Promising solutions for railway operations to cope with future challenges — Tackling COVID and beyond

Wang, Ziyulong; Aoun, Joelle; Szymula, Christopher; Bešinović, Nikola

DOI
10.1016/j.jrtpm.2023.100405

Publication date
2023

Document Version
Final published version

Published in
Journal of Rail Transport Planning and Management

Journal of Rail Transport Planning & Management 28 (2023) 100405

Contents lists available at ScienceDirect

Journal of Rail Transport Planning & Management

journal homepage: www.elsevier.com/locate/jrtpm

Promising solutions for railway operations to cope with future challenges — Tackling COVID and beyond

Ziyulong Wang [a,*], Joelle Aoun [a], Christopher Szymula [b], Nikola Bešinović [a,b]

[a] *Department of Transport and Planning, Delft University of Technology, Delft, The Netherlands*
[b] *"Friedrich List" Faculty of Transportation and Traffic Science, Technische Universität Dresden, Dresden, Germany*

ARTICLE INFO

Keywords:
COVID-19
Railways
Resilience
Capacity management
Railway technology

ABSTRACT

The COVID-19 pandemic has imposed a dramatic effect on the mobility habits of both passengers and freight in the rail sector. Since the relaxation of COVID-19 restrictions worldwide, rail transport has been revitalised gradually. However, the new normal emerges with unprecedented issues, such as changed travel behaviour, lost profits, and a lack of personnel. In this paper, we determine the arising challenges due to COVID-19 and pandemics in general and subsequently propose several solutions to tackle these challenges in rail transport. These solutions cover multidisciplinary aspects such as passenger demand management, freight demand management, service design, automation, decentralisation and advanced railway technologies. By reviewing the relevant literature on COVID-19, public transport and particularly rail transport, we synthesise and identify promising lines of research that should devote more attention to a more efficient, effective and sustainable rail transport service. This paper provides policymakers, researchers, railway infrastructure managers and undertakings with an overview and an outlook for the impacts of the pandemic crisis and similar situations. It supports decision-making with more evidence and facilitates rail transport to restore its performance and reach its societal goal.

1. Introduction

During the age of the COVID-19 pandemic, the planning and operations of Public Transport (PT) including railways have been exceptionally challenged, which lingers in society even after the period (Awad-Núñez et al., 2021). Although governments worldwide stress the point that rail transport is essential, the travel demand still dropped significantly by 90% to 95% at its peak. For instance, some of the substantial usage drops were seen in approximately 80% in the Netherlands (De Haas et al., 2020), 40% to 60% in Sweden (Jenelius and Cebecauer, 2020), and 57% to 63% depending on the mode in Germany (Anke et al., 2021) as shown in Fig. 1. A simple return of the public to the pre-pandemic level is unlikely even though the COVID-19 crisis was gradually and slowly handled and lockdowns in most countries were lifted. A few societal norms could foreseeably stay much longer, such as 1.5 m physical distancing, remote working, avoiding crowdedness and wearing a mouth cover (Van Leeuwen et al., 2020). These rules exist to prevent the massive spread of the virus and block the main transmission routes via droplet, contact, and aerosol (Li et al., 2020). Moreover, the mobility pattern of passengers has changed from inter-city and inner-city levels to more local community-oriented. This leads to a potential change in Origin–Destination (OD) demand patterns and its associated activity level, due to modal shift or flexible homeworking.[1] On a community level, these changes may differ among groups with various mode preferences (Das et al.,

* Corresponding author.
E-mail addresses: Z.Wang-19@tudelft.nl (Z. Wang), J.Aoun@tudelft.nl (J. Aoun), christopher.szymula@tu-dresden.de (C. Szymula), nikola.besinovic@tu-dresden.de (N. Bešinović).

[1] https://www.intelligenttransport.com/transport-whitepapers/128588/arriva-public-transport-europe-pandemic-recovery/

https://doi.org/10.1016/j.jrtpm.2023.100405
Received 24 March 2023; Received in revised form 31 July 2023; Accepted 19 August 2023
Available online 4 September 2023

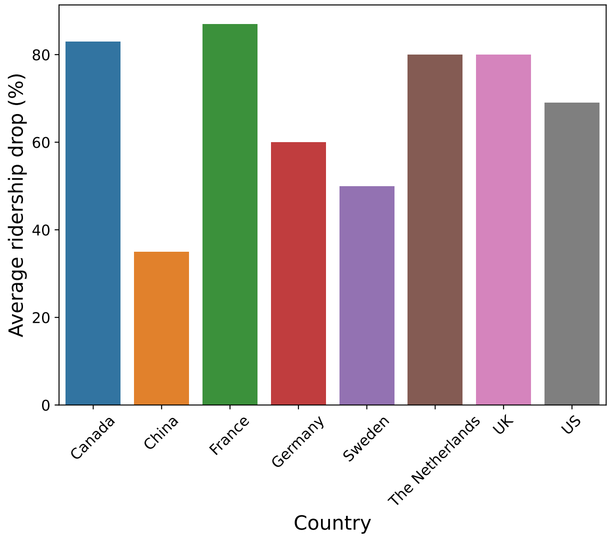

Fig. 1. Impact of COVID-19 on PT usage shortly after it struck.

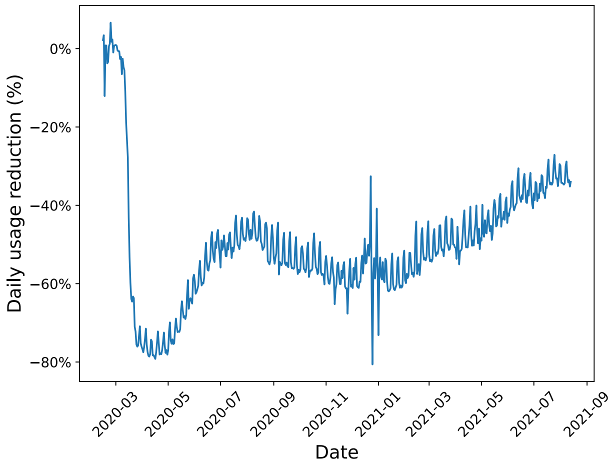

Fig. 2. Change in PT usage of all cities monitored by the mobile app Transit.

2021), socioeconomic status (Almlöf et al., 2021), and even personality traits (Chan et al., 2021). Notwithstanding, the migration of mobility to individual transport systems does not happen across all demographic groups, and an increase in car use can only be associated with low car-dependent groups (Ton et al., 2022; Vega-Gonzalo et al., 2023). We present the change in PT demand in all cities monitored by the mobile app Transit[2] after the pandemic struck and a slow recovery in Fig. 2

To cope with the pandemic, direct and indirect measures were taken, leading to railway supply shortages in most countries. A direct measure was the corresponding reduction of the railway services, such as a special timetable issued by the main railway undertaking (e.g., NS, Nederlandse Spoorwegen in the Netherlands), temporal stations shut (e.g., in London and Washington DC) or decreased frequency (e.g., in France and Italy). These measures were established to limit financial losses and to handle the absence of staff because of reported sickness, whilst supporting the essential workers. A visualisation of the relative amount of service provided by the main rail-bound companies during the first wave of COVID-19 in the Netherlands is presented in Fig. 3. Besides the direct and intentional service limitations, other indirect measures formed another cause for the rail transport supply shortage, i.e., by trying to cut off the transmission, in terms of passenger and staff management, equipment hygiene, information communication and operation regulation (Yin et al., 2021). All these direct and indirect reasons restrict the PT service and result in a declined quality after the pandemic hit. Furthermore, a shortage of staff emerges in several countries after COVID-19 due to e.g., the tight labour

[2] https://transitapp.com/coronavirus, visited 15 August 2021.

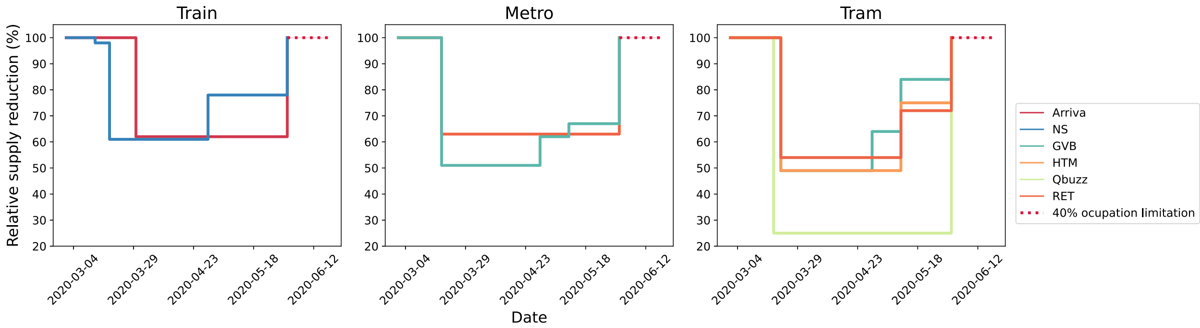

Fig. 3. Relative reduced rail-bound services per company per mode in the Netherlands (Van der Horst, 2020).

markets, working conditions and new work-life balance lifestyle.[3] Therefore, long-term viability studies for the rail sector are critical to gain the revenue loss back and prosper afterwards.

