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APPROACH METHOD FOR FLEXIBLE REALLOCATION OF RESERVED SEATS ON LONG - DISTANCE TRAINS

Summary. Finding a reserved seat on long-distance train travel is supported by aids on platforms and within the train in order to keep the passenger's journey as short as possible and to minimise unnecessary walking within the train. The allocation of a seat to a carriage number on the reservation and the consideration of the carriage position indicator devices on the platform provide the opportunity to wait for the arrival of the train on a section of the platform that is close to the reserved seat. Nevertheless, there are various situations in reality in which this can only be achieved to a limited extent. Varying carriage order, the provision of a replacement train or tight transfer connection can lead to the train being entered at an unfavourable position. This is followed by the passenger trying to find a seat on the train which can amount to considerable traffic. Equipped with a flexible seat reservation procedure, this kind of traffic could be drastically reduced. The solution provides the opportunity to reallocate reserved seats in order to minimize the way a passenger has to walk inside the train to his seat. By means of microscopic simulations, various boarding scenarios demonstrate the effectiveness of this approach. Less passenger movement on the train results in an increase in passenger comfort and reduces the space that is required for such movement, which could instead be used for other purposes. On the platform, this procedure means that passengers no longer need to wait for the arrival of the train at a location that is closest to the allocated seat. Instead, passengers can choose a place on the platform convenient to them, without this having a disruptive effect on system performance.

1. INTRODUCTION

The issue of passenger changes on long-distance rail transport is a well-researched topic within the transport sector. The necessary time to wait on a platform for entering and exiting trains should be as short as possible in order to minimise the time that is required for a train to stop at a platform. Essential technical parameters that can influence the passenger change are the interface between the railway station infrastructure and the train, typically the arrangement of the doors, their dimensioning and their height offset to the platform. The behaviour of people also influences the speed at which passengers enter and exit a train. Most of the current research focuses on the perspective of railway operations. Extended passenger change times have a negative impact on the efficiency of resource use because travel times and track occupancy are extended. In the sense of the shift in travel/transport patterns that has been in planning for several years, to which rail traffic is intended to make a significant contribution

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by increasing the share of the modal split, a change in perspective towards the passenger is, however, worthwhile. The passenger is most likely to be unaware of their personal contribution to the time necessary for a train to stop at a train station and is probably more concerned about finding “the right place” quickly and without disturbance. The right place can be a suitable or even a reserved seat or at least a satisfactory place to stand. The search for this spot is often still being carried out when the train has long since left the platform and the passenger change seems to have been completed. In fact, there is a migratory movement in some trains that has to take place on paths that are not really scalable, namely in the aisles and transitions of the carriages. These necessary path areas reduce the marketable potential for seating accommodation or, in some rail systems, are used as a place to stay for passengers without a seat who stand in the way of passengers looking for seat. In individual cases, the rededication of such areas requires the consideration of the path areas prescribed by regulations, for example in the case of an evacuation. In this paper, a contemporary solution to minimise the traffic within the train that is required to find a seat on long-distance trains and to enable a more comfortable access to the rail system for all passengers is presented. The change of perspective towards the passenger shows how a more flexible seat reservation system is more compatible with current needs in a user-oriented manner instead of demanding technology-oriented discipline and system understanding from customers.

2. TOPIC RESEARCH

2.1 Seat reservation

Seat reservations on the railway are particularly well known in long-distance transport, where longer travel times and longer distances between train stops are common. While it is mandatory on some rail systems to make a seat reservation upon booking a trip, others merely provide the option of making a seat reservation and leave the decision to do so up to the customer. The differences in booking rules within a rail system are often predetermined by differentiated rail products. At Deutsche Bahn, for example, a distinction is made between the express train system ICE (Inter City Express) and the ICE Sprinter. The former is offered with an open booking system in which the reservation of a seat is optional and is only recommended in order not to have to travel standing [1]. On the other hand, the ICE Sprinter is a rail product derived from the normal ICE with fewer intermediate stops and shorter travel times on routes that are in competition with air traffic, for example the Berlin-Frankfurt am Main route. Until 2015, a seat reservation was always included in the travel price of the ICE Sprinter. In the meantime, a tariff adjustment to the normal ICE has taken place and the compulsory reservation has been discontinued. Other representatives of a closed system, in which a reservation is stringently required, are the French TGV, the Eurostar - which connects Great Britain to the European mainland - and the majority of the American Amtrak connections by the provider National Railroad Passenger Corporation. Typical representatives for open booking systems, in which a journey is also possible without optionally available reservations, include the Austrian Railjet and the long-distance trains of the Finnish provider VR. Local and regional trains often do not provide the option of making a seat reservation; occasional offers do, however, exist, for example for commuters with subscription tickets for the Munich-Nuremberg Express [2].

2.2 Passenger changes

This paper examines the question of how boarding passengers of a long-distance train can be supported in minimising the number of encounters with other passengers on the train and the time until a seat is taken. Thematically related to this is the subject area of passenger change. However, its focus refers to the exit and entry process, i.e. to the door areas and the areas close to the doors. The various rail and metro systems in the world differ strongly in terms of the duration of passenger change. Metros with many stops and short travel times therefore have many and wide doors in order to optimise the change of passengers. In a study using the example of the metro system in Beijing, China, boarding times of well under one to just under two seconds per passenger were documented [3]. Hennige and Weiger (1994) come to a similar result and give a value of 0.81s per person for the passenger change of a metro in Stuttgart [4].

