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IMPROVED OPERATING QUALITY THROUGH OPTIMIZED VEHICLE LAYOUTS BY MEANS OF SIMULATION

ABSTRACT

In addition to customer comfort, the degree of capacity utilization and the passenger exchange time are key factors influencing the quality of rail operations and efficiency. Further important factors for the shortest possible passenger exchange time are the adequate and customer-friendly dimensioning of luggage racks as well as the overall layout and the arrangement of the doors.

KEY WORDS

efficient rail vehicles; interiors simulation; occupancy rate; dwell time

1. INTRODUCTION

The design and development of modern passenger coaches often follows the principle of seat maximisation, with the aim of transporting as many passengers as possible and thus increasing efficiency and economy.

However, the intensive scientific investigation of passenger wishes and needs as well as actual passenger behaviour under real conditions prove that instead of the expected increase in efficiency, in reality there is a loss of efficiency! In addition to a decline in passenger satisfaction, in reality the achievable seat occupancy rate decreases and the passenger exchange time increases noticeably. This in turn leads to more delays, which have to be reduced with higher energy consumption, and to a decrease in operational quality.

2. DATA BASIS - SIMULATION

Based on the twenty years of know-how of the Research Center for Railway Engineering at the Vienna University of Technology in cooperation with the company netwiss including: extensive investigations and data collection in the field of passenger behaviour in rail vehicles (observations of the behaviour of around 300,000 passengers in about 100 different types of vehicles, surveys of about 50,000 passengers and analysis of about 20,000 passengers during passenger exchange) algorithms were developed by the company netwiss that exactly map the specific behaviour of rail passengers. Taking into account different basic conditions such as travel purposes, age distribution or region-specific influences, this makes it possible to compare different vehicle layouts in order to find out which vehicle layouts are best suited for stowing luggage, which layout has the highest number of seats that can actually be used leading to a maximum seat occupancy as well as which layout has the shortest passenger exchange time (*Figure 1***Error! Reference source not found.**).

These special algorithms based on data from real operation led to the development of the vehicle simulation software **TrainOptimizer®** at www.TrainOptimizer.com. When planning or ordering new vehicles or when redesigning existing vehicles using the know-how described above, it is now possible with the help of TrainOptimizer® to determine with just a few clicks the most efficient layout variants in terms of best possible luggage stowage, highest possible seat occupancy and shortest possible passenger exchange times. The algorithms and thus the software TrainOptimizer® can be applied to all

public transport vehicles: from high-speed trains to intercity trains, local trains, metros, trams and buses.

