2020	98	4,072	63.2%	442	44.2%	483	76.5%	492	52.5%
13.01.2021	98	5,966	92.6%	936	93.7%	596	94.5%	842	89.8%
08.02.2021	98	5,948	92.3%	930	93.1%	596	94.5%	838	89.3%
01.03.2021	92	5,590	86.8%	846	84.7%	570	90.3%	775	82.6%
29.03.2021	93	5,396	83.8%	827	82.8%	547	86.7%	761	81.1%
03.05.2021	94	5,574	86.5%	875	87.6%	560	88.7%	791	84.3%
07.06.2021	98	5,692	88.4%	891	89.2%	574	91.0%	805	85.8%
30.08.2021	98	5,679	88.2%	887	88.8%	572	90.6%	801	85.4%
02.09.2021	99	5,889	91.4%	931	93.2%	597	94.6%	826	88.1%
14.10.2021	99	5,892	91.5%	936	93.7%	597	94.6%	826	88.1%
15.11.2021	99	5,909	91.7%	929	93.0%	596	94.5%	832	88.7%
27.12.2021	101	6,044	93.8%	943	94.4%	612	97.0%	843	89.9%
25.02.2022	99	6,022	93.5%	943	94.4%	612	97.0%	837	89.2%

Tab. 2: Variation in the number of journeys by public transport on weekdays in Bratislava between February 5, 2020 and February 25, 2021
Source: Authors' elaboration based on internal road traffic databases of Bratislava City Hall Office

Both Bratislava and Lodz implemented similar measures to protect public transport passengers from COVID-19. These included daily disinfection of vehicles, automatic door opening at stops, and the implementation of a buffer zone near the front door to separate the driver from the passengers (Annual Report 2020, DPB Bratislava; Łódź, Raport o stanie miasta, 2020). Throughout the analysed period, the number of journeys by public transport was generally higher during the morning (6:00–8:00) and afternoon (3:00–5:00) peak hours compared to midday (lunch time). However, this trend was disrupted during the first and second COVID-19 lockdowns in Bratislava. A key difference between the two cities lies in the variation in journey numbers across these time periods. In Bratislava, the differences between the number of journeys during peak hours (morning vs. lunch, evening vs. lunch) were significantly larger compared to Lodz – except during the pandemic-related peaks in Bratislava, when these variations were less pronounced (see Fig. 5). The statistical analysis of public transport operations in Lodz and Bratislava confirms that pandemic-induced service reductions were deliberate and structured, rather than random fluctuations. The t-tests comparing daily journeys before and during the pandemic indicate a significant decline in both cities. In Lodz ($t = 10.85$, $p < 0.001$), service reductions were moderate and gradual, while in Bratislava ($t = -6.48$, $p < 0.001$), they were more abrupt and extensive, reflecting a more aggressive adjustment strategy in response to demand fluctuations. Analysis of peak-hour variations through ANOVA reveals significant differences in transport service levels across different time periods ($p < 0.001$ in both cases). The impact

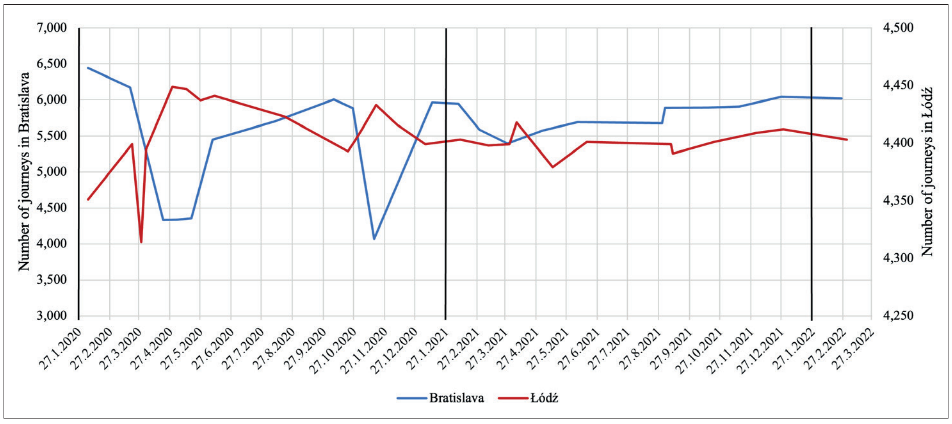

Fig. 5: Variation in the number of vehicle journeys by public transport on weekdays in Bratislava and Lodz between January 27, 2020 and February 25, 2021
Source: Authors' elaboration based on data from ITS in Lodz and GTFS data of PTS in Bratislava