In comparison to local trains, long-distance trains have fewer numbers of doors and their width is often narrower. In addition, there is often a difference in height between the platform and the carriage, which has to be bridged with steps, and there are often gaps between the platform and the step, which can make it difficult to enter the train. The different train heights and profiles result from the various historical and current standards and sometimes lead to unfortunate pairings of different platform and carriage levels. In [5], average passenger change parameters were determined for the German ICE and three other carriage types. Thus, the time it takes to enter the train, without or with only little luggage, takes between 1.8 seconds per passenger when there are two steps and 2.8 seconds per passenger when there are 4 steps. This duration increases to more than five seconds for people with restricted mobility.

Weidmann [6] has evaluated a large number of parameters in his comprehensive work on the subject of passenger change. The representation of the passenger change time as a function of the passenger change rate for various full-track systems is an important aspect in this work. Between about 50 and 200 seconds with a 100% passenger change rate (100% of the seats as the number for disembarking passengers + 100% of the seats as the number for boarding passengers) are mentioned as the total duration. Since in our study a validation of the passenger change times could not take place due to a lack of real data availability, an average passenger change duration of 159.7 seconds over our total of 66 simulation runs is deemed realistic. In [7] there is the number of 2.5 minutes as an upper limit mentioned for an excessive passenger change that correlates to our generic findings. However, it should be taken into account that different passenger change rates were used in the scenarios. In a more recent study from Switzerland, the average passenger change times are 1.0 to 3.0 minutes and these times are also maintained for the future rail system [8]. Even for the brand-new twin-layer concept train described in [9] called “Next Generation Train” with horizontal separation of travel classes and doors in two different levels serving the corresponding “Next Generation Station” [10], the total stop time of about 2.5 minutes was the design benchmark.

The human model in the simulation of passenger changes is mainly determined by the distribution of walking speeds in the undisturbed case. According to Weidmann [11], a passenger moves at an average of 1.34 m / s, according to the compilation from various sources. For pedestrians crossing a road in a targeted manner, a value of 1.28 m / s was documented on average. In [12], a measurement was carried out which, on average, is 1.29 m / s ± 0.03 m / s and is recognised as the speed for "obviously free walking"; this comes very close to the value determined by Weidmann in his secondary study in 1993 [11]. That these results are still valid is shown by a more recent study by Schmaranzer, Braunel and Doerner [13], in which the authors refer to the investigations of Weidmann from 1994 [6]. One of the most cited sources related to walking speeds is Fruin [14], who published the following values. The average walking speed is 1.37 m / s for men and 1.29 m / s for women. Furthermore, empirical data was published that formulates the walking speed in relation to the density of people. With a density of 0.65 m^2 per person, the lower limit for normal walking is reached, and with less than 0.28 m^2 per person, a flow of people comes to a complete standstill. In addition, four categories were defined for the spatial distance between humans ("personal body buffer zone concept"), which include the context of human interaction. The passengers in the model of the ICE move in simulated public space, but people are willing to gradually reduce their social distance in order to achieve their goal. The simulations use the Social-Force-Model, which is already part of the simulation solution of Anylogic and is defined there in the Pedestrian Library. In our simulation, the passengers receive an individual preference for a certain walking speed between 0.5 and 1.5 m / s. The actual speed then results from the interaction with other passengers and the geometry of the interior of the carriage.

In this study, an investigation of the possibilities of influencing the time that elapses before a boarding passenger reaches their seat or standing place in the carriage is presented. This view differs from the consideration of passenger processes of passenger changes in that it is a change of perspective. If the classic passenger change is operationally justified and completed as soon as all passengers have entered or exited, now it is considered that the entering of a train from the passenger’s perspective, for whom the beginning of the subsequent process of "finding a seat" only begins upon entering the train. While the train has to come to a stop at the platform to allow passengers to change trains, the train can already be leaving the platform while passengers are still finding their seats.

According to Weidmann [15], a scheduled stop of a passenger train consists of a fixed and a variable proportion of the time that the train stops in the train station. If a passenger's search for a seat lasts longer than until the starting jolt, the completion takes place only during the journey and with acceptance of the longitudinal dynamic and cross-dynamic accelerations. Some studies, such as those by Buchmueller, Weidmann and Nash [16], confirm the validity of Weidmann´s results and use them in their more recent investigations.

3. PROBLEM DESCRIPTION

Passengers may have arrived on the platform before the train arrives or at least long enough before departure. Or they may have a tighter connection due to their own arrival on the platform shortly before departure, for example caused by a delayed shuttle-transport. In the first case, they have the opportunity to find their way around the platform themselves and to find a preferred waiting area near the intended entry point. In the second case, this opportunity is less appropriate, as there is a risk of missing the train because the passenger is still hurrying across the platform to another entrance of the train.

