Sustainable Urban Mobility Measures in response to COVID-19: A Systematic Literature Review and Emerging Policy Challenges

Marta Bubicz[a], Elisabete Arsenio[a], Rui Henriques[b], José Barateiro[c]

[a]*LNEC – Department of Transport, Av. Do Brasil, 101, Lisbon, 1700-075, Portugal*
[b]*INESC-ID and Instituto Superior Técnico, University of Lisbon, Lisbon, Av. Rovisco Pais, 1049-001, Portugal*
[c]*LNEC, Information Technology in Civil Engineering Unit, Av. Do Brasil, 101, Lisbon, 1700-075, Portugal*

Abstract

Urban mobility was strongly impacted by the COVID-19 pandemic, with several sustainability vulnerabilities, namely environmental and social ones, becoming visible. This work analyses worldwide sustainable urban mobility measures adopted in response to the COVID-19 pandemic, aiming to provide a comprehensive taxonomic picture of emerging policy and research issues. A systematic literature review is carried out using N-Vivo software to analyse the main addressed concepts that may leverage the sustainability and resilience of urban mobility systems, providing directions to future research agendas. Results show that most measures/policies were reactive to a public health emergency and that the paradigm of urban systems resilience in response to these measures (i.e. proactive paradigm) is one of the most addressed by the authors. Findings suggest a lack of strategic planning to achieve sustainable urban mobility in an equal and fairway as advocated by Sustainable Urban Mobility Plans (SUMP) and Sustainable Development Goals (SDGs). On the other hand, research results show that most of the articles in the analysed period, between 2020 and 2022, providing case studies for assessing the pandemic impacts on urban mobility. The focus of the sustainability lens is still mostly tackling the environmental dimension with few studies on the social dimension. Nevertheless, some aspects of the impact of the pandemic on society have been widely addressed, such as those related to technological advances in mobility services. These are especially related to shared mobility and micro-mobility options, Internet of Things (IoT) solutions, as well as at improving the level of urban mobility management through intelligent traffic systems. Overall, the pattern of responses suggests that further policy and research efforts are required for cities to advance towards the full implementation of smart and sustainable mobility strategies.

Keywords: Sustainable Urban Mobility; COVID-19; Public Transport; Micro-mobility; SUMP; Transport planning; Transport policy; Transport resilience; Systematic Literature Review

1 – Introduction

In the last two years, 2020 and 2021, urban mobility and transport systems around the World were strongly influenced by the outbreak of the COVID-19 pandemic. Factors such as quality of life and sustainability have gained greater visibility and, consequently, greater policy importance, influencing government officials to make rapid decisions, namely to address health related issues and improve transport resilience. It is undeniable that the pandemic accelerated changes (Allam and Jones, 2021) that were necessary but not prioritised. Similar changes were observed in other times when urban spaces and urban transport systems underwent significant changes and remodelling due to pandemics and previous health crises (Corazza and Musso, 2021). However, they did not have the dimension and severity of COVID-19. Recent literature has shown how these changes took place in different parts of the world and also the impacts of these changes on people's daily lives, in the different dimensions of sustainability, whether social, environmental or economic.

Mobility is essential for all economic activities, and it was severely impacted by the lockdown measures imposed by the COVID-19 pandemic. Decisions with direct impacts on the population, such as capacity constraints and interruptions of transport services, have been gradually resumed while safeguarding infection risks (Zhang et al., 2021). These measures generated a change in human behaviour, causing a mode shift, with increasing demand for individual transport (cars) and micro-mobility modes such as shared bicycles, e-scooters, among others (Abdullah et al., 2021; Joao T. Aparicio et al., 2021; Das et al., 2021). An increase in walking and short journeys is also noted (Campisi et al., 2020a; Mouratidis and Papagiannakis, 2021a; Nikitas et al., 2021). As a result, considerable reductions in air pollution and traffic noise were identified in urban environments and the theme of sustainability gained momentum (Karaer et al., 2020; Marinello et al., 2021). Air quality improvements registered in previously congested cities are associated with significant health benefits, motivating urban planning processes that favour social well-being (Jiang et al., 2021). However, with the relaxation of restrictive measures and the return to economic and social activities, an increase in the preference of individual motorised transport has been noted, which is worrisome for urban sustainability (Andara et al., 2021).

The need for rapid adaptation in this new socioeconomic context urged for effective policy measures in an emergency scenario. However, in cities that had already been working on sustainable urban mobility plans, these changes were taken in a context of fast adaptation and acceleration of the changes already foreseen (Combs and Pardo, 2021). In this context, concepts such as micro-mobility, sharing mobility, smart cities, 15 minutes' cities, among others, gained visibility (Dias et al., 2021; Guzman et al., 2021; Kakderi et al., 2021; Yang and Chong, 2020), but at the same time, they also exposed the fragility of unplanned urban spaces, as well as social vulnerability issues, including reduced access to public transport modes with little or no access to alternative modes of mobility (Borkowski et al., 2021; Pisano, 2020). Pedestrian spaces are also a barrier in many regions, with obstacles still imposed by the culture of prioritising individual cars (Anastasiadou et al., 2021).

Many authors have been addressed the impact of the pandemic on different urban mobility aspects, including public transport (Aparicio et al., 2021; Basu and Ferreira, 2021), micro-mobility (Dias et al., 2021), urban logistics (Cerrone et al., 2021; Pani et al., 2020), individual transport and sustainability in the urban environment (Campisi et al., 2020c). The need for sustainable urban planning is an important subject addressed in the literature given the ongoing behavioural changes entailed in transport demand/modal preferences and urban spaces (Echaniz et al., 2021; Kakderi et al., 2021). The democratisation of public spaces, from a perspective of equity and universal access, is one of the precepts of the Sustainable Development Goals (SDG) and also of the Sustainable Urban Mobility Plans (SUMP), initiatives establishing a set of actions to reduce accessibility barriers and minimise negative social and environmental impacts (Campisi et al., 2020b; Heras et al., 2020). Promoting these changes and improvements in urban mobility, embracing sustainability, is one of the biggest challenges for policymakers, especially in pandemic times, where resilience is required to overcome the still existing barriers in urban areas.

To better understand the scope and impact of the range of policy measures undertaken by cities around the World in response to the COVID-19 pandemic, this article aims to present a structured overview of the literature and provide a comprehensive taxonomic picture of emerging issues and new research directions in sustainable urban mobility triggered by the COVID-19 pandemic. To our best knowledge, this research is the former presenting a systematic literature review around the subject of sustainable urban mobility measures and, moreover, covering the analysis of measures implemented across the World during the pandemic using a sustainable urban mobility lens, aligned with goals set by the United Nations Agenda 2030 for Sustainable Development.

To achieve this goal, three major research questions drive this work:

RQ1 - *How is the literature addressing sustainable urban mobility policy measures in response to the COVID-19 pandemic?*

RQ2 - *What are the main obstacles and drivers for a sustainable urban mobility plan in pandemic times?*

RQ3 – *As a result of RQ1 and RQ2, what are the implications for future urban mobility planning?*

Henceforth, a comprehensive understanding of ongoing and prospective urban mobility measures in response to COVID-19 is expected from answering these research questions. An in-depth analysis of these measures and the major impacts on the urban environment will enable the identification of the main gaps that still exist, and that should be better studied for an adequate response to people's needs. Thus, the opportunities for improvement identified may guide future research work to improve the development of sustainable urban mobility plans.

To do so, the article is structured as follows: Section 2 presents previous literature reviews addressing urban mobility aspects concerning the COVID-19 pandemic as a background for the present analysis. Section 3 introduces the methodological approach. Section 4 offers a structured analysis of the major

results of this literature review. Further, in Section 5, an analysis and discussion of the main findings and a guideline for future research agenda are provided. Finally, Section 6 summarises the main outcomes and conclusions of this study.

2 – Previous Literature Reviews

In view of the COVID-19 pandemic, many measures were taken by governments to reduce the virus spread. Among the most relevant measures is reducing the circulation of people asking them to stay at home, leaving travel only for essential activities. Consequently, people's mobility was reduced, and there was a sudden change in behaviour, mode choice, and public transport users' profile. This fact is also reflected in the literature, which has sought to understand the phenomenon and identify the changes that have occurred in urban mobility in an attempt to understand the impact of these measures and changes on the future of cities. Different literature reviews, shown in Table 1, explore this theme with approaches that especially follow three axes: (i) measures of pandemic control and human mobility behaviour; (ii) role of technology in urban mobility during and post-pandemic; and (iii) mobility resilience. These three axes are detailed below.

(i) Measures of pandemic control and human mobility behaviour

Lockdown and social distancing were the main measures adopted to control the spread of the COVID-19 virus and, consequently, there was a reduction of public transport demand (Hörcher et al., 2021) and road traffic (Yasin et al., 2021). With the decrease in traffic, there was, consequently, an increase in speed on the roads. However, while traffic accidents have decreased, there has been a relative increase in the severity of injuries as well as deaths from accidents (Benita, 2021; Yasin et al., 2021). It is essential to point out that dangerous driving behaviour has been identified in some studies, especially on sudden acceleration and the increase of mobile phone use (Yasin et al., 2021). However, the changes were more profound in behavioural terms, as the obligation to stay at home led people also to change habits, seeking large public spaces, whether close to nature or public leisure areas for walking and cycling, in pursuit of a better quality of life (Mouratidis and Papagiannakis, 2021b). These changes also impact the use of public transport, where users do not feel completely safe maintaining the preference for individual transport even after the restrictions were lifted (Hörcher et al., 2021; Rahman et al., 2021).

(ii) Role of technology in urban mobility during and post-pandemic

In addition to the financial impact on operators, which are severe and have a significant social impact (Wang et al., 2021), these safety/pandemic control measures also had a strong technological component in urban mobility and can be divided into three major groups: i) citizen-centric technological facilities, including remote access to services and real-time traffic monitoring (e.g. low contact ticket sales like vending machines, contactless cards, mobile payment); ii) operator-centric

technological facilities to aid planning and reforms; and iii) organic changes to the mobility scheme, propelled by the tech-supported growth of micro-mobility modes of transport (e.g. increasing of shared e-scooters and bikes use. These changes have an essential role in promoting sustainability, especially in the environmental dimension. However, they still lack efforts in the social dimension, as not all people have easy access to certain technologies, which still highlights social inequalities (Mouratidis, 2021). Regarding the public transport operations, the information and communication technologies have an essential role in monitoring and adapting the service frequency and offering real-time information for the users by mobile applications to avoid constraints and crowding in public transport (Rahman et al., 2021). Many new technologies that are part of the smart cities concepts were quickly adapted and implemented in cities to better manage transport systems, integrating services in different modes of transport. Several changes were accelerated and leave a legacy for the management of public transport. These changes pave the way for a new era with autonomous services in both micro-mobility and mass transport, with high connectivity, with policies and decision-making based on big data analysis and also integrated with the concepts of resilience and smart cities (Benita, 2021; Dias et al., 2021; Serdar et al., 2021; Shortall et al., 2021; Wang et al., 2021).

(iii) Mobility resilience

The concept of city resilience is "increasing-or at least securing-the performance of urban systems in the face of multiple hazards in crises, rather than preventing or solely mitigating the loss of assets due to a specific event" (Rupprecht Consult, 2019). In this way, changes in people's behaviour, in search of places that provide quality of life during the pandemic, also led governments to act quickly to expand and qualify public spaces, making important decisions, especially in reducing vehicle spaces to improve walking areas, cycling or other alternative modes of mobility that promote well-being (Dias et al., 2021; Mouratidis and Papagiannakis, 2021b; Serdar et al., 2021; Wang et al., 2021).

In the pandemic time, the capacity of city resilience, such as the current one COVID-19, also reflects that many cities were already in the process of changing to qualify public spaces, mainly motivated to meet the Sustainable Development Goals (Serdar et al., 2021). In the context of public transport, resilience was one of the most relevant items, given the importance of the service to society (Serdar et al., 2021). In addition to the resilience components (Reliability, Vulnerability, Risk Management, Survivability, Flexibility and Robustness), Serdar (2021) identified the main categories of urban transport resilience indicators and their form of assessment and monitoring. The leading indicators found in the literature, according to Serdar (2021), are (i) performance-based; (ii) centrality metrics; (iii) coast; (iv) statistical indicators; and (v) qualitative indicators. Monitoring these categories can increase the efficiency of service provision, providing safety for users. However, mobility is not restricted to public transport but multimodal urban mobility. Shared mobility services had a resilient response during the pandemic with a significant positive impact, although they are already part of

micro-mobility strategies in several cities (Dias et al., 2021). The use of non-shared individual means of transportation, such as bikes, has also increased during the period of the pandemic, as identified by Shortall et al. (2021) and Rahman et al. (2021) and the resilience and reorganisation capacity of public spaces has been essential to provide better conditions for individual mobility and micro-mobility.