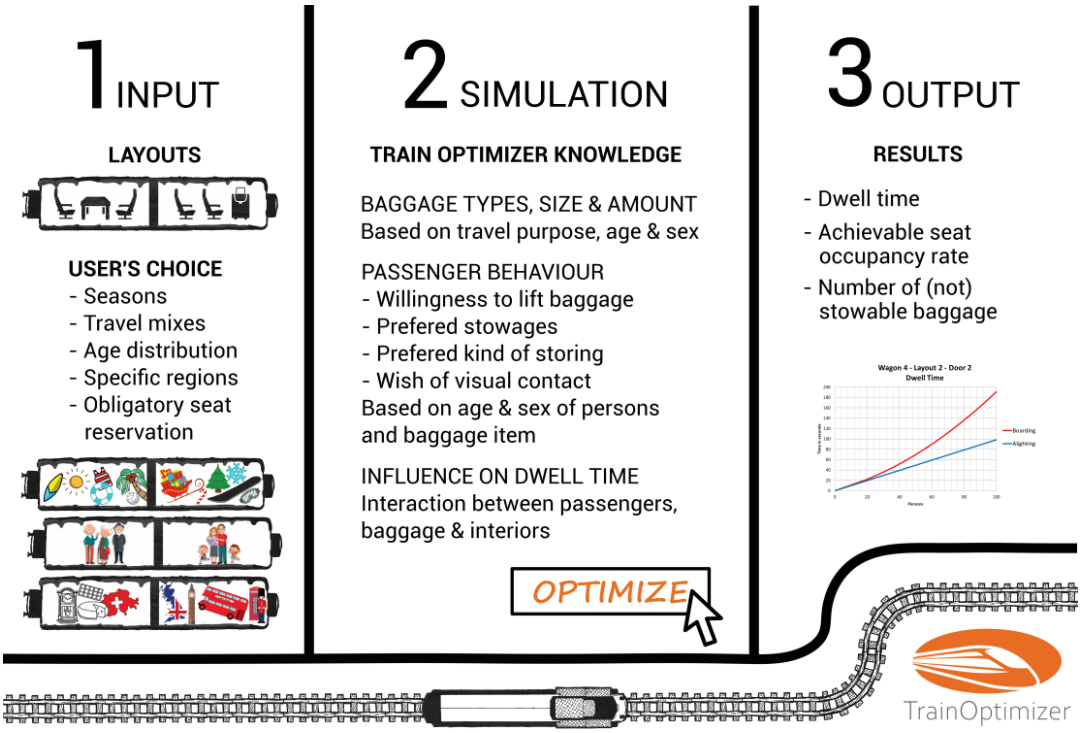

Figure 1 – Schematic functional sequence of TrainOptimizer®
Source: [7]

3. PASSENGER BEHAVIOUR VERSUS OPERATING QUALITY

There are two situations during a train journey in which the interaction of passengers with the existing vehicle layout has a significant impact on the quality of operation. They include boarding and deboarding as well as luggage storage during the journey, and both are directly related to one another.

3.1. Luggage Storage

Two factors have a significant impact on luggage accommodation. On the one hand, sufficient capacity must be available for the storage of luggage and on the other hand, passenger needs must be considered extensively with regard to luggage storage, which if disregarded will lead to negative behaviour from an operational point of view.

Passenger needs are simple and understandable but can become complex challenges when designing vehicles. The two main needs are [4]:

- Passengers do not want to lift larger pieces of luggage.
- Passengers want visual contact with their luggage.

3.1.1. Lifting and manipulating luggage

The primary distinction to be made is which luggage must be lifted. Smaller and lighter items of luggage are more likely to be lifted than larger and heavier items. The willingness to lift luggage can be divided into three *"comfort levels"*. The ***"Comfort"*** level takes into account those travellers who are already willing to lift their luggage on their own initiative. The ***"Standard"*** level takes into account those passengers who are reluctant to lift their luggage but who do so when circumstances require it. The ***"Limit"*** level takes into account the luggage actually lifted in fully occupied wagons [4]. This limit value can only be determined with the help of the "observation" method described above. This is

because depending on the situation, passengers provide different information in surveys than they would in reality, especially in borderline situations in which they behave as if the train is fully loaded.

Parallel to the basic willingness to lift luggage, a distinction must be made as to the height to which luggage must be lifted. In this respect, readiness to lift is divided between two heights: the first being a height of about one metre, which is used for luggage racks and the second being the height of an overhead rack, usually about 1.8 metres [5].

Since the required lifting not only determines the stowability of luggage in racks and is therefore an essential factor in the quality of operations but also has a significant impact on passenger comfort and thus passenger satisfaction, it is desirable whenever possible to strive to always apply the 'comfort' level. In particular, this level should be applied in coach classes with a higher level of comfort such as first class or higher. In second class, the "Standard" level may also be applied where appropriate. The "Limit" level reflects the limit that can just about be reached. In practice, no more luggage than defined in this level will be lifted.

Furthermore, the willingness to manipulate luggage must also be considered. This refers to whether passengers are willing to tilt or turn luggage. This is particularly important for all those stowage spaces into which luggage must be "threaded" such as under seats or between seat backrests when seat spacing is tight. In general, passengers do not wish to manipulate their luggage for accommodation purposes and in practice do not do so. It must therefore be possible to stow luggage in the same way as it is transported by passengers. Trolleys transported in an upright position on two or four wheels must be parked in an upright position. Travel bags should be stored in a horizontal position if possible ideally at a height of approx. one meter, which corresponds to the middle compartment in luggage racks. Smaller or medium-sized trolleys, which passengers are more willing to lift, are often stored lying down in luggage racks, for example [5].

3.1.2. Visual Contact with Luggage

For about 90% of passengers it is important for reasons of subjective security to have their luggage in view during the journey. In order to establish visual contact, approximately 75% of passengers are also explicitly prepared to place their luggage in a manner which impedes seat occupancy or passenger flow (e.g. on or in front of seats or in the aisle) [4].

