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DOI
10.1080/01441647.2020.1857886

Publication date
2020

Document Version
Final published version

Published in
Transport Reviews

Transport Reviews

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ttrv20

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To cite this article: Konstantinos Gkiotsalitis & Oded Cats (2021) Public transport planning adaption under the COVID-19 pandemic crisis: literature review of research needs and directions, Transport Reviews, 41:3, 374-392, DOI: 10.1080/01441647.2020.1857886

To link to this article: https://doi.org/10.1080/01441647.2020.1857886

Published online: 09 Dec 2020.

TRANSPORT REVIEWS
2021, VOL. 41, NO. 3, 374–392
https://doi.org/10.1080/01441647.2020.1857886

Public transport planning adaption under the COVID-19 pandemic crisis: literature review of research needs and directions

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ABSTRACT

The COVID-19 pandemic crisis has greatly impacted public transport ridership and service provision across the world. As many countries start to navigate their return to normality, new public transport planning requirements are devised. These measures imply a major reduction in service capacity compared to the pre-COVID-19 era. At the time of writing, there is a severe lack of knowledge regarding the potential impact of the pandemic on public transport operations and models that can support the service planning given these new challenges. In this literature review, we systematically review and synthesise the literature on the impacts of COVID on public transport to identify the need to adjust planning measures, and, on the other hand, the existing methods for public transport planning at the strategic, tactical and operational level. We identify intervention measures that can support public transport service providers in planning their services in the post-shutdown phase and their respective modelling development requirements. This can support the transition from the initial ad-hoc planning practices to a more evidence-based decision making.

ARTICLE HISTORY
Received 6 June 2020
Accepted 25 November 2020

KEYWORDS
COVID-19; social distancing; ridership; public transport planning; capacity management

1. Introduction

COVID-19 belongs to the category of coronaviruses, which are highly contagious respiratory pathogens. The first cases were reported in December 2019 (Du Toit, 2020). The World Health Organization (WHO) recognised COVID-19 as a pandemic on 11 March 2020 resulting in many governments implementing social distancing policies or targeted lockdowns (Xu & Li, 2020).

Following the increase in the number of cases, one country after the other implemented so-called social distancing measures affecting schools, shops, working places, public transport, and many more sectors (Anderson, Heesterbeek, Klinkenberg, & Hollingsworth, 2020; Lewnard & Lo, 2020). This has majorly affected the operations of

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public transport services by affecting ridership due to a dramatic decrease in travel demand levels as well as imposing regulations that have consequences for service capacity. The international association of public transport (UITP) considers the maintenance of high levels of service despite the reduction in travel demand to ensure safe distancing, in particular for high-risk user groups, as one of the main challenges associated with resuming public transport operations (UITP, 2020a).

This paper reviews and synthesises the public transport planning literature from the perspective of the changes in demand patterns and limited capacity requirements associated with the COVID-19 pandemic crisis. We identify studies devoted to public transport planning models that can be potentially adopted and adapted to account for these challenges. The review reflects on the potential and suitability of different planning techniques to be used for accommodating the changing demand and supply conditions. In addition, it offers a research agenda to address the remaining gaps. In this review we seek to answer the following questions:

- what are the consequences of the pandemic crisis and, in particular, the related social distancing regulations for public transport planning and modelling?
- what are the main public transport planning methods at the strategic, tactical and operational level and which of them can, or have already, been adapted to account for distancing regulations?
- what are the pressing remaining research gaps that should be addressed in future research and related research directions?

To this end, we conducted a systematic review of the rapidly emerging literature related to the challenges associated with the pandemic crisis and related public health regulations that are relevant for public transport planning. We would like to stress that, at the moment, there is only a limited number of papers on public transport planning in the context of COVID. Because of this, this review synthesises, on one hand, the literature on the impacts of COVID on public transport to identify the need to adjust planning measures, and, on the other hand, the existing methods for public transport planning at the strategic, tactical and operational level. The former allows identifying the relevant problems, whereas we review the latter to identify potential solutions that can be adopted and adapted. This allows us to propose a research agenda to address the remaining gaps.

Our search strategy was based on applying the combination of on one hand keywords related to public transport in its various forms and modes and on the other hand keywords pertaining to the COVID-19 pandemic crisis. Our search was primarily based on entrees in Scopus and Google Scholar. We then selected papers that specifically address topics pertaining to either the impacts of the COVID-19 on passenger demand or the consequences thereof for public transport service planning. In addition, we searched for publications on strategic, tactical and operational public transport planning. Given the vast literature on the topic, we focused on studies that focus on service capacity aspects. Note that our goal here is not to provide an exhaustive review of public transport planning methods as such, for which we refer the interested reader to the extensive review papers by Ibarra-Rojas, Delgado, Giesen, and Muñoz (2015) and Iliopoulou, Kepaptsoglou, and Vlahogianni (2019) which have also been instrumental in identifying relevant studies to be included in this review. Our goal is rather to synthesise public transport planning studies that can consider service capacity and can be potentially adapted to the new realities of the pandemic.