Table 1 – Literature Reviews on Urban Mobility related to the COVID-19 pandemic

Author	Year	Journal	Objective	Title	*Axis*
Benita, F.	*2021*	*Sustainable Cities and Society*	Map the scientific literature in human mobility providing insights into how academia responds to the pandemic situation	*Human mobility behaviour in COVID-19: A systematic literature review and bibliometric analysis*	*i; ii*
Dias, G. et al.	*2021*	*Sustainability*	*Discusses how shared e-scooters are used in cities and how they can help urban mobility to achieve sustainability goals and urban and transport resilience.*	*The Role of Shared E-Scooter Systems in Urban Sustainability and Resilience during the Covid-19 Mobility Restrictions*	*ii; iii*
Hörcher, D. et al.	*2021*	*Transportation*	*Explore the possibilities of implementing social distancing in public transport in line with epidemiological advice and contributes with an elaboration of demand management measures and their feasibility.*	*Social distancing in public transport: mobilising new technologies for demand management under the Covid-19 crisis*	*i*
Mouratidis, K.	*2021*	*Land Use Policy*	*Synthesises knowledge on how the Coronavirus disease (COVID-19) pandemic reshaped the relationship between cities and quality of life.*	*How COVID-19 reshaped quality of life in cities: A synthesis and implications for urban planning*	*i; ii; iii*
Rahmann, M.	*2021*	*IEEE Access*	Addresses the interactions among COVID-19 pandemic, lockdown measures, human mobility, and air quality.	*Machine Learning on the COVID-19 Pandemic, Human Mobility and Air Quality: A Review*	*ii; iii*
Serdar, M.Z.	*2021*	*Sustainable Cities and Society*	*Analyses the applied methods and associated indicators in the literature to assess a transportation network resilience and evaluates their feasibility concerning various disturbances.*	*Urban Transportation Networks Resilience: Indicators, Disturbances, and Assessment Methods*	*ii; iii*
Shortall, R et al.	*2021*	*Transport Reviews*	*Proposes a classification of COVID-19 measures aimed at passenger mobility by categories, considering the three sustainability dimensions.*	*COVID-19 passenger transport measures and their impacts*	*ii; iii*
Wang, A. et al.	*2020*	*International Journal of Geo Information*	*Explore how the research uses big data and data-driven applying to smart city development.*	*A Review of Human Mobility Research Based on Big Data and Its Implication for Smart City Development*	*ii; iii*
Yasin, Y.J. et al.	*2021*	*World Journal of Emergency Surgery*	*Review the effects of the COVID-19 pandemic on the incidence, patterns, and severity of the injury, management, and outcomes of road traffic collisions.*	*Global impact of COVID-19 pandemic on road traffic collisions*	*i*

These previous literature reviews address the COVID-19 pandemic bringing different views of the impact and changes in urban mobility, but still lack an in-depth analysis of sustainable urban mobility as a whole. Therefore, the main contributions of this work are: (i) to provide a comprehensive review of the existing literature on urban mobility measures implemented in the COVID-19 pandemic context; (ii) to analyse the main concepts addressed by authors that may leverage the sustainable urban mobility systems; and (iii) identify what are the main gaps and trends in sustainable urban mobility, highlighted by the COVID-19 pandemic, providing contributions for outlining a roadmap for future research agenda.

3 – Research Approach

To achieve the goal of this work, a systematic literature review approach based on Tranfield (Tranfield et al., 2003) is adopted. The process is based on four steps systematically designed to ensure the quality and replicability of the research, as follows:

3.1 – Material Collection

Along the first step, articles with contents in the context of the COVID-19 pandemic and urban mobility were identified. Considering the interdisciplinarity of this subject, the data collection was carried out following the specific criteria, as described below.

- Only articles written in English and published in peer-reviewed journals and proceedings, between 2020 and 2021 were analysed. The data collection was carried out in August 2021 and updated in October 2021.
- The articles were selected from an exhaustive search by the Web of Science and Science Direct databases.
- The main keywords defined for the search were “COVID-19” OR “SARS-CoV-2” OR “pandemic” OR “coronavirus”, which should be present in the title, keywords or abstract. At least one of these keywords should be combined, using the operator “AND”, with the keywords “urban mobility” OR “sustainable urban mobility” OR “urban micro-mobility” OR “public transport” OR “urban logistic” OR “mobility plan”. A preliminary result has identified 372 articles. A dataset was created, and systematic reading of the title, keywords and abstracts was carried out. Articles not related to the urban environment, and articles that mention the keywords only to provide the context in a superficial way were excluded. Further, as the final sample, 167 articles were considered for the analysis.
- To develop the content analysis identifying the patterns and the links between keywords, N-Vivo software was used. N-Vivo software provides the auto coding function from the node generated by each keyword and follows the steps proposed by Mayring (2014). The auto coding generates new nodes and sub-nodes and the theme related to each one (see Appendix 1). The patterns of

these nodes and themes are identified, providing a comprehensive understanding of how urban mobility is addressed in the context of the COVID-19 pandemic.

3.2 – Descriptive analysis

For a better understanding of the issues addressed in the selected articles, a 4W (Who, When, What, Where) 1H (How) analysis was applied. From this analysis, it is possible to bring up relevant information to enrich the discussion to answer RQ1.

Following, an overview of the "Who" and "When" dimensions of the published articles related to Urban Mobility and COVID-19 (UMob) is shown by answering two questions:

UMob 1) Who has been covering urban mobility in the COVID-19 pandemic time; and

UMob 2) When have been the authors working on urban mobility and COVID-19?

The first question aims to present what are the journals that have been published this type of research and the authors' affiliation. The second question aims to show the distribution of the research by the time interval defined for the analysis, 2020 and 2021, correlating these two years to identify the main differences in approach.

Following, three questions were defined to understand the scope of the articles and how and where have authors tackled COVID-19-related challenges to urban mobility.

UMob 3) *What are the key topics addressed in the literature and the type of analysis conducted?*

UMob 4) *Where have the authors been developed the studies in urban mobility and COVID-19 pandemic?*

UMob *5*) *How have the authors been addressing urban mobility in the COVID-19 pandemic context?*

To answer this question, six categories of analysis were defined: a) Research methodology, including research methodology design, data collection method and data analysis method; b) Main concepts; c) Government policy and resilience; d) Sustainability approach; e) Technology; and f) Trends in urban mobility. The assessment of the categories and a critical analysis of the results allows identifying the main gaps and trends in sustainable urban mobility, bringing up the answer for the RQ2. The result of this analysis is presented in section 4.

Based on this analysis, a discussion of the results of the RQ1 and RQ2 is performed in Section 5, namely of *UMob 5*, bringing up a framework of the main findings that can shape the future of sustainable urban mobility. Section 6 provides the implications for theory and practice and future mobility planning for smart cities, answering the RQ3.

Figure 1 presents the research methodology, objectives, methods and tools applied to conduct this study, as well as the section where each main step is presented.

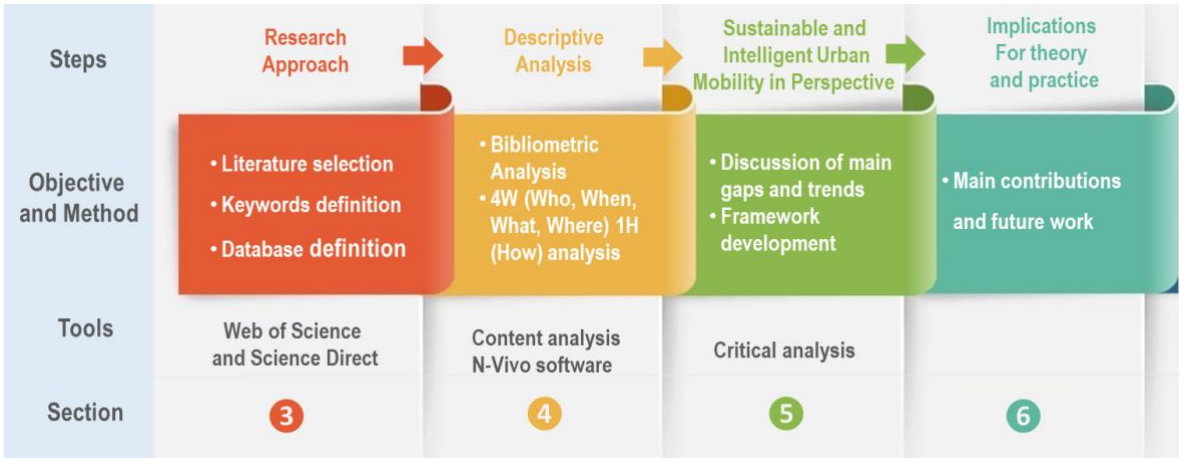


Figure 1. Structure of the research methodology

4 – Descriptive Analysis

This section presents the main characteristics of the articles analysed in order to better understand the focus and the main contributions of research addressing the COVID-19 pandemic and urban mobility. A bibliometric analysis was performed to identify the main patterns and the evolution of the subject in order to answer the RQ1.

4.1. Bibliometric analysis

A bibliometric analysis was carried out for the 167 selected articles. The word correspondence was extracted, and the relation between the word frequency and keywords was identified. The network of the words in the abstract and titles, shown in Figure 2, represents the occurrences of each word by the size of the circle, and the connections between words are represented by the lines. It is possible to notice that the most cited words in each cluster are directly interlinked and related to the variations of the keywords used in selecting articles. For example, the term “sustainability” (green cluster) is connected to “transportation” (blue cluster).

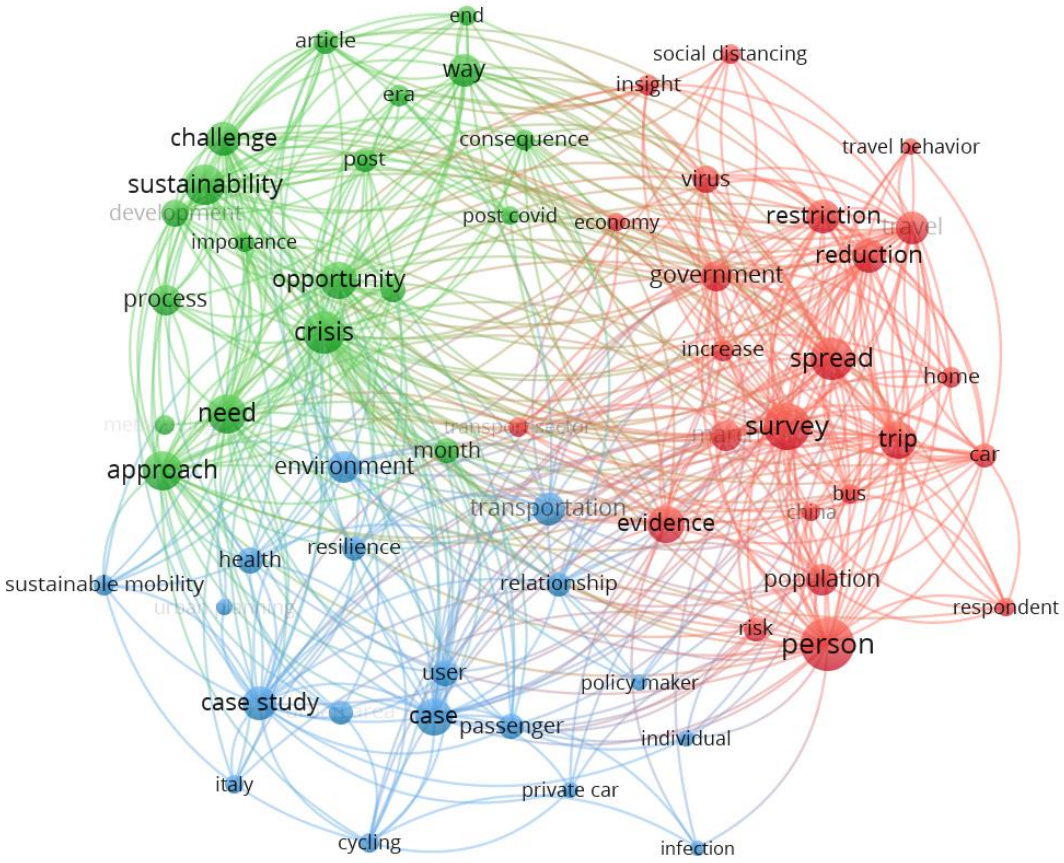


Figure 2. Word network, occurrences and clustering of the themes in the abstract and titles

The word frequency was carried out to complementarily identify the prevalence of themes. The most cited word in the articles was “transport”, with 1816 occurrences in the 167 articles. The second one was “urban”, with 1293 occurrences. Each word presents a correlation with other words, being important to identify the occurrences of the keywords selected for the analysis. The word map is shown in Figure 3. The result shows that the keyword “urban mobility” had 44 occurrences and the keywords “sustainable urban mobility” had only 3 occurrences. However, different combinations of this word has several occurrences (e.g.: “sustainable mobility” (n=33); “sustainable transport systems” (n=14); “sustainable mobility modes” (n=12); “sustainable mobility policies” (n=9); and “sustainable mobility systems” (n=7). There were no direct results for the keyword “urban micro-mobility”. The keyword “public transport” had 44 occurrences (however “public transport system” (n=60); “public transport services (n=43); “public transportation” (n=41); “public transport modes” (n=24); and “public transport operators” (n=21). The result of the auto coding process and the word frequency related to the keywords are presented in Appendix 1.

