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Real Standing Capacity of Public Transport Vehicles: Area-Differentiated Passenger Densities at the Behavioural Capacity Limit—The Case of Vienna

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Abstract

The standing capacity of public transport vehicles is usually derived from flat area assumptions of four to 6.7 passengers per square metre (P/m^2) or from structural load assumptions, while empirical values from regular service are lacking. This study determines real standing densities from 227 structured observations of stopping events in the Vienna metro, tram, bus and suburban rail network; in 126 of these, waiting passengers were left behind although space was still geometrically available (limit capacity). Densities were recorded separately for the door, aisle and transition areas of nine vehicle types and compared with field experiments with test persons. At limit capacity, mean densities were 3.19 P/m^2 (door area), 2.37 P/m^2 (aisle area) and 2.30 P/m^2 (transition area), differing systematically with the accessibility of the areas. Service disruptions raised the door area densities to about 3.3 P/m^2 and major events to around 4 P/m^2; the experimental maximum occupancy reached 4.0 to 4.4 P/m^2 without luggage and up to 40% less with luggage. Regulatory and manufacturer values were practically never reached in Vienna. Capacity figures for procurement, service planning and simulation should therefore use area-differentiated, empirically calibrated densities—about 3 P/m^2 in door areas and 2.3 P/m^2 in aisle and transition areas—instead of a single flat value.

Keywords: standing capacity; passenger density; public transport; limit capacity; passenger behaviour; vehicle interior; field observation; crowding

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1. Introduction

1.1. Problem Statement

The capacity of a public transport vehicle is usually stated as the sum of seats and standing places. While the number of seats is geometrically unambiguous, the number of standing places is the result of a calculation: the available standing area is divided by an assumed area demand per person. In the practice of German-speaking transport operators, 0.25 m^2 per person and thus 4 P/m^2 are common [1]; comparable dimensioning conventions are discussed for light rail operations internationally [2]. Legal regulations such as the German BOStrab or the Austrian tramway ordinance, by contrast, do not define any passenger density at all. They only specify load assumptions of 5000 N/m^2 of standing area, which, according to the implementing decree, serve "exclusively for structural design" and include safety margins [3,4]. Comparable load assumptions for coach bodies and

their components are laid down in UIC Leaflet 566 [5]. Vehicle specifications issued by manufacturers, however, frequently assume 0.10 to 0.15 m^2 per person, corresponding to 6.7 to 10 P/m^2 [6].

These values are not observed quantities but conventions. They implicitly assume that passengers use the available area evenly and in an area-optimising manner. This is precisely what they do not do: passengers preferably remain in the door area, avoid poorly accessible zones and refrain from boarding when a vehicle appears full [7,8]. Capacity limits are therefore not primarily physical but behavioural. Critical analyses point out that manufacturer figures are derived from the permissible payload or from evacuation and structural considerations rather than from the area that can actually be used [6,9].

The consequences of overestimated capacity assumptions are considerable. Vehicle procurement, service dimensioning, headway definition, economic assessments, simulation models and the valuation of crowding costs all rely on these figures [10,11]. If the usable capacity is set too high, services appear sufficient on paper although in operation they lead to denied boardings, extended dwell times and missed connections [12–14]. Realistic planning therefore requires empirically validated, area-differentiated density values.

Crowded standing conditions are not an exceptional situation but part of everyday peak-hour operation in many networks. On a typical autumn weekday in 2025, one in five rail passengers travelling into or out of major cities in England and Wales during the peak hours was standing, and one in four in London [15]. In a survey of Paris metro users, more than half of the respondents expected to travel at densities of 2.5 to 3 P/m^2, the average density estimated by the respondents was 3.2 P/m^2, and over-closeness to other passengers was ranked as the most unpleasant aspect of crowding [16]. Reliable values for the density at which standing areas are actually used are therefore needed not only for exceptional loads but for regular peak-hour service.

1.2. State of Research and Normative Background

The design values used internationally differ by more than a factor of three. The VDV practice in the German-speaking countries assumes 0.25 m^2 per standing passenger [1]; the Swiss ordinance on technical requirements for road vehicles states 0.125 to 0.15 m^2, and the historical Austrian tramway ordinance 0.20 m^2 on platforms and 0.25 m^2 inside the vehicle [17]. The Transit Capacity and Quality of Service Manual differentiates by level-of-service steps: LOS D with 0.36 to 0.50 m^2 per person is regarded as a "comfortable standee load for design", LOS E with 0.20 to 0.35 m^2 as the maximum scheduled load [18,19]. The British Department for Transport uses 0.35 to 0.45 m^2 per standing passenger in its official crowding statistics [20], Australian vehicle regulations 0.16 m^2 [21]. Chinese standards set 6 P/m^2 as the maximum density of the nominal capacity [22], and the TransMilenio bus rapid transit system in Bogotá was designed for seven standing passengers per square metre [23]. For rail vehicles, EN 15663 regulates the load cases for "normal" and "high density" as mass per square metre of standing area but does not define a passenger density [24]. Table 1 compares the most important reference values.

Table 1. Normative and empirical reference values for the dimensioning of standing places (own compilation).

Regulation/Source	Reference Value	Corresponds to	Character
VDV practice (DE, AT) [1]	0.25 m^2/person	4.0 P/m^2	design convention
ÖStrabVO 1957 [17]	0.20–0.25 m^2/person	4.0–5.0 P/m^2	historical ordinance
VTS SR 741.41 (CH) [17]	0.125–0.15 m^2/person	6.7–8.0 P/m^2	ordinance
BOStrab § 33 (DE) [3]	5000 N/m^2 standing area	no passenger density	structural load assumption