The remainder of this paper is structured as follows. In section 2, we provide an overview of the impact of early lockdowns and social distancing regulations on public transport ridership and operations. We also discuss recent studies related to safe distancing policies to limit the spread of the virus which pose challenges relevant for service planning. In section 3, we review and synthesise works on strategic, tactical, and operational planning that can, or have already, been applied to plan public transport services while considering physical distancing. Finally, in section 4 we draw conclusions and provide future research directions aimed at developing public transport planning models that address the changing realities and challenges imposed by the pandemic crisis.

2. Impact of COVID-19 on passenger demand and preventive measures in public transport services

2.1. Impact on passenger demand and ridership levels

The impact of COVID-19 on public transport varies depending on the stage of the coronavirus spread in the area of study. Public transport is one of the most disrupted sectors of the COVID-19 pandemic with early estimates suggesting that the drop in ridership during lockdown periods has been as much as 80%–90% in major cities in China, Iran and the United States, and as much as 70% for some operators in the United Kingdom (UITP, 2020b). Ridership reductions vary from 60% and 67% in Philadelphia and Detroit, respectively (Hughes, 2020), 80% for Singapore mass rapid transit (Chong, 2020) and between 85% and 95% for Toronto (Jeffords, 2020), New York City subway (Teixeira & Lopes, 2020), Budapest (Bucsky, 2020), the Netherlands (de Haas, Faber, & Hamersma, 2020), Lyon and Nice (Chivers, 2020), San Francisco and Washington DC (Hughes, 2020). These figures are the result of changes in public behaviour following government guidelines, with demand reduced to essential travel only. Shifts in work practices, including home office, have also contributed to the reduction of ridership levels and have impacted all forms of travel (Gray, 2020; Nicola et al., 2020).

While concerns about using public transport have partially been alleviated since the initial restrictions, passengers remain reluctant and there are higher levels of concern about public transport hygiene than pre-COVID (Beck & Hensher, 2020). Risk perceptions may thus not only impact immediate travel decisions and trade-offs made between time and crowding (Shelat, Cats, & van Cranenburgh, 2020), but may also have major implications for the ridership levels of public transport in the post-lockdown period and possibly even at the aftermath of the pandemic. There is therefore a great level of uncertainty in relation to demand forecasting during the different phases of this unprecedented crisis.

To reduce operational costs in the face of limited travel demand, some public transport service providers halted their services altogether (e.g. in Wuhan, China – Jiang et al. (2020) and India – Gettleman and Schultz (2020)), or permitted the use of public transport for essential travel only (e.g. California and several other states in the US, Asia and Europe) (Rodríguez-Morales, MacGregor, Kanagarajah, Patel, & Schlagenhauf, 2020). Notably, even in cases where public transport services operate as usual, passengers are reluctant to use them out of fear for contamination (Qiu et al., 2020). The extent to which commuting patterns change depends not only on prevailing perceptions of personal safety but also on travellers' access to alternative means of transport as was found in the context of the transition to a nationwide lockdown in India (Pawar, Yadav, Akolekar, & Velaga, 2020).

In the face of a dramatic reduction in ridership, governmental regulations and public health fears, public transport service providers worldwide have resorted to limiting their service span, cancelling certain services, and closing selected stations to adapt their operations. Namely, Transport for London (TfL) has suspended the night tube service and closed 40 metro stations that do not interchange with other lines (TfL, 2020). Similarly, the Washington Metropolitan Area Transit Authority (WMATA) closed 19 metro stations (out of 91), reduced its service frequencies from 10 trains per hour to 3–4 trains per hour during peak hours, and limited the operations of the daily metro services until 9 pm (WMATA, 2020). In Italian cities, such as Rome and Naples, services are running with reduced frequencies and early closures at 9 and 8 pm, respectively. Valencia in Spain has also seen service reductions of up to 35% (UITP, 2020b). In contrast, other transit operators, such as Hong-Kong MRT, maintained the service frequency levels even when the daily patronage was significantly reduced (UITP, 2020a).