Nevertheless, the current COVID-related literature mostly addresses problems and impacts caused by COVID-19. These papers provide a specific focus on one aspect of the system. We find scientific research in railways on assessing influences on transport capacity (Bešinović and Szymula, 2021), adjusting timetable and resources based on the situation (Kang et al., 2022), expected virus spreading in metro system (Krishnakumari and Cats, 2020), infection estimation (Li et al., 2021), rail-bound ridership change (Wang and Noland, 2021), and onboard impact due to social distancing (Coppola and De Fabiis, 2021). Also, many reports focus on qualitative or conceptual frameworks to address a single aspect and offer one single solution, such as transporting parcels as passengers (Yang and Song, 2020), coaches as Intensive Care Units (ICU) when necessary (Patel et al., 2020), prevention of spreading (Yin et al., 2021) and using micromobility (Campisi et al., 2020). However, these conceptual studies typically do not present in-depth quantitative models and algorithms, and tools on how to apply and implement these solutions. This essentially leaves practitioners short of final solutions. Although few articles assess the transportation strategies amid the COVID-19 crisis (Tirachini and Cats, 2020) and propose adaptions in the future (Gkiotsalitis and Cats, 2020), they mainly focus on a PT context. To this end, there is currently no such paper that both holistically gathers the problems due to COVID and provides detailed solutions supported by mathematical approaches in the rail transport domain.

Enlightened by the railway operation at the time of the pandemic and its likely rough future, a resilient rail transport system can be highly beneficial. By definition, resilience in a system mostly refers to the ability to provide effective services in normal conditions as well as to recover from unexpected disruptions (Bešinović, 2020). Such an ability is often measured from infrastructure- and weather-related failures (Aydin et al., 2018). Nonetheless, the COVID-19 reality suggests that we almost forgot another different threat – pandemic – that imposes long-lasting impacts and demands resilience from society as a whole. Even more, the recovery from its consequences on rail transport could be measured in months or even years. In this paper, we introduce potential research directions that could help us to understand and improve railway operations during and particularly after the pandemic, crafting the best recovery measures. We first state the main challenges in the railway system occurring due to the pandemic. Then, we define promising research directions to tackle these challenges from the perspective of railway infrastructure managers and undertakings. This paper would be useful to both academics and practitioners as it provides new solution directions to the latter, along with new challenging scientific problems to the former.

The remainder is organised as follows. Section 2 presents the possible challenges and then Section 3 offers promising solutions that could prompt the railway operations in the expected bumpy future. Finally, Section 4 concludes and discusses the way forward.

2. Research gaps

During COVID-19, some changes in passenger behaviour have been observed by recent studies such as mode choice changes or remote working. For instance, Van Oort and Cats (2020) showed that 40% of passengers intend to travel less often during the peaks after the pandemic. This allows a better spread of passengers over time and space and ensures that PT remains accessible for all groups in society. Additionally, a joint study of NS and TU Delft[4] shows that 33% of the train passengers expect to work more from home and 1.5% of the participants of the survey purchased a new vehicle in the last months to replace their train trips (of which approximately were 50% cars). Other research sketches similar mode change tendencies for German passengers and the potential of lasting changes in the purpose of trips, i.e., a remaining drop of labour-related travel and increasing leisure trips, such as Knie et al. (2021) and Brockmeyer et al. (2020). In contrast, several studies (e.g., Ku et al. (2021), Mashrur et al. (2022) and Pan and Ryan (2022)) as well as the international PT organisation UITP[5] confirm that PT is COVID-safe, particularly when wearing a face mask. Therefore, and also due to an overall improving pandemic situation, passengers have been regaining trust in PT and have started returning to using PT again.[6] In 2021, nearly 70% of train passengers have returned after the summer holidays in

[3] https://www.eurofound.europa.eu/nb/publications/blog/the-pandemic-aggravated-labour-shortages-in-some-sectors-the-problem-is-now-emerging-in-others
[4] https://nielsvanoort.weblog.tudelft.nl/how-do-dutch-train-passengers-expect-to-travel-during-and-after-covid/
[5] https://www.uitp.org/news/public-transport-is-COVID-safe/, accessed 5 November 2020.
[6] https://www.tagesschau.de/wirtschaft/unternehmen/bahn-fahrgaeste-anstieg-101.html, accessed 25th of August 2021.

the Netherlands, compared to the number of travellers in the same period in 2019 (pre-pandemic level).[7] This implies the Dutch railway counts on a full recovery of the number of train passengers in the long term.[8] However, this requires more research efforts in studying changed travel behaviour in rail transport to capture the dynamic demand pattern (such as Currie et al. (2021) and Ton et al. (2022)) and investing in rail freight demand when the passenger rail market downturns as rail freight was much more resilient during the pandemic (Schofer et al., 2022).

To counter the pandemic, the rail sector has taken multiple measures for adapting to the lower demand levels and the potential risk of virus-spreading in their facilities and vehicles, which unavoidably incurs a shortage of supply. One of the main measures has been adjusting timetables by reducing the number of train services since a limited number of passengers have been travelling due to lockdown measures imposed by the government. This action was successful in reducing the operational cost as fewer trains were running in the network. Other pandemic containment and relaxation measures were taken as well, such as deep cleaning of stations and rolling stocks, automatic opening of all doors, seat reservation and mandatory face masks (Rasca et al., 2021; Haque and Hamid, 2022). Bešinović and Szymula (2021) found that by assuming 25% of vehicle capacity available, about 50% less passenger demand could be transported compared with the original, i.e., pre-COVID-19 demand. In addition, link utilisation would be significantly higher over the whole network, leading to about 70% of all trains being at least 90% full at some point in their journey. Aiming for lowering infection risks (i.e., for rebuilding the trust of passengers and keeping employees safe), these measures were mostly causing additional costs due to additional services, extended process times or lost ticket fares (Haque and Hamid, 2023).

Moreover, an increase in the number of infections can cause specific cases of lack of personnel since the quarantine measures are deployed due to either reported sickness or having been in close contact with an infected person, albeit with all the precautions and countermeasures. In particular, train drivers constitute a critical group in pandemic situations, since most of the train fleets are driven manually, especially in medium and long distance and in freight transport. On the one hand, a lack of drivers can lead to cancellation of services, thus making it difficult to transport essential services workers, medical and basic supplies and even the transport of patients in trains prepared specifically for the occasion. On the other hand, in the case of passenger transport, some measures such as the maximum capacity or the minimum interpersonal distance added to the transport demand may require adding extra services, with the resulting extra staff requirement and the impact on the capacity of the railroad network. Furthermore, some companies aim to reduce the number of employees over the same period, for instance, the Netherlands has a saving plan that impacts approximately 2,300 jobs, although no one will be forced to lay off.[9] In addition, the lack of traffic dispatchers and controllers is becoming an apparent challenge already. For example, at the Dutch infrastructure manager ProRail, it became critical such that it led to cancelling some services during the summer of 2021,[10] and later on, the Dutch railway undertaking NS applied serious reductions due to a serious lack of drivers throughout 2022.[11] When the passenger demand recovers, it will not be possible to transport all passengers with the current way of traffic operations, network capacity and the number of employees. Hence, significant operational challenges will be created for ProRail and NS and most likely for other infrastructure managers and railway undertakings across the world.

All the aforementioned difficulties from both the demand and supply sides of the rail sector imply an uncertain further ahead. Consequently, it is evident that the rail sector needs to reorganise its services and advance in response to these new societal conditions, especially when higher passenger demand returns to the system, the needs of passengers change, and the supply shortage is long-lasting. Therefore, great challenges arise within the railway industry during and after pandemics that give rise to the following questions:

1. How to address changed passenger mobility behaviour?
2. How to compensate for reduced fare profit due to limited passengers travelling by prompting freight transportation to utilise the potential capacity?
3. How to redesign the rail service during and after the pandemic to lessen potential virus-spreading risks?
4. How to address the expected lack of operational staff such as drivers and dispatchers?
5. How advanced railway technologies would help in coping with pandemics and similar situations?

