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Influence of the Rail Vehicle Layout on Efficiency and Railway Operation

Bernhard RÜGER[1]

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[1] bernhard.rueger@tuwien.ac.at, Research Unit of Track-bound Transportation Systems, Faculty of Civil and Environmental Engineering, TU Wien, Vienna, Austria

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ABSTRACT

Railway efficiency is increasingly significant given the competition with road and air transport, where usability of travel time, passenger comfort and operational reliability play key roles. This study investigates the influence of passenger rail vehicle layout on efficiency, focusing on aspects such as passenger changeover time, luggage storage, seating usability and overall comfort. Since 2001, empirical research at TU Wien has combined extensive passenger observations, surveys of more than 60,000 travellers, detailed luggage measurements and video analyses of over 20,000 boarding and alighting processes, complemented by controlled changeover tests in multiple vehicle layouts. These data informed the development of a calculation model and the TrainOptimizer software to evaluate and optimise layouts. Findings show that maximising seating capacity often reduces efficiency by limiting luggage storage, blocking seats and extending changeover times, whereas layouts with fewer but better-positioned seats and distributed luggage racks increase usable capacity and passenger satisfaction. Results also indicate that interior design directly affects time use, stress and well-being during travel. The study concludes that vehicle design has a significant impact on operational performance, energy use and the competitive position of railways, with well-balanced layouts offering both higher efficiency and an enhanced passenger experience.

KEYWORDS

rail vehicle layout; passenger changeover time; dwell time; capacity utilisation; efficiency modelling; railway operations.

1. INTRODUCTION

The efficiency of railways is of great importance on several levels, given its intense competition with aviation and road transport. Efficiency here refers to both economic efficiency and the performance of the rail system. It is also a very complex system that must always be viewed holistically. There is a large number of requirements and criteria that railway operators must fulfil in order to be efficient. One important and often underestimated criterion for overall efficiency is the structure and layout of passenger transport vehicles. In order to increase efficiency, for decades the aim has been to maximise the number of seats in trains, in the mistaken assumption that this will allow more passengers to be transported and thus generate more profit [1]. However, the resulting standardised systems no longer meet many comfort requirements and do not offer the necessary options for genuine time utilisation due to the lack of flexibility or individualisation. However, the usability of time, whether productively for working or passively for relaxing and many other activities, is a decisive market advantage of the railway [2]. This is because the time lost when travelling by train is nominally the least compared to all other modes of transport, but to achieve this, it must be possible to actually use the time according to personal requirements [3].

The design of the vehicles also has a significant influence on the actual possible degree of capacity utilisation and punctuality [4]. Another important factor at present is the influence on energy consumption [5].

In order to quantify the effects of vehicle design in general and the interior in particular on operational components and to be able to derive optimisation options from this, a series of projects was launched at the TU Wien in 2001, which intensively examined the behaviour and requirements of rail passengers, especially in the interior of the carriage.

2. METHODS

Since 2001, the behaviour of over 400,000 passengers in over 100 different vehicle types in Central Europe has been analysed in detail and supplemented by surveys of 60,000 passengers. The surveys were conducted as part of various projects with different focal points. The population for each survey is therefore smaller (usually in the range of several thousand people), which is also indicated in the sample sizes (N) for each survey. The core countries of the studies were Austria, Germany and Switzerland. Surveys were also conducted in Slovenia, Hungary, Serbia, Bulgaria and Denmark. From these and other methods, it has been possible to derive a calculation model which can be used to assess and thus optimise vehicle layouts with regard to the criteria of passenger changeover time and seat usability. The methods used are described below.

2.1 Passenger observations

In order to generate an objective dataset, it is important to record the behaviour of passengers in such a way that they do not even realise that their behaviour is being recorded. To this end, snapshots were taken in the vehicles. Surveyors walked through the train and recorded on a floor plan of the carriage exactly where people were sitting, what they were doing and what luggage was stored where in each section. Apparent characteristics such as the estimated age and gender of the people and their choice of seat (or standing room) and the activities they were carrying out were recorded. Furthermore, it was recorded exactly what type of luggage (trolley, travel bag, backpack – in each case according to the size categories small, medium and large) was deposited where and in what form. All these studies were carried out in over 100 different layouts of rail vehicles in Europe, both in local and long-distance trains, in order to determine the influence of vehicle design on passenger behaviour.

A precise statistical analysis of the data thus provided the knowledge of which carriage areas are more and less popular depending on the luggage storage facilities, design or location. The information also reveals which equipment elements are used in which form. In addition, there are precise findings on passenger preferences regarding luggage storage. For example, there are clear insights into which items of luggage are placed in overhead racks or luggage racks and in what quantities, how many items of luggage block seats or aisles or lead to other restrictive situations. The observations also provide precise insights into which activities are carried out by which people and whether the interior design of the vehicles or individual equipment components has an influence on the selected activities.

2.2 Surveys

The observations were supplemented by a survey of around 60,000 passengers. The surveys, which comprised a total of over 10 different projects related to the behaviour and preferences of rail passengers, were conducted in the form of questionnaires during a period of approximately 15 years. Passengers were given A4-sized questionnaires (two to four pages) and a pen, and asked to complete the questionnaires.

There was no special selection process for the passengers surveyed. All passengers on the trains surveyed were politely asked to participate in the survey. In all projects from which the survey data were used here, the aim was always to achieve a balanced ratio of age and gender among the respondents.

For this reason, the data were also evaluated during the ongoing survey with regard to demographic distribution in order to determine whether there was any imbalance. If this were the case, the plan was to specifically address the underrepresented groups again. However, as the survey data matched the objective data from the respective observations very closely, no adjustments were necessary.

The questions themselves were usually closed questions, with a few additional options for open-ended answers. Since 2020, the surveys have increasingly been conducted electronically, with flyers containing QR codes and information about the surveys and the projects being distributed on trains or on station platforms.

The electronic questionnaires were created using either the SurveyMonkey or LimeSurvey tools. The questionnaires were usually completed by passengers on their smartphones during their train journey.

The aim of the surveys was to gain the following insights into the behaviour and needs of passengers, depending on age, gender, purpose of travel, group size and other personal characteristics:

— Type, estimated size and weight and number of items of luggage
— Luggage storage location
— Reason for the choice of storage
— Difficulties when boarding and travelling with luggage and accommodation
— Specific requirements for luggage storage
— Activities carried out during the journey (time utilisation)
— Seating requirements
— Other

The data were used to create an exact model of the amount of luggage and the type of luggage storage depending on the individual characteristics of the travellers. In combination with the observation data, it is thus possible to predict very precisely where which items of luggage are stored in a defined vehicle layout, how many items of luggage are not properly deposited and, conversely, how much can potentially form a nuisance (e.g. when it is placed on the seat, in the aisle, in the boarding area, etc.). In addition, the data can also be used to show exactly which activities travellers carry out in terms of time usage, which they would like to do but cannot do due to a lack of equipment and which elements they would need in order to carry out the activities.

2.3 Baggage data collection

In order to obtain an exact overview of the different pieces of luggage and their characteristics, several thousand pieces of luggage were recorded in detail. The exact dimensions in centimetres, the exact weight in kilograms and the type of luggage were recorded by survey staff by using a tape measure and a luggage scale. One person always took the measurements and a second person noted them down in a list. The type of luggage (e.g. trolley, travel bag) was also recorded. It was also recorded whether and how many wheels the luggage had, and whether it was soft or hard cover. In addition, passengers were asked about their luggage and their subjective perception of the size and weight of the luggage was recorded. Passengers were also asked about the purpose of their journey and whether they were using the luggage piece alone or with other people. These data were then correlated with the survey data.

Across all surveys, the following distribution of respondents emerges:

Distribution of age groups: Up to 20 years: 25% / 21-30: 21% / 31-40: 16% / 41-50: 15%/ 51-60: 12% / 61-70: 8% / over 70 years: 3%. The gender distribution was very balanced, with 49% female and 51% male.

The reasons for travelling depend heavily on the region, the season and also the route. On average across all surveys in Germany, Austria and Switzerland, it can be said that private travel accounts for approximately 70% and business travel for approximately 30%.

2.4 Video analyses of the passenger changeover

More than 20,000 passengers were filmed by a video camera when boarding and alighting to determine the exact passenger changeover time. Permission was obtained from the respective railway operators for the video recordings. Analysing these videos enables statements to be made to the nearest tenth of a second about how long it takes a person to board or alight the train, depending on their age, gender, any physical limitations, the luggage they are carrying and the design of the vehicle. The exact width of the vehicle doors, the number of steps to be negotiated from the platform, the size of the boarding area and the design of the interior were determined.

In addition to the exact representation of the time required for boarding, the data also allow the influence of the interior design on the passenger backlog and the increased time required to be calculated.