was more pronounced in Lodz (F = 659.29) than in Bratislava (F = 21.72), suggesting that Lodz transport authorities prioritised specific peak hours, adjusting schedules dynamically rather than applying uniform reductions. The adjustments in Bratislava, though structured, were less targeted, indicating a broader, more generalised approach to service reductions. The comparison highlights two distinct strategies: while Lodz maintained relative operational stability, adapting service frequencies to peak demand, Bratislava implemented deeper cuts, responding more directly to overall drops in ridership. These findings confirm that the public transport systems under study were actively managed during the crisis, with decisions shaped by travel demand, financial constraints, and pandemic-related policies.

The results underscore the importance of flexible, data-informed strategies in urban mobility planning. While both cities relied on similar types of operational and demand-side data, the ways in which this information was interpreted and acted upon varied significantly. Bratislava applied a more cost-oriented and reactive approach, whereas Lodz maintained relative service stability. These differences highlight that data served as a shared foundation, but institutional preferences, financial capacities, and local policy goals ultimately shaped the strategic choices.

The comparative analysis of public transport operations in Lodz and Bratislava during the COVID-19 pandemic, based on the data presented in Tables 1 and 2, reveals distinct adaptation strategies and service adjustment patterns in the two cities. While both transport systems faced disruptions due to lockdown measures and fluctuating passenger demand, the scale and timing of service reductions and recoveries differed significantly, highlighting divergent approaches to maintaining urban mobility during the crisis. At the onset of the pandemic, both cities implemented modifications in their public transport services in response to restrictions and a sharp decline in ridership. However, Bratislava experienced far more drastic reductions in service levels compared to Lodz. In March 2020, daily vehicle journeys in Bratislava dropped from 6,442 to 4,331 (a 33% reduction), whereas in Lodz, service reductions were far less pronounced, with daily vehicle journeys fluctuating around 4,400–4,300 during the first wave of restrictions. This discrepancy implies that the transport authorities in Bratislava implemented more aggressive cost-saving measures, whereas Lodz opted for a more stable service provision, ensuring continuous operations despite the fluctuating demand.

The impact of service reductions was particularly evident in morning peak-hour frequencies, which dropped by nearly 50% in Bratislava (from 999 to 507 journeys) during the strictest lockdown period. In contrast, morning peak-hour service levels in Lodz remained relatively stable, with around 500–530 journeys. The more pronounced decline in Bratislava suggests a higher reliance on work-based commuting, which was significantly disrupted by remote work policies, leading to lower early-morning transport demand. As restrictions were eased, both cities began reinstating transport services, but at different rates and with varying priorities. By June 2020, Bratislava saw a substantial increase in service frequency, with daily journeys rising to 5,448, signalling a strong attempt to restore mobility. Lodz, on the other hand, maintained a gradual, more measured approach, keeping daily journeys at around 4,400, with slight fluctuations.

During the second wave of the pandemic (October 2020–March 2021), both cities faced renewed challenges. Bratislava once again implemented significant reductions, cutting services in November 2020 to just 4,072 daily journeys – a 32% drop from October levels. Meanwhile, Lodz continued operating at relatively stable levels, with only minor reductions in service frequencies. This contrast indicates that Bratislava adopted a more reactive strategy, reducing service in response to the declining ridership, whereas Lodz prioritised operational consistency that was intended to maintain accessibility and ensure transport availability for essential workers. By mid-2021, both cities began stabilising their operations, with Bratislava progressively restoring service levels, reaching 6,022 daily journeys by February 2022, thus effectively returning to pre-pandemic frequencies. In Lodz, the number of daily journeys remained slightly below pre-pandemic levels, suggesting that either passenger demand had not fully recovered or that authorities had implemented permanent efficiency measures to optimise transport operations (Figs. 6–8).

