Public Transport (2024) 16:419–447
https://doi.org/10.1007/s12469-023-00344-5

ORIGINAL RESEARCH

State of the art of passenger redirection during incidents in public transport systems, considering capacity constraints

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Accepted: 20 September 2023 / Published online: 5 December 2023

Abstract

This paper gives a comprehensive insight into the investigations done in passenger redirection during incidents in public transport systems. In public transport operations, incidents such as traffic accidents, deployment of emergency forces, or technical failures happen every day and disrupt the service. Most of the investigations done in the field of incident management focus on the readjustment of the supply towards the incident situation and are therefore referred to as *supply-centric* part of incident management. However, especially in recent years, more and more investigations have also been done on the *passenger-centric* part of incident management. These rather focus on the effects of incidents on passengers or even include them in the solution of the incident situation, either by informing them adequately about the given situation (passive redirection) or by providing them with concrete path advice (active redirection). The results show that adequate passenger information during incidents can reduce the average delay of affected passengers and support the recovery of the public transport system. This improves the reliability of a public transport system and boosts its attractiveness.

Keywords Public transport · Passenger redirection · Incident management · Disruption · Literature review

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1 Introduction

In daily public transport (PT) operations, incidents occur and disturb the PT service and its schedules. Incidents are understood here as any event which disrupts the PT service. Typical examples are traffic accidents, technical failures, falling passengers, and similar events. Those events cause disturbances such as delays and trip cancellations. From an operator's point of view, dispositive measures, like rerouting PT lines or dispatching extra vehicles, need to be carried out to return the service to its schedule (Ceder 2016, pp. 309–332; Bachmann et al. 2022; Briem 2023). These measures focus on adjusting the PT supply to the present incident situation to mitigate its negative consequences (e.g. delays) and the recovery of the PT service to its schedule. They can, therefore, be understood as the *supply-centric* part of incident management. In contrast, the *passenger-centric* part of incident management focuses on the passengers' needs. It considers the number of affected passengers, their respective origin–destination (OD) relations, as well as their possibility of completing their trip despite an ongoing incident. Their consideration can also influence decisions on dispositive measures.

From a passenger's point of view, incidents firstly mean a reduction of reliability and a more considerable deviation from the planned arrival times. During incidents, they can adjust their trip plans according to a disposition timetable, which depicts the PT service as shaped by the incident and the dispositive measures taken in its consequence. Thereby, it represents the PT service as it is operating during the incident. If passengers adjust their trips according to the disposition timetable, they can contribute to the improvement of the reliability of their planned trips. However, to be able to do so, passengers need to be informed adequately about the incident and the temporal changes to the PT service. This kind of passenger information (PI) enables passengers to become part of the solution to incident situations either by redirecting themselves based on the given PI (passive redirection) or by being redirected through given path advice (active redirection). Therefore, passenger redirection is understood here as a crucial part of *passenger-centric* incident management (PCIM). Passenger redirection supports travellers in adjusting their trips to reduce travel time under disrupted conditions. Considering the PT system's remaining capacity is critical to avoid secondary incidents by over-demanding alternative paths (Cats and Jenelius 2014).

It needs to be emphasised that *supply-centric* and *passenger-centric* incident management do not replace but complement each other. Therefore, PCIM is understood here as an extension or advancement of *supply-centric* incident management. The detection of incidents, including the determination of its location, an estimation of its duration, and affected PT services, is considered here as part of *supply-centric* incident management and thereby as known prerequisites for PCIM. Hence, they are not further analysed in this work; nor does this paper focus on dispositive measures, even though they might consider passenger needs. The purpose of this paper is to give a comprehensive overview of the investigations and projects which have been done on *capacity-aware passenger redirection* (CAPR) in mass PT systems (e.g., bus, tram, light rail transit (LRT), metro, trains) and to present its state of the art.

The body of this paper is structured as follows: The second section gives a short insight into today's incident management in PT and explains the background of this paper. The third section describes the methodical approach with which the reviewed literature has been acquired and analysed. The fourth section introduces and summarises studies that have been done in the area of CAPR and divides them into academic investigations and approaches in practice. The fifth section compares the similarities and differences between the introduced works. Based on the findings, requirements for CAPR are derived in the sixth section. Additionally, the gap between these requirements, the academic investigations, and the approaches in practice are discussed. The last section concludes the findings and provides an outlook on the field of PCIM.

2 Background

In practice, any issues concerning the incident management of PT are tackled in the operations control centres (OCCs) of PT operators. OCC's personnel, the dispatchers, use operational software to monitor the PT service and detect deviations from the schedule. Pangilinan et al. (2008) describe such an Intermodal Transport Control System (ITCS) in detail. Vehicles of modern PT systems are equipped with localisation and communication technologies, which enable the ITCS to track their positions and compare them to their schedule. It determines their deviation from the schedule and compares it continuously to pre-defined thresholds, stressing deviations that exceed the threshold values. Therefore, the dispatchers in OCCs have a clear overview of the service status and can take dispositive measures to keep the service as close to schedule as possible. Whenever PT drivers encounter an incident, they report it to the OCC, the most commonly used way of detecting incidents in practice (Bachmann et al. 2022). These can be severe incidents such as line blockages, vehicle breakdowns, or accidents, or less severe, for example, door failures or signal malfunctions, deployment of emergency forces, or other events which disrupt the planned PT service. The dispatchers manage the situation by taking dispositive measures to return the service to normal operations and mitigate the negative impacts of the incident on the PT system as effectively as possible (Carrel et al. 2010; Bachmann et al. 2022; Briem 2023). Typical dispositive measures are rerouting, short-turning of PT vehicles or whole lines on one or both sides (line-splitting) of an incident, dispatching extra PT vehicles, and measures to restore the scheduled headway with holding or stop(s) skipping strategies, among others (Ceder 2016, pp. 309–332; Bachmann et al. 2022; Briem 2023). Rail-bound services like the metro and trains have different characteristics than buses. Rail services often cannot be rerouted due to wide-meshed railway networks. Buses offer more flexibility in movement due to their operations on roads, which usually provide for a denser meshed network compared to railway networks. These *supply-centric* measures have been widely investigated and reviewed in the literature. Ibarra-Rojas et al. (2015), Ceder (2016, pp. 309–332), Gkiotsalitis and Cats (2021); Ge et al. (2022) give comprehensive overviews of studies on these and other dispositive measures.

In the event of significant PT schedule changes, travellers using the affected services need to be informed as quickly and accurately as possible. That way, they can adjust their trip plans. Typical channels to inform travellers are collective media: speaker announcements, as well as dynamic PI, displays at stops and in PT vehicles, the operators' representation on their websites and in social media, or individualised media like trip planner mobile phone applications of PT operators or third-parties, e.g., CityMapper, GoogleMaps, or Öffi (Citymapper 2023; Google 2023; Schildbach 2023).

ITCS supports broadcasting real-time PI to manifold media. In complex situations with multiple dispositive measures that alter service patterns, the effort to maintain automated real-time information often exceeds the system's capabilities, which cannot automatically adapt to spontaneously re-planned schedules. Thus, operators often switch to manual information provision using pre-defined text templates. Since every incident has its characteristics in terms of its location, severity, duration, and affected services, in most cases, these pre-defined texts need to be manually adjusted to the respective incident (Bachmann et al. 2022).