3.1.3. Storage Space Dimensioning

In addition to the above-mentioned principles, it is also essential to provide sufficient luggage storage capacity. For this purpose, precise knowledge of the average luggage volume in the intended area of use of the vehicles is important. Furthermore, luggage must always be viewed in three dimensions. In practice, the volume of luggage is often taken as a basis, but this corresponds to a one-dimensional view. Here, any cross-sectional areas, e.g. between seat backrests are often used and multiplied by the available depth, e.g. from aisle to window. All volumes obtained in this way are summed up to form a total volume for luggage storage in the vehicle, which makes large luggage storage capacities seem likely. In practice, many of these cross-sectional areas cannot be used at all as the dimensions of the luggage are larger than the respective cross-sectional areas!

3.2. Effects of Insufficiently Dimensioned Luggage Racks

Failure to comply with the above-mentioned requirements for luggage storage means that travellers are either unable to store their luggage at all because there is too little storage space available in practice, or they do not make sufficient use of the available racks because they do not meet the basic needs of visual contact or avoidance of lifting operations. This leads, for example, to overhead racks remaining partially unused and yet luggage not being stowed properly.

In both cases, pieces of luggage that cannot be stowed away are placed close to the passengers on or in front of seats or in the aisle. Non-stowable luggage results in seats being blocked and passengers

having to stand at full capacity. On average two to three pieces of luggage that have not been properly stowed will result in the effective loss of a seat [2].

3.3. Passenger Exchange

Passenger exchange is a highly complex process and an interaction between passenger characteristics and the overall vehicle layout. Passenger-specific influencing factors are age and gender, any physical restrictions and the luggage carried, which in turn depends on the chosen purpose of the journey.

The vehicle layout gives rise to three main areas with different influences. These are: the entrance door, the entrance area, which can also serve as a catchment area especially in local traffic and the entire interior, which essentially corresponds to the seating area. At the entrance door, the door width, the gap between platform and vehicle and the number of steps have a significant influence. The design of the boarding area determines how well passengers can continue into the seating area and how many passengers can remain in it in case of a bottleneck so that the train can still depart [3].

There are several influencing variables in the interior. The stowability of luggage has a significant influence. As described above, pieces of luggage that cannot be stowed are sometimes parked in the aisle area, where they block the flow of passengers. Another influence is the simplicity of luggage storage. Ideally, if passengers can deposit their luggage "in passing" and then go straight to the nearest seat, the flow of passengers is faster than if passengers have to manipulate their luggage several times for storage. The passenger flow slows down considerably especially when luggage has to be lifted to be stored in the overhead storage or when the distance between two seat backrests is too short and the luggage can only be stored by tilting, if at all [3].

Furthermore, the aisle width and possible alternative spaces have an important influence on passenger flow. The width of the aisle is important for the ease of movement with luggage as well as when people are busy stowing their luggage with other passengers trying to pass by.

4. DESIGN PRINCIPLES IN VEHICLES

In order to achieve a high degree of seat occupancy and at the same time the shortest possible passenger exchange time, the following principles must be observed:

4.1. Luggage Racks

The luggage racks should comply with the above principles of visual contact and avoidance of lifting, especially the lifting of large pieces luggage up to the height of the overhead storage. When dimensioning luggage racks, for reasons of efficiency reference may be made to the actual willingness of different passengers to lift luggage. Smaller and medium-sized pieces of luggage, which tend to be lighter, are placed by passengers to a greater extent in the overhead rack, larger pieces of luggage to a lesser extent of approx. 20% [4]. This means that the calculation may well be based on overhead storage but only to the extent that passengers are willing to use it and not per se for all luggage.

It is also important to note that luggage racks are well distributed in the seating area. This applies in particular to luggage racks and the space between the seats. A good distribution leads to appropriate use, as most travellers can see their luggage. At the same time, distribution also means that luggage can be more easily stowed by passengers, thus allowing passengers to change seats more quickly.