An additional observation highlights notable differences in the volume of public transport journeys on weekends between Bratislava and Lodz. In the latter, the number of journeys on Saturdays shows significant variability, with a significant reduction occurring after April 25, 2020, coinciding with the first COVID-19 pandemic-related lockdown. A marked increase in journeys was observed more than a year later, starting June 16, 2021, reflecting the easing of several pandemic-related restrictions during the summer. However, identifying a clear pattern in the number of journeys on Sundays that directly correlates with the pandemic is challenging for Lodz. Meanwhile, Bratislava maintained a more consistent public transport schedule, with the exception of a significant reduction in journeys during the first lockdown period.

The impact of COVID-19 is also evident in Figure 9, which illustrates the number of passengers carried by public transport in the two cities. The lowest passenger numbers in both Lodz and Bratislava were recorded in 2021. That year, Lodz experienced a decline of over 81 million passengers compared to the pre-

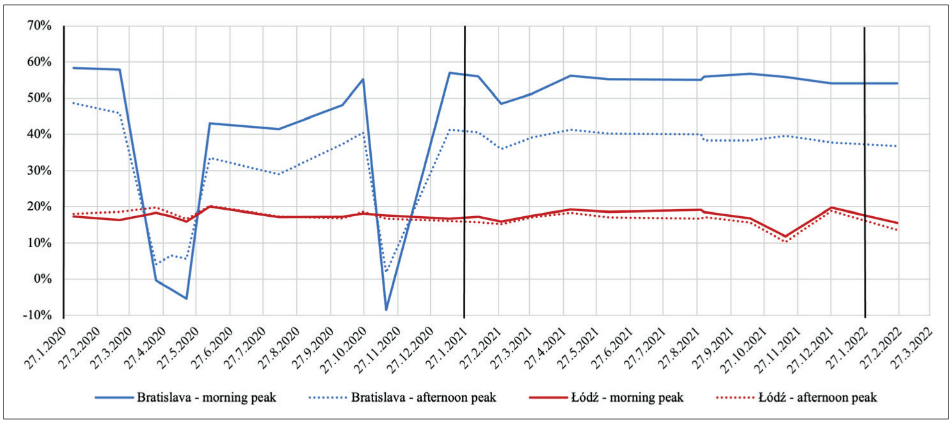

Fig. 6: Variation in the number of journeys by public transport during peak and off-peak periods on weekdays in Lodz and Bratislava between January 27, 2020 and February 25, 2021
Source: Authors' elaboration based on data from ITS in Lodz and GTFS data of the PTS in Bratislava

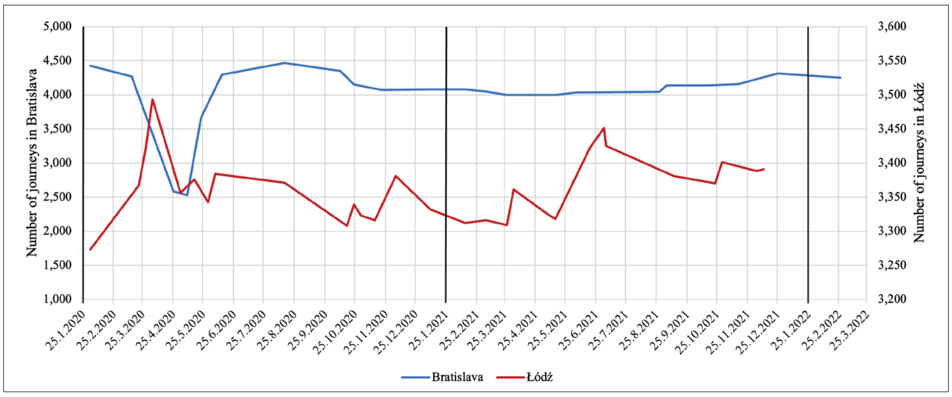

Fig. 7: Variation in the number of journeys by public transport on Saturdays in Lodz and Bratislava between January 25, 2020 and February 26, 2022. Source: Authors' elaboration based on data from ITS in Lodz and GTFS data of the PTS in Bratislava

