Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Human mobility behavior in COVID-19: A systematic literature review and bibliometric analysis

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ABSTRACT

This article maps the scientific literature in human mobility behavior in the context of the current pandemic. Through bibliometrics, we analyze the content of published scientific studies indexed on the Web of Science and Scopus during 2020. This enables us the detection of current hotspots and future directions of research. After a co-occurrence of keywords and evidence map analysis, four themes are identified, namely, Land Transport — Operations, Land Transport — Traffic Demand, Air Transport and Environment. We show how air transportation- and environmental-related studies tend to be more mature research whereas the understanding of changes in travel behavior (e.g., telecommuting, preventive measures or health protection behavior) tends to be immature. By using a topic modeling approach, we identify multiple sub-themes within each theme. Our framework adopts a smart literature review approach that can be constantly updated, enabling an analysis of many articles, with little investment of the researcher's time, but also provides high degree of transparency and replicability. We also put forth a research agenda that can help inform and shape transport policy and practice responses to COVID-19.

1. Introduction

The outbreak of the novel and infectious coronavirus disease 2019 (COVID-19), produced by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was first reported in Wuhan (China) in mid-December 2019. On March 11, 2020, the World Health Organization declared the outbreak as a pandemic and by December 31, 2020, the disease caused more than 80 million confirmed cases and more than 1.8 million deaths. During the first months of the pandemic, the wide range of major non-pharmaceutical interventions (stay-at-home order, closure of schools/workplaces, ban of public events, internal movement limits, flight restrictions, etc.) substantially reduced human mobility and created several unprecedented effects on the transport sector worldwide.

The early empirical evidence for COVID-19's impact on sustainable transportation systems was related to the reduction of urban traffic volumes with a respective drop in traffic emissions (Le Quéré et al., 2020). Some other researchers timely reported the consequences of highly disruptive travel restrictions on the aviation sector such as difficulties for cash flow forecasting (Agrawal, 2020; Vinod, 2020) or the risk of importation and exportation of the disease (Nakamura & Managi, 2020). Within a matter of few months, a plethora of literature evaluating multiple sources of transportation-related data was published during 2020. Among them are changes in individual's preventive behavior (Hotle et al., 2020; Kamenidou et al., 2020; Parady et al., 2020), the replacement of commuting to workplace by telecommuting (Beck & Hensher, 2020; Shamshiripour et al., 2020; Wang & Ozbilen, 2020) or the increasing adoption of innovative and sustainable transportation modes (e.g., lightweight vehicles such as e-scooters, e-bikes or mopeds) which complement existing transportation networks and ensure physical distancing (Bruzzone et al., 2020; Button et al., 2020; Choi, 2020), to name a few.

Nonetheless, to the best of our knowledge, this body of *rapidly* emerging research has not yet been systematized in a way to give transportation operators, public stakeholders and practitioners alike easy access to main topics (themes), trends and ramifications of research lines (sub-themes) around the impact of sanitary crisis in human mobility. The identification of *response patterns* of academia in the wake of the global pandemic is valuable because it allows us to gain a deeper understanding towards controlling and stopping outbreaks. This paper provides insights into how academia responds to the pandemic situation through a comprehensive analysis of published research in the Web of Science and Scopus. Two main research questions frame this study: (i) What are the relevant topics during the year 2020?; (ii) Is there any identifiable response from transportation researchers to COVID-19 emergency? If so, what are the characteristics of publication dynamics, distribution by country/region and field of study. To address these questions, we propose a machine learning-based framework that

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has the potential to provide a clear mapping of the research landscape related to COVID-19 and human mobility behavior. It also sheds light on the *efficient* process of keeping track the body of evidence that has been increasing at an impressive pace and requires a framework that is more automated and has wider scope that current gold standard methods (e.g., scoping and systematic reviews Munn et al., 2018).

After a careful screening of published articles, a total of 194 manuscripts are found to meet the selection criterion (English-language peer-reviewed journal articles that exclude freight transportation studies). Our framework identified four main themes, namely, Land Transport — Operations, Land Transport — Traffic Demand, Air Transport and Environment. In a second stage of analysis, we showed that four sub-themes are emerging among Land Transport — Operations (technological tools and rail transport; control measures for urban traffic; non-motorized mobility, and; public transit), three among Land Transport — Traffic Demand (protective behavior and working from home; spreading speed and travel behavior trends, and; sustainability of urban mobility), four among Air Transport (aviation's recovery flight plan; passenger preferences and willingness to fly; safety and security in aviation, and; airlines' strategic responses), and three sub-themes among Environment (changes in concentration of air pollutants; air transport mobility and noise emissions, and; energy systems and renewable fuels). The comprehensive information presented in this study could also help policymakers and stakeholders develop better strategies for greater upward mobility while evaluate the risk of local outbreaks.

In Section 2, we discuss the method by which the bibliometric and systematic literature review has been obtained. Particularly, we identify four emerging clusters of research by means of keywords co-occurrence networks and qualitative methods. We show that the use of evidence maps provides a simple graphical format for summarizing main characteristics of existing literature, such as region of study, main tools utilized or transportation mode analyzed. After the identification of the four main research themes, a topic modeling framework is implemented in order to derive relevant research topics within each theme, i.e., sub-themes. The results of this macro-level analysis of the literature are presented in Section 3 whereas a detailed discussion of the emerging research avenues is carried out in Section 4. Finally, the conclusions, including a discussion about the mobility of future sustainable and healthy cities are presented in Section 5.

2. Data and methods

2.1. Search strategy

The current pandemic is showing the incredibly adaptability of the research community as scientists are working around the clock to develop solutions. Nevertheless, the expediting and enormity of these scientific efforts have also led to a flood of papers and preprints which in no few cases, either resulted in articles published in the so-called *predatory* journals, withdrawals or retractions (Soltani & Patini, 2020). Considering such studies in our search strategy is not advisable, as they may contain seriously flawed or erroneous content resulting in unreliable findings.

There are many databases of peer-reviewed literature (Web of Science, Scopus, ProQuest Central, DOAJ, etc.), digital libraries (IEEE Xplore, ACM Digital Library, PubMed, etc.), web-based academic search engines (CitiSeerX, Google Scholar, Microsoft Academic Search, etc.) and preprint servers (arXiv, medRxiv, bioRxiv, etc.). Among them, Web of Science (launched in 1997) and Scopus (2004) are the two world-leading and competing citation databases as they index high-quality peer-reviewed publications and have large coverage of different literature topics and studies across all domains.

We retrieved bibliographic records and full-text articles from the Web of Science and Scopus only. There are two reasons behind this decision. First, articles indexed in these databases have passed a rigorous peer-review process. For instance, some of the preprints among the massive body of *gray* literature published in open access repositories (such as arXiv or medRxiv) may not meet accepted academic peer-reviewed standards and their methodologies may be poorly reported (Egger et al., 2003; Sterne et al., 2008). Second, their classical journal citation indexes are well-known and widely used in academia on the one hand, and there is an increasing number of papers mentioning Web of Science and Scopus in their topic field on the other (see Liu, 2019; Sharifi & Khavarian-Garmsir, 2020; Verma & Gustafsson, 2020).

The search period was set between Jan 1, 2020 and Dec 31, 2020. Only English-language publications were considered, and the filtering criteria included items with the following terms in titles, abstracts or keywords: Coronavirus* (including its variations) AND transport* OR mobility, see Fig. 1. A total of 6969 items were obtained and the search was narrowed by focusing on transport-related areas of knowledge such as Transportation; Business and Economics; Environmental Sciences, and so forth. We ruled out articles addressing topics in supply management, logistics and operations (e.g., road freight operations or maritime transport). A comprehensive literature review on the impact of COVID-19 on supply chains, business and management can be found in the study of Verma and Gustafsson (2020). Then, after a careful screening process of titles, abstracts and keywords, a total of 194 articles were selected for detailed discussion in the literature review.

2.2. Co-occurrence of keywords

We also present an analysis of the frequency of keywords to describe the internal structure of our sample of studies. Keywords provide an adequate description of articles' content and keyword co-occurrence frequency is useful for understanding the conceptual structure and trends of a specific field by measuring the relationship intensity among representative keywords in the selected documents (Ding et al., 2001). Co-occurrence refers to the case where two keywords appear together within documents. It is a network analysis that requires raw keywords to be cleaned up and standardized before performing the analysis. This is a manual, lengthy and careful examination of the extracted keywords as detailed in Appendix A.1. We performed our keyword co-occurrence analysis through the R-package *bibliometrix* developed by Aria and Cuccurullo (2017).

2.3. Evidence map analysis

Evidence maps is a systematic approach to identifying and describing the research activity in a topic area or policy domain (Miake-Lye et al., 2016). This analysis led to a broad and comprehensive overview of an evidence base, often through a focused study of systematic reviews. Evidence maps can also provide a foundation for further and more focused research synthesis as they typically show what evidence is there, not what the evidence says. In the context of human mobility behavior and sustainable transportation systems, evidence maps have been adopted by recent literature to derive some new insights into urban policy interventions meant to reduce traffic emissions (Sanchez et al., 2020) or to increase road safety (Mohan et al., 2020).