Figure 3. Word map of the 167 analysed articles

4.2. UMob 1) Who has been covering urban mobility in the COVID-19 pandemic time

To answer this question, all the journals were identified and grouped, as shown in Figure 4. Sustainability is the journal with the majority of articles published (n=49), which represents 29,3% of the publications covering the subject of urban mobility and the COVID-19 pandemic. The scope of this journal is cross-disciplinary, especially related to sustainability and sustainable development. Articles of this analysis in the sustainability journal are mainly related to the smart cities concept, environmental and social sustainability impacts, resilience, and sustainable urban mobility or mobility planning. The second journal with a high number of articles is Transport Policy (n=33), which represents 19,7% of the articles selected for this analysis, being most related to the impact of the changes and policy measures for public transportation during the pandemic time. The studies cover the disruption and changes on different modes of transport, like taxis and bikes, identifying the increase of shared mobility (Frank et al., 2021; Lei and Ozbay, 2021; Wang and Noland, 2021), decrease in PT demand (Bohman et al., 2021), resilience (Valenzuela-Levi et al., 2021) and the

acceleration of some policies already planned in public transport (Marsden and Docherty, 2021). These two journals represent almost half (49%) of the total articles analysed, as shown in Figure 4.

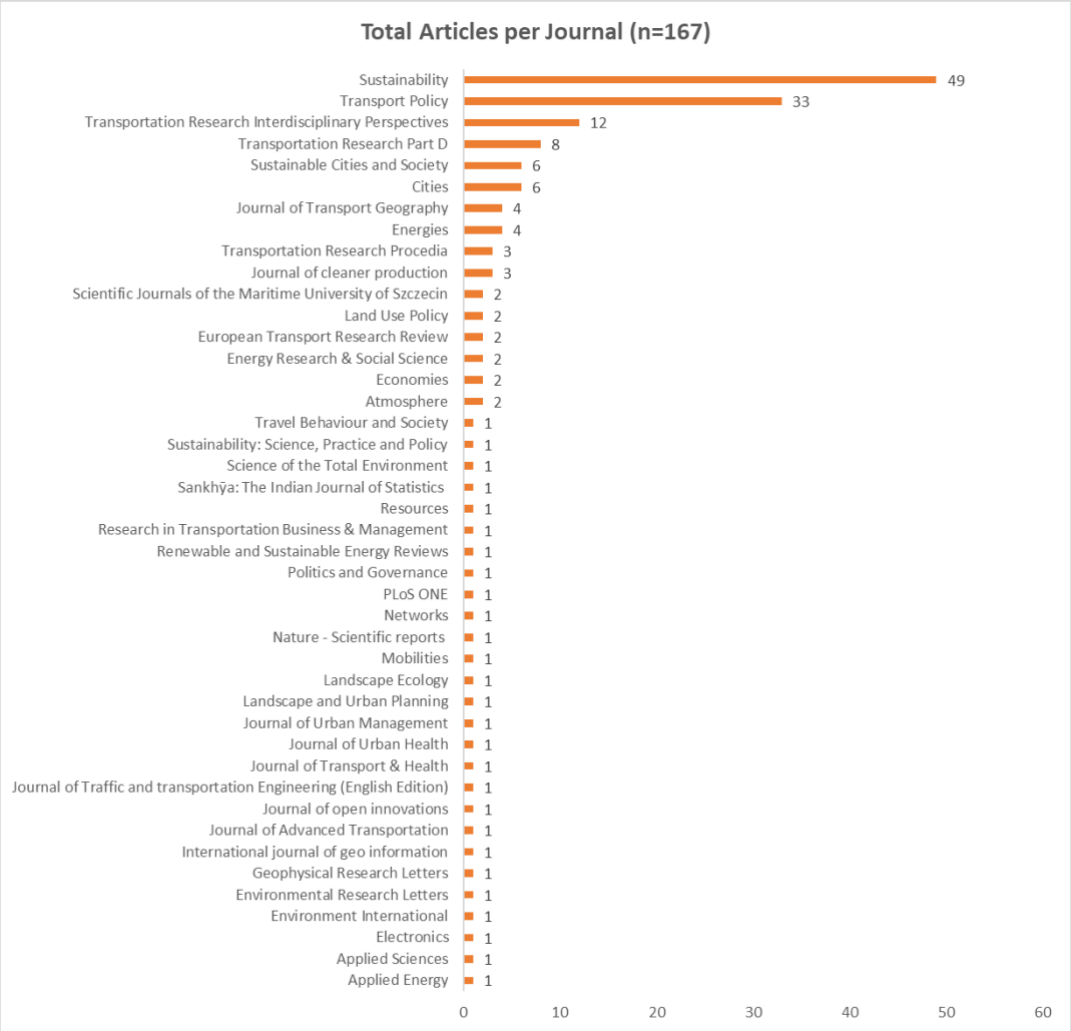


Figure 4. Total articles per journal

From each article, the authors' affiliation was identified by country. Italy (n=78) has the majority of authors covering the COVID-19 pandemic and urban mobility issues, followed by China (n=69), USA (n=51) and Spain (n=50). In the 167 articles analysed, 640 authors were identified and almost a third of them are affiliated in only 4 countries, as shown in Figure 5.

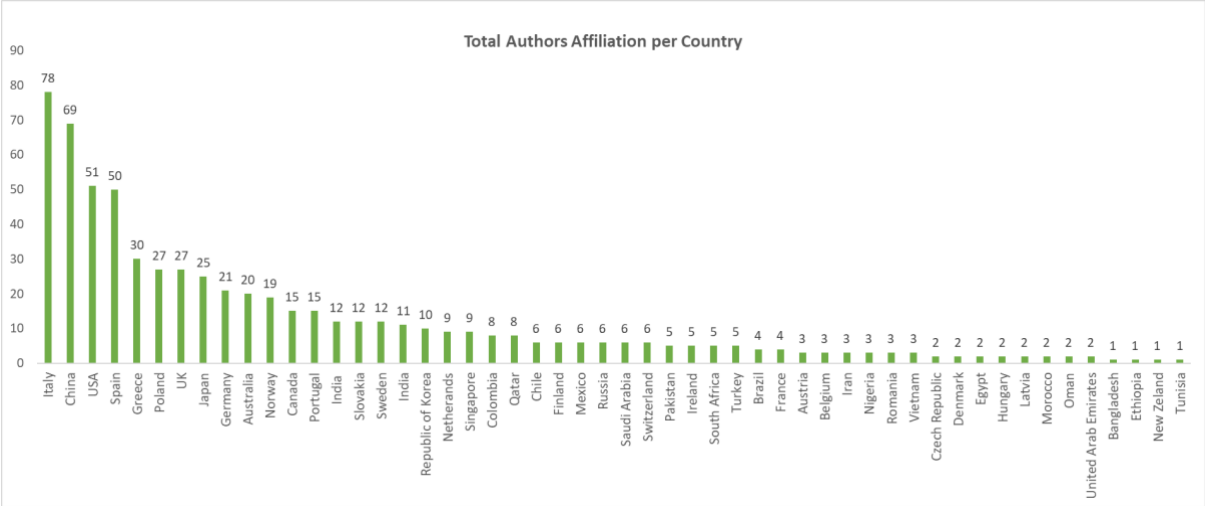


Figure 5. Total authors affiliation by country

4.3. UMob 2) When have been the authors working on urban mobility and COVID-19?

Considering the publication year of the selected articles, Table 2 shows the prevalence of research by year, indicating that 23% of the total articles were published in 2020. Note that this percentage does not necessarily represent the total number of researches carried out in the year, as the publication process can often be time-consuming and works carried out in the year 2020 may only have been published in the year 2021. These statistics are complemented in Figure 6 with the analysis of the major shifts in research themes.

Distribution of the articles by years (n=167)		
Year	**Total articles**	**%**
2020	39 articles	23%
2021	128 articles	77%

Table 2. Distribution of the articles in the years 2020 and 2021

4.4. UMob 3) What are the key topics addressed in the literature and the type of analysis conducted?

An analysis was developed to identify the most relevant and predominant themes in each of the two years. The result shows that in 2020 the authors were more likely to address the impact of the COVID-19 pandemic, representing 31% of the articles (e.g. Barbieri et al., 2021; Fatmi, 2020; Jenelius and Cebecauer, 2020; Nian et al., 2020), while in 2021 the most discussed issues were sustainability and mobility transitions and policy measures effects (e.g. Basu and Ferreira, 2021; Glaser and Krizek, 2021; Kakderi et al., 2021; Maestosi et al., 2021; Schmidt et al., 2021). Mobility behaviour presented the same percentage both years, while the issues of environmental impacts by reducing carbon emissions, because of the lockdown measures, had a reduction of seven percentage points in the

year 2022 (6%) compared to the year 2021 (13%), as it is possible to see in Figure 6.

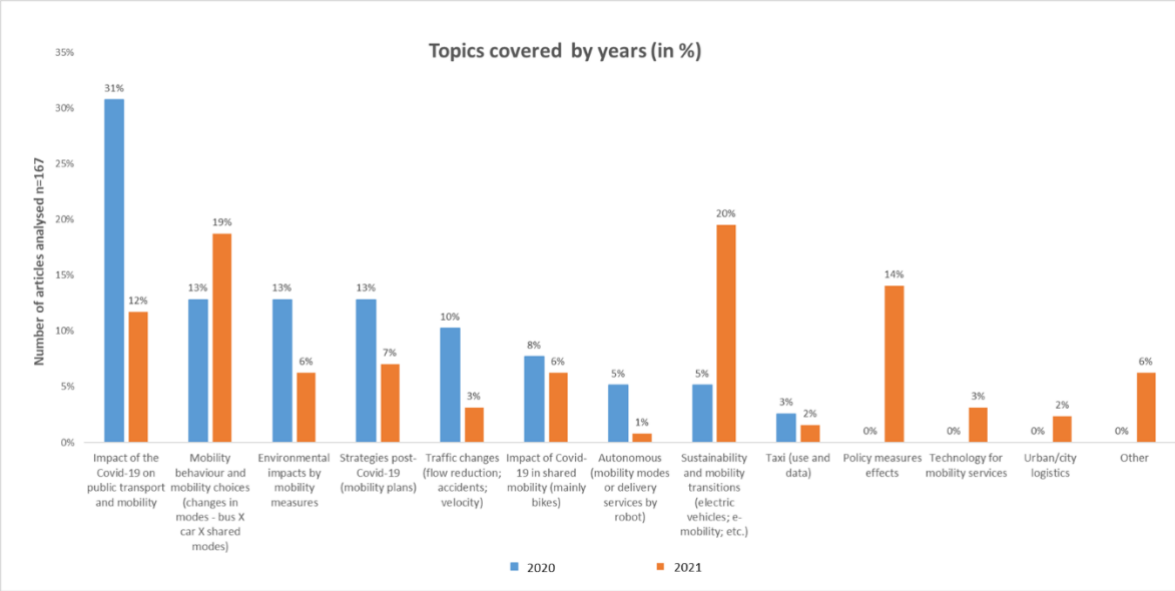


Figure 6. Main topics covered by the years of analysis

From the identification of the general characteristics of the articles and the main themes addressed in related work, the next step proposes a detailed analysis of the selected literature for a better understanding of how sustainable urban mobility has been treated by the ongoing research works in the COVID-19 pandemic. A critical analysis is also performed in order to answer the RQ2.

4.5. UMob 4) Where have the authors been developed the studies in urban mobility and COVID-19 pandemic?

The analysis undertaken in section 4.5.1 suggests that Case Study methodology (applied research) is the most employed one (see section 4.5.1). We were careful to identify the geographic location of the case studies whenever the authors mention it. The 4 countries with the highest concentration of case studies are Italy (n=23), USA (n=18), Spain (n=14) and China (n=13), which generally coincide with the authors' affiliation, although not in the same order. It is possible to identify that Italy is the country with the highest number of studies, as it is possible to see in Figure 13, and the country with the highest representation (see section 4.2).

Note that the sum of the total of countries is greater than the total of case studies and greater than the total of analysed articles (n=167) as many articles present studies pertaining to more than one country.