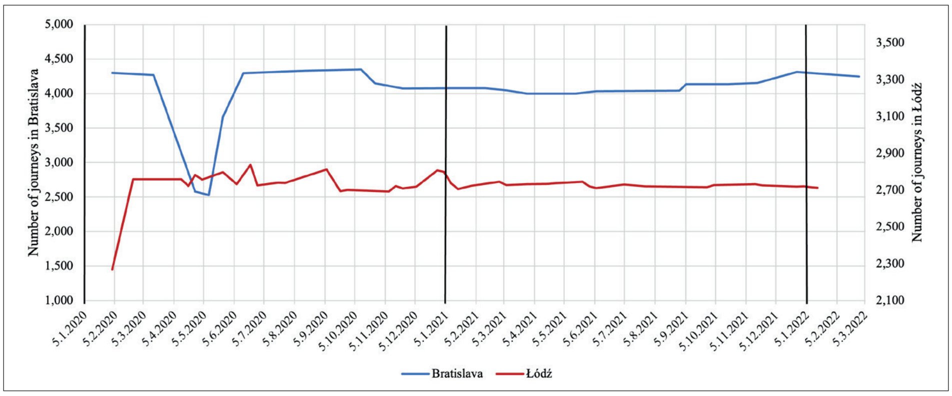

Fig. 8: Variation in the number of journeys by public transport on Sundays in Lodz and Bratislava between January 5, 2020 and February 27, 2021. Source: Authors' elaboration based on data from ITS in Lodz, GTFS data of the PTS in Bratislava

COVID-19 levels of 2019, while Bratislava reported a reduction of more than 86 million passengers. However, the data suggests that the pandemic had a more severe impact on public transport performance in Lodz, with a sharper decline in passenger volumes compared to Bratislava.

The public transport systems of Lodz and Bratislava rely on two primary types of vehicles: rail-based transport (trams and trolleybuses) and rubber-tired transport (buses). In Lodz, the tram network plays a dominant role, having accounted for approximately 55% of public transport journeys before the pandemic, while buses constituted the remaining 45% (MPK Łódź, 2019). In Bratislava, where trolleybuses complement the tram system, the combined share of rail-based transport was 42%, while buses accounted for 58% of the total public transport usage. During the pandemic, significant shifts occurred in the modal split, directly affecting public transport efficiency/performance. Both cities experienced a decline in tram and trolleybus ridership, with passengers favouring bus travel. This shift can be attributed to multiple factors. Firstly, rail-based vehicles were perceived as higher-risk environments due to their larger passenger capacity and longer dwell times at stops, increasing exposure to potential infection. Secondly, buses provided greater operational flexibility – their routes could be adjusted more rapidly than tram lines, and operators were able to modify frequencies in response to the changing demand. The most substantial drops in ridership were recorded during the strictest lockdown periods. In Lodz, tram usage declined by up to 40% in the first months of the lockdown, while bus ridership dropped by around 30% (source: MPK Łódź, 2020). In Bratislava, where public transport is strongly linked to work commutes – particularly in the service sector – these changes were even more pronounced. Trams and trolleybuses lost approximately 45% of passengers, while bus ridership fell by 35% in the initial phase of the pandemic.

One key operational challenge faced by transport companies during the pandemic was staff shortages due to illness and quarantine requirements. In Bratislava, public transport authorities experienced driver shortages of up to 15% at peak pandemic periods, forcing temporary service reductions on selected routes. The impact of these workforce shortages was most visible in bus and trolleybus operations, as these modes require larger numbers of personnel compared to tram services, which are less labour-intensive on account of their higher passenger capacity per vehicle. Similar challenges were reported in multiple European cities, where the temporary unavailability of drivers necessitated emergency timetable adjustments.