With its extended systems, the OCC is the heart of incident management in PT. Figure 1 shows the rough system architecture of a state-of-the-art ITCS, including the OCC and PI systems (VDV 2001, pp. 182–183). Whereas communication with drivers and emergency forces (e.g. police, fire department) is done verbally via phone and radio, position and corresponding delay information is exchanged automatically between PT vehicles and the OCC. The dynamic PI displays and speaker announcements are controlled by the OCC (Briem et al. 2020; Bachmann

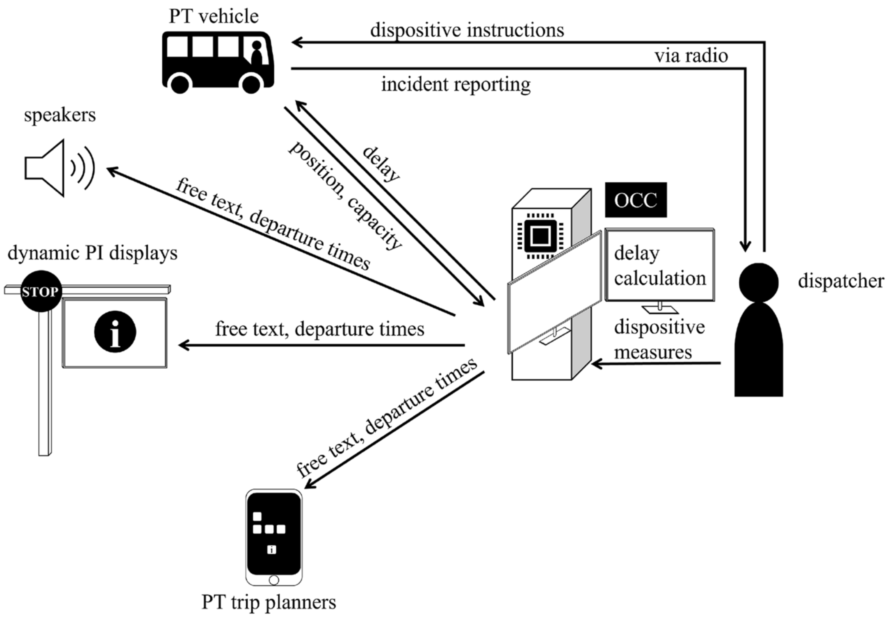

Fig. 1 System architecture of an ITCS

et al. 2022). Trip planners, as part of websites and mobile phone applications of the PT operators and third parties, however, get the timetable information through specific interfaces. One widely spread interface standard is the General Transit Feed Specification (GTFS) (Wong 2013). Moreover, in some countries, an interface has been established from the official sides, for example, in Germany by the Association of German Transport Companies [Translated from German: Verband Deutscher Verkehrsunternehmen] (VDV) who developed the VDV454 (VDV 2018a). Such interfaces provide access to the real-time timetable as it also exists in the ITCS. Hence, the trip planners can propose paths across the PT system based on real-time schedule information.

3 Methodology

This section describes the methodological approach used to acquire, select, and analyse the literature about CAPR.

3.1 Literature acquisition and selection

For the past four years, the databases Web of Science, Google Scholar, and Science Direct have been frequently searched (Clarivate 2022; Google 2022; Elsevier 2023). In addition, for the preparation of this paper, the Transport Research International Documentation (TRID) of the Transporation Research Board (TRB) of the US National Academies has also been used (National Academy of Sciences 2023). The goal of these searches has been collecting works investigating the potential or effect of passive or active passenger redirection during incidents in PT systems.

The used keywords included public transport or transit, incident or disruption management, passenger or traveller information, and redirection or redirecting or rerouting. The results of these searches and the references of the found publications have then been scanned to select the ones which can be associated with CAPR as understood here (Sect. 1). Exclusion criteria cover, for example, works that do not consider any kind of PI or other communication with the travellers during incidents and works which did not contain capacity analysis or constraints in any way, either by analysing the effects of incident information dissemination on the occupancy levels and exceedance of the system's capacity or by involving capacity constraints in concrete path advice.

For a comprehensive overview of works done on CAPR we also looked for approaches conducted in practice. In a well-equipped PT system, its users are informed by the PT operator or agency about incidents and deviations to the schedule in the form of real-time expected arrival times. As elaborated in the previous section, dispatchers in OCCs are well aware of the state of the PT service. However, in which way such PI considers the available capacity in the system or if there are systems or approaches in practice which actively redirect passengers through the capacity-aware provision of path advice is another question that this paper aims to cast light on. In practice, the publication of results and developed methods are uncommon, which makes the search for corresponding reports and publications much more difficult. Especially when private companies, which have a commercial interest in developed tools and methods, are involved, detailed information about their approach is rarely published. Therefore, in addition to the previously described searches, websites of PT agencies, operators, ministries, and departments of transportation of selected countries have been searched to find corresponding project reports. To limit the effort of this approach, the focus has been put on countries from Europe, North America, and Oceania, which are expected to have a certain minimum level of PT service quality. Furthermore, only publications in English or German have been considered.

3.2 Literature analysis

A further goal of this paper is to reveal the differences between academic research and approaches done in practice. The publications about CAPR are very diverse in their developed approaches, conducted case studies, and used assumptions. Thus, it has been an important step to find criteria of the works that can be compared.

First, most works have the main goal of reducing passenger delay; however, each has an individual investigation focus. To make this visible, both the focus and the main goal of each work have been defined as comparison criteria. Second, as capacity is an essential element of CAPR, it is also used as a criterion of comparison, as some of the works just consider it, while others actively change the distribution of capacity as part of their approaches. Third, as CAPR depends on the possibility of communicating with travellers, PI is an essential part of it. Different aspects of PI are discussed here: PI content, describing what information is given to the travellers; PI schemes, depicting different assumptions regarding the timing and location of information dissemination; and PI channels, comparing the information channels considered by the papers. Fourth, the passengers, of course, are a criterion of comparison for CAPR, especially how they are represented and handled in the introduced methods, as well as to which extent compliance rates and path choice models are taken into account. That is, how does the influence of PI change the outcome of the path choice models (Prato 2009) or, in the case of concrete path advice, how many travellers are assumed to follow given advice? Fifth, the various resources used, such as simulation and calculation tools, as well as developed algorithms, are comparison criteria. Moreover, some of the works included optimisation. Sixth, the case studies of the publications are compared. This group of comparison criteria contains the used networks, the assumed incident properties, the source of the demand input, and which transportation modes have been taken into account. Finally, the considered *supply-centric* dispositive measures, which alter a PT service in accordance to an occurred incident, are defined as a criterion of comparison and, in connection to that, the works' consideration regarding the integration of their approaches in OCCs.

The analysis is used to derive requirements for CAPR and identify gaps in the state of the art, mainly concerning the contrast between academic investigations and approaches in practice. It discusses the necessary steps for real-life implementation of CAPR.

4 Literature review

This section briefly introduces the existing works in the area of CAPR and summarises their various features in Tables 1 and 2 for comparison. The papers and project reports are divided into academic investigations and approaches in practice. Whereas the umbrella focus of the academic investigations lies mainly on the modelling and simulation of optimal PI and its consequences for the PT users and system, the approaches in practice focus on the feasibility of CAPR systems with the currently available means of PT operators. Note that in Tables 1 and 2, among other entries, in some rows, it is differentiated between *"not mentioned"*, which means that the named criterion of CAPR is not mentioned in the corresponding reference; *"mentioned"* meaning the corresponding criterion is mentioned; however, it is not implemented in the introduced method of the particular reference, and *"considered"* which indicates that the criterion is mentioned and implemented in the introduced method of the corresponding reference.

4.1 Academic investigations

Twelve academic investigations in the field of CAPR have been found (Table 1). Cats and Jenelius (2014) develop a stochastic and dynamic notion of a PT system to study the vulnerability and betweenness centrality of a network in context with PI during incidents. The authors conclude that the importance of a link in a PT network depends not only on its betweenness centrality but, more importantly, on the available real-time PI during incidents. Moreover, to avoid secondary incidents, the authors suggest that the risks of such can be reduced through effective PI schemes and proactive PT fleet management.