We adopted a variant of the *Evidence Gap Map* (Saran & White, 2018) which has been used in a wide range of research domains to characterize topic distributions and to inform priority setting in future research. In doing so, each publication is categorized into one of the following research themes: "Land Transport — Operations", "Land Transport — Traffic Demand", "Air Transport" and "Environment". The selection of the four themes was based on the keywords co-occurrence findings as well as the approach of past published literature review studies addressing supply- (Calderón & Miller, 2020) and demand-side (Jorge & Correia, 2013) of the human mobility behavior; aviation (Tanrıverdi et al., 2020), and; environmental and sustainability impacts (Vieira et al., 2007). The Land Transport — Operations

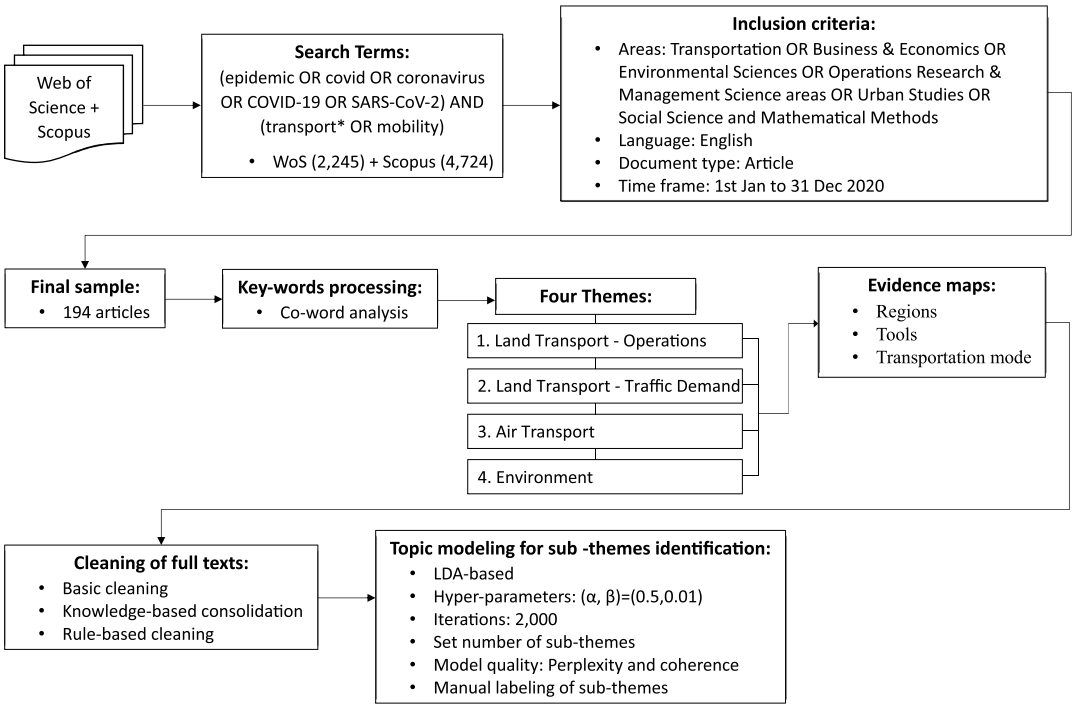


Fig. 1. Flowchart of the experimental procedure to identify the emerging COVID-19 research trends in human mobility behavior..

theme covers topics related to the supply of all land-based transportation systems such as management, operations and maintenance of vehicles and facilities. Land Transport — Traffic Demand has to do with changes travel behavior limiting land-based transport demand. Air Transport focuses exclusively in studies documenting commercial air travel. Lastly, the Environment theme groups together articles addressing changes in environment during the implementation of nationwide lockdown due to the pandemic.

Finally, we further classified articles into pre-determined region of study, main tools used and transport mode analyzed. According to the region of study publications are focusing at, articles were classified as "Africa", "Asia", "Europe","North America", "Oceania", "South America" or "Worldwide". In function of tools used, articles were classified as "Machine Learning/Artificial Intelligence", "Optimization", "Simulation", "Statistics" or "Review"(e.g., systematic review-, overview- or outlook-articles). Based on the primary focus of the articles, we classified them into one of the following transportation modes: "Air travel", "Active transport", "Private transit", "Public transit", "Ride-sharing" or "Multimodal".

2.4. Topic modeling

We used a topic modeling framework with the goal of grouping articles within each theme of human mobility behavior into sub-themes. Topic modeling is based on similarity and it is used to learn the "aboutness" of collection of documents. Based on the outcome of this framework, relevant sub-themes can be selected for a qualitative literature review (Quinn et al., 2010). We started by cleaning the articles by performing (i) basic cleaning; (ii) knowledge basic consolidation; and (iii) rule-based cleaning, see Appendix A.2. After articles are cleaned, we obtained a set of single terms within each theme and we used the Latent Dirichlet Allocation (LDA) method for topic modeling (Blei, 2012). This is an unsupervised, probabilistic modeling method able to extract topics, e.g., sub-themes, form our collection of articles within each theme. Topic modeling does not provide a full meaning of the text but provides a good overview of the sub-themes. Our collection of articles, made up of 194 documents, is relatively small, and we could simply perform a manual analysis of the literature instead. However, under the explosive growth of the COVID-19 research, topic modeling not only enables an analysis of many articles, with little investment of the researcher's time, but also provides high degree of transparency and replicability. For instance, with a collection of 14,172 COVID-19 related publications from PubMed and ArXiv, Ebadi et al. (2020) implemented structural topic modeling to investigate the weekly evolution of topics and provide a clear mapping of the COVID-19 research landscape. Further details of our topic modeling implementation can be found in the Appendix A.2. Our topic modeling approach was implemented by using the R-package *topicmodels* of Hornik and Grün (2011). Finally, Fig. 1 illustrates the process overview of systematic literature review and bibliometric analysis.

2.5. Relevance of our analysis framework

With several hundred new papers available every day (see https://covid19primer.com/dashboard for paper counts), the extremely rare opportunity to examine so many aspects of the pandemic posed new challenges for everyone to stay abreast of these developments. Stakeholders and decision-makers need a timely clear mapping of the COVID-19 research landscape as new topics, including health-related and sustainable-related issues, emerge to reflect new realities and strategies. Screening references is a time-consuming step required for systematic reviews. However, automated text mining techniques for searching, reading and summarizing articles may be particularly effective not only in reducing that human effort but also in identifying set of clusters/topics sharing similar vocabulary that gradually becomes hard to distinguish (even by just reading the abstracts) when the number of topics is large and unknown. Our analysis framework combines systematic review and automated text mining methods to offer a good balance between accelerating the identification of relevant studies, precision and interpretability. In other words, it is a semi-automated method that recognizes the importance of human assistance in the bibliometric analysis. Whether this or any other semi-automated tool in systematic review outperforms traditional methods in supporting review and guideline development is an interesting open question that is largely driven by multi-criteria factors (e.g., total saved time, replicability, linguistic sensitivity and so forth) (Przybyła et al., 2018).

3. Results

3.1. Bibliometric features and evidence maps

The total number of journals within the 194 selected articles is 70. Fig. 2 enlists the academic journals publishing most of the studies. 23 out of the 70 identified publication venues have published at least 2 articles, and interestingly, *Transportation Research Interdisciplinary Perspectives*, lunched in 2019 as part of the "Transportation Research" family of journals, has been actively publishing novel results since beginning of the pandemic. The corresponding authors of articles were from 48 different countries (Fig. 3(a)). United States and China produced the higher output with 34 (17.5%) and 29 (14.9%) articles, respectively. Articles from Europe ($n = 78$), Asia ($n = 53$) and North America ($n = 43$) represented 40.2%, 27.3.6% and 22.2% of all articles, respectively, while confirmed cases, as of 31 Dec, 2020, of these same regions represented and 22%, 25.8% and 27.5% of global cases, respectively. Fig. 3(b) enlists the total number of articles by country/region of study. The literature examined 36 different countries but about one third of the articles ($n = 59, 30.4\%$) focused on worldwide cover. The top five studied countries are United States ($n = 28, 14.4\%$), China ($n = 24, 12.4\%$), Italy ($n = 10, 5.15\%$), India ($n = 5, 2.6$) and Spain ($n = 5, 2.6$) while the five countries with highest number of infections by the end of 2020 are United States (24.6% of global cases), India (12.3%), Brazil (9.2%), Russia (3.8%) and the UK (3%). It is worth noting that, although reported cases are relatively low in countries like Japan (0.28%), Greece (0.17%), China (0.10%) or South Korea (0.07%) the impact of the pandemic on the sustainable transportation systems has been well documented.