2.2. Risk of virus transmission and related preventive measures

As part of their exit strategies, governments provide guidelines for using public transport services. These guidelines consist of more frequent and rigid cleaning of vehicles and surfaces, temperature checks for staff and in some places also for passengers and improving the ventilation of facilities and vehicles. Tirachini and Cats (2020) discuss the emergence of physical distancing, the debate surrounding the use of face masks, and what seems as a consensus concerning the importance of hygiene, sanitisation, and ventilation. Shen et al. (2020a) provide an overview of measures for managing public transport in the context of COVID ranging from staff management and materials disinfection to information campaigns.

There is only scarce, albeit rapidly growing, evidence insofar concerning virus transmissions in public transport. Troko et al. (2011) reported a statistically significant association between acute respiratory infection and bus or tram use in the five days leading to symptom onset for acute respiratory infections such as COVID. Zheng, Xu, Wang, Ning, and Bi (2020) concluded that public transport played an important role in the spread of COVID-19 from Wuhan to other cities in China. This conclusion was, however, solely based on correlations between COVID cases and service frequency between city pairs, while no causation can be implied. Presumably, this relationship stems from the same cause, namely, demand flows between the respective cities. Yang et al. (2020) reported COVID-19 infection of a coach bus passenger at a 4.5-meter distance. Similarly, Shen et al. (2020b) reported an increased risk of infection for passengers riding a bus with air recirculation. Hernandez (2020) reported that the distribution of infected people in a bus in Ningbo, China did not follow a clear pattern, as passengers travelling both close and far from the infected passenger got the virus. Severo, Ribeiro, Lucas, Leao, and Barros (2020) found no consistent association between proximity to urban rail station and infection rates based on an analysis at small spatial units in Lisbon, Portugal.

Musselwhite, Avineri, and Susilo (2020) highlight the importance of internal cleaning and sanitation of public transportation vehicles in light of medical research on viruses remaining on surfaces and the transmission of microorganisms. Improved ventilation is especially important given the increasing evidence that the virus can also be spread through airborne transmissions, albeit evidence suggests that most spreading occurred through close contact and those airborne transmissions are limited to special circumstances such as a prolonged exposure in enclosed spaces with inadequate ventilation (Morawska & Milton, 2020). In some contexts, especially where paratransit is prevalent, partial compliance to the policy of using face masks in public transport may hinder the mitigation of virus spreading in public transport (Dzisi & Dei, 2020). Zheng et al. (2020) highlight the importance of improved ventilation in reducing the risk of virus spreading in public transport. Similarly, Vuorinen et al. (2020) emphasise the importance of minimising crowding, improved ventilation conditions, physical proximity, as well as time spent indoor in places where a high level of aerosol production is anticipated. Di Carlo et al. (2020) concluded from an empirical analysis of surface and air samples for a trolley bus in Italy that the measures taken in terms of sanitation, ventilation and interpersonal precautions are effective.

Based on the synthesis of evidence so far, Jones et al. (2020) summarised how the combination of environmental factors such as the settings (outdoors and well ventilated, indoors and well ventilated, or poorly ventilated), the level of group activity (the occupancy level, contact time and whether one remains silent) and whether face covering is applied, jointly determine the level of risk transmission. Even under high occupancy, transmission rates remain low as long as the environment is well ventilated, people wear face coverings and remain silent when contact time is short. For a prolonged contact time, the transmission rates increase to medium. Countries differ however greatly in their position in relation to wearing facemasks – ranging from wearing them at all times outside of one’s house, when staying indoors outside of one’s house, only on-board public transport vehicles or limited to healthcare facilities. In addition, some countries make the wearing of facemasks under different circumstances obligatory and support it with enforcement while others offer it as advice.

In conjunction with movement restrictions imposed by governments worldwide, public transport service providers have reduced their offered capacity. Islam et al. (2020) performed an intriguing time series analysis of COVID-19 cases based on data from 149 countries of regions between 1 January and 30 May 2020, considering the physical distancing interventions as a natural experiment. They found no evidence that public transport closure had a reducing effect on the number of cases once controlling for other interventions (i.e. closures of schools and workplaces, restrictions on large and public events and lockdown restrictions).

Governments worldwide instruct the public to maintain a minimum distance to reduce the chance of virus transmissions. These measures are arguably the most consequential for mass transit operations amongst all the measures introduced. The recommended distance to ensure public safety is a hotly contested topic and different governments and health organisations provide different distancing recommendations. The World Health Organization and most countries recommend a 1.5- to 2-meter social distancing. However, in a comprehensive literature review, Bahl et al. (2020) reported that the 1-

to 2-meter limit is based on very limited epidemiologic and simulated studies of some selected infections.