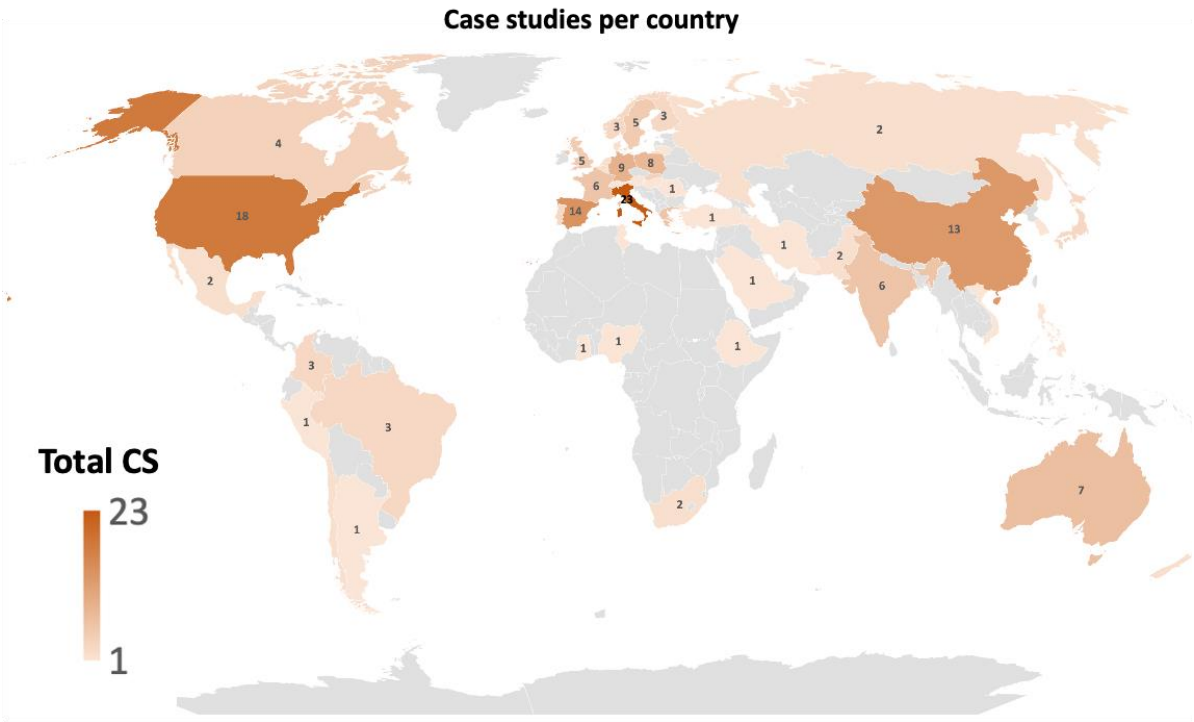


Figure 13. Total of case studies per country

4.6. UMob 5) How have the authors been addressing urban mobility in the COVID-19 pandemic context?

To answer this question, six categories were defined to analyse the articles (see Section 3.2).

4.6.1. Research Methodology

Aiming at a better analysis and understanding of the methodological process adopted by the authors, this category analyses: a) research methodology design; b) data collection method; and c) data analysis method. The definitions follow the guidelines proposed by Karlson (2009) for operations management research.

Regarding the research methodology design, qualitative approaches are in most articles analysed, especially considering case studies, explanatory research and frameworks developed. This fact may be related to the fact that the pandemic is a relatively new event, due to its global and severe dimension, leading the authors to develop analyses that can lead to an understanding of the phenomenon, especially related to urban mobility and analysis of the impacts on daily activities. Case study is the most used methodology (n=38), followed by modelling (n=36), Explanatory Research (n=24), survey (n=22) and framework (n=17). The main methodologies used are exploratory, which reinforces the need to still seek an in-depth understanding of the effects of the measures to hold COVID-19 measures in the urban environment, as it is possible to see, for example, in Campisi et al., 2020d , Lei and Ozbay, 2021 and Rasca et al. (2021).

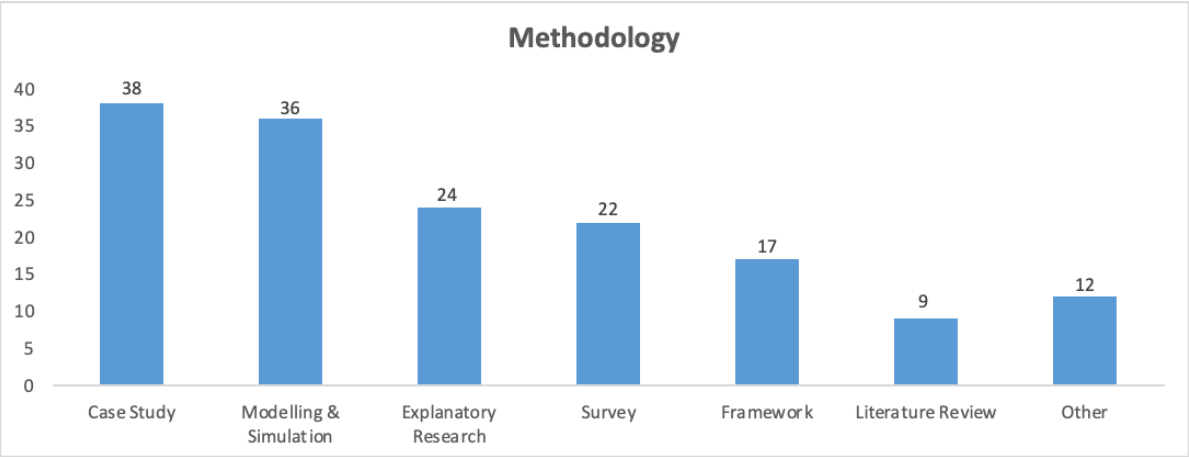


Figure 7. Methodologies applied in the articles analysed

In addition to identifying the methodologies of the studies, we also sought to identify data collection methods and data analysis methods, thus enabling a better understanding of the origin of the data and the way in which they are treated by the authors. What was identified is that in terms of data collection (see Figure 8), most authors used secondary data (n=73), that is, information available from governments or companies, such as data on the use of public transport (Advani et al., 2021; Aparicio et al., 2021; Campisi et al., 2020 and Konecný et al., 2021) and city traffic data (Arimura et al., 2020; Basu et al., 2021 and Parker et al., 2020) where it was possible to analyse the changes that have taken place. The questionnaire was the second most used method (n=45), applied by authors like Borkowski et al. (2021), which have identified changes in mobility behaviour in different groups, according to socio-demographic characteristics, and Molloy et al. (2021) which have identified a reduction in the public transport use at the same time that there was an increase in alternative mobility modes, especially bikes. The high incidence of secondary data use can be explained by the lockdown period, which made it difficult to access data sources that require field trips and researchers' travel. Most secondary data is obtained through platforms and systems already in operation by governments (e.g. Antar et al., 2021 and Jiang et al., 2021), as well as data from technology companies for mobile phone applications (e.g. Jenelius and Cebecauer, 2020 and Huang et al. 2021) which make it possible to access information remotely. Workshop (n=2) and focus groups (n=1) were less representative data collection methods, which is understandable since these are methods that usually require face-to-face meetings, which is not entirely feasible given the restriction measures in many countries. In several articles, the authors do not expose the data collection method clearly, so it is defined as “other”.

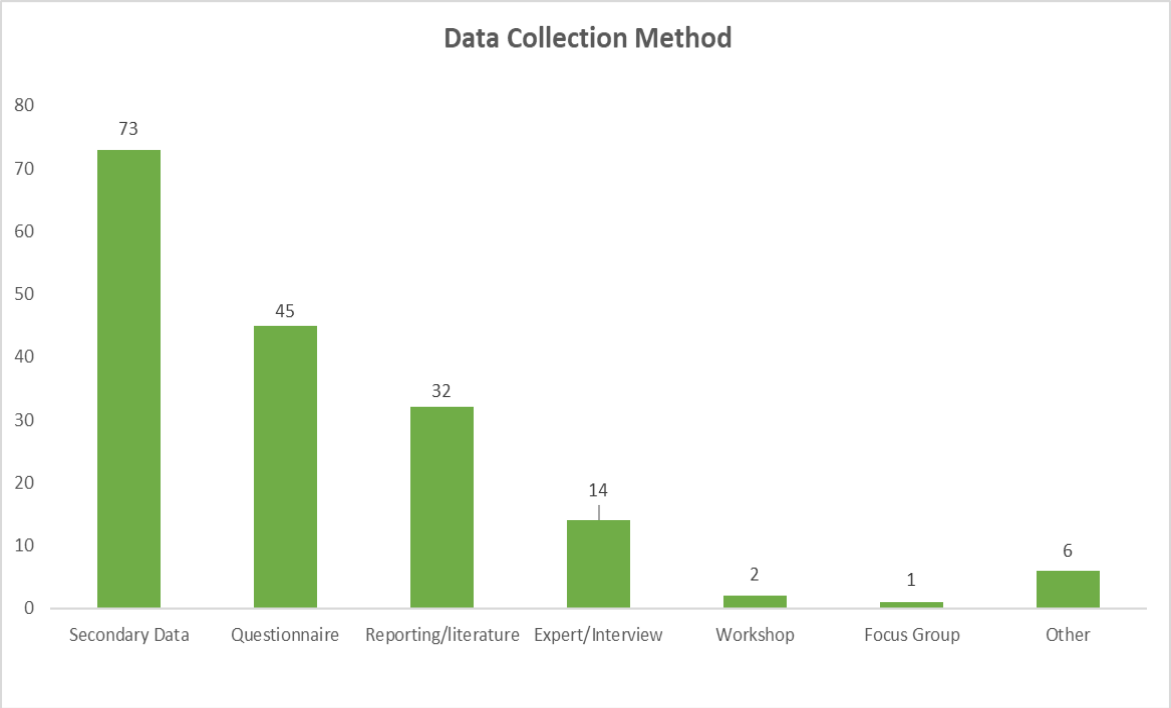


Figure 8. Data collection method applied on articles analysed

Regarding the data analysis, statistical analysis was the main method applied (n=62) as it is possible to see in Figure 9, and it represents almost 30% of the total articles. This method appears to be particularly correlated to the use of secondary data with the aim of assessing changes in the use of public transport (Konecný, V. et al. 2021), as well as changes in access and demand of shared mobility modes such as bike (Kubal'ák, S. et al. 2021) and e-scooters (Dias et al., 2021). Content analysis is the second data analysis method most used (n=31), being especially related to secondary data sources such as government documents of policies and measures adopted (Kanda and Kivimaa, 2020; Patlins, 2021 and Tiboni et al., 2021) followed by hypothetical example (n=13) and correlation analysis (n=12). Category “other” (n=21) includes the theoretical analysis, especially related to Explanatory Research Methodology. Important to note that some authors do not identify the data analysis method. These cases are also classified as “other”.

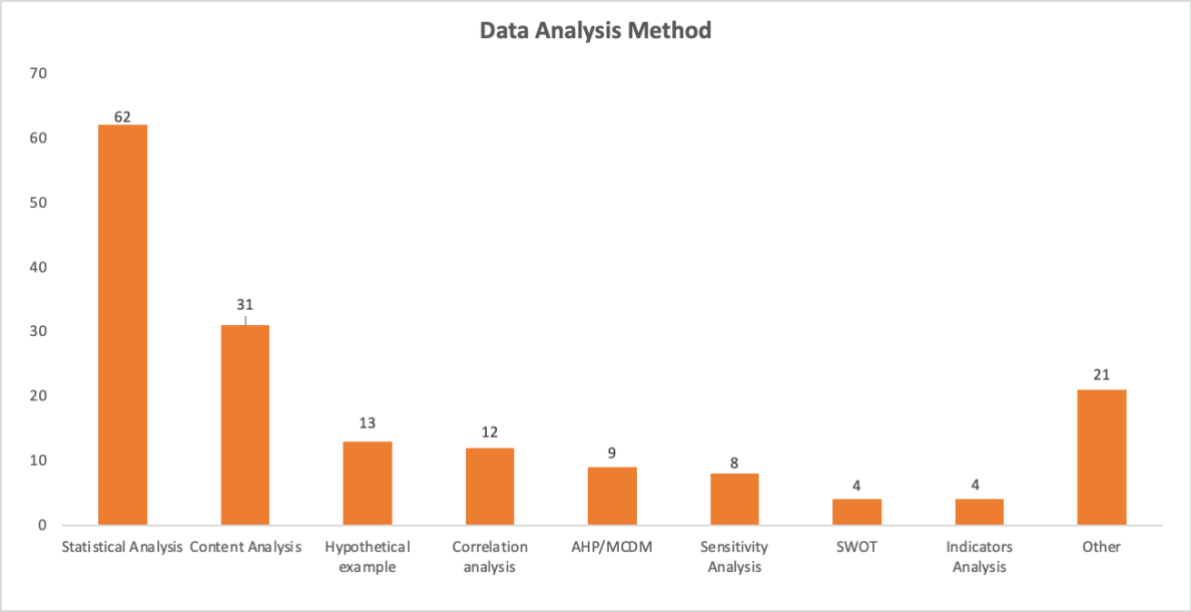


Figure 9. Data analysis method applied in the articles analysed

4.6.2. Main concepts

The main concepts that emerge in the literature when approaching sustainable urban mobility were identified and the top five are shown in Figure 10. Resilience, Mobility Planning, Sharing Mobility, Smart Cities and 15-Minutes City were widely addressed by the authors, often being treated together. Resilience is the most addressed concept being strongly related to the ability of cities and modes of mobility to adapt in times of crisis, acting in proactively to guarantee people safety (Rupprecht Consult, 2019), being addressed in the literature, especially regarding the infrastructure conditions of both transport and the quality of urban spaces. As an example, Krellenberg and Koch (2021) identify that several cities still need to go through many transformations to have the resilience capacity that can provide the quality of life recommended in the Sustainable Development Goals set by the United Nations Agenda 2030 and must deal with different constraints to achieve it. Resilience is also connected by the concept of Smart City where the themes like green and blue infrastructure are also mentioned, as essential for sustainable urban mobility (Bar et al., 2021; Herman and Drozda, 2021; Pamukcu-Albers et al., 2021). Furthermore, what can be observed through the analysis is that many of these concepts are interrelated, such as, for example, 15-minutes city is only possible from mobility planning and effective actions that allow access to the main city services, like schools and stores, in this time lapse (Nieuwenhuijsen, 2021; Pozoukidou and Chatziyiannaki, 2021) and mobility policies and plans play an important role in making cities accessible, inclusive with social justice and equity.