Well-known aids are available for orientation on the platform, for example via carriage position indicator devices - which are displayed on information boards or are digitally available - and the corresponding platform markings. If a passenger has a valid reservation for a particular seat, the traveller can try to estimate the most suitable place to wait on the platform in order to quickly find the right seat in the right carriage of the train. In addition to the rather insignificant estimation errors, however, there are influences that make these preparations for entering the train more difficult. These include the occurrence of unexpected carriage positions on the platform due to the so-called "varying carriage order", by using a replacement train with a different appearance, the absence of individual carriages or by stopping at an unusual location on the track as well as short-term track changes. On the platform side, other factors may also stop passengers from taking the best waiting position on the platform, such as the selectively placed range of service and information facilities. This can include a platform kiosk that attracts waiting passengers, or the smoking area, which does not have to be close to the optimal entry. Or it might be a sheltered area that does not exist at the expected stop of the target carriage. Some passengers who travel without a reservation have developed their own strategies to maximise success in finding vacant seats, such as identifying less-busy platform areas. Nowadays, there are even systems that indicate the level of occupancy of a train via display screens. These are intended to support a load distribution. Such systems are particularly relevant in local transport with its very high occupancy and lack of reservation options.

As soon as the train has been entered, the search for the desired seat begins. In particular, passengers with reservations now have to pass through the train, whereby the route depends on the success in finding the best starting position on the platform and the actual train carriage order. Passengers also lose their right to the reserved seat (at Deutsche Bahn AG in long-distance transport) if they do not arrive at their seat within 15 minutes of departure. If the seat has already been occupied by someone else by that time, they cannot claim the seat. It can therefore become stressful when streams of people are moving in both directions on the train and only the - usually narrow - aisle (ICE 1 carriage 1-7: 602 mm in the large capacity area of the second class) is available. With increasing occupancy, this aisle is also used as a lounge area for standing passengers, which is not conducive to mobility on the train.

The passenger is therefore busy with the task of preparing their entry before the train has even arrived and, once he or she has boarded, with finding their seat. The passenger is thereby prevented from pursuing their actual preferences on the platform and may suffer stress as a result of having to go through a train to find their right place, especially if many are doing so at the same time. If the train is already on the move again, this is aggravated by rolling movements, especially near the train station as a result of the change of track, which in addition to loss of comfort can also reduce safety due to the risk of falling over. Since 2020 and the outbreak of the global COVID-19 pandemic, another serious problem has been identified. The more passengers who walk through the train, the greater the risk of contact with an infected person who, despite the constant number of passengers, can become a "superspreader" solely due to the migratory movements. It will therefore continue to be the goal in the future to minimise passenger contacts when finding a seat by using as few movements as possible within the train.

4. SOLUTION APPROACH

Through the use of simulation studies, authors were examining a method to significantly increase passenger comfort by offering a more flexible approach to seat selection.

4.1. Flexibility of seat reservations

Seat selection is made more flexible by equipping trains with a wireless communication interface and connecting this with the (existing) reservation system on passengers' mobile devices. The functional scope of this system allows the passenger to enter the train at any door and is digitally recorded via the communication interface. If the reservation system recognises that the passenger has a valid reservation in another carriage, it determines the closest and most comparable seat available to where the passenger is entering the train and instantly offers it to the passenger in exchange for their original reservation. If the passenger accepts the exchange offered by the reservation system, their way to the seat is shortened and a change of carriage is no longer necessary. If the passenger does not use this service, then their original seat reservation remains. Therefore, the idea to let the passenger decide where they wish to enter the train allows them to focus on activities of their choice instead. The reservation system assigns the passenger to a nearby available seat instantly and, ideally, contactless and simultaneously frees the original seat which is no longer required for the passenger. A suitable mobile device such as a smartphone serves the customer as a front-end interface. If necessary, there could also be receipt printers at the ends of the carriage to document the passenger´s seat reservation change. Although this seems like an anachronistic option, this is likely to meet customer needs, for example in the case of GST receipt (Goods and Services Tax) for business trips.

4.2. The simulation model

The microscopic simulation model was created using the software Anylogic. Their passenger model uses the Social-Force-Model for conflict resolution when people are finding their way. The German multiple-unit train of class 401, better known as ICE 1, served as a model for a train to be simulated. This train ran in numerous combinations and existed in different configurations depending on the redesign phase. For our modelling, an ICE 1 was used, consisting of a total of 12 carriages and dating from the time after the second redesign around 2005. Carriages 1 to 7 form the second class, carriage 8 is the dining carriage, carriage 10 is the so-called service carriage, which in our configuration belongs to the first carriage class, and carriages 11, 12 and 14 form the further first carriage class. The carriage numbers 9 and 13 were not assigned by the Deutsche Bahn and simulöations have adopted this analogously. In the second class of our model train there are 497 seats, and 203 seats in the first class. This also includes the six seats in the infant section, which actually belong to the second carriage class, but can be booked separately. For reasons of model simplification, these seats were assigned to the first class, which is otherwise kept in carriage number 9. Among the passengers, there are those with and without reservations in both carriage classes. Groups or different personal characteristics as well as luggage and such items were not modelled, but the simulation contains an individually stochastically assigned running speed profile for walking through the train undisturbed. The choice of the ICE 1 is based on its widespread use in German long-distance travel and also on its impressive length of approx. 360 m (without the two locomotives, in which no passengers are carried). Other series of the ICE fleet operate with shorter units in single or double traction, but do not have the total length that can be experienced by passengers because passengers cannot walk through the individual carriages.