While the empirical evidence concerning the importance of physical distancing in reducing the risk of contagion when people wear face masks is still inconclusive and contested (Greenhalgh, Schmid, Czypionka, Bassler, & Gruer, 2020; Javid, Weekes, & Matheson, 2020), public transport service providers in many countries have to transform their services to adhere to physical distancing measures. It is against this reality that service providers around the world are currently implementing measures that result in significant reductions in service capacity. Many public transport service providers have resumed or will resume services following the national regulations of 1–2-meter physical distancing and this will imply a major capacity drop of 60%–90%. There is, therefore, an urgent need to develop and deploy methods and tools that support planners in maintaining the critical functionality of public transport systems while minimising the public health risks associated with mass transportation and managing crowds.

In some cases, service providers have established reduced capacity limits to ensure that distancing regulations are not violated, but so far this has been implemented in an ad-hoc manner. In Denver, the Regional Transportation District limited ridership to 15 passengers per city bus and 30 per rail car (Hughes, 2020). In the UK, public transport services will be restored while accounting for a 2-meter distancing (Guardian, 2020). This will mean that only 10% of the usual number of passengers will be able to travel. Even though there is evidence that COVID-19 might spread beyond the 2-meter limit, most governments and health organisations consider the 1.5-meter to 2-meter physical distancing to be safe enough. This is presumably the outcome of a trade-off between allowing society to function while minimising the risk for transmission. What is generally unanimously accepted though, is that an increase in transmission risk is not proportionally linked to the reduction in the corresponding physical distance. In fact, the risk might increase exponentially for distances below 1 m and physical distancing policies of 1, 1.5, or 2 m try to ensure a low transmission risk (Jarvis et al., 2020).

While there is a significant reduction in public transport ridership when COVID-19 and related lockdown measures are at their peak, when ridership increases in the post-lockdown phase, it became difficult to maintain sufficient levels of physical distancing among travellers. A recent study by Krishnakumari and Cats (2020) about the Washington DC metro system showed that if passengers are evenly spaced across platforms, each train operating can carry only 18% of its total capacity when implementing a 1.5-meter distancing and 10% when implementing a 2-meter distancing. Gkiotsalitis and Cats (2020) showed that the average train occupancy in the Washington metro can be reduced to 11.6%, 8.7% and 6.5% when implementing 1-meter, 1.5-meter, and 2-meter social distancing policies, respectively. They also showed that 23% of the total number of passenger-trips can remain unsatisfied during the peak hour when implementing 1.5-meter distancing and 43% when implementing 2-meter distancing.

The dramatic changes in ridership levels and patterns, as well as the introduction of measures aimed at preventing the virus spread, poses unprecedented challenges to the public transport sector. Moreover, these changes are subject to great uncertainty and the dynamics of the pandemic often do not follow a consistent recovery path. Public transport service providers had to rely on limited knowledge and ad-hoc procedures to cope with these rapid and dramatic changes. In the following, we review the public transport literature to identify how planning methods can be adopted and adapted to address these new challenges.

3. Public transport planning considering social distancing

3.1. Strategic planning

Public transport planning at the strategic level refers to the design of the public transport network which comprises of the determination of public transport stations and the development of the public transport routes (Bagloee & Ceder, 2011; Shrivastava & O'Mahony, 2009; Yu, Yang, Jin, Wu, & Yao, 2012). Network designs can account for mild passenger demand variations if they have been designed in a robust way (Cats, 2016; Jenelius & Cats, 2015), but the one-in-a-century demand variations due to COVID-19 require further adjustments.

Despite the need for public transport network adjustments, long-term decisions, such as the locations of stations or the roads/tracks that a bus/train line should follow, cannot be easily adapted to the needs of the pandemic. Because public transport service providers are confined by the limitations of the already developed network, their strategic measures are limited. Notwithstanding that, as mentioned above, several operators have either completely suspended or altered certain line services by selecting which stations to close based on the passenger demand (UITP, 2020b).

Although the station closure decisions are made based on the local expertise of transit operators, there is a broad literature on deciding which stations to skip for improving the efficiency of a service based on the prevailing demand patterns. Such literature does not consider the effect of social distancing, but there are several works that propose which stations should be skipped for a given demand pattern (Liu, Yan, Qu, & Zhang, 2013; Wang, De Schutter, van den Boom, Ning, & Tang, 2014). Stop-skipping has been consistently used at the real-time operational level to decide which stops should be skipped by a given bus or train trip while considering the adverse consequences for those using these stops (Altazin, Dauzère-Pérès, Ramond, & Tréfond, 2017; Fu, Liu, & Calamai, 2003; Muñoz et al., 2013; Sun & Hickman, 2005; Wang et al., 2014; Wang, Ning, Tang, Van Den Boom, & De Schutter, 2015). At the "offline" strategic level, public transport service providers are willing to identify which stops should be completely suspended to reduce the operational costs or the transmission risks. To produce a strategic schedule of skipped stops for all daily trips, methods for determining stop-skipping strategies consider a broad range of key performance indicators. These key performance indicators should not include only the passengers' waiting and in-vehicle times (passenger-related costs), and vehicle travel times (operational costs). They should also include equity considerations related to vulnerable groups. In addition, key workers should be taken into consideration when making stop-skipping decisions. A summary of such strategic stop-skipping models that can be used for an educated decision regarding which stations should be suspended due to COVID-19 is presented in Table 1.