Table 1. *Cont.*

Regulation/Source	Reference Value	Corresponds to	Character
StrabVO decree (AT) [4]	load assumptions with margins	no passenger density	structural load assumption
EN 15663 [24]	mass load cases per m^2	no passenger density	standard (vehicle masses)
TCQSM LOS D [18,19]	0.36–0.50 m^2/person	2.0–2.8 P/m^2	design recommendation
TCQSM LOS E [18,19]	0.20–0.35 m^2/person	2.9–5.0 P/m^2	maximum scheduled load
DfT (UK) [20]	0.35–0.45 m^2/person	2.2–2.9 P/m^2	official statistics
Vehicle regulation (AUS) [21]	0.16 m^2/person	6.25 P/m^2	approval regulation
Nominal capacity (CN) [22]	6 persons/m^2	6.0 P/m^2	national standard
TransMilenio (CO) [23]	7 standing passengers/m^2	7.0 P/m^2	system design
Manufacturer specifications [6]	0.10–0.15 m^2/person	6.7–10.0 P/m^2	vehicle specification
Pedestrian research [25]	0.15 m^2/person (physical)	6.6 P/m^2 (max. 7–9)	empirical upper limit
Field measurements [8,26–29]	mean to maximum values	0.7–3.0 P/m^2	empirical observation

Large-scale field studies are based on smart card, vehicle location or weighing data and provide vehicle or cross-section averages. For one line of the Hong Kong MTR, a mean standing density of 0.73 standing passengers per square metre is obtained with a maximum of about 5.1 P/m^2; the authors explicitly note that the actual density may be considerably higher in parts of the vehicle, particularly near the doors [26]. On the basis of weighing data from Amsterdam trams and buses, a highest quarter-hour density of three standing passengers per square metre is reported, while 4 P/m^2 is assumed as "full capacity" [27]. In the Singapore metro, the maximum observed mean density is likewise 3 P/m^2 [28]. Direct counts in the Paris metro yield 2.3 P/m^2 compared with only 1.7 P/m^2 from aggregated operator data—an indication of how strongly operational statistics smooth real peaks [29]. Field observations in Beijing recommend 4.0 to 5.0 P/m^2 for the design of new lines [30], and analyses of the Chengdu metro across 133 line sections show a pronounced uneven distribution inside the vehicle [31].

The crowding literature shows that density directly affects perceived travel quality and thus willingness to pay and demand. A meta-analysis of 208 valuations from 17 studies reports travel time multipliers of 1.19 for seated and 2.32 for standing passengers [10]. Further work quantifies the increase in time valuation with rising density and the disutility of standing at about 2.5 times that of sitting [9,32]; densities of four to five passengers per square metre are regarded as a reliable indicator of discomfort [33]. Beyond valuation effects, sustained crowding in rail transport is also associated with elevated stress levels and reduced perceived well-being among passengers [34]. The valuation studies themselves, however, criticise the data situation as "too aggregate" and note a "dearth of data collected on crowding levels" [11]. From a theoretical perspective, environmental psychology distinguishes between density as a physical condition and crowding as the subjective experience that arises when the demand for space exceeds the space available [35]. On trains, stress depends more on the immediate proximity of other passengers than on the overall density of the car [36], and crowding as experienced by rail passengers comprises evaluative as well as affective components that can be measured as distinct dimensions [37]. This distinction provides the theoretical basis for a behaviour-based capacity limit: boarding ends not when the physically available area is filled but when the expected crowding at the remaining free positions exceeds the level that passengers are prepared to accept.

Laboratory experiments with vehicle mock-ups show a highly uneven distribution: at about 1.6 to 1.8 P/m^2, 8.6 of 20 persons stood in the central door vestibule in the base-

line layout but only 1.0 person in the side aisles; a change of layout tripled aisle use [7]. Zone-resolved measurements in a mock-up yield 0.47 to 4.42 P/m^2 in the door vestibule and 1.01 to 5.23 P/m^2 in the centre aisle and demonstrate that average densities cannot represent the distribution inside the vehicle [38]. Vehicle design directly affects passenger exchange: door width and vestibule depth determine the number of flow lanes [39], the boarding rate increases only up to about 2.5 to 3 P/m^2 [12,40], and above 4 P/m^2 the door flow decreases [41]. Door blocking occurs at up to 60% of peak stops, and the intended door capacity differs between networks by a factor of 1.8 [13]. Luggage carried on board aggravates the situation further: the area demand rises from 0.15 to 0.20 m^2 to 0.35 to 0.55 m^2 with a suitcase and to as much as 1.15 m^2 with a pram [18], boarding and alighting times increase by up to 83% per affected passenger [42], door capacities fall by up to 25% [43], and insufficient luggage storage reduces seat occupancy by up to 20% [44,45]. With mobility aids, dwell time increases from 13.8 s to up to 118 s [46].

Research on pedestrian densities at major events quantifies the pure projected area of the human body at about 0.085 m^2 and, taking clothing and foot position into account, at about 0.15 m^2; 7 to 9 P/m^2 are stated as the theoretical maximum, while observed maxima lie between 5 and 6 P/m^2 and mostly below 4 P/m^2. The 8 P/m^2 partly assumed in vehicle regulations is regarded as "not scientifically justifiable" [25]. In pedestrian flows, stopping pedestrians appear only at densities above about 3 P/m^2 [47]. Area-based analyses of pedestrian densities in public transport interchanges using Voronoi methods confirm this order of magnitude [48]. These findings mark the physical upper limit but do not explain which density is voluntarily accepted in everyday operation.

1.3. Research Gap

A clearly delimited gap follows from the state of research. First, practically no area-differentiated, empirically measured standing densities are available for regular service. The existing large-scale data sources average over vehicles, runs and stations [26,27,29] and are criticised by the valuation literature itself as too aggregate [11]. Zone resolution so far exists almost exclusively from laboratory experiments with test persons [7,38,39], the transferability of which to everyday operation remains open. For real operation, comparable values are found only as side remarks, for instance 2.5 P/m^2 in door areas compared with "perhaps 0.5 passengers per square metre" in seating aisles [8]; field studies explicitly state that too little attention has been paid to how passengers use the vehicle interior [31,49]. Studies on passengers left behind at stations show that this operationally relevant indicator of saturation can be measured at stations or inferred from automated fare collection and vehicle location data [14,50]; such approaches, however, identify that passengers were left behind but not the in-vehicle density at which this occurred.

Second, the normative design values remain high, inconsistent and empirically untested: 4 P/m^2 in VDV practice [1], 5 P/m^2 as a level-of-service limit and 6.7 to 10 P/m^2 in vehicle specifications [6], 6.25 P/m^2 in vehicle regulations [21], while BOStrab and the Austrian tramway ordinance define no passenger density at all [3,4]. That these values are not reached in operation has repeatedly been documented indirectly—despite being designed for 6 P/m^2, the MTR reaches only about 4 P/m^2 in practice because passengers avoid a vehicle that appears full [51]—but it has not been quantified systematically. Third, a methodologically clean separation is missing between the maximum occupancy that can be reached under experimental conditions (experimental maximum occupancy) and the behaviour-based limit capacity that actually occurs in everyday operation.