2.5 Passenger changeover tests

In order to determine the exact behaviour of individual people inside vehicles boarding or alighting, various passenger changeover scenarios were simulated in around 20 different vehicle layouts with over 100 extras over five days in 2022. In each scenario, luggage had to be taken into the vehicle and stowed away, and/or special seats, including reserved seats, had to be found. Six cameras were positioned in each of the boarding sections to record the exact movement sequences under the different personal and vehicle-related conditions. Finally, these data were also compared with the above-mentioned video recordings at the boarding door in regular traffic in order to be able to determine whether the re-enactment of the respective situations resulted in a change in behaviour compared to real operation and whether the data could therefore be falsified. This comparison and targeted observations by the organisers of the tests on the train have shown that the simulated scenarios could hardly be distinguished from real scenarios in terms of the time required.

2.6 Creation of the calculation model

The evaluation of the extensive data led to a calculation model that can be used to assess the expected passenger changeover time, stowability of luggage and usability of the seats in the best possible way for new vehicle layouts in terms of efficiency. The passenger changeover time largely follows a quadratic parabola when boarding and a linear one when alighting. The gradient of the curves is influenced by the various parameters of the carriage at the boarding area and in the interior (number of steps, door width, aisle width, layout of the seats and luggage racks, size of the luggage racks and much more) as well as by the personal characteristics of the travellers and the luggage they are carrying. Based on the calculation model, a software called TrainOptimizer® was developed, with the help of which layouts can be easily created and evaluated in terms of passenger changeover time, luggage storage and seat usability. By using this software, the calculation model was applied for the calculations in this paper.

3. USABILITY OF TRAVEL TIME

Air travel and car journeys can often be shorter and faster when measured from door to door. However, the problem with these modes of transport is that much of the time spent travelling is considered dead time, as it is inherent to the system but cannot be used for personal purposes. When travelling by plane, for example, you have to be at the airport early, check in your luggage, go through security, board half an hour before departure, etc. All of this is time that cannot be used efficiently for work or relaxation. The same applies to a large extent to car journeys, especially for drivers.

Compared to other modes of transport, rail has the great advantage that travel time can be used efficiently. When travelling by train, the door-to-door time is often longer, but the actual time spent on the train is usually the longest and, ideally, can be used continuously for your own needs. For example, you can work or use the time to relax. However, it is important to know the requirements of travellers and to actually offer the relevant facilities and services so that the theoretical advantage of time utilisation is actually realised [8].

3.1 Actual time use

A key factor in the information on the use of travel time is the question of whether the journey takes place in a professional context (travel to/from work, business trips, travel to/from educational institutions) or for private reasons (holiday trips, leisure trips, private errands). For example, more than half of all surveyed business travellers state that they use a laptop, tablet or smartphone during the journey, while only a quarter of private travellers do so. It is particularly important for people travelling for business purposes to have all the necessary facilities to enable them to work effectively, to a large extent also using their own mobile devices [6].

A third of business travellers also use the time to read work documents. Between 60% and 70% of travellers use the time during the train journey to read books or newspapers, and 60% to 80% also want to use the time during the train journey to relax and unwind (see *Figure 1*) [6].

Another important factor influencing the information on the actual use of travelling time is the age of the respondents. In general, there is a decrease of around 20% between the 19-39 age group and the over-60 age group in the number of activities mentioned during the train journey. However, not all activities decrease to the same extent. For example, the activities of reading a newspaper or book and looking at the scenery are mentioned more frequently with increasing age, whereas the use of technical devices decreases with age. The intensive frequency of use of technical devices among younger travellers in particular must be taken into account for vehicle construction in the future, as it can be assumed that younger and more tech-savvy people today will continue to use such devices in the future and at an older age [7].

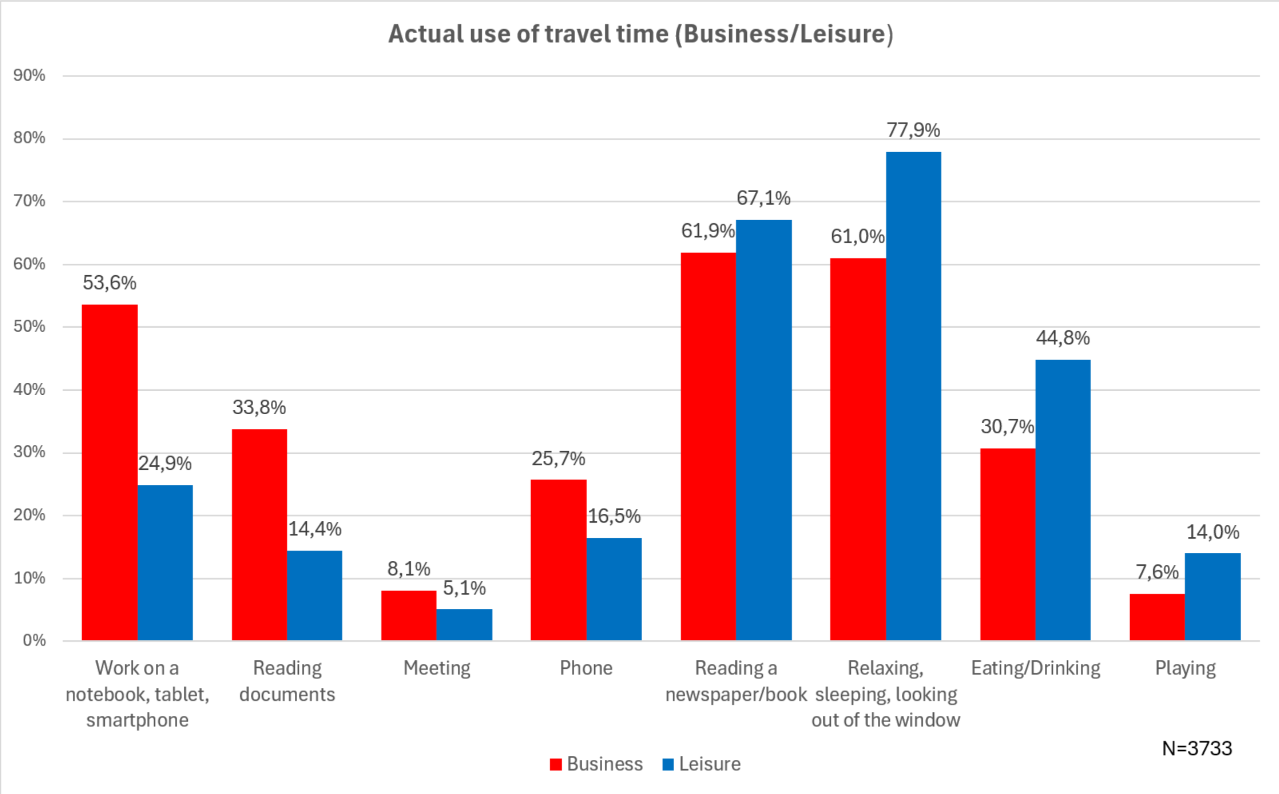

Figure 1 – Actual time use during the train journey (source: FLEXICOACH, AP7 report)

Visual observation of the activities actually carried out as part of a snapshot shows that with a lower utilisation rate of up to 30%, around 70% more people are working on a laptop than with a high utilisation rate of over 70%. At the same time, the proportion of people who appear to do nothing at all increases by 40%. This is a significant indication that the conditions for concentrated work are no longer sufficient when the train is heavily utilised [8].

It was also found that people sitting at a fixed table in a vis-à-vis seating group work on a laptop 35% more often than people sitting in a row with a folding table. Window seats are also used a good 30% more often for working on a laptop than aisle seats. This can be explained by the fact that people in aisle seating may have to stand up for those in window seating, which also means folding away a table and putting the laptop away [2].

3.2 Desired use of travel time

The desired but not feasible activities also depend on whether the journey is business-related or private, although not as clearly as the activities actually carried out. *Figure 2* shows those activities that travellers would like to carry out but were unable to do on the trip in question for various reasons not described in detail here.