The first and the second questions emerge with the demand side while the following three questions target the supply side. Solutions to these significant challenges would restart providing sustainable and reliable railway operations for customers of both passenger and freight rail services in the period within as well as during the recovery from the pandemic. Different phases of the pandemic and its alike come with different focuses. Health is among all prioritised during the peak of the pandemic and the passenger behaviour is adapted accordingly along with the promotion of freight and redesign of the service. On the contrary, revenue recovery is one of the priorities after the pandemic and hence not only the previously mentioned strategies but also automation, decentralisation as well as future technologies should be proposed. Even though investment in new technologies would require high costs, it would reduce operational costs in the long term. Thus, some of the used strategies could contribute to further improved performance compared to the pre-COVID time. Eventually, it would lead to achieving even greater long-term resilience of the railway system.

7 https://www.spoorpro.nl/materieel/2021/09/03/ns-bijna-70-procent-van-de-treinreizigers-is-weer-terug/

8 https://stadszaken.nl/artikel/3699/prorail-rekent-op-volledig-herstel-treinreizigers-op-lange-termijn

9 https://www.ovpro.nl/personeel/2021/03/04/ns-werkt-krimpplannen-verder-uit-opnieuw-minder-banen-op-stations/

10 https://www.railtech.com/infrastructure/2021/07/30/staff-shortage-in-train-traffic-control-causes-problems-in-the-netherlands/?gdpr=accept

11 https://www.iamexpat.nl/expat-info/dutch-expat-news/ns-scraps-trains-and-reduces-timetable-result-staff-shortages

3. Solutions

Following the defined research gaps, this section provides point-to-point solution directions where each subsection targets one gap. The solutions are organised as follows: Sections 3.1 and 3.2 focus on the demand side regarding passenger and freight, respectively. On the other hand, the supply side is analysed from the aspects of rail service redesign (Section 3.3), automation and decentralisation (Section 3.4) and advanced technologies (Section 3.5).

Our set of selection criteria was mainly based on the defined research gaps and a combination of keywords pertaining to rail transport and the COVID-19 pandemic. We searched the state-of-the-art literature in related multidisciplinary fields including the demand and supply of rail transport as well as changed railway passenger behaviour, railway technology and operations. Then, we checked the suitability of these papers that specifically addressed the proposed topics, focusing on the impacts of the pandemic, situation alike or post-pandemic. Besides, we searched for studies on strategic, tactical and operational rail transport planning where applicable. Next, we also applied our domain knowledge to filter and identify relevant studies to be included. Our main objective was not to offer an extensive literature review, given the amount of literature on this topic. Instead, we aimed to synthesise solutions that could tackle COVID-related challenges. These solutions would have been effective during the pandemic and have the potentials to be adopted in the long term.

3.1. Passenger demand management

Effective and efficient demand management would benefit every stage of railway operations, from the strategic level to the tactical and operational levels. Strategic planning in rail transport normally refers to determining the assignment of rolling stocks, according to the timetable (Jonaitis, 2007). The effect of COVID-19 on travel behaviour changes is non-negligible, particularly for passengers who would like to see an increase in supply and a more often vehicle disinfection (Awad-Núñez et al., 2021). Besides, thorough surveys and extensive latent demand studies are needed before building new infrastructure and purchasing rolling stocks such that sufficient but not superfluous supply can be provided.

From a tactical planning level (e.g., timetabling), a tailored and activity-based service can add value to both passengers and operators. Passengers make significantly fewer trips during the pandemic and would like to work from home more often, which demands the operators provide a more personalised offer for the passengers while ensuring safety. Therefore, incentives are necessary to encourage travellers to conduct non-working trips, such as pricing policies during peak/off-peak hours (Dai et al., 2021), temporarily utilising the seats at different classes, loyalty schemes or packaged offers (Goodwin, 2008). Moreover, the pandemic also changes the habit of working from a regular daily basis to virtually any time of working at home (Kniffin et al., 2021). Thus, it correspondingly changes the travel time choice of passengers, in particular, non-essential workers and students. Customised travel behaviour modelling should be carried out to derive a new timetable for the new norm. Additionally, revising the current routes and providing greater integration between the railway and active modes (such as bicycles or scooters) as well as demand-responsive transport is necessary to meet the new lifestyle. This new lifestyle might also drive people to relocate from urban to suburban areas due to various reasons (e.g., crowdedness, environmental degradation or traffic congestion), which demands adequate and flexible interconnected suburban transport between railway stations and residential areas.

With respect to the operational level (short-term planning), crowdedness can be expected with the social distancing if the demand comes back to the pre-pandemic level (Bešinović and Szymula, 2021). It will lead to safety concerns and risks if the passenger demand cannot be spread (Biscayart et al., 2020). Despite the travel behaviour might have changed, there still could be a peak hour with a high influx of people on the trains. Trip planners, as a proxy, could provide the same granular level of spatial and temporal information about possible trips in advance before the trip has been realised (Ferreira et al., 2017). By utilising trip planner data combined with the recent historical smart card data, reliable predictions can be performed to the short-term passenger demand (Wang et al., 2022b). With the predicted demand, operators could provide the corresponding transport supply or provide information to spread the passengers by indicating the forecasted crowdedness level. Furthermore, seat reservation could be introduced to disperse the travellers as they have a strong preference in seat choices (Hu et al., 2020) and it could help in avoiding concentrated boarding (Oliveira et al., 2019). In addition, real-time crowding monitoring and prediction (Peftitsi et al., 2021; Jenelius, 2020) can play a significant role in the comfortable and safer travelling of passengers. Lastly, a close collaboration between the railway and the use of Mobility-as-a-Service (MaaS) can play an important role in developing today's and tomorrow's transport service, for instance, the eight MaaS mobile applications in the Netherlands.[12]

3.2. Freight demand management

There has been an existing potential for using the railway networks in Europe, which are traditionally passenger-centred, to transport more freight in the years ahead, e.g., due to uneven use of the transport capacity throughout the day. This potential could be leveraged by using available empty space on existing passenger train services or adding more freight train services. Eventually, more efficient utilisation of the rail network and more profitable operation for infrastructure managers can be expected.

[12] https://www.rijksoverheid.nl/documenten/rapporten/2022/11/29/bijlage-2-evaluatierapport-programma-maas

3.2.1. Freight on passenger trains

On national railways, there is an opportunity to transport a delivery partly by using long-haul air and/or rail operations, where mixed usage of one aircraft or train is available (Ghilas et al., 2013). This idea is not entirely new but is not much investigated. In essence, the main goal is to use the overcapacity in some parts of the rail system to carry freight for long-haul and short-haul first-last mile operations. This would mean that an unused capacity on passenger trains could be used to transport parcels.

In the urban metropolitan environment, there is currently an extreme traffic load on last-mile parcel deliveries. This is even more critical in the COVID-19 pandemic when the number of online ordering is ever-rising and after the pandemic when online shopping becomes more popular than the pre-COVID-19 time (Shaw et al., 2022). The (urban) rail transport may be used efficiently in peak hours, however, there tends to exist spare capacity in off-peak hours. Thus, parcels can be transported by the rail system with an independent right of way and reduce the pressure on the road network, increase the speed of the delivery, lower energy consumption, and lead to a better use of the urban space and more sustainable mobility of cities. Even more, railway operators could yield extra profits from freight operators. For example, Trentini and Mahléné (2010) gave the first survey of existing cities adopting strategies for shared transport of goods and passengers and presented a conceptual model. Cheng et al. (2018) studied the flow of packages in the PT system without hindering the quality of service. To optimise such a system with mixed use of passengers and goods, Masson et al. (2017) proposed a two-tiered model which is solved by an adaptive large neighbourhood search. To transport parcels and passengers on the same train, several countries are investigating the possibilities, for instance, the UK has launched a trial in 2021.[13] The service can be further enhanced by combining rail transport with another sustainable mode — bicycle.[14,15]

Correspondingly, emerging problems are expected in all planning phases. At the strategic level, line planning is critical in determining which lines to use, the location of drop-in/drop-out points and the trade-off between capacity and benefits as an objective. From the tactical level, the size of the rail network and the type of fleet that can be used are most relevant to be studied while the daily schedules for parcel delivery and dispatching parcels to trains should be studied at an operational level. Compared to the current transport schemes, the benefits of such an integrated passenger and freight system can be quantified by several key performance indicators related to improvements in operational, environmental and social performances, which are proposed by Bruzzone et al. (2021). The last-mile delivery of the integrated system in urban areas can also be simulated in simulation software like MATSim (Ribesmeier, 2023).