Figure 10. Main concepts addressed in the literature

Urban mobility plans and policies are related to all the aforementioned concepts. So the next natural step is to identify how the authors approach these themes. In many cases, although authors only address urban planning, we provide this broader focus for a more comprehensive view on sustainable mobility. According to this criterion, seven sub-themes were found, as shown in Figure. Ten authors addressed the topic Sustainable Urban Mobility Plans (SUMP), a European concept and planning tool developed with various stakeholders and policymakers with already established guidelines since 2013 for cities to advance towards sustainable mobility (Rupprecht Consult, 2019). These authors relate the capacity for urban resilience in the pandemic scenario with structured and designed plans to provide better accessibility to urban spaces, combining the concepts of smart cities (Moraci et al., 2021; Maltese et al., 2021; Kakderi et al., 2021, Triboni et al., 2021).

Following the analysis, the most discussed topics were Urban Mobility Plan (n=6), followed by Urban Plans (n=4), Sustainable Urban Mobility (n=3), Urban Plan of Sustainable Mobility (n=1) and Sustainable Mobility Planning (n=1). All these themes address urban sustainability as essential and indicate paths for mobility policies that seek solutions to improve services with the integration of transport systems and the inclusion of new mobility modes (e.g. Turoń et al., 2021; Basu et al., 2021; González-Sánchez et al., 2021).

Finally, transport planning was considerably addressed (n=17) and it is purposely highlighted in the graph for two reasons. First, although it does not directly address sustainable urban mobility (the focus of this analysis), sustainability themes are present in most of the articles, especially in analyses

of the need and usefulness of shared transport modes in the urban context (e.g. Carteni et al., 2021; Combs et al., 2021; Glaser and Krizek, 2021). Second, although this topic has been addressed in many articles in an urban planning context, it is still being addressed in an isolated way. This may mean that, in some cases, there is still not a joint analysis of the different mobility modes that make up urban spaces and their infrastructure in an integrated way, in which the need for people to move is in the foreground, corroborating the analysis of Vatavali et al. (2020).

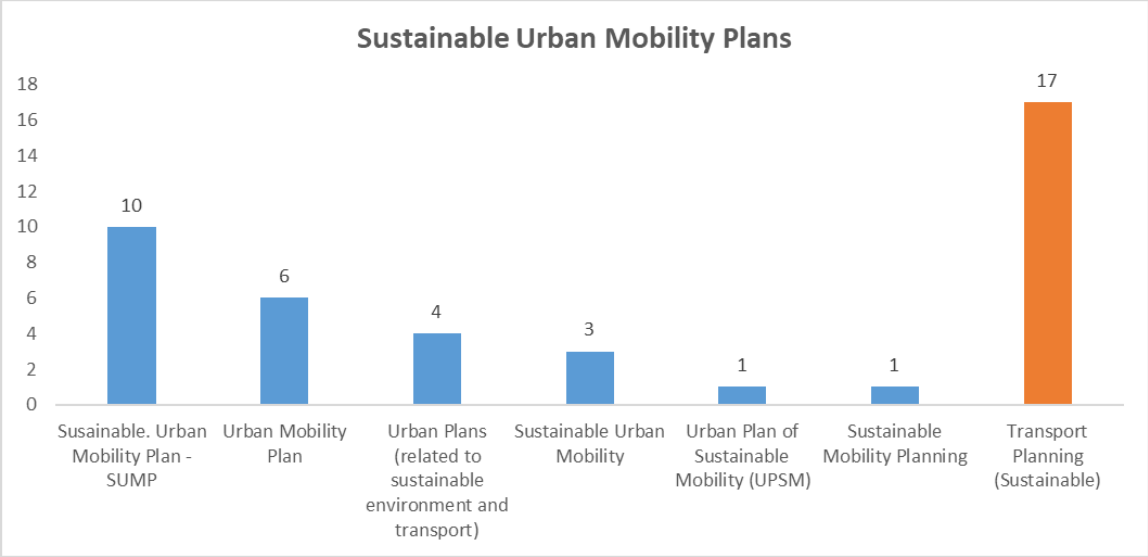


Figure 11. Sustainable urban mobility plans in the literature review

4.6.3. Government policy and resilience

From the auto coding process carried out by N-Vivo software, the most relevant themes related to "policy" that address transport and urban mobility were identified, as well as their relationship with resilience. The results were grouped, considering that it often addresses the same topic but with variations in words (such as transport and transportation or sustainable and sustainability) and present the articles that address the theme (sources) and the total citations found (references), according to Table 3.

Transport and urban transport policy are some of the most discussed topics in the literature related to resilience in the face of the measures adopted during the pandemic. In addition to the analysis of the implementation of reactive policies to contain the spread of the COVID-19 virus, the authors have deepened the issue by discussing urban transport planning and management also in the face of users behavioural changes (Zhang et al., 2021; Hasselwander et al., 2021; Beck et al., 2021a; Abdullah et al., 2021).

One of the topics covered comprehensively is the integration of mobility modes into the green-blue infrastructure. Mobility resilience and sustainability depend on a profound transformation of urban spaces to better serve the needs of people, who seek green and natural spaces that allow social

interaction with quality of life, but that these spaces are close to their homes (Pamukcu et al., 2021; Przybylowski et al., 2021; Pozoukidou and Chatziyiannaki, 2021). This shows that the authors are aware of these changes and point to a need to re-evaluate current transport systems, seeking innovation and integrating sustainable and healthy multi-modes (Campisi et al., 2020c; Pozoukidou and Chatziyiannaki, 2021; Thombe and Agarwal, 2021).

Policy	Sources	References
transport and urban transport policy/policy measures	*47*	*63*
lockdown/restrictive policies/policy impact	*27*	*35*
policy measures/policy decision	*18*	*27*
sustainable transport and sustainable mobility policies	*15*	*26*
urban policy/urban mobility policies	*17*	*21*
environmental policy	*10*	*13*
government policy	*10*	*11*
mobility policies/alternative modes policy	*9*	*11*
land use policies	*6*	*7*
social policies	*5*	*5*
Total sources and references	164	219

Table 3. Topics related to government policy and resilience

4.6.4. Sustainability Approach

In order to analyse how sustainability has been addressed by the authors, we observed which of the three dimensions of sustainability (Social, Environmental and Economic) have been studied in the context of urban mobility. The results of the analysis are shown in Figure 12 and indicate that the environmental dimension has been most explored by the authors (n=32), followed by articles that address the environmental and social dimensions (n=29) and the three dimensions (n=17). The environmental dimension is mostly related to the reduction of CO_2 emissions and noise in the cities (e.g. Kunze and Fromme, 2021; Marinello et al., 2021; and Parker et al., 2020) while the social dimension is more related to general well-being and the access to urban activities (Bracarense and Oliveira 2021; Nian et al., 2021) and inequality in access to public transport and services (Hasselwander et al., 2021; Liu et al., 2021; Parker et al., 2021).

It is important to note that most of the articles that deal with the environmental and social dimensions together are mostly related to the themes of Sustainable Urban Mobility Plans and Mobility Planning, like in Corazza and Musso (2021), Campisi et al. (2020b) and Moraci et al. (2021), reinforcing the need to better plan and prepare urban spaces to improve the well-being of people in urban environments, where weaknesses were highlighted both in lack of security (Cerrone et al., 2021) as well as in social inequalities (Dias et al., 2021 and González-Sánchez et al., 2021). The social dimension has been less explored individually (n=12) and it is important to highlight that sustainability is only achieved when the three dimensions are treated in balance.

Considering that a pandemic is an event that affects society as a whole, the economic dimension has not been addressed isolated and only two articles address the economic and environmental dimensions together (Campisi et al., 2020a and Jiang et al., 2021). This indicates that the authors are more likely to establish a better understanding of the social and environmental phenomena of the pandemic in sustainable urban mobility than with the economic impacts that, although important and also affect the social dimension, have been seen by some researchers such as Arribas-Ibar et al. (2021), Barbarosa (2020) and Kanda and Kivimaa (2020) as a strategic opportunity for innovation and transition to sustainable mobility.

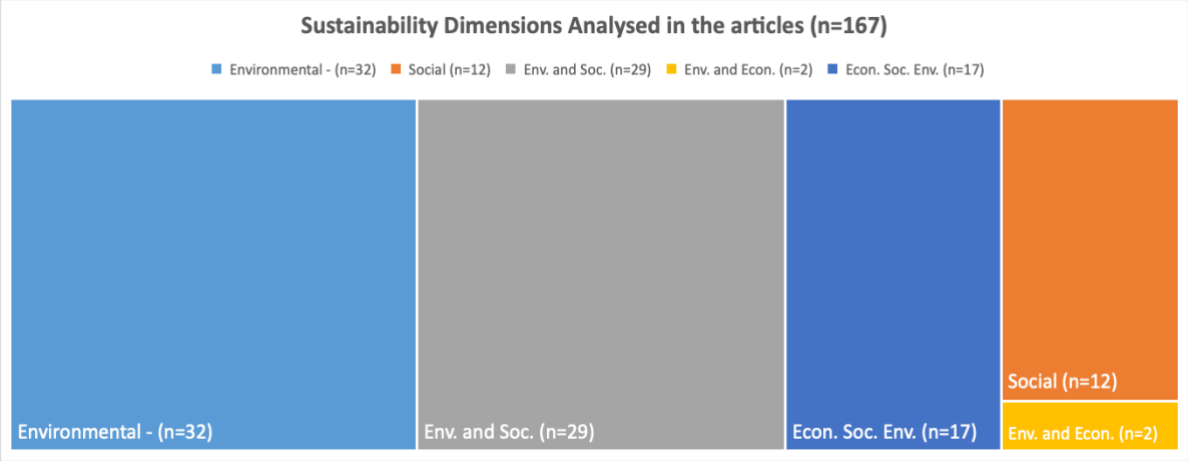


Figure 12. Sustainability Dimensions addressed in the articles

4.6.5. Technology

What can be noticed in the analysis of the articles is that technological advances are present in several areas and present different facets.

First, initiatives for city sensorisation are highlighted as increasingly important due to the delineated mobility changes since the starting of the COVID-19 pandemic. Essential sources of traffic data include road traffic data from stationary sensors and mobile GPS devices, pedestrian traffic data from privacy-compliant sensor technologies, and shared- and micro-mobility data from mobile app logs. In this context, emerging secure technologies associated with the Internet of Things (IoT) solutions and remote sensing via privacy-aware satellite vision are gaining momentum (Allam & Jones, 2021). Second, advances in machine learning for integratively mining the heterogeneous data sources produced by the aforementioned sensorisation initiatives are further rising. Such advances, many propelled by the field of neural processing and deep learning, are necessary to deal with the rich spatial, calendrical and modal content of traffic data, as well as the massive size of traffic events produced by mobile, ticketing and stationary devices.

The pandemic showed that the value of static studies is of limited relevance as their findings easily become obsolete. Instead, multimodal traffic data analysis should be fully automated and updatable once more recent data becomes available. In this context, there is the need to guarantee that the ongoing mobility changes are reflected in the computational models, as well as the real-time ability to learn from continuously arriving traffic data observation and detect emerging traffic patterns. Third, intelligent traffic systems are an important part to optimise urban mobility. Adaptive traffic signal controllers (TSCs) are paradigmatic examples that ensure a response to actual traffic conditions based on the sensorisation of intersections, and accordingly produce policies capable of mitigating traffic bottlenecks. The integration of TSCs with the surrounding status, including active mobility and location of emergency viatures, is still at its early stage of development. Another essential need of an intelligent traffic system is computational solutions for bus route adaptation and schedule redesign to ensure efficient transit systems that quickly adapt to the dynamic changes in demand of the passengers.