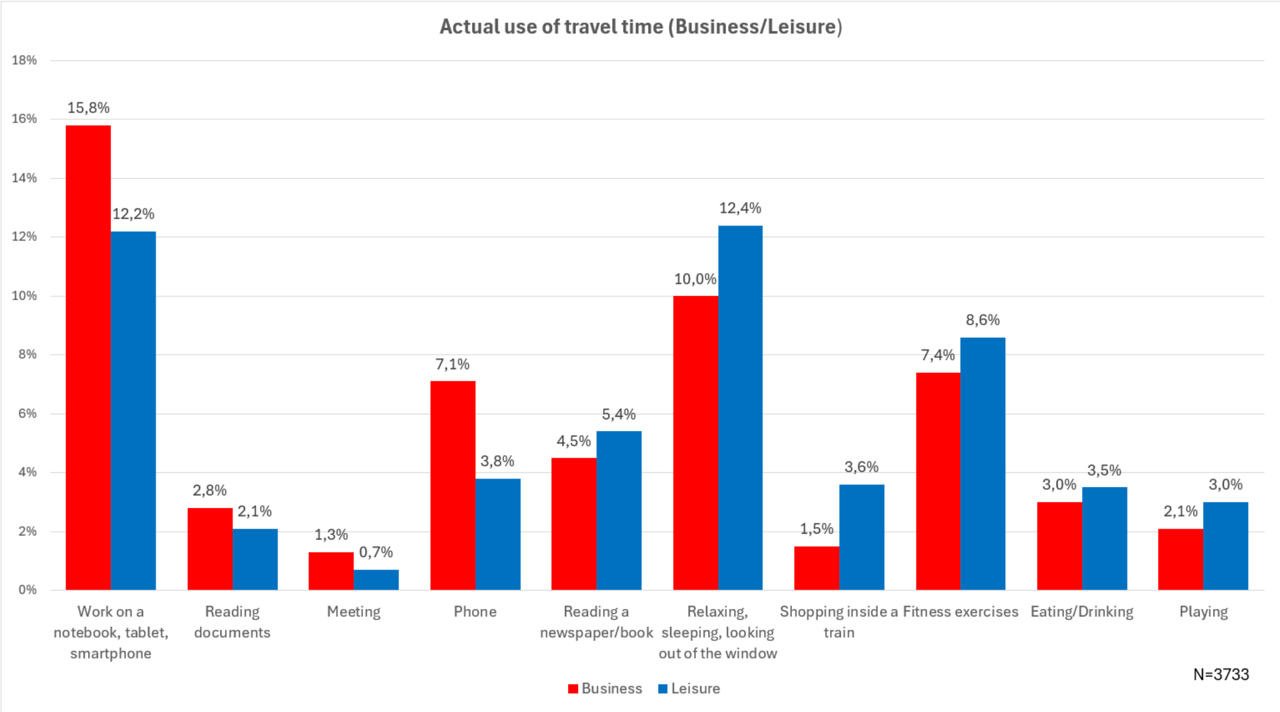

Figure 2 – Desired activity, but not feasible during the respective journey (source: FLEXICOACH, AP7 report)

The most common complaint (from about 20% of respondents) was poor mobile phone connection. Based on the comments, it is clear that this often refers to a lack of Wi-Fi connection or internet connectivity in general. Together with the lack of suitable tables (cited by 12% of respondents), this is the main reason that makes it difficult to use a laptop, tablet or smartphone. Around 17% of respondents criticised uncomfortable and non-adjustable seats as well as a lack of rest (12%), which is contrary to the desired activity of relaxing and sleeping. The need for more motion, which was surveyed in another context, is reflected in the desire for the opportunity to do fitness exercises [8].

The age of the respondents has a recognisable influence on their wishes for time use. The younger the travellers are, the more frequently desired but not feasible activities are stated. Older passengers are significantly more satisfied with the options available and are less likely to express a desire to use their time differently. The different colours in the columns in *Figure 3* show the individual desired activities (e.g. the bottom section (blue) stands for working on a laptop, the next for working on a tablet or smartphone, etc.). *Figure 3* shows the frequency of the non-feasible activities mentioned. Similar correlations with great age-dependent changes can be found for many questions (well-being, stress factors, activities, etc.).

This graph deliberately does not address individual factors, which can be seen in *Figure 2*, but rather aims to show that satisfaction apparently increases with age, while expectations decrease. While 90% of people under the age of 18 say that there are some activities they would like to do but are unable to, this figure drops to only 40% among people over the age of 60.

In this context, it should be noted that younger travellers have higher expectations of the journey and the activities that can be carried out in terms of time usage and that this group also represents the passenger potential of the future. It is therefore particularly important to understand the needs and expectations of younger travellers as well as possible and to take them into account in order to keep them on the rail system in the future [7]. For example, younger people in particular have different and more critical expectations when it comes to the use of electronic devices.

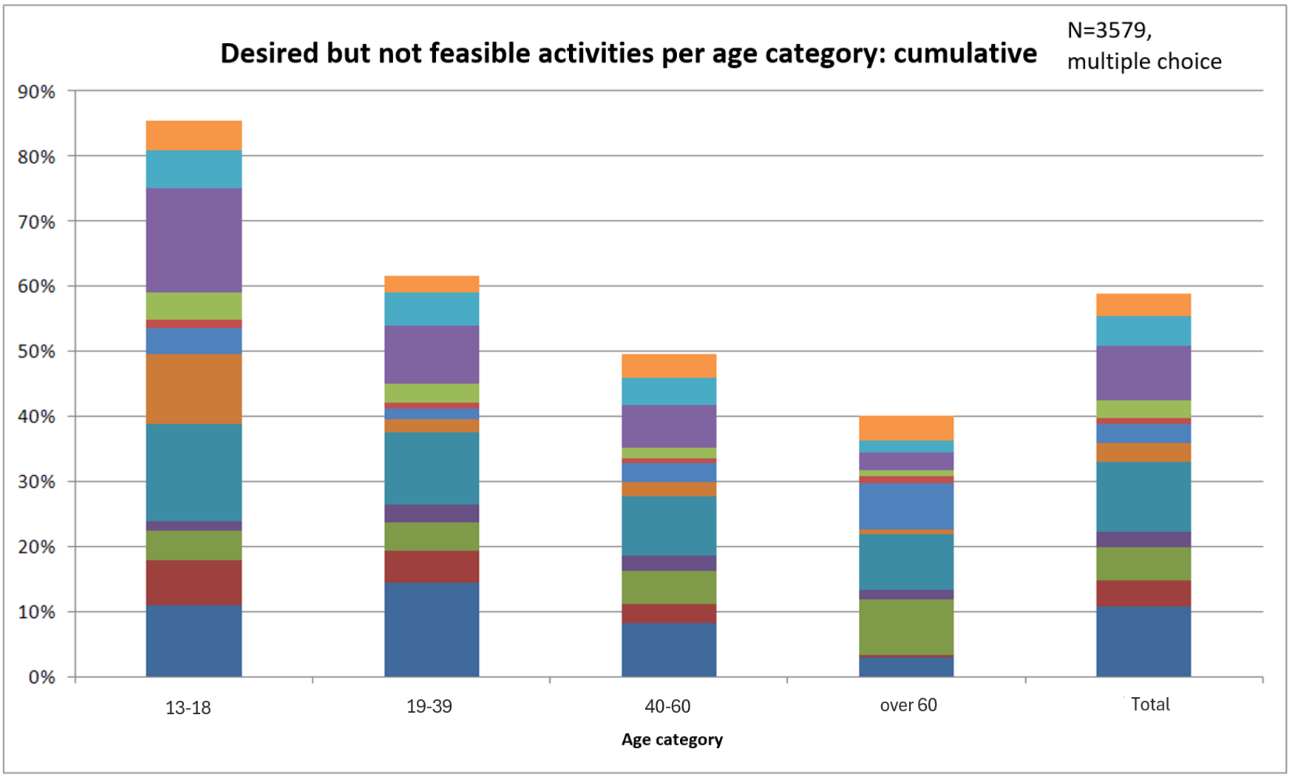

Figure 3 – Frequency of mentions of desired but not feasible activities per age category (source: FLEXICOACH, AP7 report)

The duration of the train journey also has an impact on the information on usage preferences. The longer the journey, the more frequently usage requests are mentioned, especially for a journey time of more than two hours.

The longer the journey, the greater the need to move around on the train. While around 20% of those surveyed stated that they wanted to use the journey time for exercise for journeys of up to one hour, this rises to 40% for travellers with a journey time of more than five hours. Younger people are significantly more likely to feel the need for more exercise during their train journey than older people. It is also interesting to note that around 8% of travellers would like to have the opportunity to do fitness exercises on the train. Among travellers under the age of 18, this wish is even expressed by 16% [8].

3.3 Wellbeing

In addition to looking at time usage, the general well-being of travellers is also particularly important. After all, only travellers who generally feel comfortable will use the train more often.

A third of passengers on the trains surveyed stated that they felt very comfortable, just over half felt rather comfortable, 14% felt rather uncomfortable, and 1% felt completely uncomfortable. Here too, the age of the respondents had a significant influence, with satisfaction during the train journey increasing with age [8].

Any assumptions that this finding could be related to the fact that younger passengers make more journeys with a professional or educational background, while older travellers are more likely to pursue more pleasant private travel purposes such as holiday trips, prove to be incorrect. The proportion of holiday trips lasting several days remained constant at around 50% for all age groups during the survey period. Although there are differences in leisure journeys without an overnight stay, these journeys are made most frequently by the 13-18 age group, the age group that apparently feels most uncomfortable when travelling by train. A correlation between the purpose of the journey and well-being is therefore not apparent.

Feeling comfortable in the coach or at your seat also includes the indoor climate in particular. 75% of travellers state that they are satisfied with it, for around 10% it is too warm and for another 10% it is too cold. This discrepancy in particular is due to different subjective perceptions and will require an intensive examination of customisable heating and cooling systems in future vehicles, including in the immediate vicinity of the seat [6].