Fig. 4 depicts the keyword co-occurrence network with the top 50 keywords. Louvain method for community detection (Blondel et al., 2008) suggested the existence of four emerging research lines. The first of them has strong focus on the change of traffic emissions (nodes in red color), particularly in air pollutants. The second research line (purple color) relates to air passenger traffic. The third and more sparse research line (green color) has focus on the changes in travel behavior induced by the social distancing and lockdown policies. These changes include, for example, the adoption of innovative and sustainable modes of transportation (e.g., bike, e-scooter or telecommuting). Lastly, the fourth research line (blue color) relates to risk of COVID-19 infection among public transport users. Fig. 4 is useful because keywords density will reveal more mature research lines (An & Wu, 2011). This is the case of the roles of air transportation systems in pandemic management (purple color) or the temporary reduction of air pollution due to lockdown periods (red color). Alternatively, the lower the density, these research fields tend to be immature, such as the changes in travel behavior (green color).

Fig. 4 supports our idea of choosing four themes related to human mobility behavior, namely, Land Transport — Operations (perhaps articles clustered within the nodes in blue color), Land Transport — Traffic Demand (nodes in green color), Air Transport (nodes in purple color), and Environment (nodes in red color). By article theme and region of study (Fig. 5(a)), Land Transport — Traffic Demand in Europe ($n = 28, 14.4\%$) and Environment worldwide ($n = 24, 12.4\%$) were the most common. Moreover, the proportion of articles reporting changes in Land Transport — Traffic Demand or Land Transport — Operations within Europe, Asia and North America is significantly higher than the proportion of such articles with focus on Oceania, South America or Africa. In terms of tools employed, Statistical methods predominated with 93 out of the 194 studies (47.9%) using such techniques. Interestingly, Review studies have scaled rapidly within the literature ($n = 48, 24.7\%$) as an attempt to timely document worldwide initiatives to lighten the burden of the crises on transportation systems. Articles focusing on Multimodal transit, e.g., combined transport, where the most common ($n = 62, 31.9\%$). Finally, Fig. 5(b) plots the number of articles published by month during 2020. Air Transport research was intensively conducted as early as May due to one of the first government's response strategies to this pandemic was the suspension of all passenger flights and ban of passengers arrivals from specific countries. Although there has been a big explosion of scientific literature growth over the months in repositories like PubMed or ArXiv (covering topics such as epidemiology, public health, genomics, rehabilitation, etc., see Ebadi et al., 2020), in the case of human mobility studies we did not noticed that the volume of research has augmented over time.

3.2. Identification of sub-themes

Fig. 6 shows the results of the topic modeling framework for sub-themes identification. To select the right number of sub-themes within each theme, a balance must be found between having a usable number of sub-topics, with as low (high) perplexity score (coherence) as possible. Whereas a low number of sub-themes is used for a general overview, a high number of sub-themes is used for a fine-grained view (Asmussen & Møller, 2019). After a careful inspection of the articles classified according to the different number of sub-themes, we selected 4 sub-themes for Land Transport — Operations, 3 sub-themes for Land Transport — Traffic Demand, 4 sub-themes for Air Transport and 3 sub-themes for Environment. Having grouped the documents, we named the sub-themes based on the most frequent terms in each sub-theme as well as article's content review, see Table 1. High-frequency terms were relabeled again to match standard keywords in the context of human mobility behavior literature. For example, sub-theme *Energy systems and renewable fuels* within the Environment theme reported "vehicl", "reduct", "lower", "fuel" or "Electri" among the high-frequency terms. Then, after a revision of full texts, we relabeled these high-frequency terms as "Energy System Balancing", "Electric Vehicles" and "Hybrid-Engine Vehicles" keywords.

4. The emerging research agenda in human mobility behavior within the context of the COVID-19 outbreak

4.1. Land transport — operations

Technological tools and railway operations. Transit and transportation leaders are exploring how to operate networks safety and efficient. Mobile ticketing, self-service options (e.g., self-service baggage drop, check-in), interactive vending machines or voice-enabled screening are some of the recent safety technologies for public transport hubs (Cserdi & Kenesei, 2020; Gaskin et al., 2020). The increased demand for touchless traveler services makes the introduction of new systems of customer service particularly important for public transport operators. Cserdi and Kenesei (2020) show that it is critical to understand the factors that may help the acceptance of the new systems by passengers. The second focus of this research stream has to do with disruptive technologies to manage cascading failures in rial service operations (Jiao et al., 2020). Moreover, local governments are shifting their *traditional* public transport subsidy scheme (e.g., road infrastructure construction or rail fare subsidies), towards massive stimulus packages to bridge the drop in revenues of firm's business operation. In this vein, a better understanding of the temporary efficiency effects of rail transport subsides is required. For instance, will it make a difference if the subsidy goes to unit operations cost rather than "lump-sum" fixed cost? (Choi, 2020).

Control measures for urban traffic. Governments have relying on strictly controlled urban traffic to contain the spread of the virus. Testing and tracking were the two pillars allowing blunt the exponential spread of the disease in countries like South Korea (Lee & Lee, 2020). Close tracing of contacts of (possibly infected) individuals has been done by mobile phone tracking, credit card transaction history or video footage from public surveillance cameras. The temporary suspension of public transport services and private taxis was also quickly implemented worldwide because the existing public transport

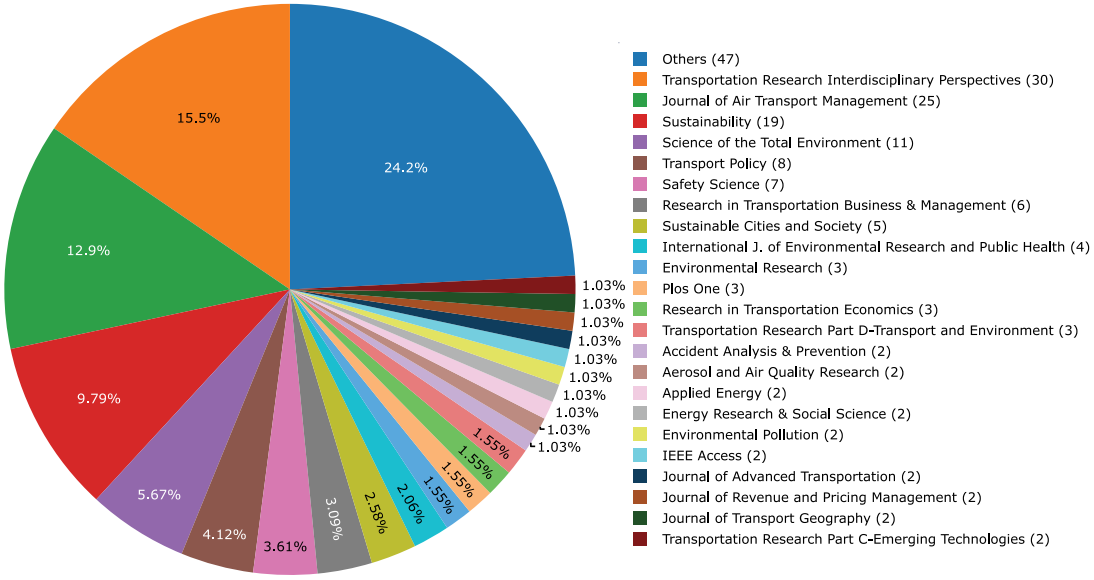
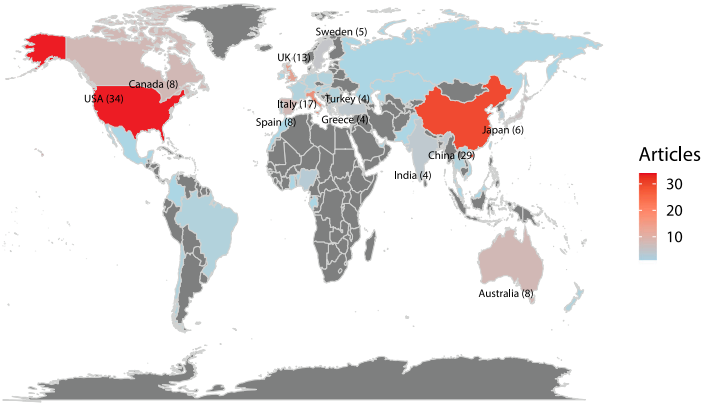
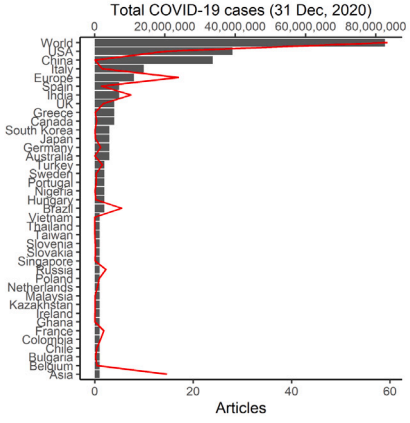


Fig. 2. Publication venues.