The simulation was essentially designed as a two-dimensional image of the passenger compartment of the ICE 1 set. Obstacles in 3rd dimension (height limitations) or a height offset between the platform and the carriage have not been modelled, so the mapping of door-related passenger changes is greatly simplified. Rather, there is a model boundary at the transition between the platform and the carriage, as it also exists at the transition between the carriages. As a result, a modular structure could be ensured, whereby structurally identical carriages only have to be modelled once, but these can be used several times in their own simulation instances. The focus of this research is on the effectiveness of the novel method, according to which boarding passengers experience a reallocation of their seat at the moment of entering a carriage. Therefore, the actual passenger change is not part of the investigation. For this purpose, the doors would have to be replicated in more detail and also examined and validated with regard to a height offset and an inevitably resulting gap to the platform.

Fig. 1. ICE coach 2nd class (Source: Deutsche Bahn AG)

In our simulation, the passengers gather on the platform before boarding. The majority of passengers go to an area that is conveniently close to the right entry when they have a reservation. Passengers without a reservation are randomly distributed over the entire platform, which roughly corresponds to the length of the train. Some of the passengers with a reservation ignore the possibility of already positioning themselves close to the door and instead just distribute themselves randomly over the entire length of the platform. The probability of incidentally standing in the right area of the carriage for which they have a seat reservation is on average 1/11 (the dining carriage as the 12th carriage in the middle of the train has no entrance doors). All passengers choose the closest entry point of the incoming train to the current position on the platform, which means that no one walks outside the train to their carriage. The proportion of boarding passengers with reservations who are already waiting in the correct place on the platform and boarding the right carriage directly amounts to 75% in all simulation scenarios. The rest, as well as all passengers without a reservation, are distributed across the entire platform with the same probability over all areas and therefore more or less suitable for the destination seat, if available. All passengers must also take into account the carriage class they have booked. If a passenger with a ticket for the second class enters the first-class area, this passenger will leave this area of the train before they start their actual search for a seat. The reservation system always allocates the closest seats according to the passenger's carriage class. For example, if a passenger with a ticket for the second class enters carriage 12 (first-class carriage), the system will offer them a free seat, depending on availability, starting in carriage 7 to the carriage before their original booking. The system does not allocate closer seats within the same carriage because the additional effort would be disproportional to the effect. In the scenarios in which the flexible reservation system is to be active, approximately 90% of passengers with a reservation participate in the procedure and are assumed to agree to an offered seat exchange. The remaining 10% do not participate in the procedure and represent the proportion of the passengers who either have no interest in the use of this system, cannot use the option or do not want to accept the seat exchange for other reasons. In all comparison scenarios without the flexible seat reservation system, the parameter is set to ZERO and thus deactivated.

4.3. Simulation scenarios

The simulated scenarios vary as regards parameters and have been selected in such a way that they can always be grouped in pairs with one difference for the comparison.

In particular, the number of people occurring in the simulation during the passenger change are varied. For this purpose, there are the categories "Disembarking passengers", "Maintaining in train passengers" and "Entering passengers". "Disembarking passengers" are those who get off the train at the beginning of the passenger change. "Maintaining in train passengers" do not take part in the passenger change, but stay on the train and occupy seats or are standing. With the beginning of the passenger change, the up until now standing "Maintaining in train passengers" use the opportunity to occupy seats that have become vacant due to disembarking passengers ("Disembarking passengers"). The "Entering passengers" are those passengers who are essentially in the focus of this investigation and whose journey into the train up to the final seat is recorded. As in real life, what happens is that passengers without a reservation occupy a vacant seat that is claimed by a passenger with a reservation a little later and which must then be vacated. This can even happen several times and for some passengers it prolongs the time required to find a permanent seat. In the sum of the passenger types "Disembarking passengers", "Maintaining in train passengers" and "Entering passengers", there are always the same number of passengers in scenarios 1 to 16 as the total number of seats available on the train as can be seen in table 1. Therefore, these scenarios are called the 100% scenarios, even if this "utilisation" does not lead to an actual 100% utilisation in every scenario (simultaneous presence of the people on the train). The influence of lower capacity utilisation was investigated in a separately marked study. Hence, scenarios 1 and 5 were simulated repeatedly, but this time with smaller proportions of "Entering passengers" in the order of 75%, 50% and 25%. In these scenarios, there are no "Disembarking passengers" and no "Maintaining in train passengers", so the "Entering passengers" enter an empty train. These scenarios were based on their baseline scenarios 1.25, 1.50, 1.75, 5.25, 5.50 and 5.75. On the other hand, the simulation of scenarios with higher capacity utilisation were disregarded, because the narrowness on the train causes very large dispersions of the time that is required to reach the seat. This prevents an investigation of the influence of a flexibilisation. In real rail operations, very high utilisation rates are also observed if there is no reservation requirement and thus demand limitation. For example, at Deutsche Bahn AG a capacity utilisation of up to 200% is still considered acceptable. According to its own statements, the average utilisation of long-distance trains by Deutsche Bahn AG in the year 2019 was 56.1%.

5. RESULTS

This chapter explains how these simulations compare to each other and observations that have been documented.