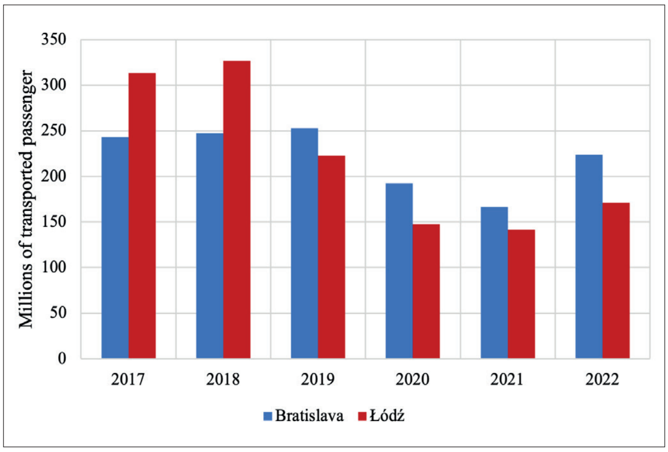

Fig. 9: Number of passengers carried by public transport in Bratislava and Lodz
Source: Authors' elaboration based on data from Lodz – Raport o stanie miasta (2017, 2018, 2019, 2020, 2021, 2022), Štatistická ročenka hl. mesta Bratislavy (2018, 2019, 2020, 2021, 2022)

In response to social distancing regulations, many public transport operators introduced capacity restrictions to limit crowding on buses, trams, and trolleybuses. These measures required transport agencies to adjust operational strategies, particularly for rush-hour services. In some cases, instead of increasing the number of vehicles to maintain spacing between passengers, operators chose to reduce frequencies and rely on natural demand suppression caused by remote work and school closures. Furthermore, some services were merged or temporarily suspended, particularly on low-demand routes. In Bratislava, certain night bus services were either combined with daytime routes or reduced in frequency to optimise vehicle use. These service rationalisation strategies were designed to balance financial sustainability with passenger needs, reflecting a cost-driven approach rather than purely epidemiological considerations. A significant yet often overlooked aspect of the pandemic-era transport management was the use of lockdown periods for infrastructure maintenance and vehicle upgrades. With reduced ridership and lower service frequencies, transport companies took advantage of this period to accelerate scheduled repairs and system upgrades. In Bratislava, tramway infrastructure projects that were originally scheduled for later years were expedited due to the reduced disruption risk for passengers. Similar initiatives were observed in Lodz, where rolling stock maintenance schedules were adjusted to complete major refurbishments while minimising passenger inconvenience. However, despite similarities in infrastructure efforts, the timing, scope, and institutional rationale behind these decisions differed. In both cases, the pandemic served as an enabling context, but the local execution reflected distinct operational logics. This strategic use of pandemic-related service reductions for infrastructure improvements highlights a proactive transport management approach, ensuring that the public transport systems emerged from the crisis in an improved operational state. The long-term impact of these investments will likely contribute to enhanced service reliability and reduced maintenance backlogs, potentially offsetting some of the negative financial consequences of pandemic-related ridership losses.

6. Discussion

Although both cities faced comparable pandemic-related constraints and had access to analogous sources of data, their responses diverged, revealing the influence of local contexts in shaping how data were applied in crisis management. The COVID-19 pandemic drastically affected urban transport systems worldwide, leading to a dramatic decline in public transport ridership, a surge in personal vehicle use, and evolving policies aimed at stabilising mobility patterns. This study of Lodz and Bratislava aligns with these global trends but also reveals regional distinctions in how the two cities adapted to pandemic-related disruptions. The findings provide insights into behavioural shifts, operational responses, and long-term planning challenges. Public transport ridership declined significantly during lockdown phases across all major cities. In Europe and North America, reductions of 70–90% were reported, such as in New York, London, and Madrid (Almlöf et al., 2021; Wielechowski et al., 2020). Similar trends were observed in Lodz and Bratislava, where lockdowns and health concerns suppressed mobility. However, the pace of recovery varied: the transport system in Bratislava rebounded more quickly, in line with cities such as Berlin and Vienna, where authorities retained consistent public transport service levels. Lodz, by contrast, experienced a prolonged decline, mirroring Warsaw and Krakow, influenced by recurring lockdowns and service reductions (Christidis et al., 2023).