Passengers in first class tend to feel more comfortable than passengers in second class. Furthermore, the well-being of passengers during the train journey is highly dependent on the degree of utilisation of the trains.

On weekdays from Monday to Thursday, for example, around 95% of travellers say they feel very or rather comfortable. On Fridays and weekends, on the other hand, around a third of passengers feel uncomfortable or rather uncomfortable. The apparently high capacity utilisation of the trains on these days leads to an increased feeling of stress and increased mentions of the stress factors, high capacity utilisation, looking for a seat, noise and other passengers and consequently to a lower level of well-being.

The most frequently cited reason for feeling stressed during the current journey is finding a seat. Just under 20% of passengers felt stressed as a result. Also frequently mentioned were high occupancy rate, noise and other travellers. The main stress factors are therefore those that occur when trains are full to capacity and, as described above, often lead to a reduction in well-being (see *Figure 4*) [8].

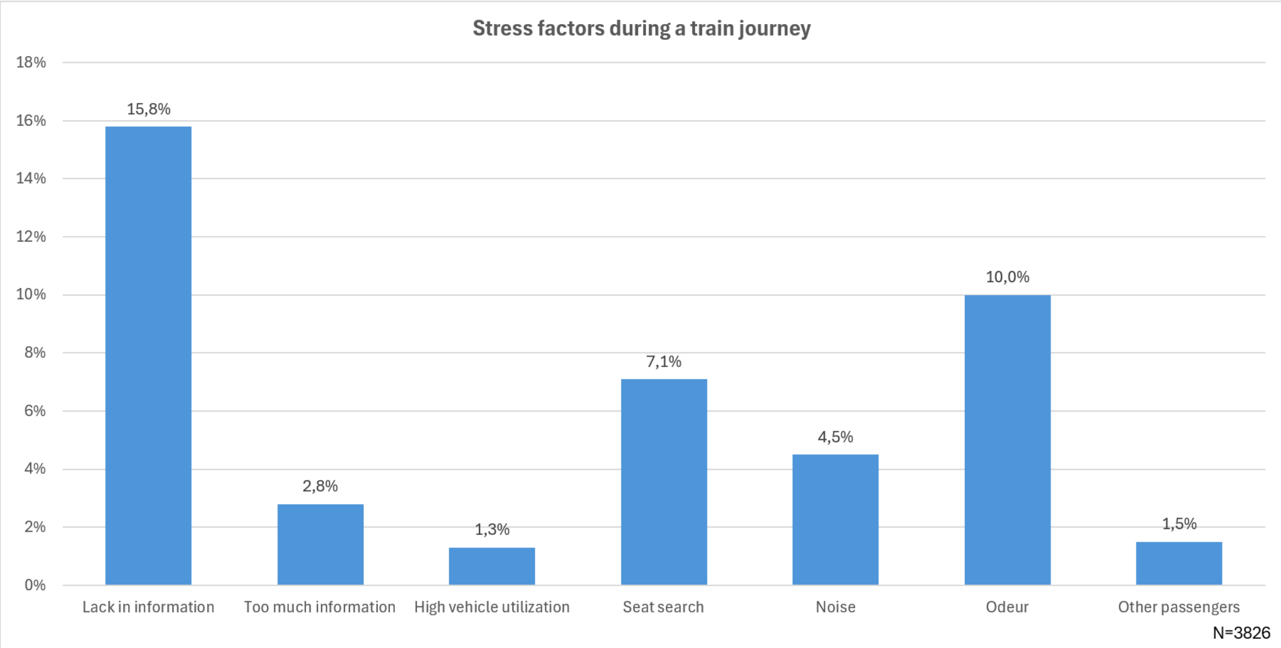

Figure 4 – Stress factors during a train journey (source: FLEXICOACH, AP7 report)

Similar to the information on well-being, the age of the respondents also has a major influence on the perception of stress. Younger travellers feel stressed more often, older travellers feel stressed less often, or at least give fewer responses. From the 13-18 age group to the over-60 age group, the number of mentions of causes of stress occurring during the current trip falls to less than half. The most frequently mentioned stress factor, looking for a place to stay, even falls to a third of 13–18-year-olds, up to the over-60s age group. This is particularly remarkable for a stress factor such as finding a seat, because it can be assumed that finding a seat (also with regard to luggage) becomes more difficult rather than easier with increasing age [16]. Conversely, it is reasonable to assume that older people make more frequent use of the option of reserving a seat, although this was not explicitly ascertained as part of the research.

3.4 Summary of the most important well-being criteria

The following factors play an important role with regard to the well-being components and usability, whereby the following contradictions also inevitably arise:

— *Lighting*: Good lighting is required for working, ideally no lighting at all for sleeping. In saloon coaches, there is usually only continuous lighting, which can be dimmed slightly in the evening or at night if necessary, and additional reading lamps can be placed at the seat.

— *Room acoustics*: Quiet is required for working or relaxing, but noise is caused when telephoning, talking or playing. There is no suitable noise reduction in current vehicles.

— *Indoor climate*: For approx. 75% of travellers, the temperature in the coach seems pleasant, for the other 25% it is either too warm or too cold. There is no standard temperature that suits all travellers. The same applies to ventilation. Unpleasant odours are a nuisance when relaxing or working, and they arise when eating.

— *Privacy*: Travellers travelling alone generally want to be shielded, while those travelling together want to be close to each other.

— *Space efficiency*: In classic passenger carriages, numerous seats or seating areas are not very popular and are therefore underutilised, which reduces the efficiency of a vehicle. Conversely, seats are deliberately blocked to create privacy.

— *Accessibility*: As a rule, accessibility is limited to the application of standards. However, these are a minimum compromise that does not adequately cover the individual requirements and needs of people with limited mobility in terms of sensory factors.

— *Time usability*: The usability of time during the rail journey is a major market advantage of rail over other modes of transport, but this is often only partially exploited or not exploited at all due to a lack of equipment elements.

4. LUGGAGE

4.1 Baggage volume

The type, size and weight of the luggage essentially depend on:

— Age and gender of travellers

— Purpose of trip (business, private; differentiate between holiday, visit, day trip, etc.)

— Duration of stay

The three main luggage categories, trolley, travel bag and backpack, can be divided into small, medium and large as well as light, medium and heavy. The size categories are particularly important for storing the items of luggage and therefore have a decisive influence on the dimensions of the compartments. Weight, on the other hand, has a significant influence on storage when it comes to lifting items of luggage. This must be taken into account when arranging the luggage racks [9].

The limit sizes of the respective baggage categories are shown in *Figure 5*.

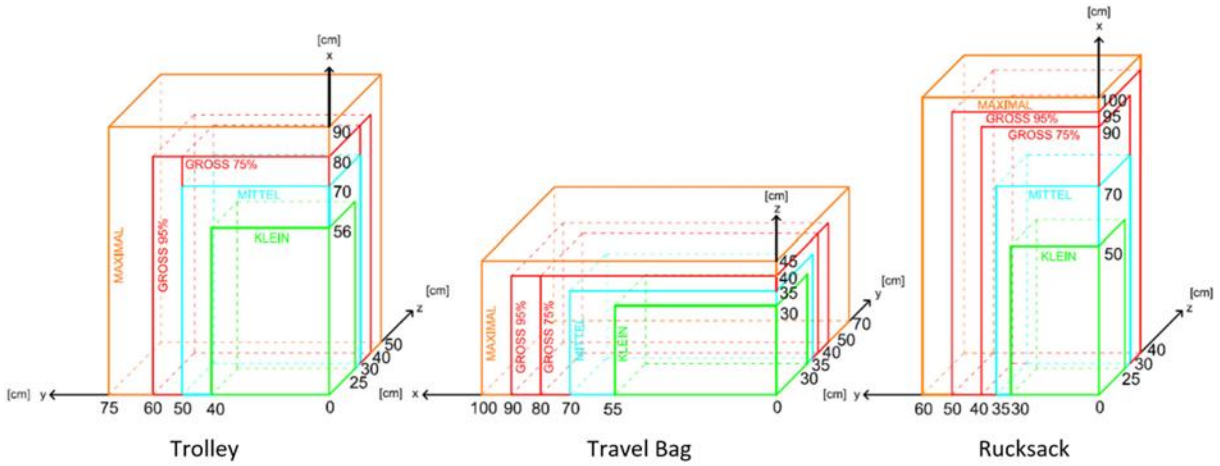

Figure 5 – Limit sizes of the respective baggage categories (source: [9])

The statistical distribution of sizes within the respective luggage categories also shows that a difference of just a few centimetres in the design of the storage compartments determines whether a large proportion of the respective items of luggage can be accommodated.

Experience to date shows that, on average, a luggage volume of between 110 and 150 dm^3 per passenger can be assumed. However, the indication of the volume of luggage items is incomplete and therefore not suitable on its own for dimensioning luggage racks. It is also necessary to take into account the cubic capacity, the shape of the respective items of luggage, and the associated dimensions as the key criterion for the design of racks. This report, therefore, uses the findings from numerous studies on the statistical distribution of the respective sizes of items of luggage to assess the trays. For the sake of clarity, however, only the number of stowable items of luggage or hand luggage is shown [9].