It is precisely this gap that the present paper addresses: it provides area- and vehicle-differentiated density values from 126 documented limit-capacity situations in regular

service, complemented by field experiments on the experimental maximum occupancy, and thus quantifies the gap between normative design and operational reality.

1.4. Aim and Research Questions

The aim of the study is to determine real standing capacities in public transport vehicles. Instead of computational area assumptions, empirically documented passenger densities per vehicle area and vehicle type are to be provided that can serve as reference values for vehicle assessment, service planning and simulation. Four research questions follow from this:

- RQ1: Which passenger densities are actually reached in door, aisle and transition areas at limit capacity in regular service?
- RQ2: How do these densities differ between vehicle types and interior concepts, and which design features explain the differences?
- RQ3: What influence do operating states such as service disruptions and major events, as well as luggage carried on board, have on the densities reached?
- RQ4: How large is the difference between the behaviour-based limit capacity, the maximum occupancy achievable under experimental conditions, and the normative design values?

2. Materials and Methods

This section describes how the standing areas were delimited and measured, how the occupancy of these areas was observed in passenger service, how the central comparison parameter of limit capacity was operationalised, and which supplementary field experiments were evaluated. It also documents the statistical treatment of the data and the data protection and research ethics framework of the survey.

2.1. Research Design

The investigation follows a three-stage, predominantly observational research design (Table 2). In a first step, the standing areas of the vehicles under investigation were recorded geometrically and divided into the three functional areas of door area, aisle area and transition area (Section 2.4). In a second step, the occupancy of these areas in passenger service was surveyed by structured, non-participant observation (Section 2.5); the central comparison parameter is the limit capacity (Section 2.6). In a third step, field experiments with specifically recruited test persons were evaluated, in which defined vehicle areas were filled up to the experimental maximum occupancy (Section 2.7). The combination of both approaches makes it possible to distinguish the density voluntarily accepted in everyday operation from the maximum occupancy achievable under experimental conditions, and both from the normative design values. Table 2 summarises the purpose, method, data basis and output of each stage.

Automatic passenger counting systems, weighing equipment and Wi-Fi-based methods were deliberately not used. Such systems provide vehicle or cross-section totals but no area-related densities; in addition, their accuracy decreases markedly precisely at high occupancy and in the door area [26,52]. The question relevant for this study—how passengers distribute themselves inside the vehicle and when boarding stops—is accessible only through observation. All data from regular service were therefore collected by manual counting; no photographic, video or audio recordings were made, and no personal data were processed (Section 2.9).

Table 2. Three-stage research design: purpose, method, data basis and output of each stage.

	Stage	Purpose	Method	Data Basis	Output (Section)
1.	Geometric recording	Delimit and measure the standing areas	Manufacturer floor plans, re-measured in the vehicle on a sample basis; division into door, aisle and transition areas	Nine vehicle types	Reference areas per area and vehicle type (Sections 2.3 and 2.4, Table 3)
2.	Observation in passenger service	Determine the densities reached at limit capacity	Structured, non-participant observation of stopping events; limit criterion: waiting passengers left behind	227 stopping events on 19 lines, of which 126 at limit capacity	Area-differentiated densities by vehicle type and operating state (Sections 2.5, 2.6, 3.1–3.3 and 3.5)
3.	Field experiments with test persons	Determine the experimental maximum occupancy	Test persons admitted to a delimited area until it was perceived as fully occupied; luggage share 0 to 100%	Class 4746 and KISS double-deck vehicle (TrainOptimizer2.0, 2022)	Experimental maximum occupancy with and without luggage (Sections 2.7 and 3.4)
	Synthesis	Quantify the gap between the density levels	Descriptive comparison of limit capacity, experimental maximum occupancy and normative design values	Results of stages 1–3 and literature values	Discussion and recommendations (Sections 4 and 5)

Table 3. Vehicle types investigated, reference areas of the standing zones per vehicle section and number of evaluated limit-capacity situations (own illustration).

Vehicle Type	Mode	Door (m^2)	Aisle (m^2)	Transition (m^2)	*n*
Type U	metro	5.1	2.4	–	12
Type V	metro	5.1	2.3	3.3	21
Type X	metro	5.1	3.1	3.3	14
Type T	metro	4.8	2.4	5.0	16
ULF	tram	3.4	2.5	2.5 (joint with aisle)	15
Type D	tram	3.7	2.6	1.5	14
Citaro G NG 265 MB	bus	4.0	2.7	2.2	10
Class 4746	suburban rail	3.5	5.0	3.8	14
DOSTO	suburban rail	3.8	8.0	5.3	10
Total	–	–	–	–	126

2.2. Study Area: The Vienna Public Transport Network

Local public transport in Vienna is operated by Wiener Linien, Vienna, Austria (bus, tram, metro) and by the Austrian Federal Railways ÖBB, Vienna, Austria (suburban and regional rail). In 2025, Wiener Linien carried about 903 million passengers on a network of approximately 84 km of metro, 893 km of bus and 171 km of tram routes [53,54]. The suburban railway operated by ÖBB carries about 89 million passengers with 1410 daily trains on ten lines [55]. In addition, the City Airport Train and the Wiener Lokalbahnen operate in Vienna. The empirical investigation covers vehicles of Wiener Linien and ÖBB.

2.3. Vehicles Investigated

Nine vehicle types of Wiener Linien and ÖBB were investigated, covering the metro, tram, bus and suburban rail designs in service in Vienna. Throughout the paper, each vehicle is referred to by its type designation only. The schematic floor plans of the standing areas are shown in Figures 1–9. In all floor plans, the investigation areas are marked uniformly: blue denotes the boarding or door area, orange the aisle area and green the transition area.