3.2.2. Increasing number of freight train services

In conditions of significantly reduced passenger demand, e.g., during the peak of COVID-19, passenger trains have been running nearly empty throughout the day, both in peak and off-peak hours. Instead, freight demand has a tendency to recover much quicker than passenger demand (Windle, 2020). However, their further growth in the number of services remains limited to the originally scheduled passenger services. Thus, railway infrastructure managers could consider providing more space for freight trains by reallocating train paths from passenger to freight operators during such a period as a contingency plan. This would generate extra profits for infrastructure managers. These reallocated train paths would require not only accurate freight demand estimation (Vaezi and Verma, 2017; Khan and Khan, 2020; Laage et al., 2021) but also long-term passenger demand estimation, particularly considering the recovery of the demand to the original levels (i.e., post-COVID-19). This would facilitate the quantification of spare capacity for freight. In addition, path reservation for freight operators shall be made more flexible to allow making requests faster and shorter before the operation.[16] To achieve this, infrastructure managers should be required to use more advanced models and algorithms for adjusting railway timetables at near real-time levels. Krauth and Ribesmeier (2022) proposed a model to understand the modal shift between road and rail deliveries and determine potentials of rail networks. Finally, providing more capacity to freight in both long-haul and short-haul first-last mile delivery could be one of the real game-changers leading towards optimised usage of available infrastructure, i.e., increased capacity and quality. Consequently, it would ensure a significant modal shift from road to rail in the future and allow more sustainable transport.

3.3. Rail service redesign

The pandemic situation and the corresponding societal measures (such as curfews and working from home) caused major changes on the demand side of the railway system. Since the collected fares are largely financing the provided services, service providers were forced to adapt to the changed situation. As a consequence, service providers reduced the provided service capacity correspondingly to reduce their operational expenses. The service reductions were mostly done by using tactical measures (e.g., changing service frequencies, timetables or the total duration of daily operations) or taking operational actions (e.g., limiting vehicle capacity, managing vehicle occupation in real time and crowds in stations and providing real-time crowding information) as detailed in Gkiotsalitis and Cats (2020).

However, recent research showed that the major issue of the PT COVID-measures from a passengers' perspective is the resulting induced lack of service capacity, leading to rejected passengers. By assessing the Dutch railway network, Bešinović and Szymula (2021) concluded that even when keeping the service frequencies and the operational expenses constant, the operational reductions

13 https://www.railfreight.com/business/2020/09/04/around-europe-premium-logistics-return-to-rail/?gdpr=accept&gdpr=accept

14 https://smartcity.wien.gv.at/en/remihub/

15 https://www.linkedin.com/posts/the-rail-innovation-group_parcels-as-passengers-activity-6802872467095343104-qtfN?utm_source=share&utm_medium=member_desktop

16 https://rne.eu/capacity-management/ttr/

in seating capacity per train due to social-distancing measures would lead to a highly saturated railway system and a major share of unserved passenger demand. Furthermore, Gkiotsalitis and Cats (2022) illustrated that if the system is incapable of serving the passenger demand, significant changes in the tactical set-up of the system are required to facilitate these changed conditions, i.e., re-setting service frequencies. To this end, the reductions in service capacity artificially induce strong capacity shortages, which suddenly confront the service operators with highly utilised networks and the corresponding negative effects, such as unserved passenger demands, a high share of highly utilised services and thus a higher vulnerability due to lacks of reserved capacity (Bešinović and Szymula, 2021). Thus, the service operators need to rearrange the planning strategies and goals in order to adapt: (1) under pandemic conditions but also (2) during the post-pandemic phase, to still provide sustainable and socially valuable public services.

3.3.1. Amid the pandemic

The general goal of the pre-COVID era still holds for each division of the sector to reach its societal goal, such as maximising revenue with a certain level of service for commercial railways and maximising net social benefits with a specified level of service for passenger railways. The shortage of services during the pandemic will result in lower frequencies (or no services at all) for passenger demands. Important factors accordingly emerge such as equity regarding rejected passenger demands (Gkiotsalitis and Cats, 2020) or the value of spare capacity of both the rolling stock and the infrastructure in terms of disruptions and constructions. Therefore, service providers need to sharpen their societal role and request suitable mandates to prepare for similar situations with respect to equity concerns under extreme conditions. Also, they need to put more effort into evaluating and quantifying the value of their operational assets, i.e., the value of spare capacity on their network, rolling stocks and the crew as well as the resulting flexibility. To help the rail sector during the COVID-19 pandemic, European Commission introduced support measures in October 2020 to reduce the financial burden on railway undertakings, including reducing, waiving or deferring the payment of rail infrastructure charges.[17] Five possible ways of economic support with decreasing importance were witnessed, containing direct financial contribution, decreasing access charges, decreasing or eliminating taxes, guaranteeing loans and fair level play field between all transport modes (UIC COVID-19 Task Force, 2020). These measures minimise the fiscal disruption to the rail sector and guarantee the railway services can be sustained over the difficult period due to the revenue loss from lockdown and government-imposed restrictions.

3.3.2. Post-pandemic recovery

In the absence of the extreme pandemic environment, all efforts will focus on serving the recovering demand. For supporting a fast demand recovery and its corresponding revenue gains, service operators should aim for offering sufficient services, serving the full recovering demand. Hence, the demand and the provided services should be regularly and frequently evaluated and adapted in order to support the fast recovery of the system. However, since the goal of balancing fare revenues and operational expenses still remains, the risk of rejecting the recovering demand due to insufficient service supply exists, especially regarding the likely former financial losses during the pandemic phase. To this end, strong lobbying for bailout measures is necessary regarding the limited financial flexibility of service providers for providing such flexible (and potentially even demand excessive) services. Besides, recent research shows that the potential of lasting changes would result in a change in the mobility behaviour of passengers and therefore passenger demand (Knie et al., 2021). This might require even more drastic changes in the service characteristics, i.e., focusing on leisure activities rather than commuting and the correspondingly required adapted routes and capacities of the railway system. With the changed trip purpose plus the current high energy cost and inflation, many passenger railways worldwide report that the usage is approaching pre-COVID level while the revenue is still unsatisfied, such as Germany[18] and the UK.[19] Gkiotsalitis and Cats (2020) also suggest that the resilience of PT systems will not only depend on the management decisions of the service providers but also on public perception of health risks when travelling by PT. Thus, information, education and other measures, as already described by the International Union of Railways (UIC) Task Force, are also of major importance (UIC COVID-19 Task Force, 2020).

Generally, the pandemic as well as the post-pandemic phases show that operators are likely being confronted with rapidly changing conditions. Support measures from the government are of necessity, however, cannot be sustained in the long term as cash management issues gradually appear in several countries (UIC COVID-19 Task Force, 2020). It is worthwhile noting the post-pandemic fare experiments in Germany (i.e., the 9-euro-ticket in 2022) and Austria (i.e., the climate ticket in 2022) stimulate the railway ticket market and encourage passengers towards a more sustainable mobility approach. These experiments find that leisure activity is the most prevailing trip purpose and is generally accepted by the public (Nobis and Kolarova, 2022). For that reason, the operators should aim for more flexible planning tools and processes, allowing them to plan and evaluate their planned services under frequently changing conditions. This might support the flexibility under extreme conditions such as a pandemic, but also under regular conditions, i.e., when dealing with construction works, extreme weather events and situations where capacity is restricted.

[17] https://transport.ec.europa.eu/news-events/news/rail-transport-eu-extends-covid-19-support-measure-2022-02-24_en

[18] https://ir.deutschebahn.com/en/news-presentations/news/detail/customers-return-after-covid-19-record-revenues-lead-to-return-to-profitability/

[19] https://dataportal.orr.gov.uk/statistics/usage/passenger-rail-usage/

3.4. Automation and decentralisation

The recent chronic deficiency of required railway staff includes train drivers, traffic dispatchers and traffic controllers at control centres. This represents a great risk in maintaining and running the scheduled railway operations. To enforce that rail transport remains operational and ensure that freight shipments and passengers can reach their destinations, the dependency on human-based operations needs to be reduced over time. After the pandemic hit, hybrid working becomes in favour, leading to a transformation of the railway business mode from a commuting-oriented to a mixed commuting-leisure. This trend directly impacts railway operations, in which a reduced timetable is offered in most countries. The overcrowdedness situations on both weekdays and weekends trigger the dissatisfaction of railway staff and result in many strikes. Speeding up automation and decentralisation could help release the pressure under these conditions, regardless of absenteeism during the pandemic or the industrial disputes afterwards.