The unit is therefore a number that corresponds to the statistical distribution. These numerical values are of the utmost importance for the comparability of layouts.

For the purposes of comparison, the following *Table 1* compares the dimensions of standard items of luggage with the corresponding volume.

Table 1 – Comparison of standard items of luggage: dimensions-volume (source: [9])

	Length [cm]	Width [cm]	Height [cm]	Volume [dm³]
Trolley medium	70	50	30	105
Trolley large	80	50	35	140
Travel bag / Rucksack medium	70	35	35	86
Cabin baggage	55	40	25	55
Small hand baggage	40	30	20	24

It is noticeable that the volume of luggage is constantly increasing. The reason for this is that, due to technical possibilities, the tare weight of luggage is becoming ever lighter and the handling of luggage, e.g. due to wheels, is becoming ever more convenient. As a result, increasingly larger items of luggage are being purchased, and these are also being packed more generously.

The purpose of the journey, roughly divided into the main groups, largely determines the type and amount of luggage carried. *Figure 6* shows the volume of luggage per passenger depending on the purpose of the journey.

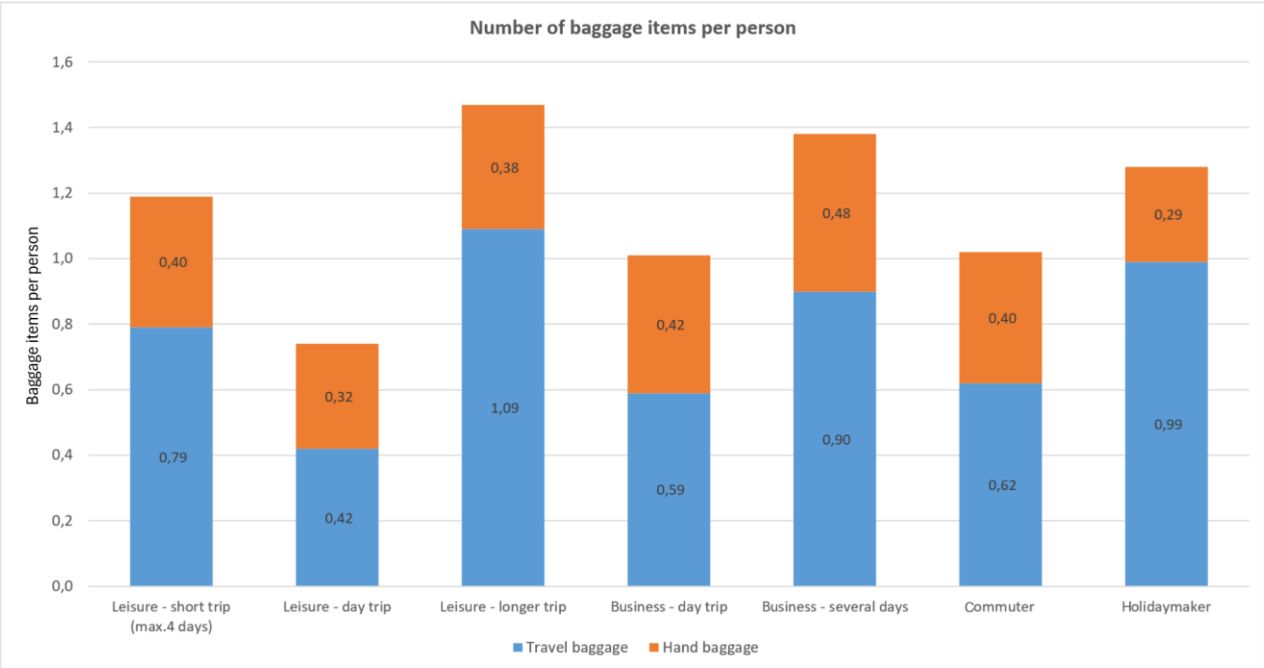

Figure 6 – Average number of pieces of baggage per passenger depending on the purpose of the journey (source: [18])

4.2 Luggage storage

There are currently the following luggage depots in passenger carriages [9]:

— Overhead racks at a height of approx. 170 to 180 cm. 80% of travellers cannot or do not want to place large and 50% medium-sized luggage on these shelves. In addition to the uncomfortable luggage storage, the shelves are not ergonomic or barrier-free due to the forced lifting process.

— Luggage racks are usually designed with three compartment heights. The lowest compartment is usually directly adjacent to the floor and is suitable for large, heavy trolleys, while the compartments above are suitable for medium-sized items of luggage. The dimensions often do not match the dimensions of the current luggage, which limits the storage capacity.

— Space between the seat backrests is very popular, but usually hardly available due to the required distances (target approx. 35 cm) between the seat backrests and is not space-efficient in the overall system.

— Multi-purpose areas are the only areas that are also suitable for storing extra luggage. In terms of the space used, there are, for example, inefficient solutions for parking bikes on the floor and solutions with hooks to hang them up, which make better use of the space but are de facto unusable for many travellers due to the lifting required (especially for heavier e-bikes).

Luggage storage location

With regard to luggage storage, there are two main requirements that result from passengers' wishes or are manifested in their behaviour [9]:
- Travellers do not want to lift their luggage
- Travellers want to have visual contact with their luggage

The desire not to lift luggage includes the easy handling of luggage when storing it. Even storage options close to the floor, which require multiple tilting or turning of items of luggage and thus increased effort, are not accepted by travellers and are therefore not used. However, lifting some of the luggage, especially the smaller and medium-sized items, at least to a medium height, is accepted, which can be used for efficient storage.

In general, it should be noted that luggage accommodation must meet the two main needs of travellers. When choosing accommodation, travellers always look for the best possible fulfilment of these basic needs and accept difficulties and inconvenience for other passengers and the train operator. Luggage racks that do not fulfil these two requirements are only accepted by passengers to a very limited extent.

When dimensioning luggage racks, not only the expected volume of luggage but also the distribution of luggage items across different heights must be determined. This calculation is based on precise knowledge of which travellers are prepared to lift which items of luggage under which conditions. A distinction is also made between how many travellers do not want to lift the luggage in question for reasons of comfort and how many are unable to lift the luggage due to its weight or for personal or health reasons [10].

The height to which luggage is lifted under different conditions is also taken into account. A distinction is made as to whether luggage is lifted to approximately hip height or to overhead height. The overhead height is also differentiated into overhead racks and luggage racks. Overhead racks are even more difficult to reach than the top shelf of a luggage rack due to the seats below and the associated distance.

Size of the luggage storage

The size of the luggage racks must be based on the distribution of luggage sizes. In general, the following principle applies. The larger the contiguous storage area is, the more luggage can be stowed. Larger areas also make it much easier to equalise the distribution of luggage items. If, for example, a luggage rack is only 50 cm wide, only one larger trolley can usually be stowed, leaving an inefficient amount of empty space. In the best-case scenario, two small trolleys can be stowed next to each other. If, on the other hand, a width of approximately 105 cm is available, three large trolleys can be stowed next to each other. A larger quantity of different types of luggage can also be stowed.

Design of the luggage racks

In principle, the luggage racks should be as wide as possible and should not be restricted in their span by any spacers.

The shelf heights with a clearance height of 85 cm at the bottom and 40 cm in the centre shelves must be adhered to as precisely as possible. It is important that there is also a clear height of 40 cm between the top shelf and the overhead shelf. If this is not the case, the centre shelf height and the top shelf (distance to the overhead shelf) can be reduced to 37 cm, but never less.

Space between the seat backrests

The space between the seat backrests is generally very suitable for stowing luggage. However, this space can only be used efficiently if there is sufficient space between the seat backrests.

If the distance is too small, the basic problem with the areas between the seat backrests is that items of luggage (except travelling bags) have to be moved several times. This means that an upright trolley has to be tilted and turned. As a rule, this is not accepted by travellers.

Another problem arises when threading the luggage into the free space between the seat backrests due to the narrow aisle width. Even if there is room for the luggage cross-section between the seat backrests, there is often too little handling space available for longer or higher items of luggage in the aisle (see also *Figure 7*) [17].

Figure 7 – Areas behind the seat backrests, too little space for threading due to the narrow aisle width (photo: Rüger Bernhard)

If the seats are pushed directly against each other, there is only enough space to accommodate a medium-sized piece of luggage (e.g. a medium-sized trolley with cross-sectional dimensions of 30 cm x 50 cm). However, there is the specific problem that this piece of luggage cannot be threaded in (see *Figure 7*: the trolley shown has a cross-sectional area of 30 cm x 50 cm). In this case, the areas between the seat backrests are therefore best used for (customisable) medium-sized travel bags.