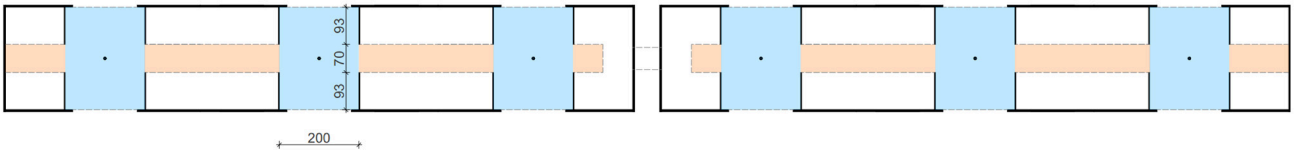


Figure 1. Schematic floor plan of the standing areas, Type U (own illustration).

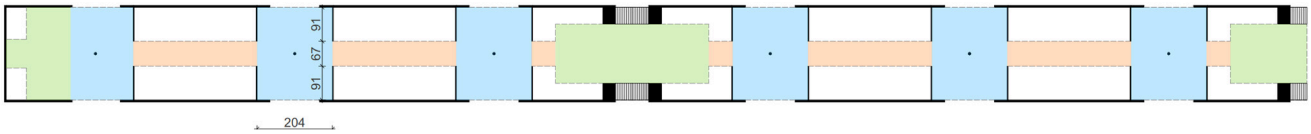


Figure 2. Schematic floor plan of the standing areas, Type V (own illustration).

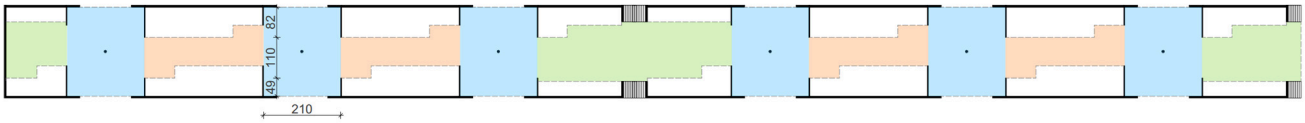


Figure 3. Schematic floor plan of the standing areas, Type X (own illustration).

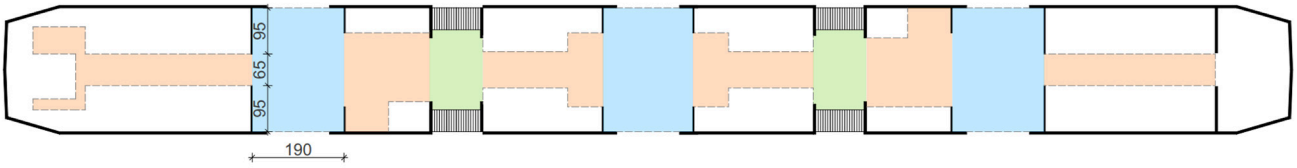


Figure 4. Schematic floor plan of the standing areas, Type T (own illustration).

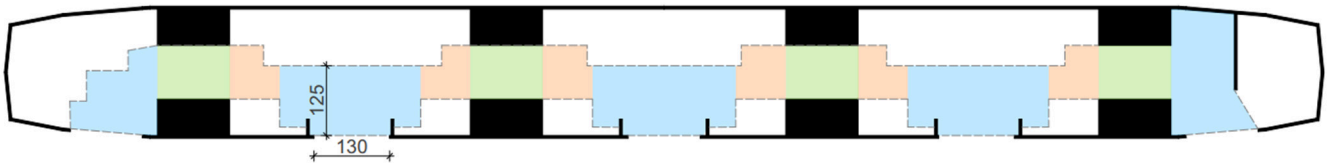


Figure 5. Schematic floor plan of the standing areas, ULF (own illustration).

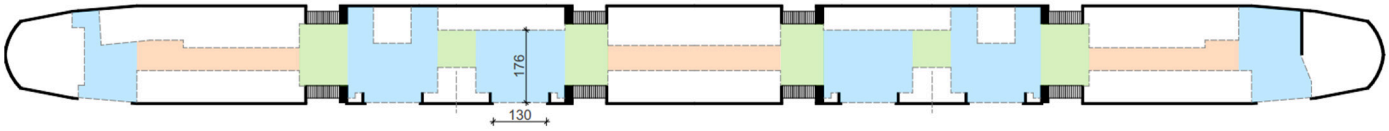


Figure 6. Schematic floor plan of the standing areas, Type D (own illustration).

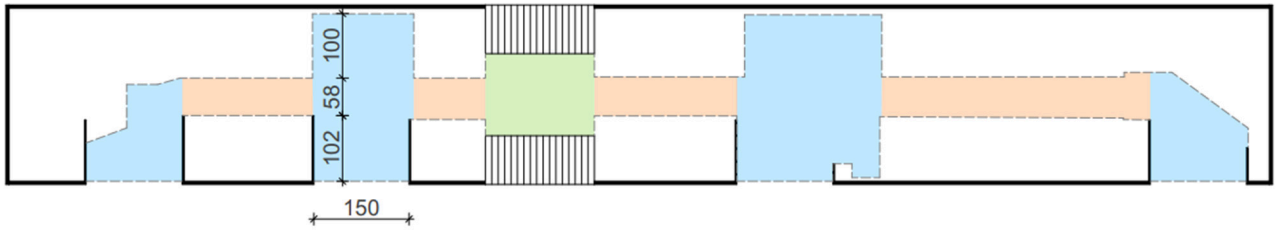


Figure 7. Schematic floor plan of the standing areas, Citaro G NG 265 MB (own illustration).

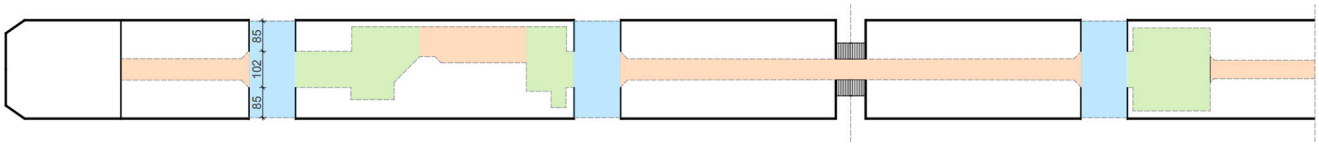


Figure 8. Schematic floor plan of the standing areas, Class 4746 (own illustration).