Finally, the growth in the use of shared mobility modes, such as bikes and e-scooters, has also been propelled by technological advances (Dias et al., 2021; Kubal'ák et al., 2021), including lower-cost supplies and smartphone applications with easy monitoring and payment facilities. In fact, the acceleration of digitalization activities is pervasive across many services related to urban mobility, especially diminishing the need for low interpersonal contact and supporting the situational awareness of the citizens.

4.6.6. Trends in urban mobility

The change in the user's profile of transport systems led governments and managers to identify some vulnerabilities and thus act to correct them. Some studies, mainly those concerning origin-destination movements, also highlight social inequalities and inequity in access to the urban transport network (Aparício et al. 2021, Cerqueira et al. 2021). A readjustment is needed, allowing people in neighbourhoods outside the central areas to have proper access to transport, avoiding thus large walking displacements. This is one of the indications in the literature, in which authors such as Liu et al. (2021) and Aparício et al. (2021) have dealt in case studies that aim to qualify access to public transport in suburban areas with network redesign. Likewise, the implementation of real-time monitoring technologies that can assist in decision-making for intervention according to demand has been pointed out by some authors as a trend that will be accelerated in the current pandemic scenario (Parashar and Cheriyan, 2021).

Sustainability social dimension has also been receiving attention from authors in studies by authors such as Barbieri (2020) and Freudendal-Pedersen and Kesselring (2021) that address social inequalities in access in accordance with different modes of mobility. Pirra et al. (2021), Campisi et

al. (2020b) and González-Sánchez et al. (2021) addresses gender equity, where women have a greater unsafety sense in the use of public transport, a situation evidenced in the pandemic time. Exposure to a higher risk of contagion in regions with low-income populations is also addressed in the literature, identifying that most users are men (Pinchoff et al., 2021; Guzman et al., 2021), reinforcing the need for mobility planning policies that consider this public health factor.

Sustainable urban mobility has been widely addressed as a necessary goal, both in investment in low-carbon modes of transport (Corazza and Musso, 2021) and in the decarbonisation of traditional modes (Więckowski, 2021; Valenzuela-Levi et al., 2021). Although this is not a new topic in the literature, it has gained strength and evidence, combined with the social pressure that evidences the search for natural spaces in the urban environment, associated with the concepts of green-blue infrastructure (Pamukcu-Albers et al., 2021).

Risk analysis, considering the public health, and system disruption that lays to "immobility" have also been addressed in the literature (Freudendal-Pedersen and Kesselring, 2021), indicating that this type of analysis should be part of sustainable urban mobility planning in the future to avoid transport systems disruptions propelled by emergency and calamity situations like the current one.

5 – Sustainable and Smart Urban Mobility in Perspective

The analysis carried out in Section 4 offered a big picture of the ongoing works that address sustainable urban mobility in the COVID-19 pandemic. We now present a conceptual framework to analyse the main outcomes, especially related to the six categories of analysis introduced in Section 3.2 UMob 5 as this focused on the "*How" research focus*. The mentioned categories were defined to provide an in-depth overview of the main concepts and themes addressed in literature, in order to answer RQ2 and RQ3. Figure 14 summarises the main gaps and directions to achieve sustainable urban mobility that were identified in this early analysis. Discussion of each category of analysis is detailed below.

5.1. Methodology and data collection

Most of the articles analysed use exploratory methodologies as seen in Section 4.5.1. The need for deepening understanding of the phenomena during the period of the pandemic has led many authors to develop case studies and explanatory research to better understand this global disruptive phenomenon with the dimension of the COVID-19 pandemic. These studies, however, expose a lack of government strategic planning to deal with situations of this magnitude. There is, however, a gap in the use of confirmatory methodologies, in which hypotheses can be approached from the moment there is a better understanding of the phenomena studied. This may be considered a future direction in research, combining new artificial intelligence methodologies in statistical analysis, considering the

large amount of data available, or identifying new ways through innovation laboratories and workshops, as proposed by Kesserling and Freudendal-Pedersen (2021).

The increase in the amount of data generated by the different technological tools available also allows for greater precision in the results and highest assertiveness, which increases the possibility of correct decision-making both for operational actions and public policies development. However, it must be considered that secondary data has limitations that may not reflect the reality that is intended to be observed, requiring a transversal and multidisciplinary approach, which is one of the characteristics of urban mobility.

Finally, it is important to emphasise that to achieve sustainable urban mobility it is necessary for cities to have a long-term vision and strategy embedded in a SUMP to analyse, understand and evaluate all the elements that compose it. For this transition, methodologies to assess the entire life cycle of the different components are needed, and integrate them into sustainable urban mobility plans, from a circularity perspective, like the purposed in "Cycling Master Plans in Italy" by Campisi et al. (2021a).

5.2. Main concepts

It is possible to notice that sustainable urban mobility is not yet treated as a priority by many government managers, since the literature reflects that transport planning is still made in isolation with a lack of sectorial integration (see section 4.5.2). Rethinking urban mobility systems in this new decade requires a holist approach and presupposes multimodal stances, integrating alternative mobility modes and further accounting for the drivers of active mobility. This holistic view is a rising topic, having been addressed in the literature as "sustainability and mobility transitions" (see section 4.4) but there are still gaps in the literature that should be better explored, such as the relationship between urban mobility, modal preferences and their public health impacts.

All the concepts developed in the articles are, in a way, interconnected. For example, SUMP guidelines help to map the city and different kinds of crises and scenarios that managers must deal with in the urban mobility system, providing the infrastructure and smart technology needs, increasing the resilience. Resilient cities are those that have the ability to adapt to changes without the need for radical interventions in infrastructure (Polis and Rupprecht Consult, 2021). Smart cities must be informed and connected cities (Heras et al., 2020) but in a holistic way so that every technology implemented has a purpose and integration with others. To do this, the implementation of Sustainable Urban Mobility Plans is essential, as they prepare cities to quickly adapt to new technologies and redesign the operations of mobility services whenever necessary, minimising negative impacts for users due to operational failures. More than that, SUMP also provides quality of life and infrastructure integration in a dynamic and collaborative way (Rupprecht Consult, 2019)

integrating the perspectives of the different stakeholders to define urban mobility strategies that meet everyone's needs in a balanced and fair way.

Another important aspect to consider, the change in the public transport commute profile during the pandemic period also generates a change in urban spaces and local commerce. In this sense, the concept of 15-minutes city gained strength, being widely addressed in the literature (e.g. Guzman et al., 2021 and Pozoukidou and Chatziyiannaki, 2021). However, there is still a need to develop studies that identify the impact of this concept on conventional urban transport modes, such as buses, subways and taxis, as well as micro-mobility modes.

5.3. Government policy

Public policies related to urban mobility are still closely related to public transport, especially bus and subways, rather than focusing on the transport system as a whole. There is no doubt of its essential role in urban environments. But there is a need to advance the approach by making the transition to an integrated transport system enabling multimodal mobility, as it is only through this holistic vision that synergies can be explored between modes and resources and sustainable urban mobility can be achieved. The literature already points out ways, especially integrating the concepts of green-blue infrastructure as part of urban mobility plans (Maestosi et al., 2020; Bar et al., 2021), as well as exploring the synergistic roles of micro-mobility modes. There is already evidence of change in urban spaces, accelerated during the pandemic (Spadaro and Pirlone, 2021), and which are a trend both in research and in the change and implementation of public policies that favour active mobility.

What the literature has shown is that many of the measures were reactive in the face of the emergency and had to be shaped and adapted in the different months, according to the evolution of the spread of the COVID-19 virus. As some restrictions were lifted, people had a natural movement to seek open, wide spaces with green areas for leisure and sport. This behaviour also led to the decision-making by public managers to provide changes in some urban spaces that proved to be inadequate or insufficiently safe. Thus, some streets were blocked for vehicles, becoming pedestrian spaces, offering more space and greater health security. Some of these changes have already become effective, closing streets to vehicles for some periods such as weekends, or permanently, becoming leisure streets, with cycling spaces and integration of other micro-mobility modes (Teufel et al., 2021).

Future research may assess the impact of these policies measures and changes on urban mobility resilience, as well as the legacy for achieving social sustainability in the context of urban mobility.

5.4. Sustainability approach

Smart cities and smart mobility are at the centre of emerging urban governance discussions to enable a more resilient city model and functioning. Moreover, the request for sustainable and smart mobility

is presented in the recent mobility strategy for Europe (EC, 2020). The concept of smart city refers to the use of various information technologies or innovative concepts to connect and integrate urban systems and services in the process of urban management and operation, so as to enhance the efficiency of resource utilization, optimize urban management and services, and improve the quality of life of citizens (Yang and Chang, 2021). The European Green Deal presents interlinked and multidisciplinary challenges for all member states to reach carbon neutrality until 2050, an endeavour that requires smart cities to tackle decarbonising transport and energy systems (EC, 2019). Having a vision of a city that works and that provides well-being is also aligned with the United Nation's 2030 Agenda for Sustainable Development, specifically on its SDG 11 -"Make cities and human settlements inclusive, safe, resilient and sustainable". To achieve this objective, it is necessary to broaden the focus and change to a collaborative and smart approach, which is currently still strongly related to the environmental dimension. It is necessary to pay close attention to other components that are also related to the process of understanding sustainability and that contribute to achieving sustainable actions. More than that, it is necessary to go beyond the three dimensions of sustainability (social, environmental and economic) and understand that sustainability will only be achieved by joint societal progress supported with enhanced mobility governance and business models to enable such cross-collaborative transition, which involves education, reduction of social inequalities, conscious consumption, rational use of resources, among others (United Nations, 2018; Rupprecht Consult, 2019).

5.5. Technology

The concept of smart cities involves an integrated network of connected information that aims to give greater efficiency to the various infrastructure services with real-time monitoring, offering information to citizens and helping managers in decision-making with quick responses to service users. The advancement of smart cities technologies for urban mobility has been noticed, however still fragmented. The integration of technologies requires planning and technological-digital infrastructure, but also a political decision since it must integrate different sectors and, in many cases, integration of information from government agencies with private companies.

The literature shows that much information from these technologies is available, and the authors have the opportunity to use it for their analysis. However, there is a gap and at the same time an opportunity, which is the crossing data or cross-case analysis, where it is possible to identify correlations between urban mobility events. For example, identify users of e-scooters and bike-sharing who also use conventional urban transport networks such as subways and buses and the sustainability impact.

Additionally, the information and control systems of the transport network may integrate new immersive technologies, such as extended reality (XR) that has already been used in architecture

(Abhari et al, 2021) and manufacturing (Gong et al., 2021), being already signalled as an opportunity in the urban mobility field (Allam and Jones, 2021).

Heterogeneous sources of urban traffic data, including those generated by mobile devices, inductive loop counters, remote sensing technologies, and integrative AFC systems, can be consolidated to provide comprehensive views on traffic dynamics across modes.

Integrative ACF systems or alternative strategies to identify cross-carrier passenger flows offer an essential means to 1) assess the efficacy of transport mode transfers in urban interfaces; 2) infer multimodal origin-destination (OD) matrices in accordance with the complete (instead of partial) commuting travel patterns of individuals; 3) discover multimodal traffic patterns to assess the needs and modal preferences of the citizens; 4) model and understand demand; and 5) support the multimodal planning of tariffs, routes and schedules with the aim of reducing commuting needs and transfer waiting times.

The presence of emerging changes in urban traffic is observed as a result of changing safety norms, emerging work habits, and new transport mode preferences triggered by the pandemic. To account for ongoing urban mobility changes, principles from incremental data mining and online learning, including those brought forth by Nallaperuma et al. (2019), should be placed to guarantee the ability to learn from continuously arriving traffic records. An additional relevant direction in pandemic contexts is the early discovery of emerging mobility patterns. Neves et al. (2020) introduced principles for the timely discovery of emerging traffic dynamics, generally corresponding to new traffic flows or road/station/vehicle (de)congestions, creating the possibility to anticipate potential mobility bottlenecks that are critical knowledge for tactical and strategic mobility planning.

Recent attention has been paid on how to incorporate context to enhance traffic data analysis (Cerqueira et al., 2020). Opportunities for the automated acquisition of situational context are broad. Public administration repositories, weather portals, online calendars of festivities, cultural agendas, theatre sites, social media and online news can be periodically explored with the aim of retrieving specific context sources of interest (Tempelmeier et al. 2019, Tang et al. 2019). In addition, in cities with well-established efforts towards the gathering and provision of situational context, semi-structured sources maintained by the city Councils and other entities have been proposed to facilitate the acquisition step (Leite et al., 2020).

Advances in machine learning, micro-simulation and optimisation yield the promise of aiding support decisions related to both individual and multimodal planning of urban mobility. Paradigmatic examples range from adaptive traffic signal controllers sensitive to the mode-specific traffic status, and dynamic optimizers of public transportation (schedule, vehicle-and route-wise) to satisfy demand needs in the presence of public (large-scale) events and other externalities. Model-based multi-agent reinforcement learning, hierarchical network agent structures and the use of deep neural

networks as the underlying representation of the control problems have been proposed towards these ends.