5. PASSENGER CHANGEOVER TIME

The passenger changeover time is made up of the time required by the passengers alighting and boarding, and is measured from the time the first person passes through the door cross-section to the last.

The time required for passenger changeover is mainly influenced by the following factors [11]:

1) Passenger-specific influences
   - Age/gender
   - Any mobility restrictions
   - Carriage of luggage, bicycles, pushchairs
2) Vehicle-specific influences
   - Door width, steps
   - Gap/gap bridging
   - Size of the entrance area
   - Forwarding to the seating areas
   - Luggage storage options
   - Seating arrangement, standing areas, multifunctional areas, luggage storage

5.1 Passenger changeover process

Disembarking passengers are usually ready to disembark immediately before the train arrives, which is why some passengers are already at the boarding door and in the boarding area, and others are preparing to disembark in the seating areas. The passenger changeover time for alighting passengers is mainly influenced by the design of the boarding area and, to a lesser extent, by the design of the vehicle interior. Provided that there are no obstructions on the platform due to waiting passengers or platform facilities that could impair the flow of passengers and thus create a backlog, the time required for alighting passengers per person is approximately constant across all passengers; the time curve as a function of the number of passengers is therefore linear. If a boarding area continues into two seating areas, a kink can occur in the time curve, as the boarding area is fed by both seating areas up to the number of passengers until there are no more passengers available in one area and the door is therefore only fed by the other area [11].

Passengers boarding local transport generally choose the door that is best suited to their individual exit situation (the door from which experience has shown the shortest route to the desired exit at the destination station). On the platform, the door closest to the waiting position is then generally selected for boarding. In long-distance transport, other criteria play a role, such as the desired carriage class, reservations or specific equipment. Passengers are ready to board at the exact door at the latest when the disembarkation process is completed. If a high number of passengers boarding the train results in a heavy backlog due to overcrowding in the relevant interior, only a small proportion of the waiting passengers will move to the immediately neighbouring door [12].

When boarding, passengers pass through the door cross-section, and a short orientation phase begins in order to find the most suitable place. When exiting the vehicle, the walking direction is virtually predetermined, and after passing through the door cross-section, there is a relatively large contact area on the platform for any orientation. When boarding the vehicle, there is always a funnel effect, i.e. the space becomes narrower, and every movement of passengers, the transport of luggage, finding seats, stowing luggage, etc., means that the time required for boarding per person is generally always longer than for alighting.

The time required for boarding is made up of two phases. The first phase is passing through the door cross-section and the boarding area, after which the passenger flow is divided into the passenger compartments (provided that there are at least two areas that can be used after the door). The time required to pass through the door and the boarding area can be regarded as constant on average for all passengers. For this reason, there is always a constant time requirement per person for a certain number of boarding passengers and thus a linear time curve calculated over several people. Depending on and due to the vehicle layout combined with passenger behaviour (finding suitable seats, accommodating luggage, etc.), a so-called backlog effect occurs after a certain number of passengers, which leads to the time required per passenger increasing as the number of passengers increases. This increase essentially follows a quadratic function. With increasing utilisation of the vehicle, this increase in the time required can also increase with a higher order function if the vehicle occupancy rate is very high [11].

If passengers are carrying luggage, this backlog effect sets in much earlier and to a greater extent; if no luggage is carried, the linear increase in time can also last over a larger number of passengers or even over all passengers.

5.2 Vehicle layout

Passengers on local public transport try to find places on the vehicle that offer a good escape, especially at times when there is a high volume of passengers. This is not about escape in the sense of safety concerns, but rather about being able to reach the vehicle exit unhindered at the desired exit station. In this context, areas from which unhindered exit is not considered easy are less frequented. For example, window seats in a two-row seating arrangement are less popular, as a person in the neighbouring aisle seat can make it more difficult to alight. In contrast, seats in a four-person vis-à-vis seating group are preferred, as the aisle, and therefore the exit, can also be reached relatively unhindered from the window seats [13].

The same applies to an area in the vehicle. If the route from one area to the exit is relatively long, it will be under-utilised. Specific examples of this are areas at the end of the vehicle that do not have a door and from which passengers have to walk more than two to three metres to the next boarding area. These areas are used around 20-30% less frequently than areas with good accessibility to the exit, especially during peak times [13].

On the one hand, this results in lower capacity utilisation in the vehicle and thus a reduction in performance and a reduction in the number of passengers boarding, which on the one hand leads to passengers being left behind on the platform and on the other hand has a strong negative impact on the passenger changeover time.

In long-distance transport in particular, the arrangement of luggage racks and the availability of alternative spaces in the vehicle are key criteria that influence the passenger changeover time. There must be sufficient luggage racks that also allow good visual contact from most seats, and where heavy luggage does not have to be lifted if possible. These racks should also be distributed along the length of the vehicle and should not be in the immediate vicinity of the boarding area in order to prevent a backlog effect [14].

For both local and long-distance trains, it is important that passengers can continue their way easily after boarding and that the flow of passengers is not impeded. The arrangement of the doors also plays an important role. If the passenger flow can be divided after boarding, as passengers can continue in two directions, the passenger changeover time is more than halved.

The door width on long-distance trains should be between 90 cm and 100 cm. Wider doors are important in local transport, but these should be at least 160 cm wide. With today's standard doors of 140 cm, up to 80%

of passengers board one behind the other or offset to each other, but not in two lanes next to each other. With a door width of 160 cm, two walking lanes are formed, which then also significantly accelerate the changeover of passengers. However, the benefits of the wide door can only be realised if the passengers inside can continue to walk unhindered. If a backlog forms quickly, e.g. due to inadequate luggage storage or narrow aisles, passengers will have to wait until they reach the boarding area and the platform, which means that the wide door is no longer useful [11, 12].

6. EXAMPLE LAYOUT COMPARISON

In order to illustrate the effects of different vehicle layouts with regard to the possible degree of utilisation and passenger changeover time, three layouts are compared with each other below.

Layouts V1 and V2 are fictitious in order not to highlight individual manufacturers or operators, but are very close to a large number of vehicles in actual service in terms of the dimensions of the vehicle body, the arrangement of the doors, seats, toilets and luggage racks. The aim of the illustrations is to show how significant improvements can be achieved by making adjustments to the vehicle layout. Layout V3 is therefore an example intended to show what an efficient vehicle can look like.

They are classic passenger coaches, in layout V1 (see *Figure 8*) with 94 seats and, apart from a small rack, mainly overhead luggage racks. In layout V2 (see *Figure 9*), only 86 seats are available, but there are many better options for luggage storage to meet travellers' requirements. In layout V3 (see *Figure 10*), the doors are arranged at the quarter points, resulting in a division of the passenger flow after boarding, which significantly speeds up the passenger changeover time. In all cases, the luggage racks have three compartments, measured from below with a height of 85-40-40 cm, above which is the overhead shelf.

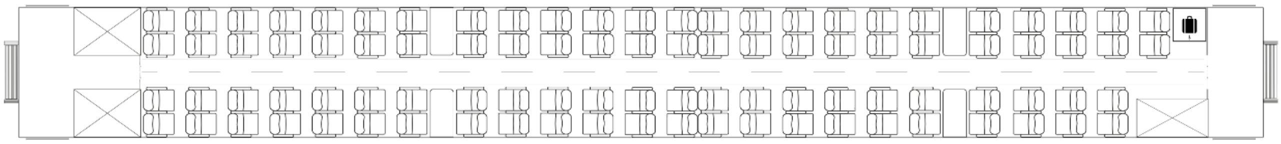

Figure 8 – Example layout V1 (source netwiss – layout creation in TrainOptimizer®)

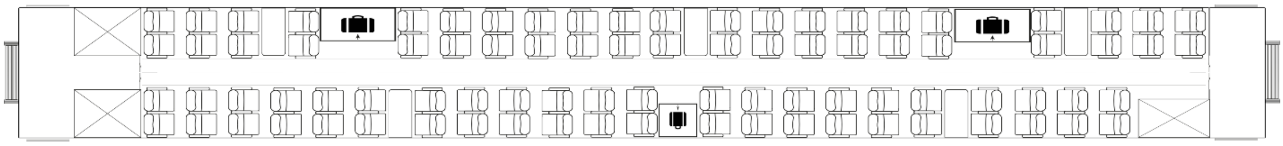

Figure 9 – Example layout V2 (source netwiss – layout creation in TrainOptimizer®)

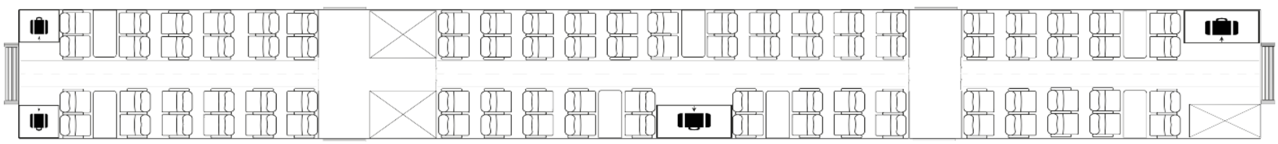

Figure 10 – Example layout V3 (Source netwiss – layout creation in TrainOptimizer®)

In this example, it is assumed that 50% of private and holiday travellers use the train. Since the distribution of the various travel purposes varies greatly depending on the season, region and route, this is an assumption made for the following evaluations. For example, 50% of private and holidaymakers arrive on main routes in Austria or Germany on many days, especially on weekends, public holidays or during the holiday season [18]. In terms of baggage volume, holidaymakers and many private travellers are the most critical group, which is why the focus is placed on them here.