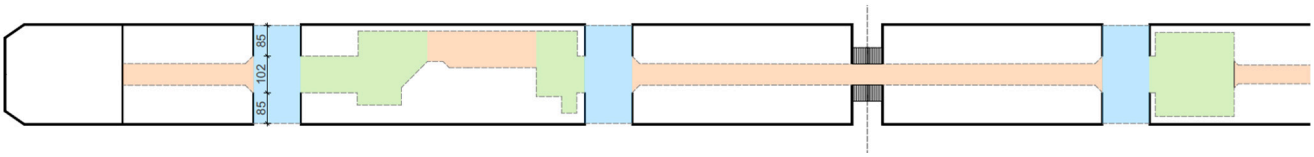


Figure 9. Schematic floor plan of the standing areas, lower deck of the DOSTO double-deck push–pull train (own illustration).

2.3.1. Metro

Type U is the oldest design, and, having no continuous gangway, is the most strongly confined to the door area. A double railcar unit is 36.8 m long and 2.8 m wide and offers 98 seats and 182 standing places [56]. Type V and Type X are six-car trains with continuous gangways and transition areas; Type X offers the largest standing capacity owing to a larger aisle area and a reduced number of seats. Type V is 111.22 m long and 2.85 m wide and offers 260 seats and 622 standing places [57]. The six-car Type X train is 111.25 m long and 2.85 m wide and offers 200 seats and 728 standing places [58]. The narrower low-floor Type T operates exclusively on line U6 and has no car-to-car gangway between the vehicles; its transition areas are the two articulations; one vehicle is 26.8 m long and 2.65 m wide and offers 58 seats and 136 standing places [59]. Figures 1–4 show the schematic floor plans of the standing areas of these four vehicle types.

2.3.2. Tram

The ULF (variants A and B) is a low-floor vehicle without platforms or steps; the interior is predominantly equipped with seats, and standing areas are concentrated in the boarding and articulation zones. The ULF is built as the 24.21 m long short version A and the 35.47 m long version B. Variant A offers 42 seats and 94 standing places, variant B 66 seats and 143 standing places [60]. Type D (Flexity Wien) is a low-floor vehicle that provides additional standing areas for prams and wheelchairs in two multi-purpose zones. The vehicle is 33.8 m long and 2.38 m wide and offers 62 seats and 149 standing places [61]. Figures 5 and 6 show the schematic floor plans of the standing areas.

2.3.3. Bus

In the articulated bus Citaro G NG 265 MB, the standing places are concentrated mainly in two multi-purpose areas and in the aisle. The bus is 18.125 m long and 2.59 m wide, has four doors and offers 41 seats and 88 standing places [62]. Because the doors swing outwards, the usable standing area in the door zone is not restricted by the door movement. Figure 7 shows the schematic floor plan.

2.3.4. Suburban Rail

Class 4746 (Cityjet, Desiro ML, Siemens Mobility GmbH, Munich, Germany) is divided into a multi-purpose area, a boarding zone and an aisle zone. The three-car trains have six doors per side and 244 seats; official figures on the number of standing places are not available [63]. In the double-deck push–pull trains (referred to as DOSTO), the standing area is likewise divided into a multi-purpose compartment, a boarding area and an aisle

area, but without continuous handholds in the aisle. The train formation investigated in this study consisted of one driving trailer and three intermediate cars. Based on the capacities stated by ÖBB—86 seats in the driving trailer and 114 seats per intermediate car—this formation provides 428 seats in total [64]. The cited vehicle description does not specify the number of standing places. Figures 8 and 9 show the respective schematic floor plans.

2.4. Delimitation of the Standing Areas and Determination of Reference Areas

The basis of the density calculation is the unobstructed usable standing area, in analogy to the definition of the "standing area" in EN 15663, which comprises vestibules, aisles and platforms [24]. Seats and the areas beneath seats, designated wheelchair and pram spaces, areas behind driver compartments and zones that are permanently not accessible because of grab poles, partitions or fittings were excluded. Tip-up seats were counted as standing area in the folded-up state if they were actually used as such in the observed situation.

The standing area was divided into three functional areas. The door area comprises the vestibule between the door leaves and the first row of seats, partition or platform edge, including adjoining multi-purpose areas. The aisle area denotes the passage between seat groups, and the transition area the articulation or car-to-car gangway zones as well as—in double-deck vehicles—the connecting and staircase landings. This subdivision follows the functional logic of passenger behaviour and is comparable with the zone-related approach used in the international literature [7,38].

The areas were derived from manufacturer floor plans and re-measured in the vehicle on a sample basis; the schematic floor plans in Figures 1–9 show the respective delimitation. Table 3 summarises the reference areas and the number of evaluated limit-capacity situations per vehicle type. For Type U, the car-to-car gangway is not continuously accessible, which is why no transition densities are available for this type. For the ULF, the aisle and transition areas were assessed jointly because of the continuous low-floor geometry without platforms.

2.5. Observational Survey in Passenger Service

The survey was carried out between 17 July 2024 and 16 April 2025 on 19 lines of Wiener Linien and ÖBB (U1, U2, U3, U6; tram lines 1, 11, 71, 72, D, O and E1; bus lines 13A and 14A; and S1 to S4, S50 and REX 1). A total of 227 stopping events were documented. The selection of runs was not random but deliberately directed at times and situations with high occupancy—morning and afternoon peak, service disruptions, partial closures and major events—in order to be able to observe limit capacity at all. This selection is a deliberate part of the design: the aim was to determine the limit capacity in real operation, which is defined not by a physical limit but by whether waiting passengers are left behind. Peak periods, disruptions and events were therefore chosen in order to capture as many situations with real limit capacity as possible. Because passenger behaviour in the limit state proved to be very similar, and the dispersion of the densities was correspondingly small, about ten limit-capacity observations per vehicle type were deliberately targeted. This target was reached or exceeded for all vehicle types (10 to 21 cases). In terms of distribution, 158 observations refer to regular operation, 40 to service disruptions, 20 to a multi-week partial closure of line U1, seven to journeys to football matches and two to the Vienna City Marathon.