We should finally note that the strategic stop-skipping models presented in Table 1 cannot be used as-is for determining the stations that need to be closed. They require the following major amendments:

Table 1. Key performance indicators considered by stop-skipping models that can be applied at a strategic level.

Study	Key performance indicators	Model formulation	Solution Method
Jamili and Aghaee (2015)	Vehicle travel times	Integer non-linear	Decomposition and simulated annealing
Gkiotsalitis (2019)	Passenger waiting and in-vehicle times and vehicle travel times	Integer linear programme	Genetic algorithm
Chen, Liu, Zhu, and Wang (2015)	Passenger waiting and in-vehicle times and vehicle travel times	Integer non-linear programme	Artificial bee colony
Wu, Liu, Jin, and Ma (2019)	Passenger waiting times and vehicle travel times	Integer non-linear	Response surface methodology

- First, the objective functions of the aforementioned models should be amended to include more key performance indicators related to the implications of COVID-19. Such key performance indicators are, for example, the transmission probability due to insufficient distancing;
- Second, the considered capacities of vehicles should be amended to comply with the national social distancing regulations;
- Finally, constraints may be added to ensure that the selected skipped stops are skipped throughout the day rather than setting those per trip, i.e. to allow for a temporary closure of the respective stations.

3.2. Tactical planning

3.2.1. Service frequencies

Service providers have significantly more degrees of freedom at the tactical planning stage. This includes the reduction of service frequencies, the change of timetables and vehicle schedules, and the reduction of the total duration of the daily operations. All of these measures translate into the dimensioning of service capacity. Several train and bus operators have reduced their service frequencies to less than one-third of the pre-pandemic frequencies (Tan, 2020; WMATA, 2020). Nonetheless, such decisions are seldom made based on a system-wide analysis and public transport service providers have an urgent need for methods that can support their decision making on how to utilise their available resources in the most efficient manner.

There are several models that try to determine the optimal service frequency as a trade-off between the generalised passenger costs (e.g. waiting times) and the operational costs (e.g. number of deployed vehicles and total km-travelled). Earlier works were limited to determining the frequency of a single line at a time (Ceder, 1984, 2002; Furth & Wilson, 1981). Given the reduced complexity of this problem, (Ceder, 1984) proposed closed-form expressions that do not require solving complex mathematical programmes (namely, the maximum load and the load profile methods).

In the last decade, a series of models have been proposed for setting service frequencies network-wide by determining the optimal resource allocation subject to limited resources. Yu, Yang, and Yao (2009) proposed a bi-level programming model for the frequency setting problem which determines the optimal frequencies by minimising the total travel time of passengers subject to overall fleet size limitations. Cipriani, Gori, and Petrelli (2012) also addressed the frequency setting problem as an exercise of balancing the passenger demand with the available supply. The optimal frequency setting and allocation of a mixed-fleet were considered by Cats and Glück (2019) and dell'Olio, Ibeas, and Ruisánchez (2012). Gkiotsalitis and Cats (2018) proposed a reliable frequency settings model that considered service variations. Finally, the frequency setting problem was integrated with the route design by Szeto and Wu (2011) and Arbex and da Cunha (2015) with the use of meta-heuristics.

The aforementioned models determine the frequencies of fixed services that serve all line stations. Furth (1987), Ceder (1989), Verbas, Frei, Mahmassani, and Chan (2015), Verbas and Mahmassani (2013), Verbas and Mahmassani (2015) and Gkiotsalitis, Wu, and Cats (2019b) developed frequency setting models that consider flexible virtual lines (e.g. short-turning and/or interlining lines) to allocate the available vehicle/driver resources in the most efficient and effective way. The works of Delle Site and Filippi (1998) and Cortés, Jara-Díaz, and Tirachini (2011) also focus on generating short-turning lines to serve the excessive demand at crowded line segments. This line of research is particularly promising for the COVID-19 era because public transport service providers do not only need to reassign their service frequencies to cater best for the prevailing and evolving demand patterns, but also implement services variations that serve only a subset of the stops. Notwithstanding the above, frequency setting methods for flexible lines typically seek to establish a trade-off between the passenger-related and the operational-related costs without always considering the vehicle capacity that can be linked to physical distancing – see Table 2.