It is absolutely necessary to avoid placing luggage racks in the boarding area of vehicles, as these are only used up to approx. 30% for visual security reasons [5]. If they are used, the luggage being stowed very close to the boarding door may lead to a bottleneck of boarding passengers. The same applies to luggage racks in the interior of the vehicle that are located immediately after the entrance

to the seating area [3]. A distance of at least two rows of seats to the first luggage rack and a good distribution of the luggage racks along the entire vehicle is better.

In addition to the arrangement of the luggage racks, it is essential to know the exact quantity and type of luggage to be expected. The type of luggage or the appropriate mix determines the required dimensions of the luggage racks. Racks that are too narrow by only a few centimetres often mean that certain pieces of luggage cannot be stowed at all or only in such a way that there is no further useable free space, which makes the racks inefficient. At the same time, care must be taken to ensure that all luggage items can be accommodated in terms of quantity, especially for all those areas of use and travel purpose mixes where full utilisation of the vehicle is expected and desired. Under no circumstances should only the total volume of the luggage and also the luggage racks be determined and then compared with each other!

4.2. Overall Vehicle Concept

The entire vehicle concept has a significant influence on the passenger exchange time. This already starts with the rail coach bodies. Shorter and thus wider coach bodies have the advantage of allowing wider aisles in addition to the advantage of up to 50% lower tare weight per seat and the resulting effect of large energy savings [1]. Aisles with a width of more than 60cm allow up to 25% shorter passenger exchange times than those with a width of 50cm [3].

Another important factor is the arrangement of the doors. The classic arrangement at the two ends of the coach means that an average of 50% of the passengers per coach have to enter through one door and then also have to walk through the same interior. Since the boarding time in the respective coach interiors essentially follows a square parabola, a higher number of passengers passing through a cross-section leads to a disproportionate increase in passenger exchange time. If on the other hand, the doors are arranged in such a way that the passenger flow can be divided up when passengers enter the boarding area, the passenger exchange time can be significantly reduced [3]. On the one hand, the number of people entering the respective passenger compartment through a cross section is halved if the doors are well located, which leads to a noticeable reduction of the boarding time. On the other hand, the division of passengers also reduces tailback effects from the seating areas.

If the seating area follows immediately after a small interior, then tailback effects from the interior are very quickly shifted to the entrance. If the way to the seating area is longer, for example due to toilets or other obstructions, tailback effects from the seating area are also reduced [3].

In the seating area described above, consideration should be given to ensuring good division as well as correct and adequate planning of luggage racks. In addition, well-distributed spreading spaces should be created. This can be done by ensuring that tables in vis-á-vis seating groups do not reach as far as the aisle, but are approx. 10 to 15 cm shorter. Likewise, luggage racks should be moved away from the aisle; this creates equally good alternative space [4].

5. EXAMPLE LAYOUT COMPARISON

In the following, two layouts which are deliberately similar in structure are compared in order to illustrate the effects that the correct consideration of luggage racks has on the achievable seat occupancy rate and passenger exchange time. If the overall concept is fundamentally revised, for example by shortening the coach body and changing the arrangement of the entrance doors, even more significant differences can be seen.

The two layouts are fictitious examples and are not in actual use in the form shown. In both cases they are classic passenger coaches, in layout 1 with 100 seats and except for two small racks, mainly overhead racks for luggage storage. In layout 2, only 88 seats are available, and there are more suitable luggage storage options to meet passenger requirements (*Figure 2* & *Figure 3*). The luggage racks have

three compartments in all cases, measured from below at a height of 80 - 40 - 40 cm with the overhead rack above.

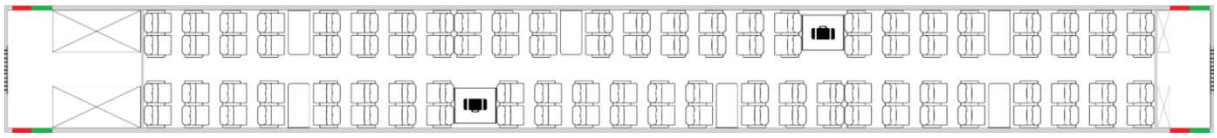

Figure 2 – Example layout 1
Source: [7]