(a) Distribution of the articles by corresponding author's country. Labels for top 10 countries only



(b) Distribution of articles by country/region of study (gray bars), and total cases as of Dec 31, 2020 (red line)

Fig. 3. Publication venues and monthly number of articles.

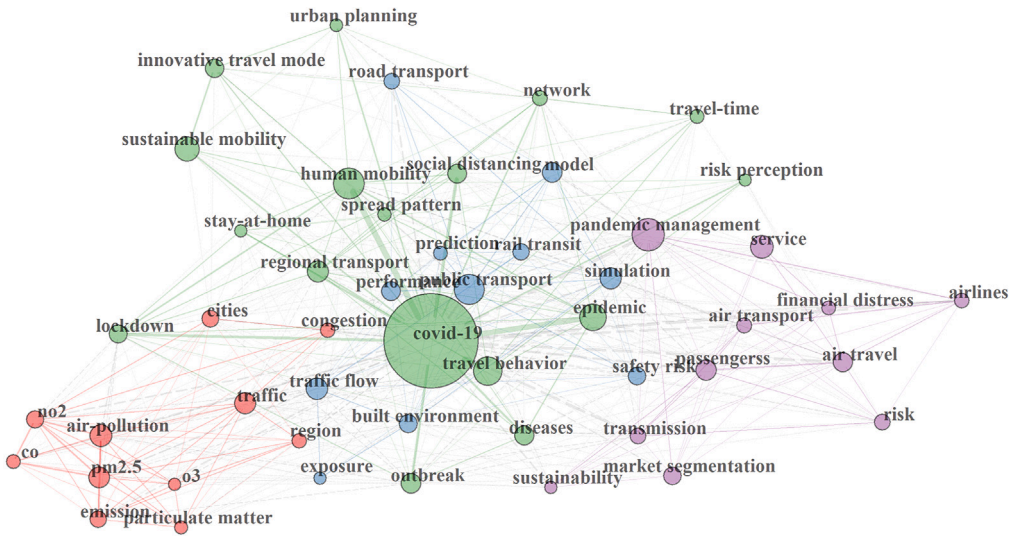
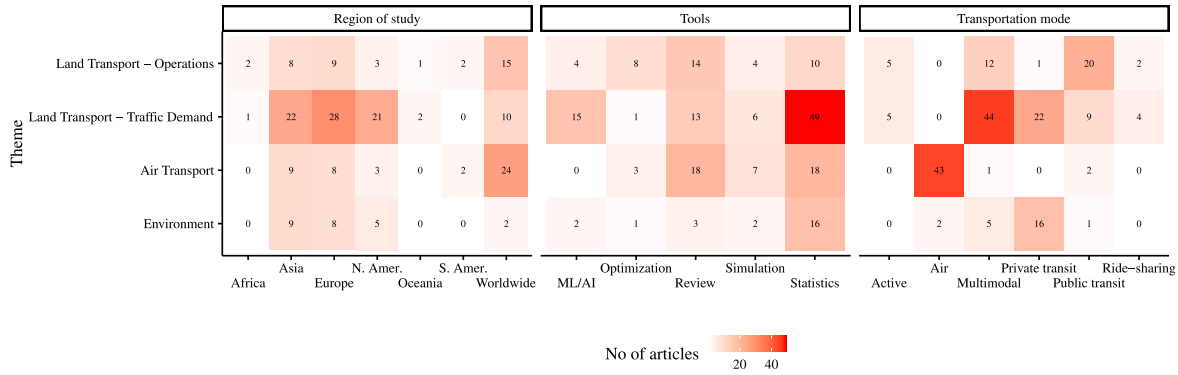
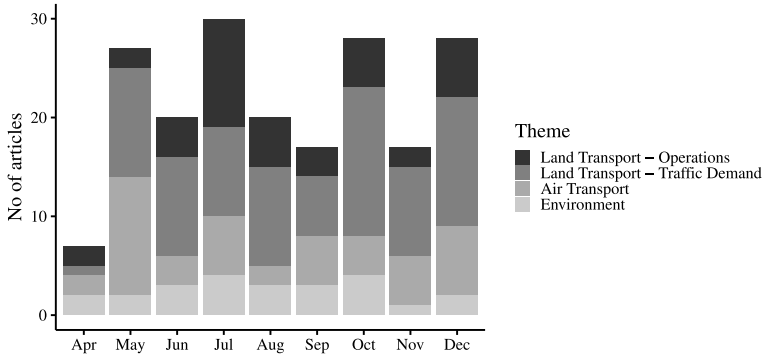


Fig. 4. Keyword co-occurrence network of COVID-19 literature in the human mobility behavior area. The network graph depicts the top 50 keywords. The size of the node indicates frequency and edges represent co-occurrence relationships. Colors are used to highlight node clusters using Louvain method for community detection (Blondel et al., 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



(a) Distribution of article themes by continent of study, methodological tools used, and transportation mode analyzed



(b) Monthly number of articles by theme, 2020

Fig. 5. Evidence maps.

could not ensure the health and safety of passengers during the outbreak (Chen et al., 2020). Compulsory temperature testing at entry to buildings, the use of face mask in crowded transportation stations (Zeng et al., 2020), increase in sanitation of surfaces (Bonful et al., 2020), and social distancing guidelines (minimum distance required between passengers De Vos, 2020; Mogaji, 2020; Sharifi & Khavarian-Garmsir, 2020) are also among the most common responses taken by transport operators as a control measure against the COVID-19 spread.

Non-motorized mobility. Due to the increased risks of infections in public transport, policy makers may lose confidence in public transit, reinforcing non-motorized mobility and active transit planning (Ceder, 2020). Cities around the globe are already involved in the transformation of mobility though innovative models of sustainable transport such

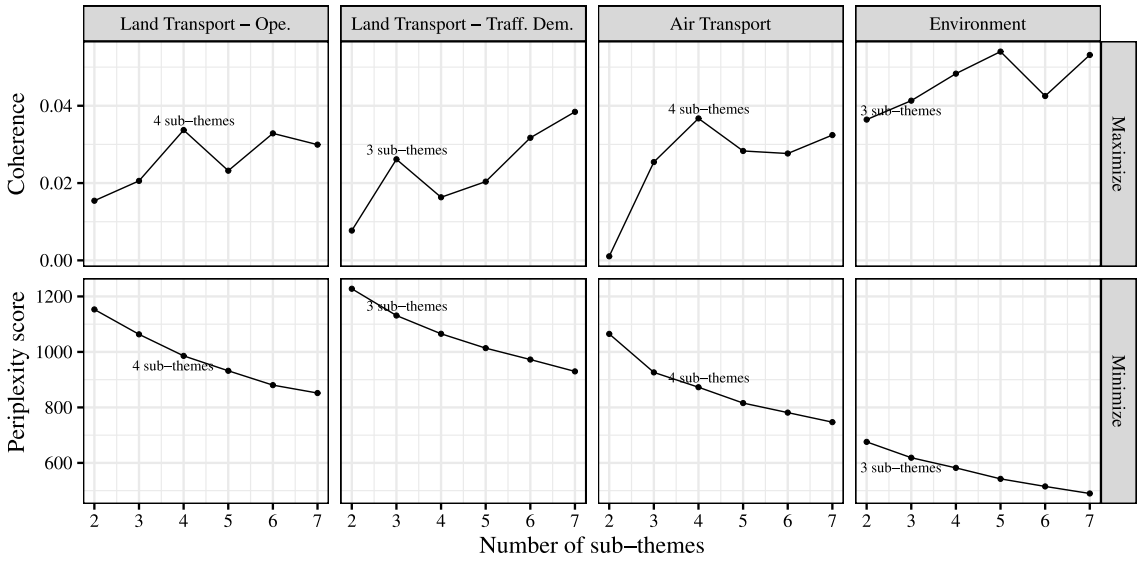


Fig. 6. Number of sub-themes vs. perplexity score (lower is better) and coherence (higher is better).

as low-cost alternative transportation options, e.g., e-bike and e-scooter sharing programs (Bruzzone et al., 2020; Teixeira & Lopes, 2020). The need to rethink the urban spaces and mobility, including street design, design of non-motorized traffic or providing technical advice on electric-mobility, is one of the most important challenges while adopting non-motorized vehicles (Barbarossa, 2020). Furthermore, of special relevance are safe route programs adopted by schools (Sagaris & Lanfranco, 2019; Schlüter et al., 2020), based mainly in the promotion of active transport such as having the children to walk and bike to and from schools.

Public transit. Accurate risk assessment during peak times is a pre-requisite for the public transport sectors to launch emergency response plans in a timely manner. To do so, some authors (Alawad et al., 2020; Romero et al., 2020; Ronchi & Lovreglio, 2020) have modeled occupant exposure in confined spaces by the simulation of people movement at a microscopic scale. Some others (Guan et al., 2020; Mo et al., 2020) have uncovered the effects on the epidemic spread of regional heterogeneity and inter-regional flows of people. Here, network models are found key mediate in the spreading of infectious diseases. For instance, Ceder and Jiang (2020) propose personalized route guidance apps that provide passengers a set of ordered *safe* paths considering their preferences for different public transport attributes.