As UIC has indicated, the post-COVID mobility situation creates favourable conditions for the railways.[20] Air transport stakeholders are downsizing their cost structures and moving towards a more sustainable organisation way, which is already seen in the environmental transition of the automobile industry. The rail sector, benefiting from its environmental-friendly nature, can reach the sustainability goal faster and gain this window of opportunity to increase market share. To do this, acceleration of investment in breakthrough technologies is a must. New concepts in the domain of automation and decentralisation can contribute to this and further improve the energy efficiency and flexibility of the system.

3.4.1. Automation

Automation may lead to a more precise railway operation, thus reducing the risk of delays and contributing to more sustainable mobility by reducing the consumed energy. This would ultimately improve overall passenger satisfaction. Moreover, in the event of a staff shortage, the highest grades of automation may mitigate or even suppress its impact. Automatic Train Operation (ATO) systems for fully automated metros have been available since the 1980s and experience showed that "passengers appreciate the higher quality of service that comes with automation".[21] However, ATO is not as widely implemented in surface railways as in metro lines due to multiple operational and management differences, such as open environment, network size, various stop distances, heterogeneous traffic, complex track layouts and multi-operator and multi-stakeholder involvement (Wang et al., 2022c). In particular, the traffic is generally more heterogeneous running on a surface railway network where trains usually cover larger distances and the running speeds can be higher, especially in the case of high-speed trains. In addition, the presence of hazards on surface tracks is often more unpredictable. Similarly, in the autumn season, the rail surface suffers from reduced adhesion due to the occurrence of leaves on the tracks in certain areas. Hence, the aftermath automation development strategy provides opportunities to increase the resilience of services and internal processes while protecting staff from the pandemic and alike.[22] At the same time, the touchless service could restore the trust of passengers and improve performance.

The research on ATO requires the development of high-precision algorithms for computing optimal train trajectories, which most often aim at minimising energy consumption (Scheepmaker et al., 2017). The future models and algorithms for ATO are expected to be based on both model-driven approaches, including optimal control theory (Rao et al., 2010; Wang and Goverde, 2016; Albrecht et al., 2016; Goverde et al., 2016), optimisation (Wang et al., 2013; Chevrier et al., 2013) as well as data-driven models including approximate dynamic programming (similar to Reinforcement Learning) (Wang et al., 2020). In particular, the latter shall be enforced by recent advances towards adopting Machine Learning (ML)-based approaches for safety-critical systems, for instance, train control (Bešinović et al., 2021; Flammini et al., 2022; Seisenberger et al., 2022). To support ATO accuracy and its uptake, train engine dynamics shall be calibrated (Cunillera et al., 2023). Further from controlling a single train, additional benefits can be obtained by controlling energy consumption in the complete network (Li and Lo, 2014; Canca and Zarzo, 2017; Wang and Goverde, 2019), and particularly focusing on reducing energy peaks (Wang et al., 2022a).

3.4.2. Decentralisation

Decentralised real-time railway traffic management systems can deal with railway traffic perturbations in the absence of a central decision maker (Marcelli and Pellegrini, 2021). It could be typically adopted in out-of-control situations where the dispatcher ceases to have an overview of the system and thus terminate all railway traffic in the affected region, even though the required infrastructure, staff, and rolling stocks might be available (Van Lieshout et al., 2022) or even if there is no such dispatcher anymore. Under these situations, decentralisation could provide a robust plan without the presence of a dispatcher and improve traffic management for enhanced service quality and greater flexibility due to greater capacity for digital automation. Yong et al. (2017) stated that decentralised real-time railway management is achieved through swarm intelligence, where a swarm is a group of trains that are locally moving in the same direction and facing a possible common conflict. Each train in the swarm uses a vehicle-to-vehicle communication system to coordinate with its neighbours. To occupy a track, trains have to send the request to a decentralised dispatching algorithm which verifies the feasibility of such requests. A decentralised model was presented in Shang et al. (2018) that considers the problem of dealing with train organisation presuming that trains can self-organise themselves and communicate with one another. The behaviour of each train is decided based on a local optimisation problem that aims to minimise its time deviation with respect to the scheduled time, resulting in two sequences: the first defines its future control strategy and the second

[20] https://uic.org/com/enews/article/mobility-post-covid-an-opportunity-for-rail-transport

[21] https://www.railway-technology.com/features/feature127703/

[22] https://assets.new.siemens.com/siemens/assets/api/uuid:d6ee3221-0c38-451e-ab1d-8ec3aff81aae/increasing-covid-19-resilience-of-public-transport.pdf

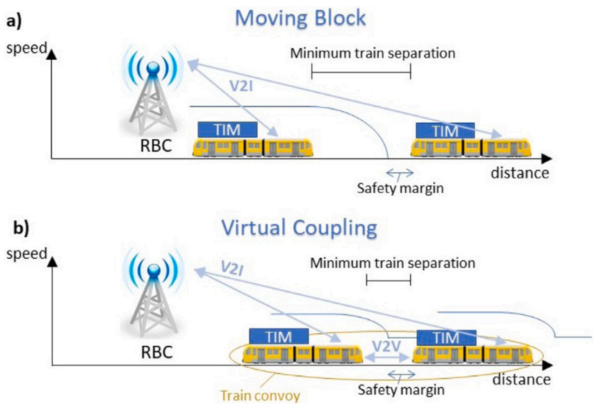

Fig. 4. Train-centric signalling systems, (a) Moving Block, (b) Virtual Coupling (Aoun et al., 2021).

establishes its future departure timeline. Marcelli and Pellegrini (2021) identified possible ways to model decentralised real-time traffic management based on a literature review. They found that decision-making approaches may succeed more than rule-based approaches since the former can allow the system to be capable of achieving performances that are comparable with those of the current state of the art on centralised approaches. However, significant effort must still be done for making them applicable to different problems at hand.

3.5. Advanced technologies

Pandemics impose high restrictions on the comfort and safety of passengers. To ensure that the railway system remains accessible for all groups in society, passengers need to be spread over time and space. Advanced railway technologies such as train-centric next-generation railway signalling systems can significantly improve capacity, reliability and flexibility. The most common train-centric signalling systems are Moving Block and Virtual Coupling (VC) as shown in Fig. 4. The flexibility of virtual coupling and decoupling can deal with the changing mobility behaviour during different phases of the pandemic. The lower cost it brings due to the absence of trackside equipment can enhance the competitiveness of the rail among different alternative modes.[23]

In moving block signalling known also as the European Railway Rail Traffic Management System/European Train Control System Level 3 (ERTMS/ETCS L3), consecutive trains would be just separated by an absolute braking distance which is the distance needed by a train to slow down from its speed to zero. The safety-critical systems are installed onboard of the train through train integrity monitoring and the movement authority and safety margin among trains are computed by a radio block centre.

VC consists of having autonomous trains that run in radio-connected platoons to significantly improve railway capacity and address the forecasted increase in railway demand. With VC, trains can run at a very short separation known as the relative braking distance which is defined as the separation stated by a train to slow down from its current speed while taking into account the braking characteristics of the train ahead. The trains move synchronously in platoons by exchanging information about position, speed and acceleration via wireless vehicle-to-vehicle communication. This matches the development trend in a decentralised railway traffic management system as proposed by Yong et al. (2017) and would enhance performance if the goals are aligned. Another main advantage of VC is that trains can be flexibly scheduled based on the travel demand given the virtual/wireless coupling and decoupling procedures of the trains while in operation. With dynamic allocation of rolling stock design to demand patterns and more space on board due to a better organised management of trips, passengers can experience increased comfort and safety in trains.