Based on a rolling stock rescheduling model with dynamic passenger flows by Kroon et al. (2015), van der Hurk et al. (2018) developed an optimisation algorithm to advise passengers in case of disruptions in railway services. The authors infer that the best results are gained when not all affected passengers follow given path advice. Moreover, they deduce that the more precise the prediction of the demand flow, the better the rolling stock schedules and thereby the fewer capacity bottlenecks in the network.

Another piece of research in the field of CAPR is done by Müller-Hannemann et al. (2019). The authors collaborated with the German railway operator Deutsche Bahn (DB) to investigate passenger redirection in long-distance railway services in case of severe disruptions. A multi-commodity flow model with an event-activity network has been developed to find optimal alternative paths. It is inferred that capacity-aware redirection of passengers can reduce passenger delays and become more important with an increase in passenger demand. Furthermore, the computational bottleneck is the calculation of candidate path sets, which offers room for improvement.

Additional CAPR-related research is conducted by Zhu and Goverde (2019a). The authors developed a dynamic passenger reassignment model for travellers

Table 1 Overview of academic investigations

Reference	Cats and Jenelius (2014)	van der Hurk et al. (2018)	Müller-Hannemann et al. (2019)	Zhu and Goverde (2019a, 2020)	*Corman group*[1]	Bachmann et al. (2021, 2023)	Mo et al. (2023)
Focus	Passenger information	Path advice, capacity adjustment	Computational implementation of path advice	Passenger reassignment	Passenger behaviour	Path advice, capacity adjustment	Passenger flow distribution
Main goal	Analysis of PT system vulnerability	Reduction of passenger delay	Reduction of passenger delay	Reduction of passenger delay	Reduction of passenger delay	Reduction of passenger delay	Reduction of passenger delay
PT system's capacity	Considered	Considered, adjusted	Considered	Considered, adjusted	Considered	Considered, adjusted	Considered
PI content	Expected arrival times	Path advice, capacity shortages	Self-informing passengers assumed	Expected arrival times, train occupancies	Affected lines, disruption duration, vehicle capacities	Path advice	Path advice
PI schemes	At stops, clustered, network wide	Perfect information is assumed	Not mentioned	At stations and/or on trains	Timely, advanced information	Not mentioned	Not mentioned
PI channels	Mentioned	Not considered	Mentioned	Mentioned	Assuming appropriate channels	On all available channels	Mobile phone, websites, displays at stops
Passenger handling	Individually	Indivisible passenger groups	Indivisible passenger groups	Individually / indivisible passenger groups	Individually	Indivisible passenger groups	Indivisible passenger groups
Compliance rate / path choice	Path choice dependent on PI scheme	Deterministic, logarithmic compliance assumed	Not mentioned	Path choice dependent on accepted delay	Path choice dependent on PI scheme	Deterministic, logarithmic; van der Hurk et al. (2018) compliance assumed	Full compliance assumed
Used tools / algorithms	BusMezzo	ARSRU[2]	RAPTOR[3], Gurobi	Event-activity network, AFaO[4]	MATSim	SUMO, Gurobi / PCIM method	Event-based PT simulator
Optimisation	Mentioned	Minimise passenger delay	Minimise passenger delay	Passenger-operator balance	Minimise passenger delay	Mentioned, minimise passenger delay	Passenger flow distribution

Table 1 (continued)

Reference	Cats and Jenelius (2014)	van der Hurk et al. (2018)	Müller-Hannemann et al. (2019)	Zhu and Goverde (2019a, 2020)	*Corman group*[1]	Bachmann et al. (2021, 2023)	Mo et al. (2023)
Case study	Stockholm inner-city rapid PT network	Part of the Dutch railway network	Part of the German railway network	Part of the Dutch railway network	Zurich PT network	Simple artificial, Mandl network	Metro network of Chicago
Incident	0.5 h, five different disrupted lines	3 – 4 h, unsure period, link closure	Train cancellations based on historical data	1 – 2 h, link closure	3 h, link closure	0.5, 1 h(s), link closure	1 h, line suspension
Demand input data	Historical travel data	Historical travel data	Historical travel data	Assumed demand	Historical travel data	Assumed demand / Mandl (1979)	Historical travel data
Modes of transport	Urban PT modes	Railway	Railway	Railway	Urban PT modes	Buses	Metro
Dispositive measures	Disposition timetable, holding	Disposition timetable, rescheduling	Disposition timetable	Disposition timetable, short turning, flexible stopping, rescheduling	Disposition timetable, rescheduling, rerouting, capacity increases	Disposition timetable, rerouting, line-splitting	Disposition timetable
Integration in OCC	Mentioned	Mentioned	Not mentioned	Not mentioned	Not mentioned	Mentioned	Mentioned

[1]Leng and Corman (2020); Leng et al. (2020); Rahimi et al. (2021); Rahimi Siegrist and Corman (2021)

[2] Advice and Rolling Stock Rescheduling problem with Uncertainty

[3] Round-bAsed Public Transit Optimized Router (Delling et al. 2015)

[4] Adapted Fix and Optimise

Table 2 Overview of approaches in practice

Reference	BMVBW (2001)	BMVBS (2009)	BMVBS (2011)	BMVI (2019)	Tsuchiya et al. (2006)
Focus	Feasibility	Concept for procedures in an OCC	Prototype development and lab test	Customer trial of the prototypes from BMVBS (2009), technical aspects	Prototype development
Main goal	Feasible path advice	Feasible path advice	Feasible path advice	Feasible path advice	Feasible path advice
PT system's capacity	Considered	Considered	Qualitatively considered	Qualitatively considered	Qualitatively considered
PI content	Path advice	Path advice	Path advice, location, and kind of the incident	Path advice, location, and kind of the incident	Path advice
PI schemes	Mentioned	Informing clustered groups of passengers	Based on the concept of BMVBS (2009)	Based on the concept of BMVBS (2009)	PI presented at all stations
PI channels	Mentioned	Speakers, displays and PT trip planners	Mentioned	Mobile phones, PT trip planners	Displays and mobile phones
Passenger handling	Passenger collective	Passenger collective	Passenger collective	Passenger collective	Passenger collective
Compliance rate / Path choice	Not mentioned	Not mentioned	Not mentioned	Evaluated compliance rate via questionnaire	Not mentioned
Used tools / Algorithms	Purely conceptual work	PT trip planner / Pseudocodes	Own prototypes / Algorithms not disclosed	OCC infrastructure / Algorithms not disclosed	Own prototype using a database with pre-selected scenarios
Optimisation	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Case study	Exemplary visualisation	Calculated examples	Multiple scenarios in Berlin and Stuttgart	Test in real operation in Berlin	Offline prototype test
Incident	Definition of incident classes	0.5 h, different service disruptions	Mentioned, not specified	31 occurred incidents	Mentioned, not specified
Demand input data	Mentioned	Mentioned	Mentioned	Mentioned	Mentioned
Modes of transport	Urban PT modes	Urban PT modes	Urban PT modes	Urban PT modes	Railway
Dispositive measures	Considered	Considered	Considered	Not considered	Considered
Integration in OCC	Considered in system architecture	Concept planned as an integral part of an OCC	Prototypes planned as an integral part of an OCC	Prototypes linked to the OCC via standardised interfaces	Considered

affected by train cancellations and delays. With the help of an event-activity network, affected passengers are identified by comparing the planned paths with the disruption timetable. The authors understand the term disruption timetable as a timetable that takes into account all the cancellations and delays of trains due to the disruption. Compared to the disposition timetable, this does not include dispositive measures taken by the OCC. Their findings reveal that broadcasting information about changes to the service and overcrowded trains helps to reduce passenger delays. In addition, they show that service disruption is more severe for people who are already on their way when the incident occurs in contrast to travellers who start their trip after the beginning of the incident, as they are more flexible in re-planning their trip.