4.2. Land transport — traffic demand

Protective behavior and working from home. It has been shown that human-mobility reduction has a significant impact on reducing COVID-19 infections and deaths (Cartenì et al., 2020; Hadjidemetriou et al., 2020; Wei et al., 2020). Therefore, chances of contracting or spreading the infection can be reduced if a person alters their travel-related behavior effectively when they perceive high risk of COVID-19 spread during their daily commuting time (Hotle et al., 2020; Zheng, 2020). This body of literature, based on survey evidence, have provided insight into the risk perception and mitigation behavior of commuters during the phase of the outbreak as well as after the quarantine was over (Fang et al., 2020; Hadjidemetriou et al., 2020; Kamenidou et al., 2020). Among the risk perception measures employed in these survey research we can find the degree of voluntary self-restriction (e.g., avoiding unnecessary travel, teleworking, etc.) (Parady et al., 2020), the risk mitigation decisions taken when (when not) infected (Hotle et al., 2020) or the use of a face mask when using public transport (Kamenidou et al., 2020). In addition, as more people work from home (also called telework, remote work or mobile work) either by choice or by compulsion, individual's activity-travel pattern have changed. The amount of time spent at home has increased, while that spent at workplaces and transit locations has fallen dramatically (Beck & Hensher, 2020). Some studies have shown great interest in documenting whether working from home has a complementary or substitution effect on people's travel demand (de Haas et al., 2020; Shamshiripour et al., 2020; Wang & Ozbilen, 2020). Many telecommuters work from home while others (sometimes called *nomadic workers*) travel to coffee shops, libraries, recreational or sports facilities to work from there. The idea of, if implemented appropriately, agreements applied to employee's telework can positively influence the process of moving away from automobile dependency to sustainable alternatives is an interesting direction of this emerging agenda (Beck & Hensher, 2020; Fatmi, 2020).

Spreading speed and traffic flow. Widely used in modeling virus transmission, Susceptible–Infectious–Recovered (SIR) models postulate that the spread of the contagion is a function of the contact rate between individuals. Under this approach, researchers (Fang et al., 2020; Li, 2020; Shen, 2020; Zheng, 2020) have developed multimodal traffic distribution models to estimate the spreading of virus. They predict the distribution of trips and the corresponding diseases supported on data from daily inter-city migration. These studies early demonstrated that human mobility restrictions delay the spread of COVID-19. Likewise, the mobility restrictions issued by local authorities since the outbreak have reduced traffic congestion. This phenomenon has been captured by traffic flow monitoring cameras, automated traffic counters and other fixed sensors installed along the road (Aloi et al., 2020; Harantová et al., 2020; Tanveer et al., 2020). In addition to traffic data, governments and researchers around the globe are rushing to unlock the potential of Big Data tools for enhancing performance, accuracy, granularity, and quality of smartphone-based mobility data (e.g., users connected to cellular networks) (Arimura et al., 2020; Monte, 2020), and data from social media sources (Chan, 2020). Similarly, the reduction of the number of vehicles in the traffic flow has been accompanied by changes in road safety and driving behavior. For instance, it has been documented an increase in vehicle speeds (Katrakazas et al., 2020) whilst at the same time, and perhaps more interestingly, a relative reduction in vehicle collisions and vehicle-related injuries (Katrakazas et al., 2020; Saladié et al., 2020; Sutherland et al., 2020).

Sustainability of urban mobility. This sub-theme is predominantly concerned with ramifications for sustainability transition research on electricity and mobility. It illustrates the short-term changes in the intentions to use ride-hailing services (Moslem et al., 2020); the characteristics of the demand of micromobility options, encompassing a range

Table 1
Emerging sub-themes detected by topic modeling analysis and indicative references.

Land Transport — Operations
Sub-theme 1. Technological tools and railway operations *Keywords: Safety Technologies; Technological Solutions; Self-service Technology; Network Capacity; High-speed Rail; Train Stations; Government Subsidy.* *Ref.*: Choi (2020), Cserdi and Kenesei (2020), Gaskin et al. (2020), Jiao et al. (2020);
Sub-theme 2. Control measures for urban traffic *Keywords: Travel Restrictions; Ridership Control; Pandemic Management; Contact Tracing; Policy Recommendation; Transport Infrastructure; Transport Accessibility.* *Ref.*: Heo et al. (2020), Lee and Lee (2020), Sharifi and Khavarian-Garmsir (2020); Allam and Jones (2020), De Vos (2020), Love et al. (2020), Mogaji (2020);
Sub-theme 3. Non-motorized mobility *Keywords: Bike Sharing Systems; Demand-responsive Transport System; Digital Mobility; Innovative Travel Modes; Mobile Crowdsensing; Safe Routes; Cycling.* *Ref.*: Barbarossa (2020), Bruzzone et al. (2020), Campisi et al. (2020), Teixeira and Lopes (2020);
Sub-theme 4. Public transit *Keywords: Public Transport Planning; Occupant Exposure; Indoor Exposure; Route Guidance; Risk Management; Traffic Scenarios; Complex Networks.* *Ref.*: Ceder and Jiang (2020), Mo et al. (2020), Romero et al. (2020), Ronchi and Lovreglio (2020);
Land Transport — Traffic Demand
Sub-theme 1. Protective behavior and working from home *Keywords: Short-distance Trips; Self-restriction; Psychological Risk; Intentions to Use; Health Protection Behavior; Telecommuting; Telework; Working From Home.* *Ref.*: Beck and Hensher (2020), Shamshiripour et al. (2020), Wang and Ozbilen (2020); Dong et al. (2020), Hensher et al. (2020), Hotle et al. (2020), Parady et al. (2020);
Sub-theme 2. Spreading speed and traffic flow *Keywords: Spread Pattern; Disease Transmission; Traffic Volume; Mobile Phone Data; Inter-city Travel; Population Flow; Congestion; Network Configuration.* *Ref.*: Arimura et al. (2020), Fang et al. (2020), Saladié et al. (2020), Shen (2020); Glaeser et al. (2020), Lawal and Nwegbu (2020), Parr et al. (2020), Xi et al. (2020);
Sub-theme 3. Sustainability of urban mobility *Keywords: Sustainable Mobility; Sustainability Transitions; Ride Sharing; E-scooters; Driving Behavior; Private Vehicles; Transportation expenses; Elderly.* *Ref.*: Button et al. (2020), Pantelaki et al. (2020), Schippl and Truffer (2020); Assoumou Ella (2020), Bucsky (2020), Cochran (2020), Scorrano and Danielis (2020);
Air Transport
Sub-theme 1. Aviation's recovery flight plan *Keywords: Airport Service; Forecast of Air Flow; Market Recovery; Operational Efficiency; Future Tourism Demand; Importation Risk; Exportation Risk; Complex Networks.* *Ref.*: Gallego and Font (2020), Gudmundsson et al. (2021), Hotle and Mumbower (2021); Czerny et al. (2021), Iacus et al. (2020), Nakamura and Managi (2020), Zhang et al. (2020);
Sub-theme 2. Passenger preferences and willingness to fly *Keywords: Outbreak Dynamics; Airline Protocol; Passenger's Behavioral Changes; Willingness to Fly; Risk Assessment; Passenger Health Filter.* *Ref.*: Graham et al. (2020), Gunay and Gokasar (2021), Pongpirul et al. (2020); Lamb et al. (2020), Oztig and Askin (2020), Tabares (2021);
Sub-theme 3. Safety and security in aviation *Keywords: Airline Strategy; Service Quality; Airplane Boarding; Airplane Seat Assignment; Carrier's Liability; Security Control; Passenger Flow Simulation.* *Ref.*: Dabachine et al. (2020), Milne et al. (2020a, 2020b), Salari et al. (2020); Di Mascio et al. (2020), Kierzkowski and Kisiel (2020), Naboush and Alnimer (2020);
Sub-theme 4. Airlines' strategic responses *Keywords: Cash Flow; Liquidity; Exogenous Shocks; Event Study; Non-market strategy; Government Support; Regulated/Unregulated Airports.* *Ref.*: Abate et al. (2020), Akbar and Kisilowski (2020), Albers and Rundshagen (2020); Budd et al. (2020), Gössling (2020), Sobieralski (2020), Suau-Sanchez et al. (2020);
Environment
Sub-theme 1. Changes in concentration of air pollutants *Keywords: Vehicle Fleet; Traffic emissions; Fine Particulate Matter; Air Quality Index; Pollution reduction; Nitrogen Dioxide (NO_2); Ozone (O_3); Monitoring Stations.* *Ref.*: Latif et al. (2020), Lian et al. (2020), Şahin et al. (2020), Wang et al. (2020); Kumar et al. (2020), Menut et al. (2020), Singh et al. (2020), Zhao et al. (2020);
Sub-theme 2. Air transport mobility and noise emissions *Keywords: Urban Noise Pollution; Noise Mapping; Sound Reduction; Airport Emissions; Black Carbon; Air traffic.* *Ref.*: Aletta et al. (2020), Basu et al. (2020), Nižetić (2020), Sobieralski and Hubbard (2020);
Sub-theme 3. Energy systems and renewable fuels *Keywords: Energy System Balancing; Electric Vehicles; Hybrid-Engine Vehicles; Fuel Consumption; Energy demand; Gasoline Passenger Cars.* *Ref.*: Chiaramonti and Maniatis (2020), Sui et al. (2020), Tian et al. (2020), Xian-Chun et al. (2020);