VC now, as one of the most promising advanced technologies in railway signalling, is steadily gaining ground within the railway industry. Scenarios and steps to increase the line capacity following the VC principles have been presented in Fenner (2016) and Schumann (2017). The aim of these scenarios is mainly to increase the line capacity following the VC principles. Di Meo et al. (2020) studied operational principles and communication configurations of VC in several stochastic scenarios by using a numerical analysis approach. Felez et al. (2019) used a predecessor-following information structure that minimises a function of desired safe relative distance, the speed of the predecessor train and the jerk. Flammini et al. (2019) analysed the effects of introducing VC according to the extension of the current ETCS L3 standard, by maintaining the backward compatibility with the information exchanged between the trains and the trackside infrastructure. Quaglietta et al. (2020) illustrated preliminary capacity benefits of VC over moving block for a mainline case study in the UK, by applying a multi-state train following model. They found that for the scenario of trains having service stops and using different routes, VC can decrease the maximum headways by 79%, 77% and 43% when compared to Train Protection Warning System, ETCS Level 2 and Level 3, respectively. Cats and Haverkamp

[23] https://www.railtech.com/innovation/2022/08/02/how-virtual-coupling-can-bring-the-needed-rail-capacity-for-the-future/?gdpr=accept

(2018) determined the capacity requirements of an automated rail-demand responsive transit system and discussed its prospects and feasibility. Aoun et al. (2021) implemented an innovative multi-criteria analysis framework to compare the impacts of VC with the ones of moving block and conventional signalling with respect to several criteria. They concluded that VC can have a positive homogenising effect on mainline railways due to the possibility for trains to follow each other in synchronised platoons, and the urban and regional railway market segments would be favoured to introduce the deployment of VC.

The implementation of VC varies based on several market segments and on the duration of a set of step-changes in the operational, technological and business domains (Aoun et al., 2023). Pandemics could impose severe amendments to the critical paths towards the deployment of VC mainly caused by delays in completing specific step-changes. This would particularly have an effect on mainline railways since results in Aoun et al. (2023) showed that this market segment is the most critical and imposes longer durations of step-changes particularly for the research and innovation on longitudinal motion control systems in convoys, as well as the integrated traffic management and train control. The scenario-based roadmaps defined for VC impact five prominent factors for the deployment of any technology/transportation project, namely demand, CO2 emissions, CAPEX, OPEX and regulatory approval. As the future time horizons are associated with uncertainties represented in the roadmaps, the timelines of the step-changes can play a significant impact on societal, environmental and economic factors. For instance, shorter timelines mean that the environment would rapidly become less polluted and that the need for high investment costs and payments for staff would be reduced.

When VC is deployed and with shorter train compositions and more frequent train services, it can provide a higher customer satisfaction with the deliverance of a more flexible service in line with the travel needs of the passengers. This reduces overcrowding since the trains would occupy fewer people and the services would be designed according to the passengers' destinations, thus reducing the necessity of interchanges for the users. VC can also provide benefits for railway service providers by using carriages that can be flexibly planned according to the demand. Therefore, VC can provide a better quality of train services to both passengers and the railway industry even when there are changes in demand patterns, e.g., during pandemics.

4. Conclusion

In this paper, we determined the challenges arising due to COVID-19 and pandemics in general and subsequently proposed several solutions to tackle those challenges in rail transport. Based on the literature and news that emerged during and after the pandemic, we defined five research questions that cover multidisciplinary aspects from both the demand and supply sides of rail transport, including passenger demand management, freight demand management, service design, automation and decentralisation as well as advanced railway technologies. We further synthesised research directions by searching relevant studies with a set of selection criteria. These recognised and concluded important promising lines of research should gain more attention in the future to provide more efficient, effective and sustainable transport services.

Different phases of the pandemic should be tackled with corresponding goals from the rail sector. Conventionally, rail transport is geared to achieve its designed societal goal such that its way of organisation is challenged during COVID-19 because of the changed mobility pattern, regulations and reduced services. The prioritised public health in the rail sector during the pandemic results in the necessary countermeasures to tackle virus spreading and avoid crowdedness. However, these strategies cannot be sustained without adjustments along with the development of the pandemic as rail freight recovers faster with a more resilient performance and the limited capacity has significant adverse effects on the passenger services when not all demands can be satisfied. After the pandemic, revenue recovery and other societal objectives should again become the limelight of the rail sector with special attention on the supply side to handle the absenteeism, staff shortage and resultant dropped service performance.

To this end, we provided effective strategies adopted during the pandemic and also detailed long-term solutions to support a resilient rail transport system and society. For an improved understanding of the demand, we offered solutions from strategic, tactical and operational levels for both passengers and freight. These solutions primarily focus on analysing the changed mobility pattern and promoting a more efficient rail freight service. To handle the issues on the supply side, we proposed utilising automation, decentralisation and future advanced technologies. Therefore, a redesigned service can be presented throughout different phases of the pandemic and beyond. To make some of these solutions realisable, such as monitoring and improving planning and operations for passengers, freight operators as well as infrastructure managers, it is necessary to further develop relevant Artificial Intelligence, Internet of Things and optimisation approaches. Investment in advanced tech-enabled systems may focus on the present-day needs for infection containment as well as creating new services and capabilities. Rail transport planners and agencies need to employ data-driven analytics and optimisation to better understand locations and commuter behaviour for the future. Greater initiatives to evolve rail transport systems should not only safeguard public health and safety but also consider passenger experience and freight demand to restore performance and reach expected societal goals.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Albrecht, A., Howlett, P., Pudney, P., Vu, X., Zhou, P., 2016. The key principles of optimal train control—Part 1: Formulation of the model, strategies of optimal type, evolutionary lines, location of optimal switching points. Transp. Res. B 94, 482–508.

Almlöf, E., Rubensson, I., Cebecauer, M., Jenelius, E., 2021. Who continued travelling by public transport during COVID-19? Socioeconomic factors explaining travel behaviour in Stockholm 2020 based on smart card data. Eur. Transp. Res. Rev. 13, 31.

Anke, J., Francke, A., Schaefer, L.M., Petzoldt, T., 2021. Impact of SARS-CoV-2 on the mobility behaviour in Germany. Eur. Transp. Res. Rev. 13, 10.

Aoun, J., Quaglietta, E., Goverde, R.M.P., 2023. Roadmap development for the deployment of virtual coupling in railway signalling. Technol. Forecast. Soc. Change 189, 122263.

Aoun, J., Quaglietta, E., Goverde, R.M.P., Scheidt, M., Blumenfeld, M., Jack, A., Redfern, B., 2021. A hybrid delphi-AHP multi-criteria analysis of moving block and virtual coupling railway signalling. Transp. Res. C 129, 103250.

Awad-Núñez, S., Julio, R., Gomez, J., Moya-Gómez, B., González, J.S., 2021. Post-COVID-19 travel behaviour patterns: impact on the willingness to pay of users of public transport and shared mobility services in Spain. Eur. Transp. Res. Rev. 13, 20.

Aydin, N.Y., Duzgun, H.S., Heinimann, H.R., Wenzel, F., Gnyawali, K.R., 2018. Framework for improving the resilience and recovery of transportation networks under geohazard risks. Int. J. Disaster Risk Reduct. 31, 832–843.

Bešinović, N., 2020. Resilience in railway transport systems: a literature review and research agenda. Transp. Rev. 40 (4), 457–478.

Bešinović, N., De Donato, L., Flammini, F., Goverde, R.M.P., Lin, Z., Liu, R., Marrone, S., Nardone, R., Tang, T., Vittorini, V., 2021. Artificial intelligence in railway transport: Taxonomy, regulations, and applications. IEEE Trans. Intell. Transp. Syst. 23 (9), 14011–14024.

Bešinović, N., Szymula, C., 2021. Estimating impacts of covid19 on transport capacity in railway networks. Eur. J. Transp. Infract. Res. 21 (1), 1–18.

Biscayart, C., Angeleri, P., Lloveras, S., Chaves, T.d.S.S., Schlagenhauf, P., Rodríguez-Morales, A.J., 2020. The next big threat to global health? 2019 novel coronavirus (2019-nCoV): What advice can we give to travellers?–Interim recommendations January 2020, from the Latin-American society for Travel Medicine (SLAMVI). Travel Med. Infect. Dis. 33, 101567.

Brockmeyer, F., Heistermann, J., Schulz, M., 2020. Verkehrswende: aufgehoben oder aufgeschoben? – Die zweite Welle und ihre Konsequenzen für den "OPNV. Technical Report, civity Management Consultants.

Bruzzone, F., Cavallaro, F., Nocera, S., 2021. The integration of passenger and freight transport for first-last mile operations. Transp. Policy 100, 31–48.

Campisi, T., Basbas, S., Skoufas, A., Akgün, N., Ticali, D., Tesoriere, G., 2020. The impact of COVID-19 pandemic on the resilience of sustainable mobility in Sicily. Sustainability 12, 8829.

Canca, D., Zarzo, A., 2017. Design of energy-efficient timetables in two-way railway rapid transit lines. Transp. Res. B 102, 142–161.