Zhu and Goverde (2020) take the passenger reassignment model from Zhu and Goverde (2019a) and a timetable rescheduling model from Zhu and Goverde (2019b), develop them further, and merge them into a passenger-oriented timetable rescheduling model. Several feasible rescheduled timetables exist according to each disruption characteristic and possible dispositive measures. The rescheduled timetable with the lowest general travel time of the passengers can be found. In contrast to the disruption timetable the rescheduled timetable can be understood as a disposition timetable. Zhu and Goverde (2020) conclude that with a passenger-oriented timetable rescheduling thousands of passenger minutes can be saved when trains are delayed by just ten minutes more compared to an operator's optimal solution. Since Zhu and Goverde (2019a, 2020) build upon each other and share the same authors, they share a column in Table 1. As Zhu and Goverde (2019a) present the CAPR aspects of their method, it is of bigger relevance to this literature review than Zhu and Goverde (2020).

Leng and Corman (2020) use the agent-based traffic simulation tool Multi-Agent Transport Simulation (MATSim) (Horni et al. 2016) to investigate the different impacts of information availability on the passengers' behaviour and delay. The overall goal is to minimise passenger delays caused by a disruption in a railway network. Leng and Corman (2020) conclude that PI is an important tool to reduce passenger delay during incidents. Furthermore, the authors conclude that there is only a slight advantage, in reference to passengers' inconvenience, in passengers knowing in advance about an incident compared to getting the information at the point of time the incident occurs.

Leng et al. (2020) broadened the work of Leng and Corman (2020) by investigating the mutual influence of dispositive measures such as rescheduling rolling stock and PI availability. In addition to the conclusion of Leng and Corman (2020), Leng et al. (2020) infer that partially cancelled train services are a significantly better solution for affected passengers than full cancellations.

Rahimi et al. (2021) further complement the investigations and findings of the previously mentioned two works and compare the different PI schemes with dispositive measures such as increasing the capacity of PT vehicles or raising the frequency on PT lines which are relevant for the passengers' alternative path options. Their conclusions point out that adequate PI during incidents can have similar effects as more costly infrastructural management actions. They also reveal that the increase in line capacity is most effective when picking specific lines (Rahimi et al. 2021).

Rahimi, Siegrist and Corman (2021) focus on the direct and indirect effects of incidents and PI dissemination during such incidents. They conclude that PI dissemination can have similar effects as providing unlimited capacities and that the better the PI is, the lower the negative effects on directly affected passengers; however, the higher the negative effects on indirectly affected passengers. As the last four mentioned works are connected, they are put together in one column in Table 1. They are referred to as *Corman group*, named after the last author of all four publications.

Bachmann et al. (2021) develop a method to redirect passengers during incidents in a PT bus system. The authors assume that concrete path advice is given to passengers affected by an incident. Bachmann et al. (2023) take the passenger redirection part of the conceptional framework from Bachmann et al. (2021), develop it further into an applicable method and implement it in a simulation study, using Simulation of Urban MObility (SUMO) (Lopez et al. 2018). These two works share one column in Table 1 as well. The authors conclude that path advice improves the situation of the directly affected as well as the not-directly affected passengers. Furthermore, Bachmann et al. (2021) show that a reallocation of capacity in forms of buses or an autonomous modular PT system, called DART (Rau et al. 2018), can further lower the delays. Bachmann et al. (2023) derive from their results that the incident duration has a significant influence on the results just like the crowding effects at bus stops influence the positive outcome of passenger redirection negatively.

The lastly introduced academic investigation has been published by Mo et al. (2023). Their approach focuses on the mathematical formulation of flow distribution during incidents. PT users, affected by an incident with the same OD and departure time are given an alternative path. The authors conclude that the insignificant improvement due to the consideration of demand uncertainties derives from a limited impact of the demand variations on the optimal path shares.

All these works of academic literature about CAPR have in common that they work on passenger redirection in PT, more precisely on passively or actively redirecting passengers by informing them during incidents. These works do this while considering the capacities and service state of the PT system. To better compare these works on CAPR their relevant features have been summarised in Table 1 and are compared in Sect. 5.

4.2 Approaches in practice

In everyday practice, most PT operators provide information on the nature and the location of major disruptions in the network. The information on alternative paths, however, is handled in manifold ways. Collective information is either displayed to passengers over station and in-vehicle displays or announced through speakers and relies on actions taken by personnel. The most common is the use of pre-planned alternative paths for recurring disruptions and crucial network parts, which are available to the PI dispatchers of the OCC. The National Rail in the United Kingdom (UK) publishes such static, pre-planned alternative paths for the lines of all railway franchises on their website for the public's access (National Rail (UK) 2023). Other agencies, such as the Transport for New South Wales (TfNSW), mention the necessity of informing passengers about an occurred incident. Disseminating the information towards the passengers is left to the responsibility of communication coordinators. Information about the content and the way of its generation are not described in the published material (TfNSW 2023). According to Transport for London (TfL), the Customer Information Strategy aims for real-time passenger information, providing customers not only with a disruption's existence but also with alternative paths (TfL 2016, 2017). This provision is done through station personnel, who in turn are provided with real-time information about the network's current situation via social media, mostly Twitter. Additionally, the PI on station overcrowding is calculated based on the electronic ticket data and made available in real time. Additionally, TfL operates an expensive open data platform that enables third parties to incorporate real-time information on their services (TfL 2023).

Steps reaching beyond this state of the art are mostly to be found in individualised PI over mobile phone applications – often branded as Mobility-as-a-Service (MaaS) applications. The autonomous administration of the Paris transport services [Translated from French: Régie autonome des transports parisiens] (RATP) offers the "monRER A" mobile application, which allows continuous journey monitoring for each individual user and offers information on delays and alternative paths tailored to their OD in case of disruption (RATP 2023). According to the product description, one major criterion for the alternative path is minimising the passenger's travel time. Consideration of available capacities is not mentioned. The German company Mobimeo GmbH offers a customisable MaaS application that is deployed under different customer-specific branding – among others, the so-called DB track agent [Translated from German: DB Streckenagent] of the German railway operator DB (Mobimeo GmbH 2023). Beyond mere trip planning, the application also monitors individual passenger journeys and proposes alternative paths in case of disruptions. The paths also include shared bikes and scooter products. The Montréal Transport Company [Translated from French: Société de transport de Montréal] (STM) uses a similar approach (INIT 2023; STM 2023). The OCC sends notifications via Twitter about the location and approximate duration of line disruptions. A short detour for avoiding the closed section using alternative metro lines is given in text with the hint to use the own STM application to calculate alternative paths by buses. A consideration of capacities or a central recommendation for further preferred alternatives is not retrievable from the published information. Approaches in other North American, European, or Australian cities do not reach beyond the spectrum presented here.

Even though providing a certain degree of advice in case of disruptions is an everyday practice with PT operators, there seem to be two main philosophies: on one hand, the collective information by the OCC and/or station personnel, which relies on pre-planned strategies and experience, and on the other hand, highly individualised trip planners employing path finding algorithms. Although operators commonly use both, a link between them and, more importantly, the consideration of the overall network capacities is not indicated in the publicly available material. However, with the aim of this work in mind, it is interesting to explore the attempts to introduce methods that use path finding and awareness of the available capacities of the network for collective information.