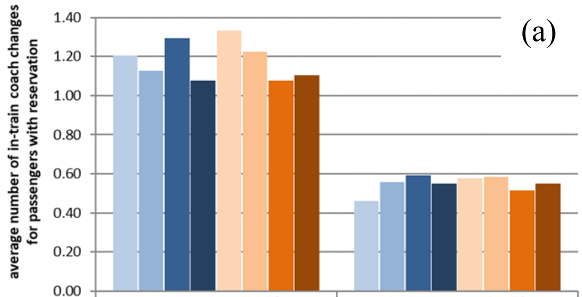
5.1. Definition of the calculated indicators

With this simulation, authors were investigating the effectiveness of making seat reservations more flexible using the example of a simplified ICE 1 model. To prove its effectiveness, a parameter variation and compare the result of the passenger change with a focus on finding the final place of the "Entering passengers" with and without the above-mentioned flexibilization was performed. This focus differs significantly from the more operationally oriented point of view of sole passenger change, in which the entry and exit process is documented. For comparison, indicators that can be recorded in a simulation on the one hand and in a field test (not performed) on the other hand were used. Even if the innovation is increasingly about the increased comfort from the customer's point of view, the effect can also be seen with values from a simulation. On the one hand, the duration of the individual seat finding as a balance between entering the train and reaching the seat, and on the other hand the required number of carriage changes as a balance between the carriage in which the passenger has boarded and the carriage in which the passenger takes their seat were used. Furthermore, a reference to the classic subject of passenger change by depicting the total duration of entering, exiting and passenger change was made. In addition to the standardised measure of location of descriptive statistics, also quantiles for the representation of the duration because the topic is usually dealing with very right-angled distributions in which individual events take a long time. The use of quantiles makes it possible to provide a statement about most of the observed behaviour, because rare events are excluded. These extreme values would probably also be observed in reality but would usually have their cause in other circumstances than the system of seat selection.

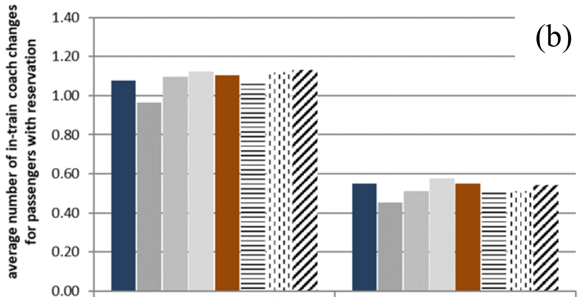
5.2. Indicator-based comparison of impacts

Figures 2 (a) and (b) compare the results of two scenarios with each other, which differ only in whether the flexible seat-exchange method is used (with 90% acceptance by passengers) or, as in the current system, such a method does not exist. Scenarios 1..8 are those with flexible seat exchange, scenarios 9..16 are those without this feature. The Table 2 shows the average time per passenger which is required to find the final seat or standing position from the moment of boarding as well as the corresponding 90% quantile of this period.

A similarly clear picture emerges with regards to the saving in the number of carriage changes per passenger for those who have a reservation. A quarter of the passengers board the train at a random door and would have to make their way through the train to reach the reserved seat. In the simulation, all passengers recognise the required direction of movement and avoid carriage changes in the wrong direction. In the scenarios 1..8 (and the sub-scenarios 1.25..5.75), the flexible reservation system is used by 90% of passengers if there is an exchange offer. Randomly selected 10% of passengers refrain from seat-exchange offers. Around half of all necessary carriage changes can be saved by using the flexible reservation system, and a corresponding number of journeys within the train do not have to be made.



	before checking seat change	after checking seat change
1.25	1.21	0.46
1.50	1.13	0.56
1.75	1.29	0.59
1	1.08	0.55
5.25	1.33	0.58
5.50	1.22	0.58
5.75	1.08	0.52
5	1.10	0.55



	before checking seat change	after checking seat change
1	1.08	0.55
2	0.96	0.45
3	1.10	0.51
4	1.12	0.58
5	1.10	0.55
6	1.07	0.52
7	1.12	0.51
8	1.13	0.54

Fig. 2. (a). Coach changes before and after seat reallocation with various passenger loads in scenarios 1 and 5, (b). Coach changes before and after seat reallocation in scenarios 1..8

An effective reduction in carriage changes can be seen not only in the scenarios 1..8 with higher capacity utilisation because also in the sub-scenarios 1.25…5.75 with each lower passenger load the profit per passenger with reservation is comparable. The level of reservation of the train also has little or no influence on this effect. In the scenarios 1…4 the reservation rate is 30% and in the scenarios 5…8 then 70%; a structural dependence of the individual duration is not recognisable from the data.

5.3. Distribution of the boarding durations (individual events) in all examined scenarios

Across all the examined simulation runs, the faster half of the passengers manage the complete boarding process from the platform to the final seating or standing place in up to 39 seconds. This value is limited downwards by the achievable movement speed and the minimum distance that has to be covered to reach this place. If this place is close to the entrance, only a few seconds are required at most, particularly if no previously boarded passengers obstruct the way. Upwards, there is barely a definable limit up to which the final place is taken. Repeated expulsions, reorientation and necessary carriage changes can lead to the consequence that individual passengers have not reached the end of their search even after several minutes. As in reality, the simulated passengers behave differently with regard to their willingness to continue the search in the next carriage if the current carriage does not offer a suitable seating place. In the simulations, probabilities were utilised in order to at least approximate realistic behaviour. 90% percent of all passengers in all experiments reach their places in a maximum of 225 seconds and therefore, to a large extent, within a time span which can be performed – at least at larger stops with longer stopping times – while the train is still standing. The longest documented search by a simulated passenger took 2811 seconds, which is almost 47 minutes (see figure 3). This is an extreme value for a passenger who tried his luck in several carriages in a fully occupied train and finally found a place to stand.