As public transport usage fell, personal vehicle dependency rose. By mid-2020, cities like Paris, Milan, and Los Angeles had already returned to pre-pandemic car traffic volumes (Lozzi et al., 2020). Our findings confirm that both Lodz and Bratislava followed this trend. Yet, the degree of resurgence differed: the former saw congestion levels in 2022 approach pre-pandemic norms, consistent with other Polish cities such as Wrocław and Gdansk (Borkowski et al., 2021). In Bratislava, car traffic recovery was more moderate, resembling trends in Prague and Budapest, where compact urban forms and transit-oriented development curbed the shift toward car dependency (Thombre & Agarwal, 2021).

These findings invite a broader reflection on post-pandemic car traffic dynamics. The resilience of car usage, despite efforts to promote sustainable mobility, underscores structural dependencies – particularly in urban areas where alternatives to private personal vehicles remain limited. In Lodz, the rapid return of congestion highlights the role of urban sprawl, insufficient public transport incentives, and underdeveloped cycling infrastructure in reinforcing car-based commuting. In contrast, Bratislava's more tempered increase in car traffic appears to reflect the relative effectiveness of compact urban design and pre-existing multimodal options. These differences suggest that pandemic-induced behavioural shifts may have exacerbated underlying spatial and policy-related transport inequalities.

In response to these pandemic-related shifts, urban transport authorities adopted a range of operational strategies. Some cities, like Stockholm, preserved full public transport operations, while others reduced services (Hadjidemetriou et al., 2020). In Lodz and Bratislava, the authorities implemented dynamic measures such as adjusted service intervals, frequency reductions, and disinfection protocols. These efficiency-driven responses highlighted the importance of adaptability, particularly in the face of constrained budgets. Our study emphasises that while both cities relied on similar data inputs, such as ridership figures and ITS indicators, the interpretation of this data and the resulting strategies diverged. Bratislava adopted a more reactive, cost-driven approach with abrupt service cuts, whereas Lodz prioritised service continuity to support accessibility. This contrast underscores how data-informed decisions are deeply shaped by local institutional priorities, financial realities, and policy cultures.

Mode-specific differences also emerged. Rail-based modes (trams, trolleybuses) were less adaptable to demand shifts due to fixed infrastructure, while buses offered greater operational flexibility. In Bratislava, authorities used this ability to expand services to peripheral districts, helping offset tram service limitations. In both cities, bus ridership rebounded faster than rail-based modes, suggesting a partial and potentially lasting modal shift. Our results support theoretical frameworks such as the habit discontinuity hypothesis (Verplanken & Roy, 2016), which posits that disruptions can trigger lasting behavioural changes. Pandemic-era increases in car use and decreases in public transport demand may represent enduring transformations. Moreover, the findings presented herein reflect theories of transport resilience (Marsden et al., 2020), showing that urban systems adapted through short-term operational shifts, though many of these were reversed post-pandemic.

The discussion also highlights issues of equity. Reduced public transport availability disproportionately affected vulnerable groups – such as students, the elderly, and lower-income residents – who depend more on mass transit services (Lucas, 2012; Pereira et al., 2017). This reinforces the need for inclusive transport planning that considers differential impacts during crises (Vickerman, 2021).

Finally, the crisis encouraged a shift in focus from large-scale infrastructure projects to smarter, more agile operational management. Dynamic scheduling, real-time adjustments, and multimodal integration proved effective in maintaining essential service levels. While such approaches may not replace infrastructure investments entirely, especially in high-density cities, they provide a complementary strategy. The findings of this study suggest that the future of urban mobility lies in hybrid models that blend selective infrastructure development with flexible, data-supported management.

7. Conclusions and policy implications

This study analysed the impact of the COVID-19 pandemic on urban transport systems in Lodz and Bratislava, focusing on changes in mobility behaviour, public transport efficiency, and road congestion. The findings confirm that the pandemic triggered significant, though mostly temporary, changes in both individual and public transport use. In both cities, public transport ridership declined sharply due to lockdowns and travel restrictions, forcing operators to adjust timetables, reduce service frequencies, and implement additional health measures. Simultaneously, car traffic patterns were also disrupted, with early pandemic phases showing a reduction in congestion, followed by a return to or near pre-pandemic levels.