For a better illustration of the size at which luggage is included in the statistics and evaluations, it is defined that luggage that must be checked in for air travel counts as travel luggage, whereas luggage that may also be taken on board an aircraft is defined as hand luggage.

Only checked baggage is taken into account in the following assessments, as experience shows that hand luggage, even if it is not properly stowed, does not cause any disruption to passenger turnaround times or seat usability.

6.1 Luggage storage and seat occupancy rate

Figure 11 shows that 48 items of baggage cannot be stowed in layout V1, 20 in layout V2 and only 11 in layout V3 on the main travelling floor.

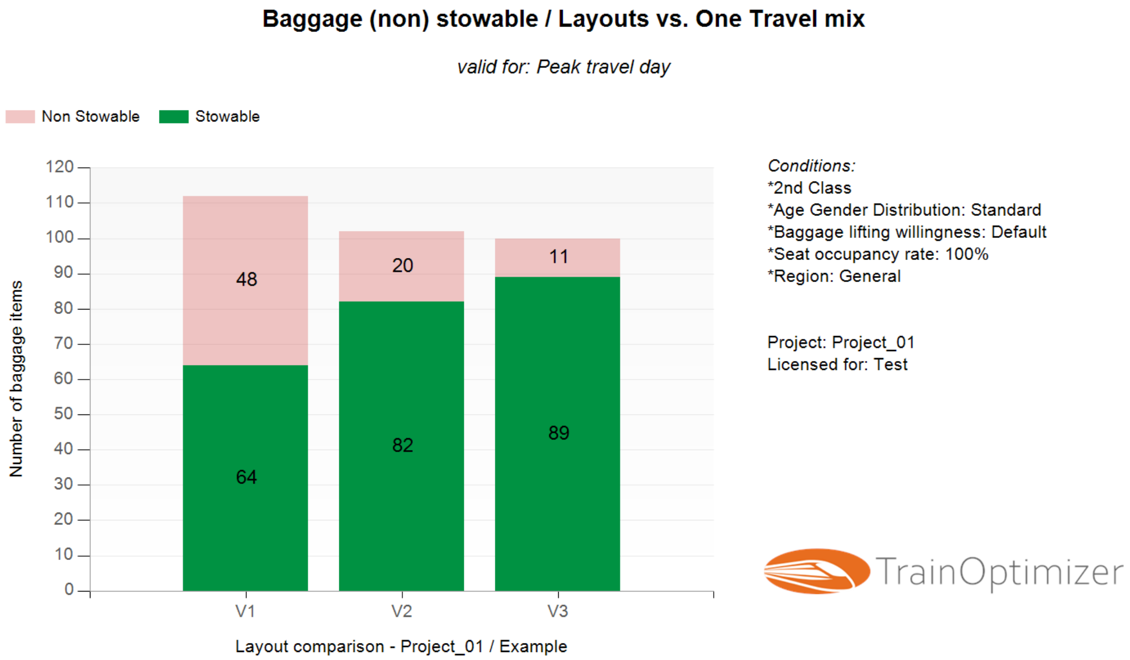

Figure 11 – (Non-)stowable luggage items in layout comparison (source netwiss – evaluation with TrainOptimizer®)

The luggage that cannot be stowed away means that only 79 of the 94 seats can be used in layout V1. In layout V2, only 86 seats are still available, of which 79 seats are de facto usable, and in layout V3, as many as 80 of the 84 available seats are usable (see *Figure 12*).

This analysis clearly shows that maximising the number of seats does not bring any added value, as more than 80 seats can never be used anyway. A reduction in the number of seats, therefore, not only leads to a noticeable increase in comfort for travellers, but also to a higher proportion of available seats [15].

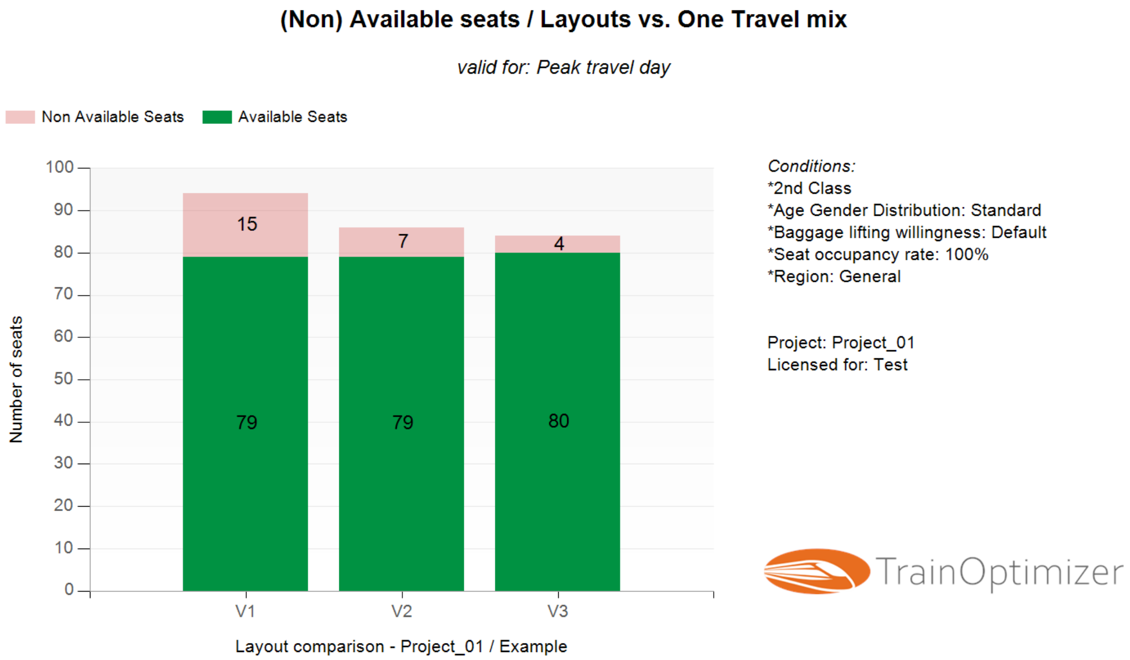

Figure 12 – (Un)available seats in layout comparison (depending on journey purpose), (source netwiss – evaluation with TrainOptimizer®)

6.2 Passenger changeover time

In *Figure 13,* it can be seen that the time required for boarding increases with higher orders as the number of boarding passengers increases. The calculations are also based on a mix of travel purposes with a higher proportion of holidaymakers. Furthermore, it can be seen that the time required for layout V2 increases less with improved luggage storage (higher capacity, better distribution in the vehicle) and better alternative options. For example, 40 boarding passengers require an average of approximately 215 seconds with layout V2, whereas the time required for 40 passengers with layout V1 is approximately 10% longer at an average of approximately 240 seconds. A particularly large difference can be seen in layout V3. Here, 40 people only need approximately 110 seconds to board, which is less than half the time required for the other variants [15].