of lightweight vehicles such as e-scooters (Button et al., 2020; Scorrano & Danielis, 2020), e-bikes (Bucsky, 2020), mopeds, etc.; and resident's switch to active transport, especially walking and cycling (Nikiforiadis et al., 2020; Pantelaki et al., 2020). Some studies (Crotti et al., 2020; Giustino et al., 2020; Pantelaki et al., 2020) further recognize the burst of the pandemic opened a big challenge for public transport authorities

to handle active aging within the framework of social distancing. There is a need to implement age-friendly measures, taking into consideration the psycho-physical needs of the elderly. Some examples of these are low-floor buses, bus route numbers clearly displayed, priority siting, safety and comfort during peak times or affordable taxi services. Although most of the mobility changes resulted from obligatory government restrictions, there is an ongoing debate whether temporary transformations seen during the crisis will inspire more permanent structural behavioral changes (Haghani et al., 2020). Some authors suggest that the long-term sustainability implications of the pandemic may link to more permanent changes connected to the digitalization of work, reduced mobility needs (especially air travel), and overall fossil-energy consumption (Kanda & Kivimaa, 2020; Uğur & Akbıyık, 2020; Wang & Wells, 2020).

4.3. Air transport

Aviation's recovery flight plan. Concerned about the ability to withstand a prolonged downturn in demand, all air transportation actors have concerns about the duration of the crisis and recovery to past volumes. While the domestic market has enjoyed a quick recovery in countries like China (Czerny et al., 2021) or USA (Hotle & Mumbower, 2021), the recovery of international services has been much slower due the relative risk of the importation and exportation of the virus. Since there was no efficient treatment or vaccine during the first months of the pandemic, government's aviation policies included country-specific lockdown measures, strict requirements for health check and mandatory home quarantine (Arellana et al., 2020). These major contractions of activities at leading airlines and airports around the globe have dramatically raising the potential risk of bankruptcy for air transport-related businesses (Gudmundsson et al., 2021). Initial expectations from the United Nations World Tourism Organization (UNWTO) and the International Air Transport Association suggested that flight picks would follow a V shape. As the pandemic was still unfortunately under progression, UNWTO remained optimistic during the last quarter of 2020, suggesting a U shape recovery. However, optimism has dwindled as time passes, suggesting a flatline L shape in which air traffic never get back to the original volume (Gallego & Font, 2020; Iacus et al., 2020).

Passenger preferences and willingness to fly. There remains the open question of whether or not people will resume the use of air transport after the pandemic. Authors have conducted online questionnaire surveys of passengers to investigate the impact of the sanitary crisis on their perceptions of air travel. Interestingly, a large proportion of respondents may consider resuming overseas travel with air transport prior to the development of a cure or vaccine (Graham et al., 2020; Song & Choi, 2020). Policies on mandatory face-coverings for passengers and masks for crew members, cleaning and sanitizing procedures of aircraft, physical distancing measures (e.g., using floor markers, controlling flows, or avoiding crowding) could help work to alleviate fear and worry about resuming commercial flights and potentially increase willingness to fly (Lamb et al., 2020). However, surviving the crisis is not enough and some authors (Pongpirul et al., 2020; Tabares, 2021) have proposed commercial airline protocols to ensure pandemic-free air travel with the intention to prepare the aviation industry for similar future health crisis.

Safety and security in aviation. Research papers within this sub-theme focus on practices that are capable to reduce the risk of passengers becoming infected with the virus. Among the precautionary measures one can find physical separators between passengers and users, barriers between boarding gates, and signage indicating itineraries, so that departing and arriving passengers do not cross each other (Dabachine et al., 2020; Di Mascio et al., 2020). Other studies have compared different policies for passenger boarding in the context of ensuring social distancing such as boarding first passengers with seats in the rear rows of the airplane, boarding using groups of 10 passengers, boarding based on passengers' seat numbers, blocking the middle seats, passengers not bringing carry-on luggage into the airplane cabin and so forth (Milne et al., 2020a, 2020b; Salari et al., 2020). Simulation experiments and optimization of mixed integer problems are the common techniques for this aim.

Airline's strategic response. In addition to massive losses attributed to suspended operations due to the uneven lift of travel bans, the aviation industry foresees a grim recession ahead. The limited economic resilience exhibited by commercial aviation have lead several researchers to reconsider the foundations of the global aviation system. New approaches based on revenue generation sources (Vinod, 2020), cost control strategies (Gössling, 2020) and integration of innovations with respect to variable demand and capacity (Serrano & Kazda, 2020) are the starting point for a resilient aviation system. The radical policy measures introduced by governments to deal with the health crisis have led all airlines to take strategic actions in (i) finance (such as loan guarantees or tax relief); (ii) employment (unpaid leave programs, wage subsidies); (iii) airport usage charges (exempting parking fees, deferring airport ancillary services, reductions in land charge); and (iv) administration (re-routing, re-scheduling) (Albers & Rundshagen, 2020; Maneenop & Kotcharin, 2020). Particularly, employment reductions are the likely response international airlines have to face the adverse effects of the crisis on the travel industry (Sobieralski, 2020). Conversely, low-cost and regional business models afford these airlines the ability to weather this crisis without the large employment reductions seen by the major carriers.

4.4. Environment

Changes in concentration of air pollutants. The series of strict lockdown measures around the globe impacted with an expected reduction in air pollution. This is, a generalized drop of sources of particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2) ozone (O_3), sulfur dioxide (SO_2), and other pollutants (Kumar et al., 2020; Lian et al., 2020). To eliminate the weather impact, these studies compared air pollutant concentrations of 2020 with that during the previous years. Some of the gaseous pollutants, such as NO_2 and CO, have shown to be linked to the transport sector, resulting in the idea that air pollution could be substantially improved in urban areas with large transportation systems (Latif et al., 2020; Singh et al., 2020; Wang et al., 2020). Outcomes from this research have suggested transport policies to foster the adoption of public transport or active modes so that citizens might experience the possibility to accommodate all their mobility needs by using low-polluting fuels. Otherwise, this improvement on air quality, in particular in urban areas, will change and finish once the economy is reactivated (Gama et al., 2020).

Air transport mobility and noise emissions. Several authors have attempted to estimate the reduction of CO_2 footprint from aviation by using number of passengers, aircraft movements and indirect emissions released due to utilization of the different building facilities (Baldasano, 2020; Sobieralski & Hubbard, 2020). For instance, the estimations of Nižetić (2020) showed that carbon footprint emissions of European airports were reduced about a factor of 1.81–3.49, depending on the country. Moreover, in cities like Barcelona or Madrid, after road traffic, the airport is the second source of air pollutants. The radical actions taken by governments in countries with severe COVID-19 transmission such as China, USA, Italy or Spain have led to sharp reductions in carbon emissions, air pollution, sound pollution and pollution in beaches. The positive picture of the environment coming out of the pandemic, has been reflected towards the decrease of noise emissions along the entire road networks, creating a better living environment. Interestingly, the significant reduction in sound levels can be attributable to reductions in both road traffic and air traffic (Aletta et al., 2020; Basu et al., 2020)

Energy systems and renewable fuels. The transport sector is a major driver of climate change globally as it is responsible for about one-quarter of global greenhouse gas emissions. The double-shock of drop

Table 2
Indicative major issues revealed by the pandemic and major recommendations.