Cats, O., Haverkamp, J., 2018. Strategic planning and prospects of rail-bound demand responsive transit. Transp. Res. Rec. 2672 (8), 404–410.

Chan, H.F., Moon, J.W., Savage, D.A., Skali, A., Torgler, B., Whyte, S., 2021. Can psychological traits explain mobility behavior during the COVID-19 pandemic? Soc. Psychol. Pers. Sci. 12 (6), 1018–1029.

Cheng, G., Guo, D., Shi, J., Qin, Y., 2018. Planning city-wide package distribution schemes using crowdsourced public transportation systems. IEEE Access 7, 1234–1246.

Chevrier, R., Pellegrini, P., Rodriguez, J., 2013. Energy saving in railway timetabling: A bi-objective evolutionary approach for computing alternative running times. Transp. Res. C 37, 20–41.

Coppola, P., De Fabiis, F., 2021. Impacts of interpersonal distancing on-board trains during the COVID-19 emergency. Eur. Transp. Res. Rev. 13, 13.

Cunillera, A., Bešinović, N., Lentink, R.M., Van Oort, N., Goverde, R.M.P., 2023. A literature review on train motion model calibration. IEEE Trans. Intell. Transp. Syst. Early Access.

Currie, G., Jain, T., Aston, L., 2021. Evidence of a post-COVID change in travel behaviour–Self-reported expectations of commuting in Melbourne. Transp. Res. A 153, 218–234.

Dai, J., Liu, Z., Li, R., 2021. Improving the subway attraction for the post-COVID-19 era: The role of fare-free public transport policy. Transp. Policy 103, 21–30.

Das, S., Boruah, A., Banerjee, A., Raoniar, R., Nama, S., Maurya, A.K., 2021. Impact of COVID-19: A radical modal shift from public to private transport mode. Transp. Policy 109, 1–11.

De Haas, M., Faber, R., Hamersma, M., 2020. How COVID-19 and the Dutch 'intelligent lockdown' change activities, work and travel behaviour: Evidence from longitudinal data in the Netherlands. Transp. Res. Interdiscip. Perspect. 6, 100150.

Di Meo, C., Di Vaio, M., Flammini, F., Nardone, R., Santini, S., Vittorini, V., 2020. ERTMS/ETCS virtual coupling: Proof of concept and numerical analysis. IEEE Trans. Intell. Transp. Syst. 21 (6), 2545–2556.

Felez, J., Kim, Y., Borrelli, F., 2019. A model predictive control approach for virtual coupling in railways. IEEE Trans. Intell. Transp. Syst. 20 (7), 2728–2739.

Fenner, D., 2016. UK railway safety & standards board research into 'closer running'. Inst. Railw. Signal Eng. (IRSE) NEWS 225, 11–15.

Ferreira, M.C., Fontesz, T., Costa, V., Dias, T.G., Borges, J.L., e Cunha, J.F., 2017. Evaluation of an integrated mobile payment, route planner and social network solution for public transport. Transp. Res. Procedia 24, 189–196.

Flammini, F., De Donato, L., Fantechi, A., Vittorini, V., 2022. A vision of intelligent train control. In: Reliability, Safety, and Security of Railway Systems. Modelling, Analysis, Verification, and Certification: 4th International Conference, RSSRail 2022, Paris, France, June 1–2, 2022, Proceedings. pp. 192–208.

Flammini, F., Marrone, S., Nardone, R., Petrillo, A., Santini, S., Vittorini, V., 2019. Towards railway virtual coupling. In: 2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference. ESARS-ITEC 2018, pp. 1–6.

Ghilas, V., Demir, E., Van Woensel, T., 2013. Integrating passenger and freight transportation: Model formulation and insights. In: Proceedings of the 2013 Beta Working Papers, Vol. 441. Technische Universiteit Eindhoven, Eindhoven, The Netherlands, pp. 1–23.

Gkiotsalitis, K., Cats, O., 2020. Public transport planning adaption under the COVID-19 pandemic crisis: literature review of research needs and directions. Transp. Rev. 41 (3), 374–392.

Gkiotsalitis, K., Cats, O., 2022. Optimal frequency setting of metro services in the age of COVID-19 distancing measures. Transp. A Transp. Sci. 18 (3), 807–827.

Goodwin, P., 2008. Policy incentives to change behaviour in passenger transport. In: OECD International Transport Forum. Leipzig, pp. 1–35.

Goverde, R.M.P., Bešinović, N., Binder, A., Cacchiani, V., Quaglietta, E., Roberti, R., Toth, P., 2016. A three-level framework for performance-based railway timetabling. Transp. Res. C 67, 62–83.

Haque, M.T., Hamid, F., 2022. An optimization model to assign seats in long distance trains to minimize SARS-CoV-2 diffusion. Transp. Res. A 162, 104–120.

Haque, M.T., Hamid, F., 2023. Social distancing and revenue management—A post-pandemic adaptation for railways. Omega 114, 102737.

Hu, M., Lin, H., Wang, J., Xu, C., Tatem, A.J., Meng, B., et al., 2020. Risk of coronavirus disease 2019 transmission in train passengers: an epidemiological and modeling study. Clin. Infect. Dis. 72 (4), 604–610.

Jenelius, E., 2020. Personalized predictive public transport crowding information with automated data sources. Transp. Res. C 117, 102647.

Jenelius, E., Cebecauer, M., 2020. Impacts of COVID-19 on public transport ridership in Sweden: Analysis of ticket validations, sales and passenger counts. Transp. Res. Interdiscip. Perspect. 8, 100242.

Jonaitis, J., 2007. Planning of the amount of trains needed for transportation by rail. Transport 22 (2), 83–89.

Kang, L., Xiao, Y., Sun, H., Wu, J., Luo, S., Buhigiro, N., 2022. Decisions on train rescheduling and locomotive assignment during the COVID-19 outbreak: A case of the Beijing-Tianjin intercity railway. Decis. Support Syst. 161, 113600.