The idea of an active passenger redirection of passenger flows in dense networks in the case of severe disruptions emerged in research and development projects in Germany in the early 2000s. The main factors that facilitated the effort were the complete equipment of PT operators in all major cities with control systems (ITCS of the second generation) and the wide availability of online PT trip planner platforms, mainly the two products Hanover Consulting timetable information system [Translated from German: Hannover Consulting Fahrplan Auskunftssystem] (HAFAS) and electronic timetable information [Translated from German: Elektronische Fahrplanauskunft] (EFA) (VDV 2001, pp. 126–257). Additionally, VDV launched two standardised interfaces for the linking of ITCS of different operators (VDV453) as well as linking ITCS to PT trip planners (VDV454), allowing passengers to find optimal paths based on real-time data (VDV 2018a, b). The process was funded by the German Federal Ministry of Transportation [Translated from German: Bundesverkehrsministerium] (BMVBW, BMVBS, BMVI) over several phases and legislative periods spanning more than ten years. In a pre-phase, efforts were made to make use of the usual practice in OCCs of having pre-defined action plans to mitigate frequently occurring incidents. In this manner, a system using pre-defined routing plans was elaborated that contained the alternative paths in the form of network meshes for a possible disruption at any given link of the network (BMVBW 2001). The idea was elaborated on paper considering the state-of-the-art technologies of that time and proposing a system architecture for the integration in an OCC. A concrete case study was not conducted; merely examples were used to highlight the functioning of the system. Applied approaches were adopted in subsequent projects.

The first phase of those projects developed the theoretical framework for calculations and procedures for the redirection of complete passenger flows in case of a severe incident. It identified three groups of passengers to be treated separately: (a) the ones already in the affected area who have no access to an alternative path, (b) the ones already in vehicles in the direction of the affected area who still can change to an alternative path, and (c) the ones that are shortly before starting their journey that also have the possibility of postponing the trip. The project developed the operational procedures for the three groups: (a) was only subject to the deployment of supplementary vehicles, (b) was subject to in-vehicle and in-station information, and (c) was subject to internet-based information. The concept was tested offline utilising the PT trip planner EFA and was discussed with a large panel of PT operators in Germany. The conceptualised system proposed, based on the assessment and the actions of the dispatchers, alternative paths for groups (b) and (c) to the dispatcher with a rough consideration of capacities (e.g., redirecting towards lines of similar or higher capacity than the affected one) and accessibility (BMVBS 2009). In conclusion, the researchers and the panel of operators verified the usefulness of a passenger redirection system, and the possibility of using existing software to elaborate the routes was explored. Open points for further research were identified in the fields of estimating redirection demand as well as residual capacities of the alternative paths in practice. Furthermore, verifying the minimum duration of a disturbance that makes a redirection meaningful, as well as the creation of the necessary technical interfaces to be able to execute the steps within an OCC, had to be investigated further.

In a second phase, two prototypes of the system were created for the cities of Berlin and Stuttgart, Germany (BMVBS 2011). They demonstrated the capabilities of such systems using offline data from the OCCs. The main findings were, besides some data and interfacing refinements, the realisation that capacities and ridership levels of the network play a crucial role in redirection decisions. Although some PT modes, such as trams and buses, may seem inadequate to cope with diverting demand from metro lines, they must still be considered alternatives to achieve a better distribution of additional passengers. However, realistic online data about the current ridership and current ODs were unobtainable due to the lack of real-time passenger counting in the demonstration areas. Another major finding of that phase was the necessity to narrow down alternative paths to keep provided measures comprehensible for the passenger collectives and the dispatchers. The study estimated that calculating and proposing alternative paths is not meaningful for incidents with a duration of less than 30 min. This considers the processing times for OCC and the prototypes as well as the approximate travel time increase through the new paths. The consensus among the participating companies and PT operators was that for shorter incidents, the information about the location and kind of the incident is sufficient for the self-re-orientation of regular passengers. The project was conducted as a non-academic product development. Thus, details on the exact test scenario are not publicly available. This phase realised the theoretical concepts into prototypical software modules. It estimated the minimum necessary incident duration and produced a proposal for smaller incidents. However, the main challenges of estimating demand in real time and interfacing with the systems were emphasised but not tackled.

In the initiative's third and most recent phase, online tests were made based on the prototypes of phase two. Here, several simplifications of the original idea were made. The availability of individualised online trip planners via mobile applications was taken into account, and the idea of wide-area redirection was abandoned in favour of individualised information. The technologically limited conditions of operators in Germany and especially the unavailability of real-time demand data were considered by further limiting alternative paths, as their residual capacity could not be assessed. The target group for collective information was confined to passengers of group (a) and part of group (b) who were already in immediate proximity to the affected area. Technical progress was made in the standardised communication of incident occurrences from the OCC towards the operator's own trip planners. The prototype for the greater Berlin/Brandenburg area, Germany, went into operation for a field test with passengers while also delivering information to the mobile trip planner HAFAS to ensure consistent personal and collective information. One technical challenge that could not be solved was the lack of a disruption timetable during one or multiple incidents, leading to the calculation of alternative paths on static timetable data. The results were evaluated from an operational and the passengers' point of view. Apart from some expected system-specific mistakes in routing, the system performed well in delivering collective path advice. From the passengers' point of view using the online application, the inconsistency between what frequent users expect to be the most suitable path and what is shown by the system caused confusion and reduced the acceptance of the system. This led operators to emphasise on indicating the existence of incidents and their effects more transparently. The field test for Stuttgart did not take place out of technical reasons concerning the interfaces of sub-systems (BMVI 2019). Generally speaking, this third phase highlighted that even though active passenger redirection is technically feasible and would achieve good acceptance by the travellers, the systems needed to provide real-time data of demand as well as capacities, and disruption timetables did not exist in the involved operators at the time.

Tsuchiya et al. (2006) present a prototypical development for the railway network of Japan that provides passengers with decision support on alternative paths in case of incidents. The system uses static data based on experience with incidents on the network. A list of feasible alternative paths has been elaborated in advance for all possible affected links. Furthermore, a historical database with incidents and their duration produces an estimated expected duration of the current incident. For each occurred incident, the system compares whether an alternative path from the database is faster than the original path for all stations, taking into consideration the probable incident duration and a certain recovery time after the incident is cleared. The calculation can take more than one simultaneous incident into account. At each station, a dynamic map shows to which destinations a faster alternative is possible and to which it is not. The affected passengers must use an online application to receive information on the alternative path fitting their itinerary. For ODs with high demand, dynamic screens can be used to display a limited number of alternative paths. The publication indicates the existence of an operational prototype, presented at fares and conferences but not yet tested in the network. The system demonstrates that in a less complex environment, only consisting of railways, a more pragmatic approach to passenger redirection can be reached that will work within the system's confines.

A parallel line of developments focuses on providing individualised path advice to passengers via mobile phone applications. The trip planners used in the works of BMVBS (2011) and BMVI (2019) already allow for operators to remove segments of lines from the path-finding algorithms and thus propose paths avoiding a disturbed part of the network. The work by Bruglieri et al. (2015) can be seen as a model for this line of thinking. They developed a prototype algorithm enabling PT trip planners to search for alternative paths in case of disruptions. The algorithm enabled the creation of a time-expanded network for the cases of the closure of a station and the closure of a line segment. The system was integrated into the PT trip planner of Milan, Italy. The OCC would ideally transmit information on the closures to the trip planner, while considerations of capacity constraints in the network and the alternative paths were not included. Since the focus of such projects does not lie on network-level CAPR, they will not be analysed any further in this paper.