5.6. Trends for sustainable urban mobility

Urban mobility is related to people's needs and also to the mobility of services in each socioeconomic context. The reviewed literature has addressed several topics related to sustainable mobility, however one of the major gaps is on the use of collaborative approaches and stakeholders' engagement in mobility planning. This is one of the assumptions advocated both in the SUMP and in the SDGs. SDG 11, which defines the criteria and goals for sustainable cities, can only be achieved by understanding the specific needs of social groups. This understanding will only be possible with the participation of different stakeholders with decisive roles as City Councils, public and private operators, city authorities, emergency services, technological companies, research institutes and local communities for collaborative planning of public policies. This topic is still one of the research gaps, and one of the future directions for a better understanding of the stakeholders' importance in decision-making and governance for sustainable urban mobility transition (Girard and Nocca, 2020). The pandemic period also accelerated the growth in the supply and demand of connected services, especially e-commerce, generating changes in the use of urban spaces that depend on a better quality of infrastructure for their fluidity. There is still a lack of studies that indicate the current stage of these changes and the type of demand in urban mobility that is related to the growth of local e-commerce, such as food deliveries and small daily purchases using apps on mobile phones. Urban logistics is part of urban mobility and there are indications of a logistics network relationship with the use of shared micro mobility services (Civitas, 2020), but it is already going further, with the possibility of services that use autonomous vehicles and delivery services by drones (Business Insiders, 2022). Analysis of the impacts of these services are still open questions to be explored in future research.

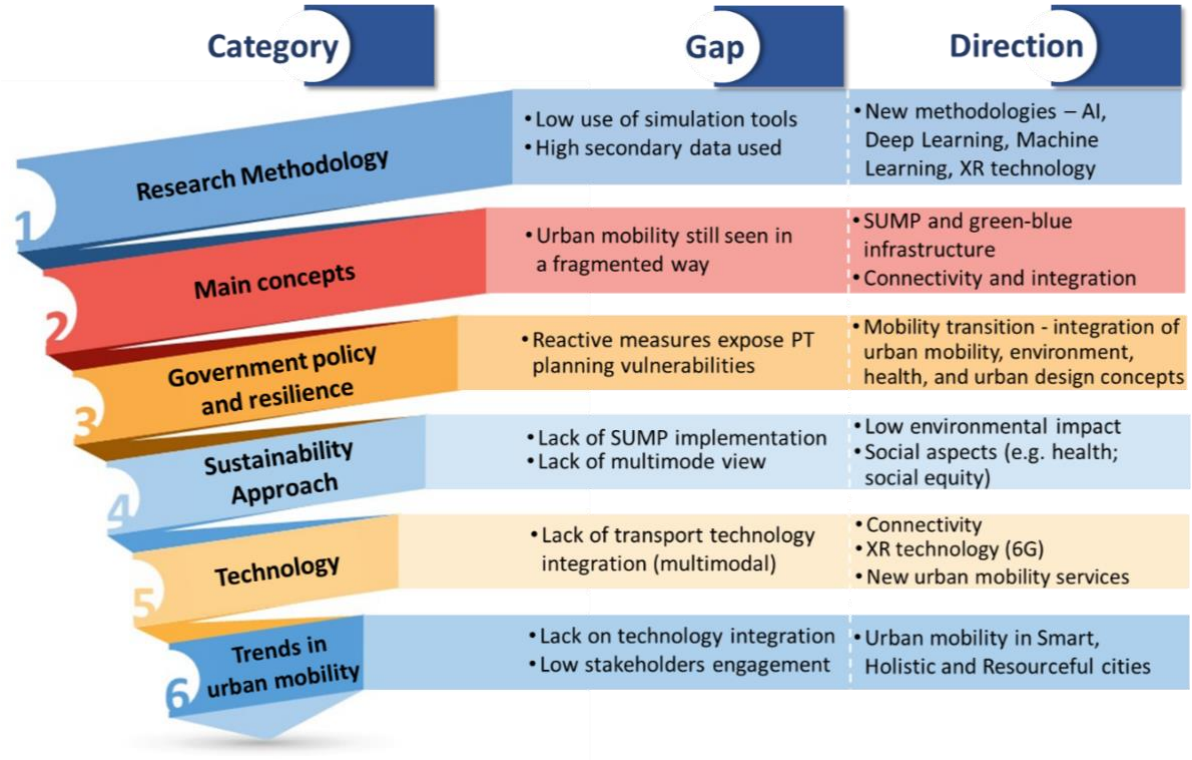


Figure 14. Summary of the findings

5.7. Implications for theory and practice

This study presents an analysis of the main themes addressed in the literature during the COVID-19 pandemic regarding sustainable urban mobility. It is clear that there has been a change both in the behaviour of users and in public policies for urban mobility and the authors were able to present the scenarios of the main events, bringing a valuable contribution to the understanding of the phenomena associated with urban mobility in the pandemic period. These changes generate a series of impacts, both negative, especially due to the disruption of services, and positive, whether in accelerating the implementation of new services or in the evaluation and restructuring of mobility management systems.

Understanding the weaknesses that became more evident during this period increases the responsibility for policymakers to provide effective solutions. At the same time, it broadens the perception that urban mobility policy and planning must integrate people's needs, considering the different aspects of daily life (equity, well-being, health, aesthetics, ecology), which can only be adequately addressed by integrating the concepts of resilience, smart cities, shared mobility, urban planning and 15-minutes city, in order to build spaces in cities "of people" and "for people", with social inclusion, integration, information, connectivity and liveability.

Future research should take a deeper look at information and communication tools that can facilitate and accelerate the transition to sustainable urban mobility in a holistic way. Cities must be more than

smart, they must have a purpose for the construction and implementation of their tools, which contemplates the needs of people's well-being, and that this is implemented in an egalitarian way in the different urban regions, without discrimination of socio-cultural and economic conditions.

Finally, we expect stakeholders' engagement to play a central role in future research to achieve sustainable urban mobility, expanding on the knowledge of stakeholders' involvement, synergic technologies, and community support to design solutions addressing local and regional needs that can be replicated in other scenarios (Rupprecht Consult, 2019).

6 - Conclusion

This work developed a systematic literature review of ongoing efforts towards sustainable urban mobility in relation to the COVID-19 pandemic. It offered a structured view on what are the main approaches, themes and concepts, as well as major issues that arise and affect the population daily life and their mobility needs. Six categories of analysis were defined for a comprehensive study of urban mobility responses with impact on major sustainable dimensions, offering a ground for research future directions.

The content analysis was developed by the N-Vivo software, aiding the study of behavioural and operational changes during the pandemic. As a result, the main gaps were identified, as well the trends and directions in sustainable urban mobility research.

Research findings highlight that the pandemic has brought significant changes in the vision of urban mobility, pinpointing the urgency to reshape urban spaces as a means to enable the transition to sustainable urban mobility along with the multimodal planning of traditional and emerging modes of transport with an emphasis on active modes. This transition requires the collaborative development and implementation of Sustainable Urban Mobility Plans, which are also aligned with the Sustainable Development Goals set by the United Nations' Agenda 2030. Moreover, this is also in line with smart cities planning, which, in addition to the great capacity for connectivity and information, has at its core, providing spaces for a better quality of life, with positive environmental impacts, which are also related to better health conditions.

Future research has the challenge of understanding the main behavioural changes and impacts that will arise from the improvement of urban spaces for liveability, promotion of active travel and new mobility modes and multimodal services, fully aligned with a sustainability approach. Yet, the behavioural changes in mode choices have to be deeply analysed, considering the available alternatives in each context, claiming that citizens are concerned about sustainability issues and feel responsible for using modes with less environmental impacts. Therefore, demonstrating the social and environmental benefits can be key for triggering the range of envisaged changes. Yet, challenges remain to be undertaken on the policy side for the development of integrated and collaborative

public policies, across sectors and stakeholders, for enabling meeting common sustainable and smart urban mobility goals, including an action plan for enhancing the resilience of urban transport systems.

References

Abdullah, M., Ali, N., Hussain, S.A., Aslam, A.B., Javid, M.A., 2021. Measuring changes in travel behavior pattern due to COVID-19 in a developing country : A case study of Pakistan. Transp. Policy 108, 21–33. https://doi.org/10.1016/j.tranpol.2021.04.023

Allam, Z., Jones, D.S., 2021. Future (post-COVID) digital , smart and sustainable cities in the wake of 6G : Digital twins , immersive realities and new urban economies. Land use policy 101, 105201. https://doi.org/10.1016/j.landusepol.2020.105201

Anastasiadou, K., Gavanas, N., Pyrgidis, C., Pitsiava-Latinopoulou, M., 2021. Identifying and prioritizing sustainable urban mobility barriers through a modified delphi-ahp approach. Sustain. 13. https://doi.org/10.3390/su131810386

Andara, R., Ortego-Osa, J., Gómez-Caicedo, M.I., Ramirez-Pisco, R., 2021. Behavior of Traffic Congestion and Public Transport in Eight Large Cities in Latin America during the COVID-19 Pandemic. Appl. Sci.

Aparicio, Joao T., Arsenio, E., Henriques, R., 2021. Understanding the impacts of the COVID-19 pandemic on public transportation travel patterns in the city of Lisbon. Sustain. 13. https://doi.org/10.3390/su13158342

Aparicio, Joao T, Arsenio, E., Henriques, R., 2021. Understanding the Impacts of the COVID-19 Pandemic on Public Transportation Travel Patterns in the City of Lisbon. Sustainability 1–18.

Barbieri, D.M., Lou, B., Passavanti, M., Hui, C., Hoff, I., Lessa, D.A., Sikka, G., Chang, K., Gupta, A., Fang, K., Banerjee, A., Maharaj, B., Lam, L., 2021. Impact of COVID-19 pandemic on mobility in ten countries and associated perceived risk for all transport modes. PLoS One 1–18. https://doi.org/10.1371/journal.pone.0245886

Basu, R., Ferreira, J., 2021. Planning car-lite neighborhoods: Does bikesharing reduce auto-dependence? Transp. Res. Part D Transp. Environ. 92. https://doi.org/10.1016/j.trd.2021.102721

Benita, F., 2021. Human mobility behavior in COVID-19: A systematic literature review and bibliometric analysis. Sustain. Cities Soc. 70, 102916. https://doi.org/10.1016/j.scs.2021.102916

Bohman, H., Ryan, J., Stjernborg, V., 2021. A study of changes in everyday mobility during the Covid-19 pandemic: As perceived by people living in Malmo, Sweden. Transp. Policy 106, 109–119. https://doi.org/10.1016/j.tranpol.2021.03.013

Borkowski, P., Jazdzewska-Gutta, M., Szmelter-Jarosz, A., 2021. Lockdowned : Everyday mobility changes in response to COVID-19. J. Transp. Geogr. 90. https://doi.org/10.1016/j.jtrangeo.2020.102906

Campisi, T., Acampa, G., Marino, G., Tesoriere, G., 2020a. Cycling master plans in Italy: The I-BIM feasibility tool for cost and safety assessments. Sustain. 12. https://doi.org/10.3390/su12114723

Campisi, T., Acampa, G., Marino, G., Tesoriere, G., 2020b. Cycling Master Plans in Italy : The I-BIM Feasibility Tool for Cost and Safety Assessments. Sustainability.