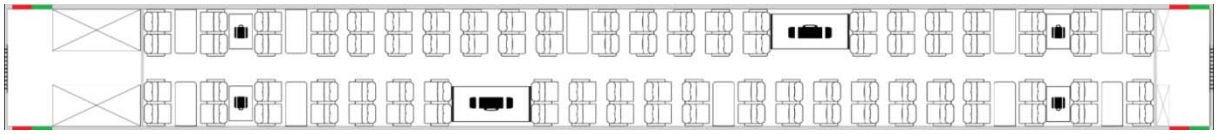

Figure 3 – Example layout 2
Source: [7]

Three equally fictitious travel purpose mixes are given below. One assumes that the majority of business travellers use the train, in a second example these are mainly holiday travellers and in a third example it is additionally assumed that an international airport is served on main travel days, which on average also induces a 20% higher luggage volume.

Luggage is considered to be only those items which are checked luggage in air travel. Luggage that may be taken on board an aircraft cabin is considered hand luggage and is not evaluated in the following; as it is assumed that it can in any case be accommodated or at least does not exert any serious negative influence.

As comfort level regarding the willingness to lift, the level "limit" is taken, which represents the limit actually occurring in real operation and should actually not be used as a basis for the calculations; as it no longer meets the expectations and comfort requirements. However, in order to show the limits of use this example deliberately uses "operator-friendly" calculations.

5.1. Luggage Accommodation and Seat Occupancy Rate

Figure 4 shows that 31 pieces of luggage are stowable in layout 1 and 66 in layout 2. On days with a higher proportion of business travel every second piece of luggage is not stowable in layout 1, but all pieces of luggage are stowable in layout 2. On days with a higher proportion of holidaymakers, two out of three pieces of luggage are not stowable in layout 1, while only 17 pieces of luggage are not stowable in layout 2 [7].

When travelling by plane on busy travel days, it can be assumed that the luggage volume is about 20% higher than when travelling by train on busy travel days [6]. This circumstance therefore represents an upper limit with regard to the amount of luggage. In Figures 4 and 5, "Airport" means that the purpose of the journey is to ensure that only air passengers are on the train. In this borderline situation, the share of non-stowable luggage is again increased but is rather a theoretical limit value consideration as it cannot be assumed that in practice all persons in the coach are air passengers with corresponding flight luggage.

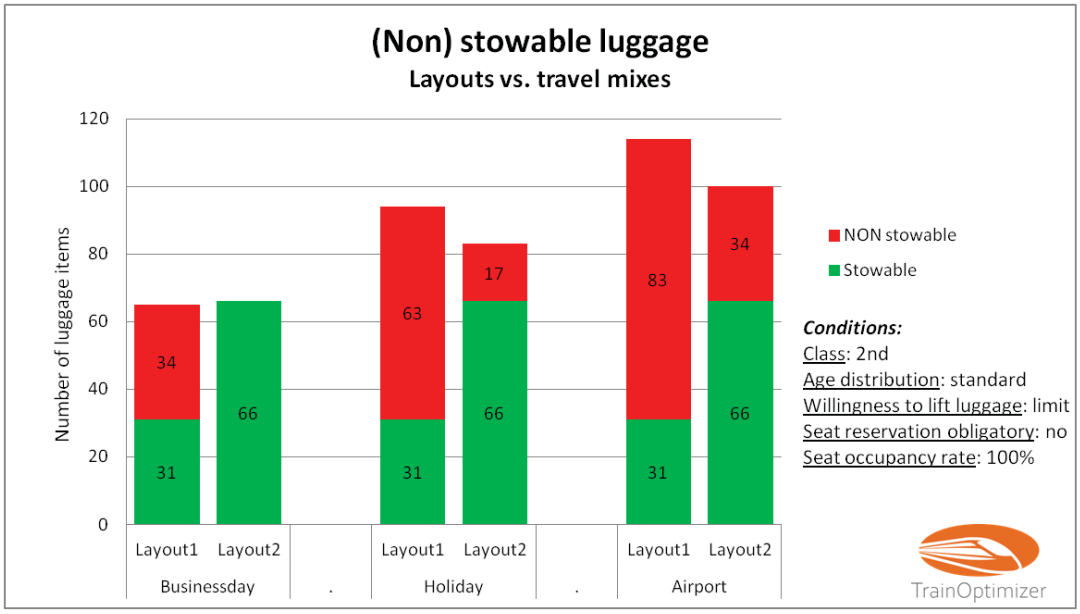

Figure 4 – (Non) stowable luggage in layout comparison
Source: [7]