Table 2 gives an overview of the approaches in practice considered in this paper at a glance.

5 Comparison

In the previous sections, several academic investigations and projects from practice have been introduced. The following discussion is meant to point out their similarities and differences to draw conclusions and recommendations for future investigations.

5.1 Foci of the studies

The main motivation of most studies is to reduce passenger delays through redirection. One exception here is Cats and Jenelius (2014), who aim at analysing network vulnerability (Table 1). The comparison of the foci of the different studies highlights one significant contrast. Whereas the academic investigations focus mainly on the development of algorithms, the approaches in practice aim at developing prototypes that utilise the technological infrastructure of OCCs. Among the developed algorithms, most of the research concentrated on identifying alternative paths and the subsequent reassignment of affected passengers (van der Hurk et al. 2018; Müller-Hannemann et al. 2019; Zhu and Goverde 2019a; Bachmann et al. 2021; Mo et al. 2023). Cats and Jenelius (2014) and the *Corman group*, however, mainly considered the analysis of the passengers' reactions to given incident information (e.g. location, duration) and its effects on the network.

5.2 Consideration of capacity constraints

As pointed out by Cats and Jenelius (2014), passenger redirection does not necessarily lead to an improvement of the overall situation if such PI leads to secondary incidents on alternative paths. Therefore, the consideration of the supply's capacity was chosen as a screening criterion for this literature review (Sect. 3). However, the manner of the capacity considerations varies from study to study. As a result, two major approaches can be identified: investigations redirecting passengers relying on the available network's capacity (Cats and Jenelius 2014; Müller-Hannemann et al. 2019; Zhu and Goverde 2019a; Leng et al. 2020; Rahimi Siegrist and Corman 2021; Bachmann et al. 2023; Mo et al. 2023) and the ones that actively change the available capacity according to the requirements of the passenger redirection. Among the second group, van der Hurk et al. (2018); Leng and Corman (2020); Zhu and Goverde (2020) couple the PI with a rolling stock rescheduling model, whereas Bachmann et al. (2021) combine it with a model for bus reallocation. Rahimi et al. (2021) couple PI with increasing the capacities and frequencies on some PT lines.

The approaches in practice belong to the first group. The initial idea, however, which is to use historical data (BMVBW 2001; BMVBS 2009), gets edited down from a weighting according to the general capabilities of the different modes (BMVBS 2011) to a pre-selection based on the experience of the dispatchers (BMVI 2019) – similarly to the approach of Tsuchiya et al. (2006). These specifications highlight the reduced ability of the specific PT operators at the time of the studies to collect real-time ridership data. However, this problem can be solved by introducing electronic ticketing systems and/or using big data analysis and artificial intelligence in the OCCs in the not-so-far future (Bagchi and White 2005; Mo et al. 2022).

5.3 Content and dissemination of passenger information

PI plays a crucial role in CAPR as it is the interface between the introduced approaches and the PT users as their potential beneficiaries. Several information channels are used in today's PT systems (Sect. 2) to inform travellers about the offered services or changes within them. The basic content of PI during incidents is the communication of the incident occurrence and the expected delay. All reviewed studies provide this information directly or indirectly. The *Corman group* and Zhu and Goverde (2019a) extend this information with available space in the still operating PT services. Roughly half of the academic investigations assume that travellers will redirect themselves using this basic information (passive redirection). The remaining academic investigations, as well as the approaches in practice, provide concrete path advice to the affected passengers (active redirection).

Most of the academic investigations test different PI schemes. Depending on the publication, the tested schemes differ either in the location or the timing of their information dissemination. This differentiation is used to evaluate the impact of the schemes on the overall passenger delay. All the other approaches assume perfect information availability or do not mention schemes. The scheme envisioned by the practical approach in Germany differentiates the information according to the location of the passenger groups in relation to the incident (Sect. 4.2). This is used as a means for a better adaptation of the path advice to the passengers' needs (BMVBS 2009). The Japanese project provides PI at all stations without further differentiation (Tsuchiya et al. 2006).

Regarding the PI channels, the approaches in practice and Mo et al. (2023) name specific means of information provision that have been considered in their respective study. All the other works assume appropriate available channels without delivering further details.

5.4 Assigning passengers to alternative paths

Another topic of interest in the introduced works, connected to the previously discussed PI channels, is the handling of passengers. Two different approaches have been identified in the examined studies, namely: as individual persons (Cats and Jenelius 2014; Zhu and Goverde 2019a, *Corman group*) and as indivisible groups (Tsuchiya et al. 2006; BMVBS 2009, 2011; van der Hurk et al. 2018; BMVI 2019; Müller-Hannemann et al. 2019; Zhu and Goverde 2020; Bachmann et al. 2021, 2023; Mo et al. 2023).

One important advantage of handling passengers individually is that finding alternative paths with sufficient remaining capacity for individual persons is comparatively easier. However, this goes along with several disadvantages. Individualised information cannot be provided by collective PI channels such as dynamic PI displays and speaker announcements, which means that PT users must actively seek path advice via mobile phones. Additionally, this individualised information might contradict the information given by the collective PI channels, which might lead to confusion. Furthermore, capacity-aware individualised information might split travel companions onto different paths. Hence, handling passengers as indivisible groups with identical OD-relations that receive the same path advice via all available channels solves the problem of inconsistent information. Nevertheless, one disadvantage of the collective PI channels is that not all of the numerous indivisible groups can be informed via those due to time and space limitations.

Staying with the topic of fitting affected travellers, handled as groups or individuals, onto the remaining capacity of alternative paths, it is also reasonable to consider the passengers' reaction to the given PI. Hereby, the studies that consider active redirection take a compliance rate into account that states the share of passengers who follow the provided path advice. Investigations that consider passive redirection use path choice models to reflect the passengers' distribution on all available alternative paths.

At this point, it should be underlined that the only study that tested the redirection scheme on actual users is by BMVI (2019). The results of the conducted survey of pre-selected users show that 57% would be willing to follow given path advice.

5.5 Algorithms and tools

The highest diversity among the academic investigations can be found in the developed algorithms and used tools. These can be grouped into simulation tools, self-developed algorithms for passenger assignment, and optimisation methods. Simulation tools and self-developed algorithms aim at calculating passenger loads on alternative paths in the network to help evaluate the passenger delay and the network capacity.

Some of the works also consider the optimisation of their approaches in certain manners. van der Hurk et al. (2018) use an iterative process to optimise the path advice to affected passengers and the rescheduling of capacities. Müller-Hannemann et al. (2019); Bachmann et al. (2023) use the Gurobi Optimizer (Gurobi Optimization LLC 2022) to find an optimal solution for the reduction of travellers' inconvenience. Zhu and Goverde (2020) use an adapted fix-and-optimise (AFaO) algorithm to find an ideal compromise between passengers' inconvenience and operator costs. The *Corman group* uses MATSim to maximise the user utility. Mo et al. (2023) assume uncertainty in the passenger demand and use the optimisation to create path advice that is robust against wrongly assumed demands.

As the approaches in practice aim at delivering tools that make use of existing technology, no particular description of used or developed algorithms was done in the publications.

5.6 Case studies

All introduced academic investigations conducted case studies, which show a wide range of results. The results span from an increase in the total delay of all affected passengers by 15% to a delay reduction of 98.9%. This significant variability of results is likely due to the diversity of the scenarios concerning the incident duration and location, network, included PT modes, and demand considerations.

In summary, it can be said that incident duration varies between 0.5 and 4 h; however, shorter disruptions were never seen as sufficient to investigate the effects of CAPR. The types of considered incidents were thus mostly link blockages and not minor disturbances. Unfortunately, the approaches in practice do not present quantitative results of delay reduction.