Ignoring the vehicle capacity when setting service frequencies is a critical issue for public transport service providers that seek to recover to normal operations while operating in a reduced capacity due to social distancing. Gkiotsalitis and Cats (2020) developed a model in this direction that reallocates the available resources (vehicles, drivers) to public transport lines so as to obtain the optimal trade-off between passenger-related and operational-related costs while taking into consideration the reduced capacity of vehicles and the revenue losses when passengers are refused service. With the implementation of their model to Washington metro, they showed that a 2-meter distancing will result in a 6.5% average vehicle occupancy rate and 43% unaccommodated passengers during the peak hour. Their work, however, does not consider flexible line characteristics, such as cancellation of stations or short-turning and interlining options.

Table 2. Overview of selected frequency setting models that consider line variations.

Study	Key performance indicators	Line flexibility	Vehicle capacities
Gkiotsalitis et al. (2019b)	Passenger waiting costs and vehicle running and depreciation costs	Yes: short-turning and interlining of lines are allowed	Not considered in the optimisation process
Verbas and Mahmassani (2015)	Ridership and waiting time savings	Yes: service patterns that only use a subset of the entire stops of a route	Considered only if passenger demand is irresponsive to the pattern structure
Cortés et al. (2011)	Waiting time, in-vehicle time, personnel costs and running costs	Yes: short-turning and deadheading for a single line	Not considered in the optimisation process
Delle Site and Filippi (1998)	Waiting times, running costs and personnel costs	Yes: short-turning	Not considered in the optimisation process

Note: Model formulations that consider the vehicle capacity can be adapted and adopted more easily to the COVID-19 requirements of reduced vehicle capacity due to physical distancing.

3.2.2. Timetables

Commonly used analytical timetabling methods are the even-load and even-headway methods that determine the dispatching times of trips to achieve an even-load and an even-headway among all vehicles, respectively (Ceder, 2016). It is important to note that the even-load method might result in irregular dispatching headways, but it is more suitable when trying to implement physical distancing because it distributes the demand more evenly since it aims to achieve an even load among all vehicles. Conversely, the even-headway method results in regular services but reduces the flexibility to accommodate demand fluctuations within a given time period because the dispatching headway cannot be adjusted to respond to local alterations (Potter, 2003). Other methods for timetabling strive to minimise the average passenger waiting times by allowing for irregular headways (Currie, 2009; de Palma & Lindsey, 2001; Gkiotsalitis & Alesiani, 2019; Gkiotsalitis & Van Berkum, 2020).

Although timetabling results in minor refinements of the trips' dispatching times within a given period, it can have a major impact on the transferred demand at transfer stations if we consider all lines in the network. Timetabling models that consider the transfers among multiple lines of the public transport network can provide substantial benefits to the planning of services during the pandemic because they can be used to identify locations for transfer coordination (Yap, Luo, Cats, van Oort, & Hoogendoorn, 2019) or coordinate services and minimise overcrowding at major transfer stations (Ibarra-Rojas et al., 2015). This line of works, known as service synchronisation models, aims at coordinating the services of different lines to reduce the door-to-door passenger travel times via minimising the transfer waiting times while maintaining regular dispatching headways for the trips of different lines (Daduna & Voß, 1995; Gavriilidou & Cats, 2019; Vansteenwegen & Van Oudheusden, 2006; Wong, Yuen, Fung, & Leung, 2008).

At this point, we should note that most timetable synchronisation approaches aim at minimising the transfer times of passengers (Ceder & Tal, 2001; Ceder, Golany, & Tal, 2001; Cevallos & Zhao, 2006a, 2006b; Gkiotsalitis, Eikenbroek, & Cats, 2019a). This reduces the waiting times of passengers at stations but might result in overcrowding if too many vehicles arrive at the transfer station at the same time to allow for interchanges. This may result in too many vehicles arriving at major transfer stations at the same time leading to overcrowding. Hence, transfer synchronisation models that rather refer to a pre-specified time window among successive arrivals (Eranki, 2004; Ibarra-Rojas & Rios-Solis, 2012) might be more suitable when planning for the pandemic.