The observing person took a fixed position in the respective vehicle section and recorded the occupancy immediately before the doors closed, that is, in the state of highest occupancy of a stopping event. The following information was recorded by hand: date, time, line, vehicle type, position in the vehicle and special event; the number of standing persons separately for the door, aisle and transition areas; the number of persons from which filling of the aisle area began; the number and type of items carried (hand luggage,

travel luggage, pram, bicycle) separately for the door and aisle areas; the assignment of the observed persons to coarse age categories and to externally recognisable gender; the number of those passengers who briefly alighted to let others alight and then boarded again; and the feature decisive for the evaluation, namely whether passengers waiting on the platform no longer boarded.

In order to limit counting and assessment errors, the survey sheets were completed immediately after each stop, observations with restricted view of an area were discarded, and part of the records was checked afterwards by means of a verification column. Of the 227 documented stopping events, 126 fulfil the criterion of limit capacity; these form the data basis of the density evaluations presented in Section 3.

Table 4 shows how the 126 limit-capacity situations are distributed across vehicle types, operating states, times of day and lines. Regular operation and service disruptions each account for slightly less than half of the cases (58 and 59), event traffic was recorded only for Type V and Type X, and almost half of all cases fall into the afternoon peak. The sample is designed to represent the limit state and not the average occupancy over the operating day. It covers all nine vehicle types in service on the metro, tram, bus and suburban rail networks, 16 of the 19 lines surveyed, both peak periods and the off-peak, as well as regular operation, service disruption and event traffic. Since limit capacity arises almost exclusively in these situations, the distribution of the cases reflects where the limit state actually occurs in the network rather than a predefined sampling quota. The adequacy of the case numbers is assessed in Section 3.1 on the basis of the precision of the resulting means.

Table 4. Distribution of the 126 limit-capacity situations by vehicle type, operating state, time of day and line (number of observation cases).

Vehicle Type	*n*	Regular	Disruption	Event	AM Peak	PM Peak	Off-Peak	Lines (*n*)
Type U	12	7	5	0	4	5	3	U1 (11), U3 (1)
Type V	21	10	6	5	6	5	10	U1 (18), U2 (1), U3 (2)
Type X	14	5	5	4	1	8	5	U2 (8), U3 (6)
Type T	16	11	5	0	2	7	7	U6 (16)
ULF	15	5	10	0	5	10	0	D (3), E1 (4), O (8)
Type D	14	5	9	0	5	8	1	11 (4), 71 (6), E1 (4)
Citaro G	10	5	5	0	1	9	0	13A (10)
Class 4746	14	5	9	0	6	3	5	S1 (1), S2 (3), S3 (2), S4 (3), S50 (5)
DOSTO	10	5	5	0	5	5	0	REX 1 (10)
Total	126	58	59	9	35	60	31	16 lines

Notes to Table 4: *n* = number of evaluated observation cases (limit-capacity situations), not persons. Disruption includes 40 service disruptions and 19 cases during the partial closure of line U1; event = seven journeys to football matches and two to the Vienna City Marathon. Time of day according to the recorded time of the stopping event: AM peak 06:30–09:00, PM peak 16:00–19:00, off-peak = all other times. The 126 limit-capacity situations occurred on 16 of the 19 lines surveyed; on tram lines 1 and 72 and on bus line 14A, no limit-capacity situation was recorded.

2.6. Definition of Limit Capacity

In this paper, limit capacity denotes the state in which passengers waiting on the platform or at the stop no longer board although space would still be available in purely geometric terms. The limit is thus defined not physically but by the behaviour of the passengers. It marks the capacity of a vehicle that can actually be used and must be distinguished both from the computational crush capacity and from the planning design capacity. Limit capacity was operationalised by the observation feature “no boarding”: a stopping event was counted as limit capacity only if at least one waiting person demonstrably

refrained from boarding or was no longer able to board. The criterion refers to the observable outcome and not to the individual motive: what is relevant for operational planning is that demand at the door is no longer served by the arriving vehicle, which corresponds to the notion of left-behind passengers in the literature [14,50]. A deliberate decision not to board a vehicle perceived as too full—for instance in the expectation of a less crowded following vehicle—is therefore not a source of error but precisely the behaviour-based limit that this study seeks to capture [51]. Non-boarding unrelated to crowding, for example by persons waiting for another line or for companions, cannot be ruled out completely, since passengers were deliberately not interviewed in order not to influence their behaviour. Such cases would tend to lower the observed limit densities. The moderate dispersion of the door area densities within the vehicle types (standard deviations of 0.31 to 0.61 P/m^2, Table 5) suggests that their influence is small.

Table 5. Descriptive statistics of the passenger densities (P/m^2) at limit capacity by vehicle type and vehicle area (own calculation).

Vehicle Type	*n*	Door M (SD)	Door Mdn (Q1–Q3)	Aisle M (SD)	Transition M (SD)	Aisle Filling M (SD)
Type U	12	3.20 (0.31)	3.33 (3.04–3.38)	1.81 (0.51)	–	2.24 (0.42)
Type V	21	3.53 (0.53)	3.53 (3.14–3.92)	2.65 (0.82)	1.99 (0.71)	2.02 (0.39)
Type X	14	3.36 (0.40)	3.24 (2.99–3.68)	2.72 (0.77)	2.55 (0.72)	1.78 (0.31)
Type T	16	3.26 (0.56)	3.23 (2.86–3.59)	2.67 (0.50)	2.55 (0.48)	1.69 (0.68)
ULF	15	3.41 (0.52)	3.53 (3.09–3.82)	2.85 (0.78)	2.85 (0.78)	1.78 (0.38)
Type D	14	2.83 (0.48)	2.70 (2.47–2.97)	1.69 (0.36)	2.34 (0.50)	1.37 (0.37)
Citaro G	10	2.65 (0.61)	2.75 (2.31–3.12)	2.05 (0.64)	2.25 (0.54)	1.23 (0.46)
Class 4746	14	3.22 (0.49)	3.14 (2.86–3.43)	2.44 (0.74)	1.83 (0.75)	1.57 (0.37)
DOSTO	10	2.82 (0.45)	2.89 (2.43–3.09)	2.01 (0.55)	1.99 (0.65)	1.26 (0.58)
Total	126	3.19 (0.55)	3.14 (2.86–3.53)	2.37 (0.76)	2.30 (0.72)	1.70 (0.53)

Notes to Table 5: n = number of evaluated observation cases (limit-capacity situations); M = arithmetic mean; SD = standard deviation; Mdn = median; Q1 = first quartile; Q3 = third quartile; P/m^2 = passengers per square metre; Aisle filling = door area density from which passengers begin to move into the aisle area. Cases per area: door area n = 126, aisle area n = 124, transition area n = 114. For Type U, the car-to-car gangway is not continuously accessible, which is why no transition values are available (–). For the ULF, the aisle and transition areas were assessed jointly, which is why the values are identical.