Khan, M.Z., Khan, F.N., 2020. Estimating the demand for rail freight transport in Pakistan: A time series analysis. J. Rail Transp. Plan. Manag. 14, 100176.
Knie, A., Zehl, F., Schelewsky, M., 2021. Ergebnisse aus Beobachtungen per repr"asentativer Befragung und erg"anzendem Mobilit"atstracking bis Ende Juli. Mobilitätsreport 5.
Kniffin, K.M., Narayanan, J., Anseel, F., Antonakis, J., Ashford, S.P., Bakker, A.B., et al., 2021. COVID-19 and the workplace: Implications, issues, and insights for future research and action. Am. Psychol. 76 (1), 63–77.
Krauth, M., Ribesmeier, M., 2022. Impacts of long distance high speed rail freight transportation on inner-city logistics and development. In: Urban Transitions 2022. Barcelona, Spain, 08.11.2022–10.11.2022, Springer.
Krishnakumari, P., Cats, O., 2020. Virus Spreading in Public Transport Networks: The Alarming Consequences of the Business as Usual Scenario. TU Delft, Delft, https://www.linkedin.com/pulse/virus-spreading-public-transport-networks-alarming-usual-krishnan/.
Ku, D., Yeon, C., Lee, S., Lee, K., Hwang, K., Li, Y.C., Wong, S.C., 2021. Safe traveling in public transport amid COVID-19. Sci. Adv. 7 (43), eabg3691.
Laage, G., Frejinger, E., Savard, G., 2021. A two-step heuristic for the periodic demand estimation problem. arXiv preprint arXiv:2108.08331.
Li, X., Lo, H.K., 2014. Energy minimization in dynamic train scheduling and control for metro rail operations. Transp. Res. B 70, 269–284.
Li, T., Rong, L., Zhang, A., 2021. Assessing regional risk of COVID-19 infection from Wuhan via high-speed rail. Transp. Policy 106, 226–238.
Li, Y., Zhang, R., Zhao, J., Molina, M.J., 2020. Understanding transmission and intervention for the COVID-19 pandemic in the United States. Sci. Total Environ. 748, 141560.
Marcelli, E., Pellegrini, P., 2021. Literature review toward decentralized railway traffic management. IEEE Intell. Transp. Syst. Mag. 13 (3), 234–252.
Mashrur, S.M., Wang, K., Habib, K.N., 2022. Will COVID-19 be the end for the public transit? Investigating the impacts of public health crisis on transit mode choice. Transp. Res. A 164, 352–378.
Masson, R., Trentini, A., Lehuédé, F., Malhéné, N., Péton, O., Tlahig, H., 2017. Optimization of a city logistics transportation system with mixed passengers and goods. EURO J. Transp. Logist. 6 (1), 81–109.
Nobis, C., Kolarova, V., 2022. The decline of public transport during the COVID-19 pandemic and the impact of the 9-euro-ticket in the summer 2022 - results of a multiple-wave study in Germany. In: European Transport Conference 2022. Milan, Italy, 07.09.2022–09.09.2022, pp. 1–14.
Oliveira, L.C., Fox, C., Birrell, S., Cain, R., 2019. Analysing passengers' behaviours when boarding trains to improve rail infrastructure and technology. Robot. Comput.-Integr. Manuf. 57, 282–291.
Pan, M., Ryan, A., 2022. The impact of confirmation bias on perceived health risk of using public transit: An evaluation during the pandemic. J. Transp. Health 25, 101428.
Patel, C.K., Selvam, V.K., Sahu, D.K., 2020. Railway anaesthesiologists and Indian railway COVID-19 management system. Indian J. Anaesth. 64 (2), 132–135.
Peftitsi, S., Jenelius, E., Cats, O., 2021. Evaluating crowding in individual train cars using a dynamic transit assignment model. Transp. B Transp. Dyn. 9 (1), 693–711.
Quaglietta, E., Wang, M., Goverde, R.M.P., 2020. A multi-state train-following model for the analysis of virtual coupling railway operations. J. Rail Transp. Plan. Manag. 15, 100195.
Rao, A.V., Benson, D.A., Darby, C., Patterson, M.A., Francolin, C., Sanders, I., Huntington, G.T., 2010. Algorithm 902: GPOPS, A MATLAB software for solving multiple-phase optimal control problems using the gauss pseudospectral method. ACM Trans. Math. Software 37 (2), 1–39.
Rasca, S., Markvica, K., Ivanschitz, B.P., 2021. Impacts of COVID-19 and pandemic control measures on public transport ridership in European urban areas – The cases of Vienna, Innsbruck, Oslo, and Agder. Transp. Res. Interdiscip. Perspect. 10.
Ribesmeier, M., 2023. Impacts of inner-city consolidation centres on route distances, delivery times and delivery costs. In: Proceedings of the 12th International Scientific Conference on Mobility and Transport. Springer Nature Singapore, Singapore, pp. 157–173.
Scheepmaker, G.M., Goverde, R.M.P., Kroon, L.G., 2017. Review of energy-efficient train control and timetabling. European J. Oper. Res. 257 (2), 355–376.
Schofer, J.L., Mahmassani, H.S., Ng, M.T., 2022. Resilience of US rail intermodal freight during the COVID-19 pandemic. Res. Transp. Bus. Manag. 43, 100791.
Schumann, T., 2017. Increase of capacity on the Shinkansen high-speed line using virtual coupling. Int. J. Transp. Dev. Integr. 1 (4), 666–676.
Seisenberger, M., Ter Beek, M.H., Fan, X., Ferrari, A., Haxthausen, A.E., James, P., Lawrence, A., Luttik, B., Van de Pol, J., Wimmer, S., 2022. Safe and secure future AI-driven railway technologies: challenges for formal methods in railway. In: Leveraging Applications of Formal Methods, Verification and Validation. Practice: 11th International Symposium, ISoLA 2022, Rhodes, Greece, October 22–30, 2022, Proceedings, Part IV. pp. 246–268.
Shang, F., Zhan, J., Chen, Y., 2018. Distributed model predictive control for train regulation in urban metro transportation. In: 2018 21st International Conference on Intelligent Transportation Systems. ITSC, pp. 1592–1597.
Shaw, N., Eschenbrenner, B., Baier, D., 2022. Online shopping continuance after COVID-19: A comparison of Canada, Germany and the United States. J. Retail. Consum. Serv. 69, 103100.
Tirachini, A., Cats, O., 2020. COVID-19 and public transportation: Current assessment, prospects, and research needs. J. Public Transp. 22 (1), 1.
Ton, D., Arendsen, K., De Bruyn, M., Severens, V., Van Hagen, M., Van Oort, N., Duives, D., 2022. Teleworking during COVID-19 in the Netherlands: Understanding behaviour, attitudes, and future intentions of train travellers. Transp. Res. A 159, 55–73.
Trentini, A., Mahléné, N., 2010. Toward a shared urban transport system ensuring passengers & goods cohabitation. TeMA-J. Land Use Mobil. Environ. 3 (2).
UIC COVID-19 Task Force, 2020. Management of COVID-19, Potential Measures to Restore Confidence in Rail Travel Following the COVID-19 Pandemic. UIC.
Vaezi, A., Verma, M., 2017. An analytics approach to dis-aggregate national freight data to estimate hazmat traffic on rail-links and at rail-yards in Canada. J. Rail Transp. Plan. Manag. 7 (4), 291–307.
Van der Horst, C.G., 2020. Public Transport During Coronavirus Outbreak: A Comparison of Public Transport Companies' Actions (Bachelor's thesis). TU Delft, https://nielsvanoort.weblog.tudelft.nl/files/2020/06/Final_Report_Gerben_van_der_Horst_4673417.pdf.
Van Leeuwen, M., Klerks, Y., Bargeman, B., Heslinga, J., Bastiaansen, M., 2020. Leisure will not be locked down–insights on leisure and COVID-19 from the Netherlands. World Leis. J. 62 (4), 339–343.
Van Lieshout, R., Van den Akker, J., Mendes Borges, R., Druijf, T., Quaglietta, E., 2022. Microscopic simulation of decentralized dispatching strategies in railways. J. Rail Transp. Plan. Manag. 23, 100335.
Van Oort, N., Cats, O., 2020. Public Transport and Shared Mobility During and After a Social Distancing Society. TU Delft, Delft, https://www.tudelft.nl/en/2020/transport-institute/public-transport-and-shared-mobility-during-and-after-a-social-distancing-society.
Vega-Gonzalo, M., Gomez, J., Christidis, P., 2023. How has COVID-19 changed private car use in European urban areas? An analysis of the effect of socio-economic characteristics and mobility habits. Transp. Res. A 172, 103679.
Wang, P., Bešinović, N., Goverde, R.M.P., Corman, F., 2022a. Improving the utilization of regenerative energy and shaving power peaks by railway timetable adjustment. IEEE Trans. Intell. Transp. Syst. 23 (9), 15742–15754.
Wang, Y., De Schutter, B., Van den Boom, T.J.J., Ning, B., 2013. Optimal trajectory planning for trains – A pseudospectral method and a mixed integer linear programming approach. Transp. Res. C 29, 97–114.
Wang, P., Goverde, R.M.P., 2016. Multiple-phase train trajectory optimization with signalling and operational constraints. Transp. Res. C 69, 255–275.
Wang, P., Goverde, R.M.P., 2019. Multi-train trajectory optimization for energy-efficient timetabling. European J. Oper. Res. 272 (2), 621–635.
Wang, H., Noland, R., 2021. Bikeshare and subway ridership changes during the COVID-19 pandemic in New York City. Transp. Policy 106, 262–270.
Wang, Z., Pel, A.J., Verma, T., Krishnakumari, P., Van Brakel, P., Van Oort, N., 2022b. Effectiveness of trip planner data in predicting short-term bus ridership. Transp. Res. C 142, 103790.
Wang, Z., Quaglietta, E., Bartholomeus, M.G.P., Goverde, R.M.P., 2022c. Assessment of architectures for Automatic Train Operation driving functions. J. Rail Transp. Plan. Manag. 24, 100352.

Wang, P., Trivella, A., Goverde, R.M.P., Corman, F., 2020. Train trajectory optimization for improved on-time arrival under parametric uncertainty. Transp. Res. C 119, 102680.

Windle, D., 2020. The effects of COVID-19 on freight rail in North America. INFROMS RAS Newsl. 4–5.

Yang, Z., Song, R., 2020. Transport scheme design for emergency supplies carried by high-speed passenger trains. In: 2020 IEEE 5th International Conference on Intelligent Transportation Engineering. ICITE 2020, pp. 551–555.

Yin, Y., Li, D., Zhang, S., Wu, L., 2021. How does railway respond to the spread of COVID-19? Countermeasure analysis and evaluation around the world. Urban Rail Transit 7 (1), 29–57.

Yong, C., Ullrich, M., Jiajian, L., 2017. Decentralized, autonomous train dispatching using swarm intelligence in railway operations and control. In: 7th International Conference on Railway Operations Modelling and Analysis - RailLille2017. pp. 521–540.