Table 1

Parameters of the investigated scenarios

Scenario ID	Number of passengers boarding (2nd class)	Number of passengers remaining in coach (2nd class)	Number of additional passengers boarding (1st class coach no. 9)	Number of passengers remaining in coach (1st class coach no. 9)	Number of passengers boarding (1st class, coaches 11-14)	Number of passengers remaining in coach (1st class, coaches 11-14)	Number of passengers disembarking (2nd class)	Number of passengers disembarking (1st class)	Share of seat reservations	Share of passengers with reservation willing to change the seat	Platform discipline (share of passengers waiting close to desired coach)	Final passenger load (entering and remaining passengers)
1	497	0	35	0	168	0	0	0	0.3	0.9	0.75	100%
2	497	0	35	0	168	0	497	203	0.3	0.9	0.75	100%
3	249	248	18	17	84	84	0	0	0.3	0.9	0.75	100%
4	249	248	18	17	84	84	249	102	0.3	0.9	0.75	100%
5	497	0	35	0	168	0	0	0	0.7	0.9	0.75	100%
6	497	0	35	0	168	0	497	203	0.7	0.9	0.75	100%
7	249	248	18	17	84	84	0	0	0.7	0.9	0.75	100%
8	249	248	18	17	84	84	249	102	0.7	0.9	0.75	100%
9	497	0	35	0	168	0	0	0	0.7	0	0.75	100%
10	497	0	35	0	168	0	497	203	0.7	0	0.75	100%
11	249	248	18	17	84	84	0	0	0.7	0	0.75	100%
12	249	248	18	17	84	84	249	102	0.7	0	0.75	100%
13	497	0	35	0	168	0	0	0	0.3	0	0.75	100%
14	497	0	35	0	168	0	497	203	0.3	0	0.75	100%
15	249	248	18	17	84	84	0	0	0.3	0	0.75	100%
16	249	248	18	17	84	84	249	102	0.3	0	0.75	100%
1.25	125	0	9	0	42	0	0	0	0.3	0.9	0.75	25%
1.50	249	0	18	0	84	0	0	0	0.3	0.9	0.75	50%
1.75	373	0	27	0	126	0	0	0	0.3	0.9	0.75	75%
5.25	125	0	9	0	42	0	0	0	0.7	0.9	0.75	25%
5.50	249	0	18	0	84	0	0	0	0.7	0.9	0.75	50%
5.75	373	0	27	0	126	0	0	0	0.7	0.9	0.75	75%

5.4. Total time for finding a seat

The focus of the present study is directed at the quality of service perceived by the passenger when searching for the intended or randomly found place to sit/stand within the train after boarding. This individual time duration was therefore extensively addressed beforehand. Nevertheless, from an operational and individual point of view, the length of the overall process of finding a place to sit/stand on the train is not uninteresting. As shown in the results, there are very long search times in the seats, which can only be validated to a limited extent but which are nevertheless entirely conceivable. In order to classify the overall process duration, authors therefore do not use the maximum values (or the mean value of the maximum values), as these provide scarcely any feeling for the focus of the process. Instead, decision fell to consider the respective 90% fastest passengers from each triple-simulated scenario. This 90% percentile is suitable for representing the majority of the passenger movements in a meaningful way, whilst simultaneously omitting extremely variable peak values from the analysis. As a result, it is no longer necessary to validly model such long search processes and, furthermore, there are no problems of delimitation in cases in which it is no longer possible to clearly determine the point in time at which a search process should actually be considered complete. In reality, there may be reasons for assigning an already reached place to further searches, which cannot be depicted in the model. The following figure 3 presents the durations for this fastest 90% of all “Entering passengers” as a function of the number of “Entering passengers” in the scenario in question. The range of the measurements reaches from 111s for 176 “Entering passengers” up to almost 500s for 700 passengers, with an average across all simulations of 248s (with a calculated average of 478 passengers). The average of the scenarios 1-8 (with dynamic seat allocation) is 223s for the 90th percentile. In contrast, 327s is the average value of scenarios 9-16, which are analogously structured but do not, however, feature dynamic seat allocation. Table 2 shows detailed boarding times for all passengers (for both with and without reservations) as well as for 90th percentile of all passengers, depending on having a dynamic seat allocation active or inactive and listed in the same row for comparable scenarios. Time savings for mean values range from 4% (scenarios 16 vs 4) up to 32% (scenarios 12 vs. 8), whereas savings increase substantially if reffered to the 90th percentile comparison.

Table 2

Time savings due to dynamic seat reallocation

Scenario ID	Mean boarding time [s] (all)	90th-percentile of all boarding times [s]	Corres-ponding scenario ID	Mean boarding time [s] (all)	90th-percentile of all boarding times [s]	Time saving (mean), [%]	Time saving (90th percentile), [%]
without dynamic seat reallocation			with dynamic seat reallocation			by dynamic seat reallocation	
13	96.46	249.06	1	83.50	197.22	13	21
14	93.24	239.94	2	75.27	168.03	19	30
15	89.19	275.55	3	71.85	186.00	19	32
16	70.08	192.00	4	67.00	152.91	4	20
9	122.01	379.56	5	86.90	207.36	29	45
10	120.15	362.82	6	88.21	207.72	27	43
11	91.65	317.88	7	62.79	131.10	31	59
12	94.18	331.20	8	63.65	170.04	32	49

5.5. Passenger change times

The consideration of the total passenger change times as given in figure 4 is performed from an operational point of view in order to calculate the minimum stopping times of a train so that the expected passenger change will remain within the permitted times. This means that it is not the event of boarding from the passenger's point of view that counts, but instead the time expended for all passengers. This consideration of the passenger change time corresponds to the conventional method. The total passenger change time is thereby calculated from the difference between the last and first passenger-change event. Either boarding or alighting can be considered as events. This consideration is to be understood as being close to the door. The only aspects that are examined are when the respective boarding or alighting took place and when the passenger is "inside" or "outside".