3.3. Operational planning

Service providers can also apply control measures at the operational stage. Crowd management at the station level may regulate entrance at stations when the current demand exceeds the desired capacity to ensure physical distancing, analogous to ramp metering. Beijing has experimented with this idea of "subway by appointment" in a recent trial by creating a booking system to reserve 30-minute slots to enter stations based on passenger demand information in an attempt to prevent crowding at stations' entrances during peak hours (UITP, 2020a; Wagner, Ibold, & Medimorec, 2020). Crowd management strategies (e.g. emergency station closures) have been applied in the past in cases of major events that lead to a sharp increase of passenger demand (Zhang, Chen, Li, & Fibbe, 2011) and the survey paper of (Li & Hensher, 2013).

Another real-time control measure pertains to skipping certain stations when a vehicle becomes overcrowded. Service providers can utilise information about the vehicle load levels to decide on whether or not to skip a station by solving a binary optimisation problem. There are several models designed to decide which stops should be skipped by a given bus or train trip in real-time (Altazin et al., 2017; Fu et al., 2003; Gkiotsalitis, 2020; Muñoz et al., 2013; Sun & Hickman, 2005; Wang et al., 2014, 2015). However, the objectives of the developed stop-skipping models are related to the improvement of the service regularity and the reduction of the total trip travel times, leaving room for extensions that consider the physical distancing requirements.

An additional real-time control measure that can prevent overcrowding is the limitation of passenger boardings. Developing models that decide about limiting the passenger boardings is a topic that gained prominence in the past decade and has been majorly used to avoid overcrowding inside the buses/trains. The developed models in this direction can be easily applied to adhere to the physical distancing requirements by replacing the nominal capacity of the vehicle with the recommended capacity according to the distancing policy. Prominent operational planning models that consider the capacity of vehicles to decide about the implementation of boarding limits include the works of Delgado, Muñoz, Giesen, and Cipriano (2009), Puong and Wilson (2008) and Delgado, Munoz, and Giesen (2012).

Finally, other operational control measures that can result in improving the service regularity and avoiding uneven passenger loads among successive vehicles that can lead to overcrowding are vehicle holding and speed control measures. Vehicle holding and speed control have a long history of being applied to improve service regularity and mitigate bus/train bunching. Most vehicle holding and speed control works consider only the improvement of service regularity and/or passenger waiting times as problem objectives without accounting for the vehicle crowding levels (Bartholdi & Eisenstein, 2012; Eberlein, Wilson, & Bernstein, 2001; Gkiotsalitis & Cats, 2019; Hickman, 2001; Sun & Hickman, 2008; Xuan, Argote, & Daganzo, 2011). In the past years, however, there are several works that consider vehicle capacity limits and can be used to incorporate physical distancing with the implementation of vehicle holding or speed control measures (Delgado et al., 2012; Hernández, Muñoz, Giesen, & Delgado, 2015; Sáez et al., 2012; Sánchez-Martínez, Koutsopoulos, & Wilson, 2016; Wu, Liu, & Jin, 2017; Zolfaghari, Azizi, & Jaber, 2004). Note that the aforementioned control measures for operational planning rely on real-time crowding information at the vehicle and station level. Hence, it is of utmost importance to leverage information from sensors and use short-term prediction models with high accuracy to support the operational planning decisions.

4. Research agenda and outlook

As manifested in the review above, the COVID-19 pandemic and the related shutdown effects have already had significant impacts on ridership levels as well as the operations and provision of public transport services. At this stage, it remains unknown whether the pandemic crisis will have long-lasting effects on public transport systems. Past experience suggests that large-scale crises, such as the energy crisis in the '70s, the 9/11 terror attacks and the SARS outbreak in the early 2000s, have not fundamentally changed travel patterns but have led to innovation and changes in security and cleaning standards in the industry. This may suggest that the so-called "new normal" may not be so different from the pre-pandemic "normal".

As described in Section 2.1, an array of shutdown measures has been introduced to maintain extremely low demand levels, often accompanied by a significant reduction in service resources and supply. At the climax of the virus, public transport ridership fell significantly by 50% to 90%, while several governments instructed a complete shutdown of public transportation making this sector one of the most affected ones by the pandemic. The pre-pandemic phase corresponds to system performance under normal conditions followed by an abrupt reduction in system functionality caused by an external shock (see the bathtub model for describing service performance changes in McDaniels, Chang, Cole, Mikawoz, and Longstaff (2008) and Ghaemi, Cats, and Goverde (2017)). Topological approaches to network robustness analysis offer relevant concepts, indicators and techniques to identify the most vulnerable and central stations (e.g. Wang et al. (2017) and Cats and Krishnakumari (2020)). Future research may adopt such approaches to support decisions such as prioritising station closuring measures.