Land Transport — Operations
Technological tools and rail transportation
Physical distancing in mass transit operations is almost infeasible to implement in crowded cities • Technology-based self-service (e.g., interactive vending machines or mobile payment systems) facilitate contactless travel Urgent need to understand the robustness of railway network to predict and anticipate large-scale disruptions • Collection of near real-time reliable empirical data • Cascading effects can largely affect the functionality of railway transport
Control measures for urban traffic
Previous forms of long-distance hypermobility are incompatible with recent lockdown policies • Encourage modal shift towards more sustainable active modes of transport • Provide transit users with information about levels of congestion inside public transport platforms/vehicles • Use smart technologies to check body temperature of users • Staff behaviors should be properly regulated • Tracking the health and movements of travelers • Transition towards *Responsible Transport* (i.e., considering the impact your travel choices have on others) Debate surrounding the use of face masks • Without face protection, frequent cleaning, and ventilation, public transportation increase risk of viral transmission • Avoid talking without wearing masks and talking loudly
Non-motorized mobility
Conventional public transport is often unable to meet the newly impose regulations • Bike sharing systems have shown to be more resilient than the subway systems with less significant ridership drops • Promote greater connectivity among users, vehicles, and infrastructures through real-time smartphone apps Rethink urban spaces and mobility • Consider cycle paths, processes, and systems, taking into account the entire life cycle of the infrastructure • Adoption of pedestrian and traffic calming areas, sharing mobility programs and temporary tactical urbanism tools
Public transit
Challenges to manage passenger flows due to the complexity of station design and unexpected passenger behavior • Operators must monitor, scan, manage, investigate factors, and update plans based on the level of expected hazard • Simulation of people movement as a powerful microscopic crowd modeling tool • Evaluate epidemic control policies from both public health side (e.g., reducing infectious rate) and transportation side (e.g., distributing departure time, closing bus routes) Human factors within the public sector (e.g., unsafe acts or unsafe supervision) play a vital role in the control of the epidemic • Human factors are likely to result in imperfect management, and the possibility of a nationwide epidemic • Artificial Intelligence through automated processes can help to complement the mitigation efforts
Land Transport — Traffic Demand
Protective behavior and working from home
Rapid and drastic changes have become apparent in people's mobility-styles due to enacted regulations • Information disseminated through television lead to higher risk perception for discretionary trips • Trade-off between the severity of the threat and crippling socio-economic activities • Reduce parking fees to encourage car owners to travel by private cars • Issue bike-sharing coupons to encourage short-distance commuting crowds to ride bicycles To how and what extent various socio-economic segments of the population have adjusted to the mitigation measures • Working from home carries high potential for moving towards a more sustainable future • Investment in maintaining working from home can lead to large improvements in travel networks and overall cost savings • Flexible working arrangements are perhaps the biggest policy lever available to government
Spreading speed and travel behavior trends
Densely populated urban environments and the heavy dependence on traffic could increase the spread of the virus • Different opening hours to distribute the demand for public transport to avoid rush hours • Minimize the lag of orders and actions designed to increase social distance between urban and rural areas • Use of mobile data instead of census population data to assess the implicit risk of the locations • Document the impact on the most vulnerable segments, e.g., those unable to socially distance Inter-city migration as a main source of local transmission • Proper advice should be given to those people who are likely to travel • Mobility, could indicate how people perceive the risk they are exposed to and the level of risk they are willing to take • Quarantine, reportage of suspected cases and shutdown of transportation as main measures to generate infection scenarios • Cities should not only prevent the epidemic from the epicenter, but also protect against infection from other areas Reduction in traffic demand heavy depends on network configuration • Cities with high road network density and compact urban structure should decisively implement mobility restrictions measures • Networks with less connectivity and lower roadway density benefits more from the demand reduction

(*continued on next page*)

in demand for transportation fuel and lower oil prices while all major economies are in lockdown, presents a key opportunity to decarbonize transport. The year 2020 has seen significant progress towards vehicle electrification but the degree of difficulty in decarbonizing transport varies across the sector. On one side of the spectrum, electrification is relatively easily for smaller vehicles that travel shorter distances. On the other side of the spectrum, electrification of larger and heavier vehicles (which are the ones with fastest growing) could be incredibly costly and is at a much less mature state of development (Chiaramonti & Maniatis, 2020).

5. Concluding remarks and lessons for planners

5.1. Policy recommendations on sustainable and health cities

The role of cities' sustainable transportation systems and their design in the post-COVID 19 world has drawn much research attention.

Table 2 (*continued*).

Sustainability of urban mobility
Lockdown periods induced psychological and physical mobility problems but also reinvented the spatial structure of social ties • Mobility sharing will reduce while the acceptance of electric cars will increase • Gradually developing landscape influence on mobility transitions • Closely monitor and analyze the governance responses (e.g., serious threat of increasingly populist or undemocratic governance) A very rare chance for industry suppliers and policy makers to learn about the role e-scooters on urban transportation networks • Regulatory regimes to handle environmental (e.g., abandoned and damaged vehicles) and safety problems (accident numbers) • Limited the number of scooters per operator • Potential demand can increase due to fiscal incentives and to the battery cost reduction induced by technological change • Regarding the manufacturers it is of great importance to use materials on which the virus has been proven less durable Challenges associated with conventional travel to stop the rapid spread of the infection • Requalification of the road infrastructure and acquisition of electric micromobility • Design of road infrastructures and the enhancement of pedestrian and bicycle lanes • Promote integrated infrastructure design and control through intelligent transport system technologies • As society is aging, shifts in the transport systems for comprehensive health promotion has become of primary importance • Take into consideration the needs of the elderly, as one of the most fragile and vulnerable social groups
Air Transport
Aviation's recovery flight plan
U/L-shaped recovery depending on duration and magnitude of the outbreak • Create safe *travel bubbles* to suit the specific circumstances of the bilateral country pair or regional grouping • Focus on the prevention of the infection at airports and on-board aircraft • Destination management organizations to improve their Big Data analytical and evidence-based, decision-making skills • Airlines to negotiate with authorities to survive the demand shortage • Restart flights too soon and too fast will result in more infections and may cause even further reduction in travel demand Imported cases is critical for containment • Develop risk indexes to accurately measure the imported case risk from different foreign countries and even specific routes • Transport flights to be categorized into high-risk flights, medium-risk flights, and low-risk flights • Local governments should provide clear instructions and countermeasures • Reduce the air transport frequency without canceling all the flights • Cut air services first while keeping most of the rail services
Passenger preferences and willingness to fly
Airport screening measures failed in halting the spread of the virus at the very early stage of the epidemic • If new confirmed cases remain stable, easing the requirements for self-isolation could increase travel demand • Contactless self-service as a means to feel safe during the passenger journey • Elderly passenger preferences for private transport to travel to and from the airport • Airlines to develop a comprehensive strategy to protect their passengers and then to explain why these steps will be effective • A clear protocol needs to be established in order to know what to do with a passenger with a positive test result (true or false) Significant differences between domestic and international travel markets • Increase airport shuttle and public transit frequencies right before the peak hours of international flights • The reliability of mass transport modes can be marketed to passengers to increase their uses • Health screening measures to be first implement within (domestic) airports, afterwards, generalization for intercontinental traffic
Safety and security in aviation
Landside capacity is crucial in the event of a health crisis • Evaluate the level of service of functional subsystems (departure/arrival halls, check-in, boarding gates, baggage claim, etc.) • Constantly supervise the movement of the passengers in security control lanes, and give them tips for keeping a distance • Develop integrated management system to meet service quality requirements (avoiding bottlenecks and long waiting times, while ensuring that sanitary measures) Social distancing norms reduce airplane capacity • Encourage passengers to carry fewer luggage aboard the airplane • Middle-seat blocking policy • Evaluate different boarding methods in terms of boarding time and health-related metrics
Airlines' strategic responses
Restrictive movements, weak tourism, and curtailed income compressed passenger demand • Focus on minimizing losses rather than profit maximization • Provide access to markets at a deeper discount for pre-purchase via corporate fares • Fleet downsizing variations and accompanying layoffs • Temporary deficits and deferred cost recovery The crisis would lead to consolidation and a significantly smaller industry • Mergers and acquisitions, tax policy, and government subsidies The need for support and the actual support to airlines provided by governments vary significantly in each country • Differentiated state aid, whether to provide financial support, guarantee existing debt, or to believe in market mechanisms • Public non-regulated airports to keep charges low during the crisis to rise after • Reorientation of public policy in the post-pandemic may limit the importance of the policy priorities (e.g., climate change)

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Our findings in Fig. 4 could help understating how this new body of knowledge has been assimilated. This is, city planners have rapidly reimagining the future of urban spaces by aspiring to create greener spaces, improve connectivity, reduce congestion and focus on adaptive traffic systems. The pandemic has also brought renewed attention to city planning and land-use management. Its impact is showing the extent to which each city can function or not during times of crisis (Megahed & Ghoneim, 2020). Some authors (Hamidi et al., 2020; Sharifi & Khavarian-Garmsir, 2020) embrace the idea that cities will be redesigned by COVID-19 and the policies put in place now are expected to become the new normal in the post-pandemic. For instance, several cities and transport authorities have already started designating *slow streets* to provide more outdoor space for communities, creating bike

Table 2 (*continued*).