Depending on the scenario, differing proportions of “Entering passengers”, “Maintaining in train passengers” and “Disembarking passengers” are included. Their total number varies in the steps depicted in the illustration. An interrelation can be recognised, according to which the total passenger change time correlates positively with the total number of passengers present. Overall, passenger change times in the range of 66s to 698s were found in the simulations, whereby the latter value, as an outlier, was not shown in the figure 6. With the second highest value of 304s, it was therefore determined passenger change times of between just over one minute and a little more than five minutes. As mentioned earlier, even if boarding is already completed, a serious number of passengers is still on their way to the desired seat or stand. The duration for the 90% fastest passengers in each scenario in figure 5 managed it to arrive within 100 up to 500 seconds, including multiple search situations when a passenger without a valid reservation was sent away by the actual owner.

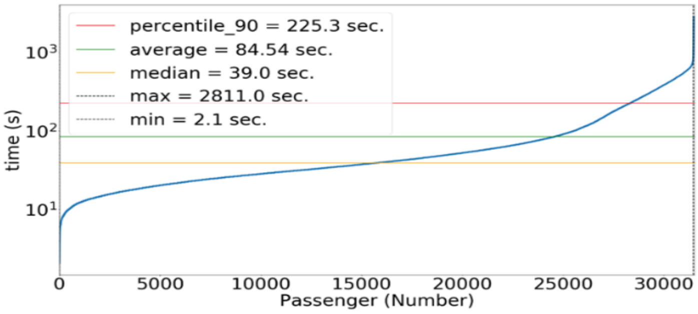


Fig. 3. Passenger change times statistics for all simulated scenarios

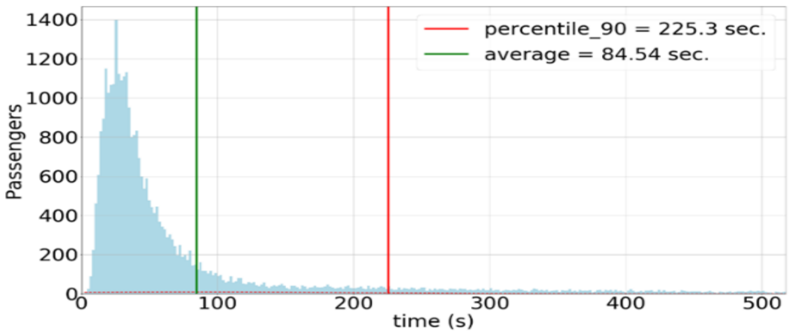


Fig. 4. Passenger change times distribution for all simulated scenarios

5.6. Discussion of the results

For an optimisation task, the potential for flexible seat reservation is unusually high if approximately half of all required foot traffic inside the train could be avoided. In fact, the achievable savings depend on the previously generated "disorder" caused by boarding a wrong carriage. With the selected scenarios, however, a moderate scenario in which 75% of the passengers board exactly the right carriage was deliberately chosen. This may work much more effectively in regular operation and fewer people randomly board a train. However, primary sources for the points where passengers choose to enter were not available according to the state of the research. Nevertheless, there are situations in which the question of choosing the right door is certainly of secondary importance. This is always the case when there is a very short transfer connection, where passengers are able to reach their destination under stress and the first best entrance is chosen. In this case, in addition to the bundling of boarding passengers at train doors, it would inevitably lead to the creation of congestion in these areas. Other situations that could potentially lead to incorrect boarding may arise from the varying order of carriages or the provision of a replacement train consisting of other rolling stock.

5.7. Error analysis / Limitations of portability to real-life events

"Essentially, all models are wrong, but some are useful." (George Box). In this case, too, the use of simulations and the selection of scenarios implies the impossibility of mimicking real-life events and presenting realistic effects comprehensively. However, our simulation series shows reproducible results through the comprehensibility of the assumptions made, whose claim to quantitative correctness for individual facts is more subject to the qualitative classification of the cumulative effects. For example, passenger movement within the train may be greatly simplified (e.g. due to a lack of secondary activities, a lack of baggage handling, group dynamics), but overall, this applies equally to all scenarios. The influence of the flexible reservation system is therefore the main difference in the simulations and thus the predominant cause of the observed effects.