Limit capacity therefore represents the maximum load under real operating conditions. It is decisively influenced by the interior design, the accessibility of the areas, luggage carried on board, the journey time and individual distance keeping. Of these factors, luggage carried on board and the composition of passengers were recorded descriptively for each stopping event, whereas individual destinations and expectations regarding the next service could not be observed. That such a behaviour-based limit lies systematically below the design values has been observed internationally on several occasions: passengers are less willing to board a vehicle that appears full [51], the boarding rate increases only up to about 2.5 to 3 P/m^2 [12,40], and above 4 P/m^2 the door flow decreases [41]. All evaluations and figures presented in Section 3 refer exclusively to situations in which limit capacity was reached.

2.7. Supplementary Field Experiments with Test Persons

To determine the experimental maximum occupancy, results of field experiments were evaluated that had been conducted in 2022 within the research project "TrainOptimizer2.0" of TU Wien on vehicles of ÖBB Class 4746 and on a double-deck vehicle of the KISS type. Test persons were specifically recruited for these experiments and given defined tasks. For the present paper, only that part of the experiments was used in which the maximum

number of persons per area was determined: the test persons were admitted to a delimited vehicle area until, in their own perception, it was fully occupied. The share of luggage was varied between 0% and 100% (0%, 33%, 50%, 66% and 100%, depending on the vehicle area). The resulting value is referred to in this paper as the experimental maximum occupancy. It approximates the practical physical limit of a vehicle area under realistic behaviour, that is, without pushing and with the distance keeping that the test persons still regarded as acceptable, but it retains a subjective component. It must therefore be distinguished both from the geometric maximum derived from the projected body area of 6.6 to 9 P/m^2 [25] and from manufacturer standing capacities of 6.7 to 10 P/m^2 [6].

Since this is a simulated situation, the realism of the behaviour was controlled separately: experts mixed with the test persons and assessed directly during the experiment whether distance keeping, choice of area and reaction to densification corresponded to the behaviour observable in operation. Runs in which this was not the case were not included in the evaluation; for the evaluated runs, realism was confirmed. This methodological approach corresponds to the established practice of combining empirical passenger observation with experiments under controlled conditions for interior and layout assessments [44,45]. In the following, the experimental values serve exclusively as a reference for the experimental maximum occupancy and are not mixed with the observational data from regular service.

2.8. Data Processing and Statistical Evaluation

For each area, the passenger density was calculated as the quotient of the number of persons standing there and the corresponding reference area according to Table 3 and is stated in passengers per square metre. Data sets with incomplete recording of an area were excluded area by area; therefore, 126 usable density values are available for the door area, 124 for the aisle area and 114 for the transition area. In addition, aisle filling was evaluated as the door area density from which passengers first move into the aisle area.

The evaluation is descriptive and uses mean, standard deviation, median, first and third quartile as well as minimum and maximum. Box plots serve as the standard representation of the distributions because they show location, dispersion and outliers together; mean value representations are used exclusively for the comparison of aggregated scenarios and for the experimental series, for which only maximum values per configuration are available. Relationships between door area density and aisle filling or temporarily alighting passengers are shown as scatter plots with a fitted trend function. To indicate the precision of the means, approximate 95% confidence intervals (CIs) were calculated as $M \pm t(0.975; n-1) \cdot SD/\sqrt{n}$. Because the observations are clustered, these intervals are likely to be somewhat too narrow; they are therefore to be read as an orientation on precision and not as exact inferential statements. Significance tests are deliberately not applied: the sample is not drawn at random, the numbers of cases per vehicle type range between 10 and 21, and the observations are clustered by line and time of day. The evaluation is therefore exploratory and descriptive; reported differences are to be read as observed tendencies and not as tested effects. Pearson correlation coefficients (r) and coefficients of determination (R^2) are reported as descriptive measures of association; the accompanying p-values are stated for information only ($p < 0.001$) and are not interpreted as confirmatory tests, since the independence assumption is violated by the clustering. Mixed-effects models would account for this clustering. They were considered but not applied because with 19 lines, nine vehicle types and between five and eleven cases per vehicle type and operating state the random effects cannot be estimated reliably. An independent validation data set is not available; the field experiments (Section 2.7) and the values reported in the literature serve as plausibility checks of the order of magnitude.

The number of cases n reported in the figures and tables consistently denotes the number of evaluated observation cases, that is, the documented limit-capacity situations per vehicle area, and not the number of observed persons. Each case yields exactly one density value in passengers per square metre; the persons counted enter this calculation exclusively as the numerator.

2.9. Data Protection and Research Ethics

The survey in passenger service was conducted exclusively by non-participant observation in publicly accessible means of transport. The observing persons noted by hand exclusively aggregate features: the number of persons standing in an area and—in each case merely as a count per area—a roughly estimated age category, the externally recognisable gender and, where applicable, luggage carried. No names, contact or ticket data, no biometric features and no other identifying information were recorded; no persons were addressed or interviewed, and no photographic, video or audio recordings were made.

The records are therefore anonymous from the outset. Conclusions about individual persons are possible neither directly nor by linkage with further information, since the protocols contain exclusively count values per vehicle area and stopping event. No personal data within the meaning of Art. 4(1) GDPR are therefore present, so that the processing does not fall within the scope of the Regulation. Consent was consequently not required and, in the case of anonymous observation in public space, would also not have been feasible without altering the observed behaviour.

Only adult, specifically recruited test persons participated voluntarily in the supplementary field experiments. They were informed in advance about the purpose, the procedure and the voluntary nature of participation and were able to withdraw at any time without giving reasons and without disadvantage. The experiments took place on stationary vehicles and did not exceed the everyday strain of public transport use. Only aggregated numbers of persons per vehicle area were evaluated; no personal or health-related data were processed or stored. As there was thus neither an intervention in the sense of medical or psychological research nor any processing of personal data, no approval by an ethics committee had to be obtained under the applicable institutional rules.