Environment
Changes in concentration of air pollutants
Global action to mitigate the pandemic has consequently involved switching off most pollutant emission sources • Differentiation between local pollutant emissions and regional pollutant transport • To enhance regional environmental cooperation and to implement a united prevention and control of air pollution • Encourage people to use public transport, sharing cars and workers to work from home Depending on the city, traffic-free conditions could not cause substantial reductions in pollution levels • Prioritize reductions in air pollution based on what air quality standards might be feasible • Investigate generation mechanisms of secondary pollutants • Car-free days or odd–even number-plate schemes are effective policies to reduce NOx and NO_2
Air transport mobility and noise emissions
Aviation is one the most carbon-intensive forms of transport and one of the most difficult to decarbonize • Development of alternative aircraft fuels, introduction of hybrid-electric, or fully electrified propulsions of aircrafts • Evaluate the efficacy and net societal benefits of policy changes related to jet fuel taxation The traffic reduction has also had consequences for noise • Significant reduction in sound levels can be achieved through aggressive traffic reduction strategies • Promote walking and cycling to improve overall sustainability of the transport infrastructure • Ordinances of traffic limitation should be accompanied by appropriate interventions to reduce speed limits
Energy systems and renewable fuels
Decarbonization of transport and economic recovery do not compete, but rather represent a win-win solution • Promote and implement well-designed and reliable sustainable low-carbon fuel refineries • Increase the ambition and promote higher amounts of domestic renewable and low carbon fuels Little understanding about temporal and spatial variation transportation emissions • If transit ridership is largely reduced, public transport can perform worst than cars on a person emissions basis • Transparency of the potential individual and societal benefits of congestion pricing plans

lanes to lighten the pressure of car mobility, taking measures to protect public transport staff from interactions with passengers, etc.

After a review of the studies within each sub-theme, Table 2 provides some major issues revealed by the pandemic as well as major recommendations into how cities can handle the present and any future similar events. Some promising evidence is emerging as how to make sustainable transportation systems safe or at least reduce considerably transmission rates, with implications particularly for the post-pandemic city. Although public transport operators and vehicle manufacturers are doing efforts to design safe buses and trains (e.g., reconfiguring internal layout of seats and circulation spaces, and installing contactless door sensors, hand sanitizer dispensers, etc.) their efficacy and levels of public acceptance are still uncertain. Policies for a sustained economic recovery may require more than short-term fiscal stimulus. For instance, transitioning from vehicles running on fossil-fuel to vehicles powered on alternative fuels such as electricity, hydrogen or biofuels will require long-term commitments (5–10 years) of public spending and pricing reform (Hepburn et al., 2020). With respect to the aviation industry, the sector is one of the worst affected economic sectors by COVID-19. Regardless of the sector's key role in facilitating human mobility and importance to the tourism economy, our literature review shows that as the pandemic continues to send economic shockwaves, the aviation sector will remain extremely fragile and sensitive. Most governments tried to intervene to ensure that the aviation industry did not collapse as it not only has a central role in ensuring the supply of pharmaceutical products needed to deal with the outbreaks but also has equally important role in the global and tourism revival project under the *new normal* with the virus. From the airline side, some of the options airlines have are reducing staff numbers, rescheduling debts, repurposing passenger plants into cargo aircraft or renegotiating fees with airports.

5.2. Conclusions

This paper combines methods of systematic literature review with those of content analysis to offer a comprehensive review of English-language articles on human mobility during COVID-19. Our search strategy revealed that in 2020, 194 articles were published in high-quality journals indexed in the Web of Science and Scopus databases. The first set of findings in Fig. 4 show substantial research activity that has already begun extensively during the early stage of the outbreak. We see notable progress towards understanding the dynamic of traffic emissions during strict lockdown measures as well as studies tracking the severe knock-on effect from the collapse of the global aviation industry. This can be appreciated from the large proportion of air transport-related articles published in May, 2020 as depicted in Fig. 5(b). Fig. 4 also shows new research areas that are immature in comparison to other clusters, such as changes in travel behavior.

With respect to our first research question regarding relevant topics, the comprehensiveness of the systematic literature review combined with the in-depth perspective of the content facilitated the identification of four themes and their corresponding sub-themes. These four dominant themes are: "Land Transport — Operations", "Land Transport — Traffic Demand", "Air Transport" and "Environment". The evidence maps, Fig. 5(a), reveal that data-driven tools of Statistical, Machine Learning and Artificial Intelligence have been of paramount importance. However, there is an urgent need for empirical studies that document human mobility changes in Africa, Oceania or South America (Fig. 3(b) and Fig. 5(a)). The existing literature has emphasized on multimodal transportation and it is skewed towards the understanding of Traffic Demand on the other. This reflects the increasing interest of researchers in understanding the impacts of the sanitary crisis on the use of all modes of transportation, ranging from traditional transport systems to innovative shared modes.

Given the explosive growth in scientific literature, we propose a topic modeling framework for effective identification of sub-themes in large collections of articles. Our procedure is based on text mining and Latent Dirichlet Allocation method. It is highly efficient for dealing with high-volume (text mining on hundreds or thousands of published articles) high-dimensional (all aspects of human mobility) data as it can capture effectively text-specific dimensions, does not make any assumptions and incorporates several steps of the text analysis with little human intervention (Fig. 1), resulting in more realistic and objective research topics. Table 1 may reflect rapidly emerging sub-areas related to COVID-19 and human mobility behavior. Our findings offer some initial insights that outline new viewpoints and shape of future directions for research in the area. In response to our second research question "Is there any identifiable response from transportation researchers to COVID-19 emergency?", Table 2 addresses each sub-theme in terms of major issues revealed by the pandemic and major recommendations. The table has the potential to improve future transport policies. For

example, it seems that one of the major lessons offered by COVID-19 is that multimodal transportation is a superior vision for sustainable cities than any one particular mode. Similarly, telecommuting is part of an effective infrastructure sustainable strategy. We recommend to repeat our study once every year to illustrate to what extent sustainable transportation systems have been discussed as a reason for spreading outbreaks around the globe but importantly also to track the adjustments cities have made in allocation of street space and other transport resources in response to changing mobility demands. By updating our study on yearly basis, we can detect possible temporal shifts in research patterns among sub-themes. Future reviews that include gray literature such as book chapters, institutional reports, conference papers, workshop proceedings or open access repositories (arXiv or medRxiv) would enrich our knowledge of human mobility. In this context, developing a transportation research agenda could be one small contribution that enables policymakers to identify best practices for transport planning that create more sustainable and resilient mobility systems. Clearly, there are many open questions and challenges to be addressed but we hope that our work will act as a stimulus for further discussion and debate.

Declaration of competing interest

The author declares that there are no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A.1. Cleaning of keywords

On the one hand, the standardization process consisted in (i) the conversion of plural forms into a singular form, e.g., “Algorithms” and “Algorithm” were summarized under “Algorithm”; (ii) the unification of synonyms, e.g., “Travel-time” and “Time-estimation” were summarized under “Travel-time”; (iii) the elimination of spelling differences, e.g., “Modelling” and “Modeling” were summarized under “Modeling”; and (iv) the unification of acronym variants, e.g., “Nitrogen Dioxide” was summarized under “NO_2”. On the other hand, the cleaning process consisted in (i) grouping of similar keywords, e.g., “Transmission” and “Disease transmission” were summarized under “Transmission”; (ii) removing generic keywords such as “Analysis” or “Analytical methods”; and (iii) lowercase conversion.

A.2. Topic modeling framework for sub-themes identification

The step of basic cleaning consisted in converting terms to lowercase, removing stop terms (e.g., “the”, “from”, “as”, ...), removing terms starting with non-alphabetic characters (e.g., “50 countries”), removing common terms in scientific articles (e.g., “introduction”), removing special characters, and stemming (i.e., reducing terms to their root form). The step of knowledge-based consolidation consisted in consolidating terms with the same steam (e.g., conversion of plural form into a singular form) whereas the rule-based cleaning removed terms appearing in only one article.

Next, LDA-based topic models require the tuning of the following parameters: (i) hyper-parameters, α and β, to control the amount of smoothing applied to the sub-themes distributions for each article and the term distributions for each sub-theme, respectively; (ii) burn-in time; (iii) number of iterations of Gibbs sampling (e.g., Markov chain-type sampling); (iv) seed values (to avoid variation in the sub-themes among runs induced by a initial *random* seed), and; (v) number of sub-themes. We have set $(\alpha, \beta) = (0.5, 0.01)$, 4000 burns iterations, 2000 Gibbs iterations and specific seed for replicability purposes. These values are akin to the ones used by Zhang et al. (2017) for generating the original topic model. Lastly, a cross-validation is run on the following number of sub-themes: 2,3,4,5,6 and 7. To select the optimal number of sub-themes within each theme, perplexity score and coherence are computed. Perplexity is the reciprocal geometric mean of the likelihood of the testing set, and lower perplexity score indicates lower misrepresentation of the terms in the collection of documents. Coherence analyze terms in each sub-theme to ensure they would make sense together from a human-like perspective, therefore, higher coherence is preferred (Mimno et al., 2011). Both metrics were calculated over five folds, where each fold would identify 75% of the papers for training the model and leave out 25% of the articles for testing purposes, hence, reducing variability, ensuring higher reliability and reducing overfitting.

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