In addition to severe comfort restrictions and general problems such as security problems or delays in passenger transfer caused by pieces of luggage that cannot be stowed properly, the pieces of luggage that cannot be stowed result in the fact that with layout 1 not all seats can be used in any of the travel purpose scenarios. Even on days with a higher proportion of business travel, only 89 of the 100 seats are available, and in layout 2 all 88 seats are available. On days with a higher proportion of holiday travellers, only 77 seats are actually available on average for layout 1 and at least 82 seats for layout 2 (*Figure 5*) [7].

This analysis clearly shows that there is no added value in maximising the number of seats, since in any case no more than 89 seats can ever be used. A reduction in the number of seats therefore not only leads to a noticeable gain in comfort for the travellers but also the majority of times to an even higher proportion of available seats.

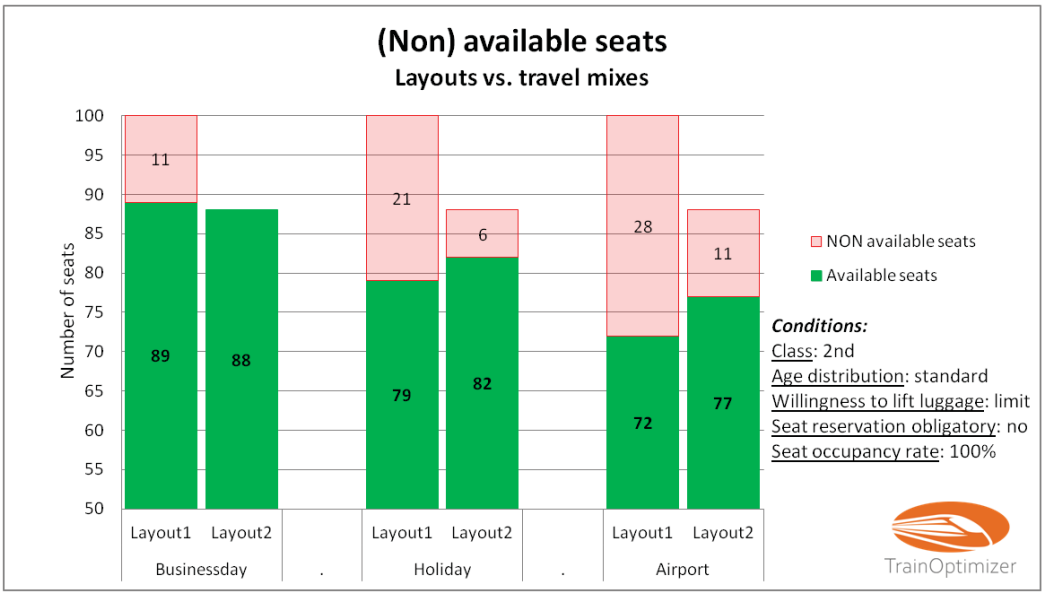

Figure 5 – (Non) available seats in layout comparison (depending on travel purposes)
Source: [7]

5.2. Passenger Exchange Time

The time required for boarding increases more than linearly as the number of passengers boarding increases (*Figure 6*). The calculations are based on a travel purpose mix with a higher proportion of holidaymakers. Furthermore, it can be seen that the time required for layout 2 with improved luggage accommodation (higher capacity, better distribution in the vehicle) and better siding possibilities increases to a lesser degree. For example, 40 boarding passengers need on average 210 seconds for layout 2, whereas the time required for 40 persons for layout 1 is already 50% higher with an average of 310 seconds [7].