The peak period of the pandemic is followed by a gradual lifting of the lockdown measures and restoring segments of civil society and the economy while maintaining many of the key principles in mitigating the spreading of the virus, including physical distancing. This study primarily addresses the challenges associated with this phase, to be followed by the restoration of the services in the long-term, post-pandemic stage. There is no guarantee that the post-shutdown recovery will follow a monotonically improving trend, setbacks might occur following even local outbreaks and alternating between relaxing and introducing restrictions, as well as due to changes in public perceptions. Furthermore, the planning solutions proposed during the course of this recovery phase need to offer adaptation strategies to be robust for future outbreaks.

Managing public transport systems during the post-shutdown phase poses a multidimensional challenge, and the perspective taken here is limited to the critical review of supply-side interventions at the strategic, tactical or operational planning levels. Notwithstanding this, the long-term resilience of public transport systems will not merely depend on supply-side management decisions. Other aspects include public perceptions of health risks associated with public transport and its consequences for customer retention and long-term propensity of the public transport sector. Furthermore, financial adversity poses a substantial threat to many public transport providers in the absence of bailout measures (Tirachini & Cats, 2020).

As evident from the review in Section 3, we expect most of the supply-side interventions to take place at the tactical or operational level. Strategic planning pertains to decisions that mostly extend beyond the horizon considered relevant for combating COVID-19. Many of the changes in supply provision can be made at the tactical planning phase by performing alterations and determining how to allocate resources to the existing network. This includes decisions related to service frequencies, changes in timetables, service variants (e.g. partial lines, stopping patterns), changes in service span. Operational planning allows deploying strategies to respond to the need to mitigate crowding, primarily by means of controlling vehicles in real-time, managing crowds at stations, deploying boarding limits, and the provision of real-time crowding information. Preventive measures pertaining to staff health checks and frequent, rigid cleaning routines also have consequences for service operations ranging from a higher absenteeism rate to reduced fleet availability. Estimates of the prevalence of such measures can be given as input to existing methods to allow for estimating their impact on service frequency settings, vehicle and crew assignment.

Given the urgency of the subject matter, public transport service providers have understandably resorted to largely responding with ad-hoc measures. After the initial shock, there is now an opportunity to devise methods and tools to support a more evidence-based decision making. We identify in Section 3 existing models for network design and line planning, frequency setting and control that can be adopted and adapted to incorporate the implications of physical distancing. A prerequisite is that a model is able to account for capacity constraints. This is, however, a necessary but insufficient condition. For the model to be suitable, it should also allow accounting for unserved demand when evaluating alternative solutions or assessing model outcomes.

Public transport planning models are conventionally geared towards maximising the efficiency and effectiveness of the service provisioned, i.e. variants of maximising the level-of-service given limited resources or minimising the resources needed to offer a certain level-of-service, or a combination thereof. The physical distancing measures introduced to combat the virus spread call for focusing on the need to avoid crowding by distributing passenger demand as evenly as possible in both time and space. This can be attained by means of re-designing services, re-allocating resources and re-distributing passenger flows. The ramifications of such decisions may not be distributed evenly across the travellers' population. This can have especially adverse consequences for passengers' accessibility when not all latent demand can be satisfied. This highlights the importance of taking into account equity considerations in the assessment of alternative solutions (Rubensson, Cats, & Susilo, 2020), and preferably integrating it into the objectives as part of problem formulation.

Designing public transport services to avoid crowded conditions is believed to be instrumental in mitigating the spread of the virus. As demonstrated by Krishnakumari and Cats (2020) and Muller, Balmer, Neumann, and Nagel (2020), the construction of a contact graph based on individual trajectories and the application of a compartmental epidemiological model can facilitate such an analysis. This offers a more advanced approach for explicitly accounting for public health considerations involving the coupling of disaggregate transport demand models (e.g. agent-based and activity-based) and epidemiological models. Such a coupling will allow answering questions such as: how many passengers are likely to get infected if a certain supply is offered for a certain assumed demand given an initial infection rate? what is the infection rate under which restoring a certain demand level can be considered permissible?

To conclude, it is evident from the existing literature of public transport planning models that further research concerning the behavioural responses and adaptation undertaken by passengers as well as the epidemiological properties of the virus will help in underpinning the strategies taken by public transport in the context of the COVID-19 pandemic and its aftermath. It is also evident that the vast literature of tactical and operational planning models that consider the capacity limitations of vehicles can already support public transport planners in the transition from the initial ad-hoc planning measures to evidence-based decision making. However, a lot of work should be made in this direction, including the planning of additional on-demand services to meet the desired distancing regulations while satisfying travel demand.

Disclosure statement

No potential conflict of interest was reported by the authors.

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