Evidently, the availability of demand data is essential for CAPR. An often-used source is historical data. Passenger demand has been assumed for case studies for which such data was unavailable. The transition from theory to practice showed weakness at this point of CAPR. In PT operations, real-time demand data was unavailable at the time of the conducted approaches in practice. Therefore, the field trial conducted by BMVI (2019) relied heavily on OCC personnel's experience in selecting the alternative paths to be communicated.

Nevertheless, all introduced works and projects conclude that, in most cases, their developed CAPR methods show a positive effect on the inconvenience of passengers during incidents. Therefore, it helps improve the reliability of a PT system and, thereby, its attractiveness.

5.7 Considered modes

Regarding the considered modes, all studies can be divided into two groups: one group considers only one mode, either railway (Tsuchiya et al. 2006; van der Hurk et al. 2018; Müller-Hannemann et al. 2019; Zhu and Goverde 2019a, 2020) or bus (Bachmann et al. 2021, 2023), the other group considers a multi-modal network (BMVBW, 2001, Cats and Jenelius 2014, *Corman group*, BMVBS, 2009, 2011, BMVI, 2019, Mo et al., 2023).

5.8 Dispositve measures and implementation in OCCs

As pointed out by Carrel et al. (2010); Briem et al. (2020); Bachmann et al. (2022), OCCs play the main role in PT's incident management through the taken dispositive measures as well as the control of PI. Therefore, it is reasonable to include those in the development of CAPR solutions. All studies use some kind of disposition timetable in order to include the changes to the PT service through these measures. Some of the works investigate the combination of PI and certain dispositive measures in more detail. Although all studies consider the output of the OCC, not all of them take the integration of CAPR into OCCs into account, as shown in Tables 1 and 2. Particularly noteworthy is that the approaches in practice consider the integration into an OCC as a basic prerequisite for CAPR.

6 Discussion

Based on the findings of the introduced works and the comparison of these, requirements are derived in this section. Moreover, the gap between the academic investigations, the approaches in practice, and the inferred requirements are discussed.

6.1 Requirements for CAPR

This subsection states three general requirements which logically need to be fulfilled by a CAPR system. These are:

1. Identify passengers whose travel plan is affected by the incident.
2. Propose alternative paths that are usable and lead to an improvement of their situation, considering the current state of the PT network.
3. Ensure consistency of information across all available PI channels.

To support travellers affected by an incident, which is the basic idea of CAPR, the challenge of identifying those passengers needs to be tackled first. Providing PI concerning the incident to passengers not affected by it is not purposeful and might be confusing. Therefore, an accurate grouping of passengers according to meaningful criteria is necessary. This identification of affected passenger groups is the core of the first requirement. Based on travel data, historical or real-time, the affected share of the passenger demand can be determined, at least in the forms of affected ODs and their time-dependent volume (Bagchi and White 2005; Mo et al. 2022). It also means determining from which location to which destination the affected travellers need to be redirected in the PT network. For affected passengers who have not started their trip at the time the incident occurred, this means that they need an alternative path suggestion at their trip's origin. However, passengers already on their trip might either require an alternative path from their current, dynamically changing position, or they might already be too close to the incident site for an alternative path to be found. Another possibility is that the incident occurred in an outer part of the network in which PT service coverage is less dense, and no alternative path can be found for any of those passenger groups. CAPR must tailor the information according to the requirements of such a heterogeneous group of passengers.

The second requirement of CAPR is that suggested alternative paths need to be usable and improve the affected travellers' situation while avoiding the deterioration of the situation of those travellers who are not directly affected by the incident. This means a reduction of the overall delay induced by the incident. The further away affected passengers are from the incident, the more alternative paths are available and the higher the chance of finding a usable one. Passengers closer to the incident may have to circumvent the incident site and return to their original path once the incident lies behind them. The usability of an alternative path is also understood as its ability to accommodate a sufficient number of redirected passengers without risking secondary incidents by exceeding its capacity. Therefore, all proposed alternatives need to have a verified residual capacity. Although single affected passengers might improve their situation by taking an overloaded alternative path, it likely leads to an increase in the overall delay for other travellers due to overcrowding. Hence, from the system's and the collective's point of view, CAPR needs to avoid such effects. As incident situations might be stressful and confusing, it is probably helpful if just one concrete path is advised for each affected OD to avoid further confusion. Moreover, in this way, determining the number of travellers who transfer to a specific alternative path is easier to estimate. Suppose alternative paths cannot be found or do not significantly improve the passengers' journey. In that case, the most probable course of action is to advise passengers to await service restoration and resume their journey on the originally intended path. This requirement makes path-finding methods an important prerequisite of CAPR. Even though there are various path-finding algorithms, some do not consider capacity constraints, making them unsuitable for CAPR. For an overview of path-finding methods and their limitations, we refer to Casey et al. (2014); Bast et al. (2016).

The third and last requirement of a CAPR system about the consistency of the PI focuses on the dissemination of information and its quality. The consistency of the information has to be ensured not only from the operators' perspective but, more importantly, from the travellers' point of view, who might get disoriented if confronted with contradicting recommendations. CAPR must guarantee that travellers who follow a path suggestion receive the same suggestion along their trip and across all possible PI channels. Since most of the PI channels are collective and ideally located in all stations and vehicles, it is reasonable to assume that they can reach all affected passengers with similar travel directions. Only PI channels, such as mobile phone applications, have theoretically the possibility of redirecting passengers individually. However, since providers of such apps are often not connected institutionally to the PT operators, CAPR must also include all individualised information channels. This leads to certain requirements on system interfaces such as the aforementioned VDV454 and GTFS, which are used by trip planners on websites and as part of mobile phone applications to retrieve real-time timetable information from the PT operators' servers. To date, the trip planners, both from PT operators and third parties, use the real-time schedule to calculate the shortest paths for their users whilst considering certain criteria such as users' preferences (Wong 2013; Ceder and Jiang 2019; Google 2019). If those trip planners are supposed to consistently transmit certain path advice, modifications of their functionalities and interfaces are necessary.

6.2 Gaps between theory, practice, and requirements

The comparison of the academic investigations and approaches in practice of CAPR clearly shows a gap between those two sides. Approaches in practice rather focus on the feasibility of CAPR approaches in today's incident management systems and make the best possible use of technologies operated in OCCs, which, however, are often not designed for the deployment of CAPR strategies. One can argue that the main limiting factor for introducing CAPR technologies into practice is not the algorithmic side of the approach but the set of capabilities of the existing technical systems in the respective PT system. In contrast, the academic papers focus on simulated consequences of different CAPR strategies in matters of information schemes and coupled dispositive measures as well as different information contents while not considering a possible integration in OCCs. The first-mentioned compromise is the innovative touch and the search for ideal solutions for the sake of practicability. The latter lacks a relation to implementation and the realities of everyday operations.

To close the gap, the academic investigations would need to adapt their required input to the information, which can be provided by OCCs, and adjust their output so it fits the available PI channels. It would probably also mean that interfaces such as GTFS and VDV454 would need adjustment in a way that is capable of transmitting the real-time schedule and transporting the redirection information of CAPR strategies. On the other hand, approaches in practice, instead of relying entirely on what the current systems are capable of, should also include technology development for those systems so that scientific developments can be implemented in future OCCs. Bachmann et al. (2022) stress potentials for improvement in incident management and also in matters of communication with passengers. Based on the gap identified in this paper, data collection, processing, and PI dissemination could be further improved to enable future OCCs to provide active passenger redirection.