Campisi, T., Akgün, N., Ticali, D., Tesoriere, G., 2020c. Exploring Public Opinion on Personal Mobility

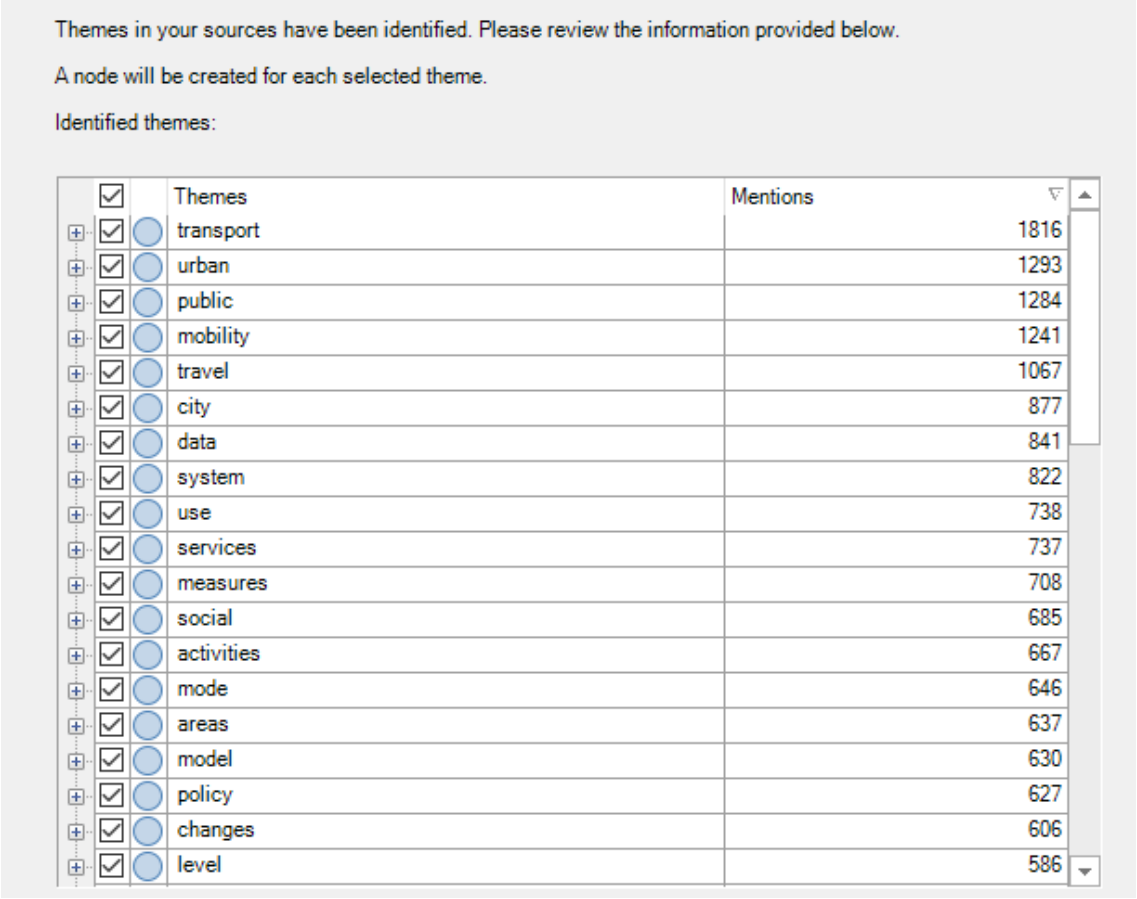
Vehicle Use : A Case Study in Palermo , Italy. Sustainability 1–15.
Campisi, T., Basbas, S., Skoufas, A., Akgün, N., 2020d. The Impact of COVID-19 Pandemic on the Resilience of Sustainable Mobility in Sicily 1–24.
Cerrone, C., Cerulli, R., Sciomachen, A., 2021. Grocery distribution plans in urban networks with street crossing penalties. Networks 78, 248–263. https://doi.org/10.1002/net.22061
Civitas, 2020. Cities towards Mobility 2. 0: connect, share and go! Smart choices for cities. Smart Choices Cities. Available online https//civitas. eu/content/civitas-policy-note-smart-choices-cities-cities-towards-mobility-20-connect-share-and-go-en (accessed 23 Oct. 2020).
Combs, T.S., Pardo, C.F., 2021. Shifting streets COVID-19 mobility data: Findings from a global dataset and a research agenda for transport planning and policy. Transp. Res. Interdiscip. Perspect. 9. https://doi.org/10.1016/j.trip.2021.100322
Corazza, M.V., Musso, A., 2021. Urban transport policies in the time of pandemic, and after: An ARDUOUS research agenda. Transp. Policy 103, 31–44. https://doi.org/10.1016/j.tranpol.2021.01.010
Das, S., Boruah, A., Banerjee, A., Raoniar, R., Nama, S., Maurya, A.K., 2021. Impact of COVID-19: A radical modal shift from public to private transport mode. Transp. Policy 109, 1–11. https://doi.org/10.1016/j.tranpol.2021.05.005
Dias, G., Arsenio, E., Ribeiro, P., 2021. The role of shared e-scooter systems in urban sustainability and resilience during the covid-19 mobility restrictions. Sustain. 13. https://doi.org/10.3390/su13137084
Echaniz, E., Rodríguez, A., Cordera, R., Benavente, J., Alonso, B., Sañudo, R., 2021. Behavioural changes in transport and future repercussions of the COVID-19 outbreak in Spain. Transp. Policy 111, 38–52. https://doi.org/10.1016/j.tranpol.2021.07.011
Fatmi, M.R., 2020. COVID-19 impact on urban mobility. J. Urban Manag. 9, 270–275. https://doi.org/10.1016/j.jum.2020.08.002
Frank, L.D., Hong, A., Ngo, V.D., 2021. Build it and they will cycle: Causal evidence from the downtown Vancouver Comox Greenway. Transp. Policy 105, 1–11. https://doi.org/10.1016/j.tranpol.2021.02.003
Glaser, M., Krizek, K.J., 2021. Can street-focused emergency response measures trigger a transition to new transport systems ? Exploring evidence and lessons from 55 US cities. Transp. Policy 103, 146–155. https://doi.org/10.1016/j.tranpol.2021.01.015
Guzman, L.A., Arellana, J., Oviedo, D., Moncada Aristizábal, C.A., 2021. COVID-19, activity and mobility patterns in Bogotá. Are we ready for a '15-minute city'? Travel Behav. Soc. 24, 245–256. https://doi.org/10.1016/j.tbs.2021.04.008
Heras, A.D. Las, Luque-Sendra, A., Zamora-Polo, F., 2020. Machine learning technologies for sustainability in smart cities in the post-covid era. Sustain. 12, 1–25. https://doi.org/10.3390/su12229320
Hörcher, D., Singh, R., Graham, D.J., 2021. Social distancing in public transport: mobilising new technologies for demand management under the Covid-19 crisis. Transportation (Amst). https://doi.org/10.1007/s11116-021-10192-6
Jenelius, E., Cebecauer, M., 2020. Impacts of COVID-19 on public transport ridership in Sweden: Analysis of ticket validations, sales and passenger counts. Transp. Res. Interdiscip. Perspect. 8. https://doi.org/10.1016/j.trip.2020.100242
Jiang, P., Fu, X., Fan, Y. Van, Klemes, J.J., Cheng, P., Zhang, W., 2021. Spatial-temporal potential exposure risk analytics and urban sustainability impacts related to COVID-19 mitigation : A perspective from car mobility behaviour. J. Clean. Prod. 279. https://doi.org/10.1016/j.jclepro.2020.123673
Kakderi, C., Oikonomaki, E., Papadaki, I., 2021. Smart and resilient urban futures for sustainability in the post covid-19 era: A review of policy responses on urban mobility. Sustain. 13. https://doi.org/10.3390/su13116486
Karaer, A., Balafkan, N., Gazzea, M., Arghandeh, R., Ozguven, E.E., 2020. Analyzing covid-19 impacts on vehicle travels and daily nitrogen dioxide (No2) levels among florida counties. Energies 13.

https://doi.org/10.3390/en13226044
Lei, Y., Ozbay, K., 2021. A robust analysis of the impacts of the stay-at-home policy on taxi and Citi Bike usage: A case study of Manhattan. Transp. Policy 110, 487–498. https://doi.org/10.1016/j.tranpol.2021.07.003
Maestosi, P.C., Andreucci, M.B., Civiero, P., 2021. Sustainable Urban Areas for 2030 in a Post-COVID-19 Scenario: Focus on Innovative Research and Funding Frameworks to Boost Transition towards 100 Positive Energy Districts and 100 Climate-Neutral Cities. Energies.
Marinello, S., Lolli, F., Gamberini, R., 2021. The Impact of the COVID-19 Emergency on Local Vehicular Traffic and Its Consequences for the Environment : The Case of the City of Reggio Emilia (Italy). Sustainability.
Marsden, G., Docherty, I., 2021. Mega-disruptions and policy change: Lessons from the mobility sector in response to the Covid-19 pandemic in the UK. Transp. Policy 110, 86–97. https://doi.org/10.1016/j.tranpol.2021.05.015
Mouratidis, K., 2021. How COVID-19 reshaped quality of life in cities : A synthesis and implications for urban planning. Land use policy 105772. https://doi.org/10.1016/j.landusepol.2021.105772
Mouratidis, K., Papagiannakis, A., 2021a. COVID-19, internet, and mobility: The rise of telework, telehealth, e-learning, and e-shopping. Sustain. Cities Soc. 74. https://doi.org/10.1016/j.scs.2021.103182
Mouratidis, K., Papagiannakis, A., 2021b. COVID-19, internet, and mobility: The rise of telework, telehealth, e-learning, and e-shopping. Sustain. Cities Soc. 74, 103182. https://doi.org/10.1016/j.scs.2021.103182
Nian, G., Peng, Bozhezi, Sun, D.J., Ma, W., Peng, Bo, Huang, T., 2020. Impact of COVID-19 on urban mobility during post-epidemic period in megacities: From the perspectives of taxi travel and social vitality. Sustain. 12. https://doi.org/10.3390/SU12197954
Nikitas, A., Tsigdinos, S., Karolemeas, C., Kourmpa, E., Bakogiannis, E., 2021. Cycling in the Era of COVID-19 : Lessons Learnt and Best Practice Policy Recommendations for a More Bike-Centric Future.
Pani, A., Mishra, S., Golias, M., Figliozzi, M., 2020. Evaluating public acceptance of autonomous delivery robots during COVID-19 pandemic. Transp. Res. Part D 89, 102600. https://doi.org/10.1016/j.trd.2020.102600
Pisano, C., 2020. Strategies for Post-COVID Cities : An Insight to Paris En Commun and Milano 2020. Sustainability.
Rahman, M.M., Paul, K.C., Hossain, M.A., Ali, G.G.M.N., Rahman, M.S., Thill, J.C., 2021. Machine Learning on the COVID-19 Pandemic, Human Mobility and Air Quality: A Review. IEEE Access 9, 72420–72450. https://doi.org/10.1109/ACCESS.2021.3079121
Rasca, S., Markvica, K., Peter, B., 2021. Impacts of COVID-19 and pandemic control measures on public transport ridership in European urban areas – The cases of Vienna , Innsbruck , Oslo , and Agder. Transp. Res. Interdiscip. Perspect. 10, 100376. https://doi.org/10.1016/j.trip.2021.100376
Rupprecht Consult, 2019. Guidelines for developing and implementing a sustainable urban mobility plan. Cologne.
Schmidt, K., Sieverding, T., Wallis, H., Matthies, E., 2021. COVID-19 – A window of opportunity for the transition toward sustainable mobility ? Transp. Res. Interdiscip. Perspect. 10, 100374. https://doi.org/10.1016/j.trip.2021.100374
Serdar, M.Z., Koc, M., Al-ghamdi, S.G., 2021. Urban Transportation Networks Resilience: Indicators, Disturbances, and Assessment Methods. Sustain. Cities Soc. https://doi.org/10.1016/j.scs.2021.103452
Shortall, R., Mouter, N., Van Wee, B., 2021. COVID-19 passenger transport measures and their impacts. Transp. Rev. 0, 1–26. https://doi.org/10.1080/01441647.2021.1976307
Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review * 14.

Valenzuela-Levi, N., Echiburu, T., Correa, J., Hurtubia, R., Muñoz, J.C., 2021. Housing and accessibility after the COVID-19 pandemic : Rebuilding for resilience , equity and sustainable mobility. Transp. Policy 109, 48–60. https://doi.org/10.1016/j.tranpol.2021.05.006
Wang, A., Zhang, A., Chan, E.H.W., Shi, W., Zhou, X., Liu, Z., 2021. A Review of Human Mobility Research Based on Big Data and Its Implication for Smart City Development. Int. J. geo Inf.
Wang, H., Noland, R.B., 2021. Bikeshare and subway ridership changes during the COVID-19 pandemic in New York City. Transp. Policy 106, 262–270. https://doi.org/10.1016/j.tranpol.2021.04.004
Yang, S., Chong, Z., 2020. Smart city projects against COVID-19: Quantitative evidence from China.
Yasin, Y.J., Grivna, M., Abu-Zidan, F.M., 2021. Global impact of COVID-19 pandemic on road traffic collisions. World J. Emerg. Surg. 16, 1–14. https://doi.org/10.1186/s13017-021-00395-8
Zhang, J., Hayashi, Y., Frank, L.D., 2021. COVID-19 and transport: Findings from a world-wide expert survey. Transp. Policy 103, 68–85. https://doi.org/10.1016/j.tranpol.2021.01.011
Polis, and Rupprecht Consult—Forschung & Beratung GmbH. Topic Guide: Planning for More Resilient and Robust Urban Mobility; Polis Publishing: Brussels, Belgium, 2021.
Rupprecht Consult (editor), Guidelines for Developing and Implementing a Sustainable Urban Mobility Plan, Second Edition, Cologne, Germany, 2019.
Mayring, P. Qualitative Content Analysis: Theoretical Foundation, Basic Procedures and Software Solution, Klagenfurt, Austria (2014)

Appendix

Auto code word frequency result


Themes in your sources have been identified. Please review the information provided below.

A node will be created for each selected theme.

Identified themes:

Themes	Mentions
transport	1816
urban	1293
public	1284
mobility	1241
travel	1067
city	877
data	841
system	822
use	738
services	737
measures	708
social	685
activities	667
mode	646
areas	637
model	630
policy	627
changes	606
level	586