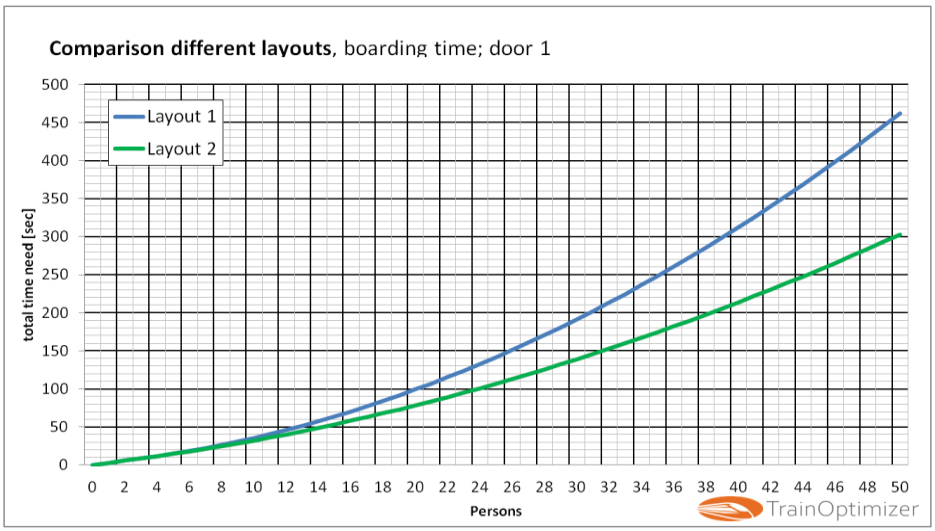

Figure 6 – Time required for boarding passengers during layout comparison
Source: [7]

The time required for a so-called 60% passenger exchange is shown in Figure 7. This includes both boarding and deboarding passengers. A 60% passenger exchange is a frequently requested comparative value for calculations which states that 60% of the passengers of a fully occupied coach exit and the same number of passengers enter. With layout 2, the lower number of seats per door also results in a three person lower number of passengers.

The boarding time for the 60% passenger exchange is just over three minutes, which is about 30% higher than for layout 2, and the total passenger exchange time including passengers deboarding still differs by 25%! [7]

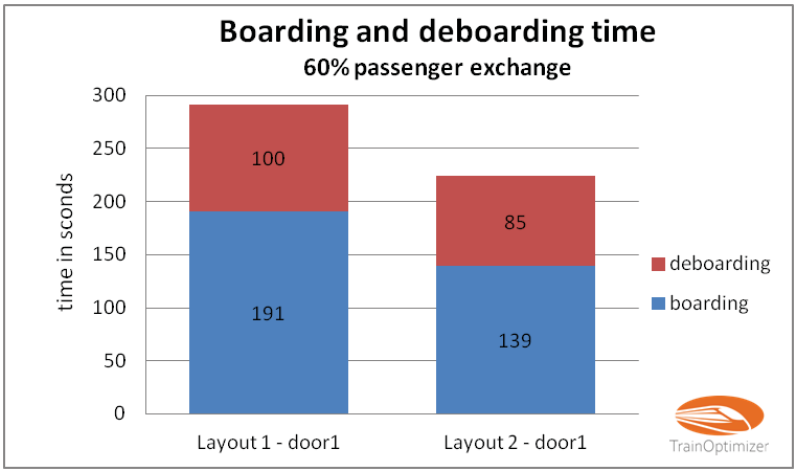

Figure 7 –Time required for a 60% passenger exchange in the layout comparison
Source: [7]

6. CONCLUSION

The vehicle layout and the associated interior design have an influence on operating quality in many ways. The correct and sufficient dimensioning of luggage racks has a significant influence. Luggage racks that do not meet passengers' basic needs, such as the desired visual contact with luggage or avoiding the lifting and manipulation of larger items of luggage, result in many items of luggage being stored in a manner that impedes passenger flow. This leads to a decreasing seat occupancy rate and significantly longer passenger exchange times. A lower number of seats if properly planned, leads to more seats being available in total even in absolute terms and to reduced dwell times.

The differences shown in this essay between the two **TrainOptimizer®** simulated variants, which differ from each other essentially only in the area of improved luggage accommodation, make it clear that with 12% fewer seats the proportion of usable seats remains at least the same or is even higher than in the seat-maximized variant with 100 seats. At the same time, the passenger exchange time is approx. 25% less with a 60% passenger exchange! If in addition to the improvement of the luggage systems, further principles for optimisation are taken into account such as shorter coach bodies with the resulting wider aisles or the arrangement of the entrance doors in the middle for short coach bodies, further significant improvements are possible especially in passenger exchange.

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