Compared to the previously stated requirements for CAPR, the introduced studies already tackle most of the challenges of CAPR, such as identifying affected travellers and considering capacity constraints. Nevertheless, whereas the projects from practice lack aspects such as the search of optimal usable paths, the academic papers need more transferability of the identified optimal paths to the passengers with realistic means of communication. Some of the works also redirect passengers individually, which stands in contradiction to the requirement of information consistency to avoid confusion. However, summarising the work that has already been done, it seems that almost all components of CAPR have been developed and are waiting to be integrated and transferred to practice.

Finally, the authors must acknowledge that the current developments at PT operators do not aim to bridge these gaps and apply CAPR but rather to provide the basis for completely individualised and multi-modal path advice. The data needs for both applications are similar, and thus, further developing those applications will simultaneously make the collective approach more suitable. The widespread use of mobile phone applications that track passengers' journeys can be expected to contribute to better real-time knowledge of the current demand and an extension of the network's available capacities.

7 Conclusion

To date, most investigations about incident management in PT have been on its *supply-centric* part. Considerably less has been done on the *passenger-centric* part of incident management, which focuses on the consequences of incidents on travellers' trips. This paper introduces a comprehensive collection of studies – both academic investigations and approaches in practice – about CAPR in PT systems to show how tailored PI can support affected travellers over the period in which the network is affected by an incident. CAPR is thereby a crucial part of PCIM. The significant criteria of the introduced works have been pointed out, summarised, and compared. Furthermore, general requirements for CAPR have been formulated, and the gap between the academic investigations, the approaches in practice, and the formulated requirements are discussed.

Due to the heterogeneity among the mentioned studies, it is difficult to compare their results directly; however, all of them show positive effects of passenger redirection. The general idea of supporting passengers during incidents by informing them adequately is common throughout all works. The mostly positive results of all investigations demonstrate the significant potential of CAPR for improving the otherwise uncomfortable passenger experience during incidents. However, the comparison of the works with the aforementioned requirements shows that further research is necessary, especially in linking academic investigations and approaches in practice. Projects from practice must catch up with the possibilities opened by big data and optimisation techniques to achieve the positive effects shown in the academic investigations. In contrast, the latter must check the feasibility of their approaches and link them to the possibilities given by the technologies available for PT operations. An implementable compromise needs to be found. Moreover, the role of trip-planning mobile phone applications during CAPR strategies needs to be further investigated. The main goal should be to answer how information for alternative paths that is planned to serve each user's individual requirements can support a PT system's recovery by the targeted redirection of passenger groups. Figure 2 shows an exemplary integration of CAPR into the system architecture of an ITCS and the related information flows. The CAPR obtains passenger demand, capacity, incident duration, and location, as well as the dispositive measures taken from the OCC. It calculates the optimal redirection strategy and sends back the path advice tailored to the corresponding PI channels and PI locations. The path advice is not transmitted indiscriminately but filtered based on its relevance for the PT users waiting at a specific stop or riding a specific vehicle. The available capacity is a crucial parameter for the redirection strategy to avoid secondary incidents. Here, it is depicted as if this information is sent by the vehicles, which is possible if they are equipped with an automatic passenger counting system. Other conceivable solutions would be to use the data of the automatic fare collection, which counts the checked-in and checked-out passengers or to use estimations based on historical data.

Ongoing developments lead to a digitalised and highly dynamic mobility system with multiple interlinked modes. This will bring challenges and chances for the guidance of travellers under all possible conditions. One major challenge will be the balance between the well-functioning of the overall system, which requires coordinated guidance considering capacities and secondary incidents, and the availability of multiple "ego-perspective" trip planners considering only the individual passenger. The easiness of spontaneously shifting from PT to a shared bike or scooter will add more layers of complexity to an already highly complex system. Moreover, the expectations of multi-modal travellers are more complex than the ones of mono-modal travellers and probably increase their expectations of PI and guidance.

However, this also might be a chance for further improvements of the passengers' situation during incidents by providing more and different options in a variety of incidents and is, therefore, worth investigating. In addition to shared mobility, on-demand services such as taxis, Uber, or comparable services have the potential to play a role in future CAPR by providing additional capacity and alternative paths for affected passengers. If a CAPR system fulfils the aforementioned requirements, it also enables the incident management of a PT system to adjust the supply side accordingly. The overall passenger load on the PT network can be estimated depending on the number of people who follow given path advice in combination with data from the undisturbed system. Dispensable supplies such as standby PT vehicles can then be used to support the CAPR strategy by sending them onto lines that are especially demanded during the incident or part of a proposed redirection strategy. Hence, the estimation of the number of people who follow a given path advice as well as investigating influencing factors in this matter are further important and yet barely investigated topics. One investigation in this direction of research is by Wilke (2023). The author presents incentives to increase compliance with suggested train connections in a long-distance railway service. Furthermore, CAPR could be used to determine matching dispositive measures, which can be suggested to the dispatchers to accomplish the ideal combination of available dispositive measures and possible redirection strategies. Briem (2023) analyses ITCS data to evaluate the robustness of timetables in terms of how much room they leave for dispositive measures. The reallocation of capacities, suggestions for passenger-oriented dispositive measures, and disposition-friendly timetable planning are, thereby, further crucial aspects of PCIM. This widens the room for further research in this area.

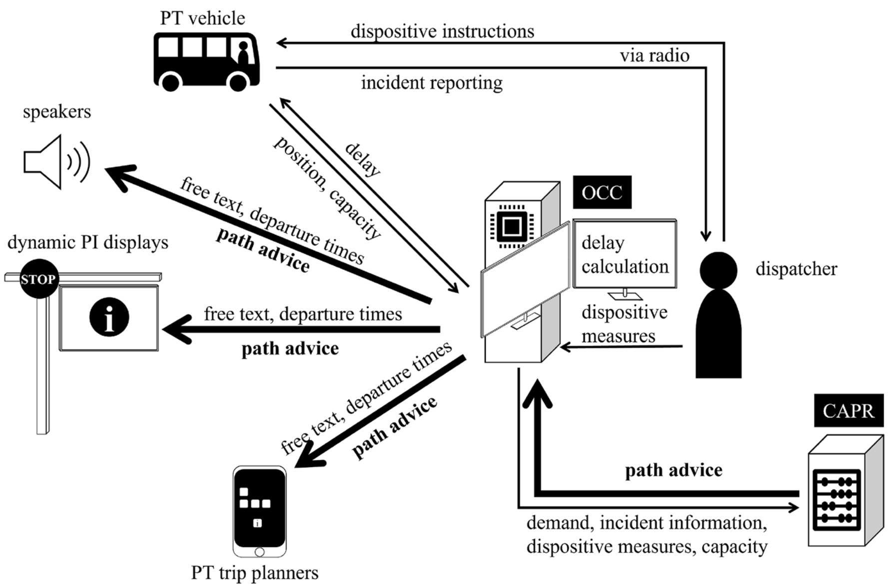

Fig. 2 CAPR integrated into the system architecture of an ITCS

In the past, major obstacles to the transition of CAPR systems to everyday practice were the availability of suitable interfaces as well as dynamic demand data. However, the evolution and mainstreaming of even more advanced technologies will most likely bring major changes in this field. Dynamic data of all modes will be increasingly available for joint use of open data platforms. The seamless electronic payment will also improve the availability of demand data. Research has delivered manifold prototypes that can be operated with this better data supply. It is shown that most of the necessary infrastructure (e.g. ITCS, PI channels) exists in well-equipped PT systems and that the presented findings can, therefore, be implemented in practice with manageable effort. Now, the time is right to make this final step from research-based prototypes to operational systems.

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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