A key finding of this study is that most changes in transport behaviour during the pandemic were temporary and driven primarily by government-imposed restrictions rather than voluntary behavioural adaptation. Although some shifts – such as the increased use of bicycles and a partial transition to remote work – may persist in specific urban contexts, broader mobility patterns have largely reverted to pre-pandemic norms. Despite similar responses to the pandemic, the transport system resilience of Lodz and Bratislava exhibited key differences. In Lodz, public transport ridership recovery was more gradual, whereas in Bratislava, congestion issues worsened post-pandemic due to increased personal vehicle dependency. These variations highlight the role of local policies, infrastructure, and urban tissue in shaping mobility responses to global disruptions.

From these findings, several implications can be drawn. Firstly, the pandemic served as a real-world stress test of urban transport systems, revealing both operational vulnerabilities and institutional flexibility. The differing responses in Lodz and Bratislava underscore the importance of tailoring transport responses to specific urban contexts rather than applying uniform solutions. The return to pre-pandemic mobility patterns, particularly in car traffic, suggests that structural conditions – such as urban sprawl, limited alternatives, and policy inertia – continue to strongly influence mobility choices.

Secondly, the case studies highlight the limits of temporary operational adaptations when not supported by broader structural or behavioural changes. While adjustments in service frequency and hygiene protocols proved effective in the short term, they did not catalyse long-term modal shifts. This suggests a need to integrate such measures into more comprehensive and sustained mobility strategies, ideally supported by investments in active transport infrastructure, long-term behaviour change initiatives, and incentives for modal diversification.

Although the pandemic illuminated the critical role of data in managing uncertainty, the divergence in policy responses between the two cities shows that data alone is insufficient – it must be embedded in coherent decision-making frameworks aligned with strategic mobility goals. Strengthening institutional capacity and improving the use of data for anticipatory planning and scenario modelling could enhance preparedness for future disruptions.

In response to these findings, several policy recommendations can be proposed to enhance the resilience, adaptability, and sustainability of urban transport systems. First of all, the importance of real-time data and intelligent transport systems (ITS) was evident. The pandemic underscored the need for better mobility monitoring tools to allow cities to respond dynamically to sudden demand fluctuations. Investing in flexible, demand-responsive transport solutions, supported by ITS and predictive analytics, could improve cities' preparedness for future crises.

Strengthening multimodal connectivity also remains crucial. Integrating public transport with cycling and pedestrian infrastructure could improve overall system flexibility and provide users with a wider choice of transport alternatives. Additionally, supporting remote work policies and promoting off-peak travel could help reduce congestion and distribute demand more evenly across transport networks.

Naturally, this study has its limitations. The analysis is based on data from two specific cities and a very limited number of intersections, which may not fully capture the diversity of urban transport experiences. Furthermore, the short-term nature of the dataset limits the ability to assess longer-term behavioural changes. The findings reflect the immediate impacts of the pandemic phases and do not account for subsequent adjustments or macroeconomic developments that may further influence urban mobility. Despite these limitations, this study offers valuable insights into the short-term impacts of the COVID-19 pandemic on urban transport systems and provides a foundation for future research. Further studies should explore longitudinal changes in travel behaviour, the role of digital mobility solutions, and institutional responses across a wider set of urban contexts. By incorporating more diverse datasets and perspectives, researchers can better assess the sustainability of post-pandemic transport trends and inform more adaptive, resilient urban mobility planning.

Acknowledgment

The project is co-financed by the Polish National Agency for Academic Exchange, under the framework of the 2% subsidy for tertiary education, aimed at academies and universities which participated in the IDUB Contest ('Inicjatywa Doskonałości – Uczelnia Badawcza') and by the National Science Centre in Poland [2023/49/B/HS4/01406].

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Please cite this article as:

Borowska-Stefańska, M., Horňák, M., Kowalski, M., Masierek, E., Wiśniewski, S., Ďurček, P., & Hluško, R. (2025). Are the changes in the functioning of urban transport systems arising from the COVID-19 pandemic just temporary change or a permanent transformation? Examples of Lodz and Bratislava. Moravian Geographical Reports, 33(3), 163–175. https://doi.org/10.2478/mgr-2025-0013