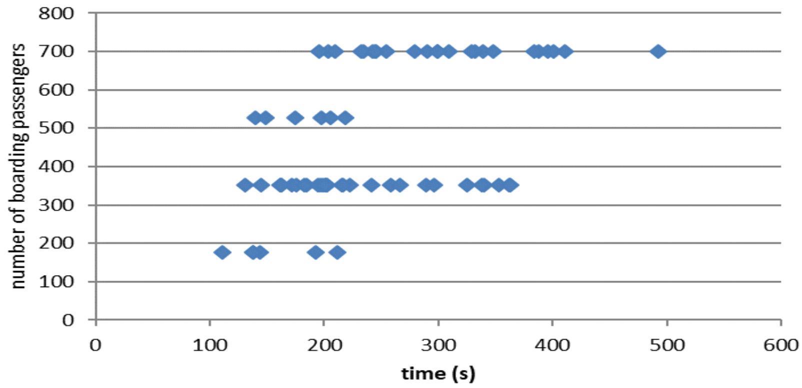


Fig. 5. 90th percentile of total boarding time (door to seat/stand)

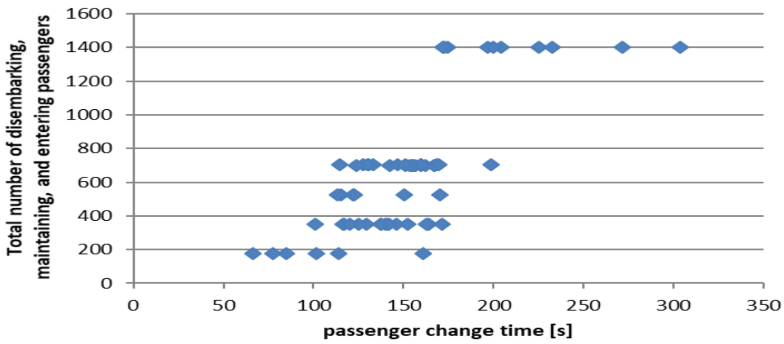


Fig. 6. Passenger change durations (without one data outlier "698s" s at 1400 entering and exiting passengers)

Moreover, 16 scenarios with a correspondingly limited selection of parameter variations were investigated. Scenarios 1 and 5 were additionally simulated with lower numbers of boarding passengers in order to estimate the effectiveness even at lower passenger volume. Each scenario has been simulated exactly three times, which is, of course, too little testing for the meaningfulness of a Monte Carlo simulation series. Due to the statistically sufficient amount of simulations, a frequency distribution of the effects would be more accurately represented. Nevertheless, even fewer simulations provide a clear result, because not only the number of simulations increases the statistical robustness but also the number of objects simulated in parallel. In the scenarios 1 .. 16, a total of 700 passengers are simulated each, which means that the number of cases in three runs for the depiction of individual behaviour penetrates into resilient areas. For the commercial application of the presented method, authors recommend that in addition to the use of an adapted train model, additional data from traffic counts and the like are to be used. The example of the parameters chosen by us in the example of the ICE 1 shows that the potential to accelerate the finding of the seat in the train is high and that the amount of distance required and thus the contact that passengers have with each other can be drastically reduced.

6. CONCLUSION AND FUTURE RESEARCH OPPORTUNITY

The need for further research is characterised by the choice and design of the relevant technology of the flexible reservation system. In the simulation study, it was assumed that the exchange of seat does not involve any significant additional process times and space consumption for operation on the train.

This requires the consistent use of mobile devices, which can be used safely during boarding. In our simulation, all passengers who would agree to a spontaneous seat exchange will pause for one second – for example, to obtain their possibly reallocated seat on their mobile phone. Most mobile phones these days would be technically capable of serving as a front-end interface for this purpose, but it is questionable whether acceptance for use would be given in this form alone. In fact, it would even be possible to arrange the seat exchange before entering the train, thus avoiding the need to use a handheld device during a boarding procedure. Technically, however, this would also require a device that is able to estimate the current position on a platform precisely enough to predict with sufficient accuracy the entrance that will probably be selected later.

Nevertheless, authors see great potential for operators of comparable long-distance trains to increase productivity. Especially in open reservation systems, where it is possible to travel with and without a seat reservation, there are advantages for customers and providers. From a customer's perspective, it is a great advantage to have a free choice of access and to be supported by the reservation system in finding a suitable seat close to the place of boarding. On the operator side, it is commercially interesting because seats that have not been reserved are spontaneously reserved at the last minute for the exchange option. Even if another seat becomes available at the same time, this increases the incentive for passengers to travel with a reservation so that they do not have to fear being expelled from their seat at every stop along the way. The new method thus opens up the possibility of maintaining the open system, which is used, for example, at Deutsche Bahn, while increasing the incentive to make reservations. This increase in incentives can be used not only purely commercially by increasing revenues but also from the demand management perspective, as an increase in the rate of reservations is accompanied by a more precise prediction of the expected utilisation if the share of passengers without a reservation decreases.

There is a further point of operational importance, which gives a previously unused advantage over conventional seat booking. If an available seat can no longer be reserved on a connection with several intermediate stops, the customer cannot make a reservation at all. However, with a flexible procedure such as the one described above, it is possible to offer the passenger a combination of seats for partial journeys. Thanks to this flexibility, it is possible to react to this even at the moment of the required seat exchange and to offer the customer concerned either a particularly close alternative seat or the boarding passenger with the reservation for the seat, which is still being claimed, is offered an alternative seat and the passenger actually obliged to change can remain in his seat.

The question also arises as to whether a reduction in traffic on the train that is required to find a seat could not actually be used to partially utilise the available aisle space in a different way – possibly more productively. In any case, however, reducing the quantity of passenger foot traffic on the train has the potential to be useful in preventing the spread of pathogens. For this purpose, it is planned to extend the simulation model by an infection model, taking into account the ventilation system and the distribution of aerosols in the carriage.

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