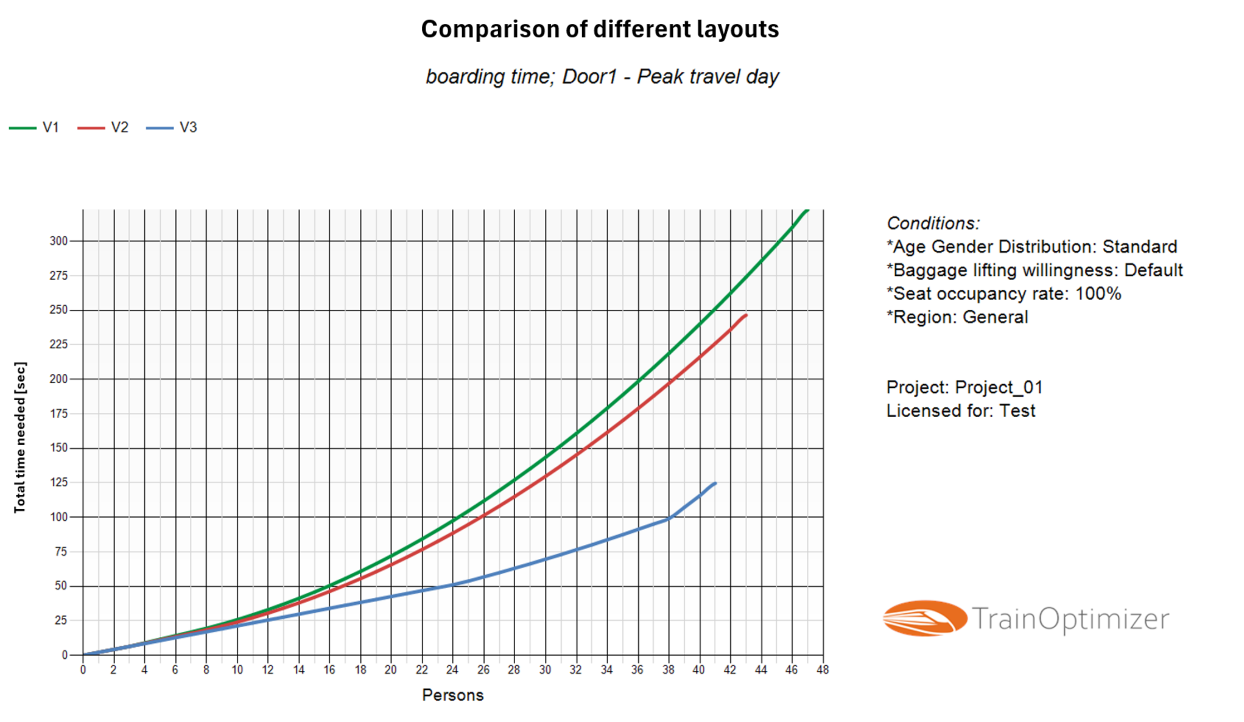

Figure 13 – Time required for boarding passengers when comparing layouts (source netwiss – evaluation with TrainOptimizer®)

Figure 14 shows the time required for a so-called 60% passenger changeover. This includes both boarding and alighting passengers. A 60% passenger change is a comparative value often required for calculations, which means that 60% of the passengers in a fully occupied carriage get off, and the same number of passengers get on again. With layout 2, the lower number of seats per door also results in a lower number of passengers by three.

At approximately 3.5 minutes, the total passenger changeover time for a 60% passenger changeover is approximately 20% longer for layout V1 than for layout V2. With layout V3, the total passenger changeover time in this case is also approximately 50% compared to layout V3 [15].

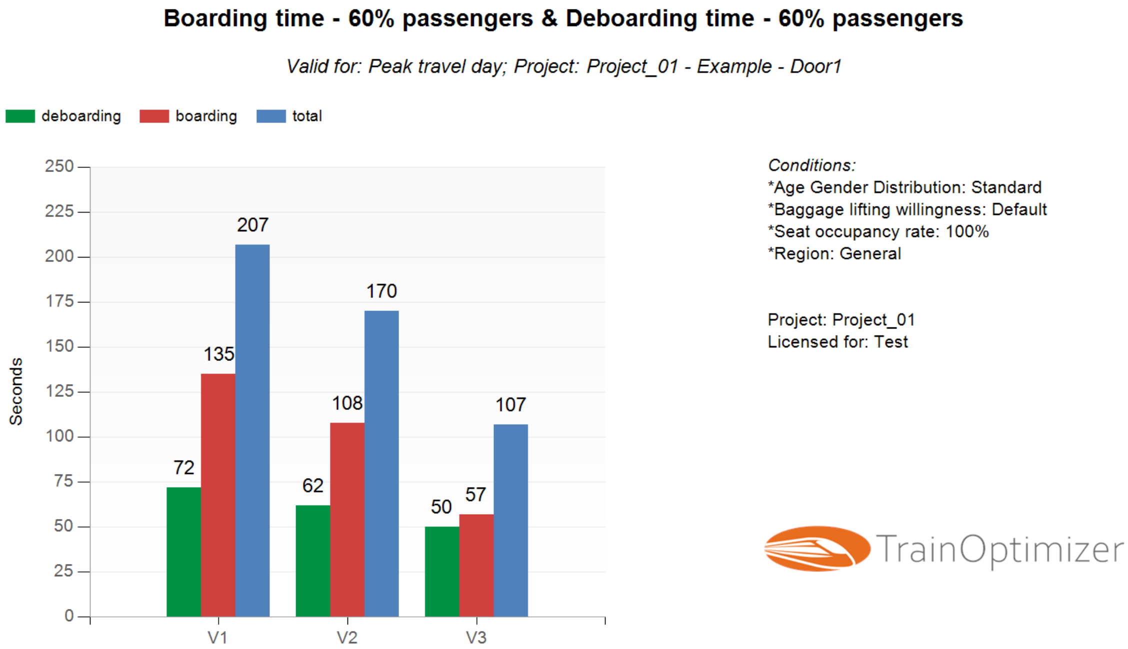

Figure 14 – Time required for a 60% passenger change in the layout comparison (source netwiss – evaluation with TrainOptimizer®)

7. CONCLUSION – IMPACT OF THE VEHICLE LAYOUT ON EFFICIENCY AND RAILWAY OPERATIONS

This study clearly illustrates how strongly the layout and interior design of rail vehicles influence operational efficiency, comfort and, ultimately, the competitiveness of rail transport. Based on extensive empirical data collection and modelling, it has been shown that simply maximising the number of seats does not lead to increased efficiency – on the contrary, it can significantly limit the usability of trains and have a negative impact on the travel experience, operational processes and energy consumption.

A key finding is that passenger behaviour and needs – particularly with regard to luggage, seat selection, use of time and well-being – are closely linked to vehicle design. The studies showed that inadequate luggage racks often lead to seats being blocked or luggage being stored in aisles, which in turn reduces actual seat utilisation by up to 20%. At the same time, the stress factor for passengers increases significantly, especially when boarding and alighting and when the train is full. Comfortable, ergonomically designed and evenly distributed luggage racks, on the other hand, contribute significantly to improving the overall experience. It is particularly important that passengers can stow their luggage without having to lift it and can keep it in their field of vision.

The non-stowable luggage significantly reduces seat occupancy, as more passengers have to stand or sit on the floor. This also results in a significant loss of comfort. In reality, a reduction in the number of seats by approximately 10% (in relation to a vehicle with full seating capacity) leads to an increase in the degree of utilisation.

In local transport, poorly accessible areas in the vehicle in particular mean that significantly fewer passengers go to these areas, which also reduces the degree of utilisation in the vehicle. In this case, however, standing room is also affected, which means that fewer passengers can actually be transported. If care is taken to ensure that all areas of a carriage can be reached in the best possible way and by the shortest route, then this significantly increases the overall occupancy rate in the vehicle.

The dwell time, influenced by the passenger changeover time, has several effects on efficiency and operation. The longer-than-necessary passenger changeover increases the risk of delays. Looking at the fictitious examples in Section 6, it can be seen that the difference can very quickly reach a ratio of 1:2. In some layouts, the passenger changeover time can be reduced even further, resulting in time differences in the order of minutes.

Vehicles with short dwell times increase punctuality thanks to additional reserves. At the same time, however, there is also great potential to shorten journey times. This is particularly relevant if, for example, expensive route expansions can be dispensed with to achieve the necessary journey time for synchronised timetables.

Shortening the dwell time also means that the journey time can be extended without increasing the total journey time. The slightly longer journey time makes it possible to travel at a lower speed, which offers significant energy-saving potential.

Another key point concerns the use of travel time. Compared to other modes of transport, rail offers a decisive advantage, as travel time can often be experienced as useful time. This is a clear market advantage for the railway. Because even if the door-to-door journey time is longer compared to other modes of transport, the proportion of usable time is often significantly higher, which puts longer journey times into perspective. However, this requires suitable seating and working facilities, stable internet connections, quiet areas and a balanced indoor climate. The study clearly shows that younger passengers have higher expectations in terms of facilities and digital connectivity, while older travellers tend to be more satisfied but less active in their use of time. For the future, this means that vehicle concepts must increasingly focus on flexible, multifunctional zones that allow for both work and relaxation.

With regard to the quality of the journey and passenger well-being, it was found that factors such as background noise, lighting, temperature control and privacy contribute significantly to satisfaction. Noise, cramped conditions and the search for seats are significant stress factors, especially when the vehicle is full. An adaptive interior design that takes individual needs into account offers considerable potential for improvement here. This includes, for example, zoned areas for rest, communication or work, as well as individually controllable lighting and climate systems.

Well thought-out layouts and suitable equipment elements also enable efficient use of time on the train.

Overall, it can be said that the design of interiors and layouts in rail vehicles has a decisive influence on the efficiency of the rail system, both from an operational and a user-oriented perspective. An optimised vehicle layout combines technical, ergonomic and psychological aspects: it enables faster passenger changes, higher actual utilisation, lower energy consumption and a significantly improved travel experience.

Efficiency should no longer be defined solely in terms of capacity, but rather in terms of the overall usability and quality of the travel experience. Only if the design of the vehicles takes into account the real needs of passengers – for example, in terms of luggage, movement, work and relaxation – can the railways play to their systemic advantages over other modes of transport in the long term and be further strengthened as an attractive, sustainable means of transport.

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