3. Results

3.1. Passenger Densities at Limit Capacity

Table 5 summarises the descriptive statistics of the densities reached at limit capacity by vehicle type and vehicle area. Across all vehicle types, the door area is the most heavily used zone with a mean of 3.19 P/m^2, followed by the aisle area with 2.37 P/m^2 and the transition area with 2.30 P/m^2; aisle filling starts on average at 1.70 P/m^2. The distributions underlying these values, including outliers, are shown in Figure 10. The approximate 95% confidence intervals of these overall means are 3.09–3.29 P/m^2 for the door area, 2.24–2.51 P/m^2 for the aisle area, 2.17–2.43 P/m^2 for the transition area and 1.60–1.79 P/m^2 for aisle filling; the interval of the door area does not overlap with those of the aisle and transition areas. For the door area density of the individual vehicle types, the half-widths of the intervals range from 0.20 P/m^2 (Type U) to 0.44 P/m^2 (Citaro G). Even the highest upper bound (Type V, 3.77 P/m^2) remains below the design value of 4 P/m^2.

3.1.1. Door Area

Figure 10a shows clear differences in the use of the door area. The highest mean densities occur in Type V, ULF, Type X, Type T and Class 4746, with the ULF and Type V showing at the same time the widest distributions. This dispersion can be explained by generously dimensioned boarding zones with direct connection to the aisle and transition

areas (cf. Sections 3.1.2 and 3.1.3). In Type X, the median is high, and the upper quartile is broad; use is high on average but increases markedly during disruptions or heavy passenger demand. Class 4746 shows a compact box with outliers, that is, largely uniform use with occasionally heavily overloaded situations, whereas Type T shows stable use, which is consistent with its continuous, wide aisle areas.

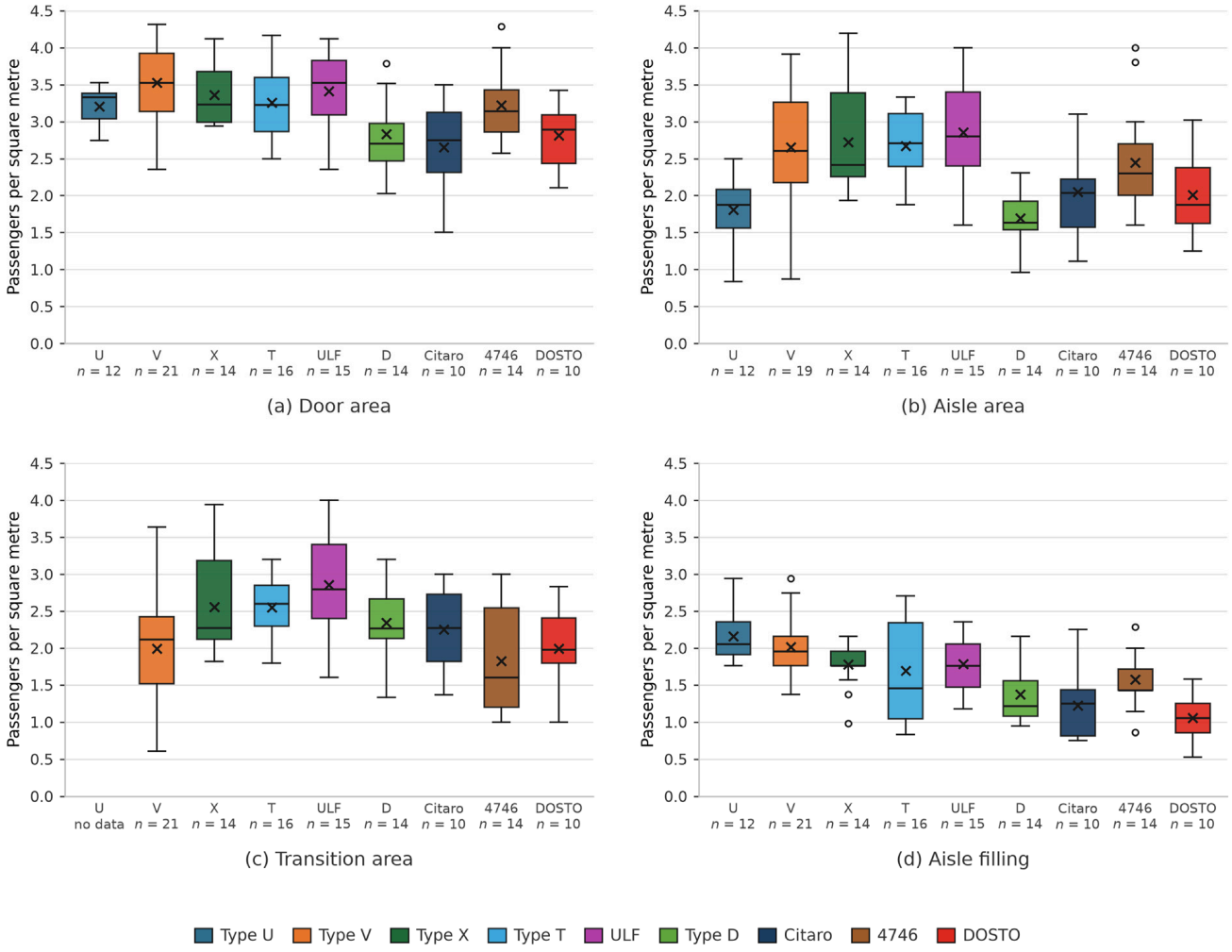


Figure 10. Passenger density at limit capacity by vehicle area—(**a**) door area, (**b**) aisle area, (**c**) transition area, (**d**) aisle filling (own illustration; n = 126/124/114/126 cases).

Lower medians are found in Type D, Citaro G and DOSTO. In Type D, the directly adjoining transition area allows rapid onward distribution of passengers (cf. Section 3.1.3); in the Citaro G, the available standing area varies because of the multi-purpose design with tip-up seats; and in the DOSTO, the door area adjoins a staircase, which leads to consistently low but stable use. Type U lies in the middle range with the smallest dispersion; it has clearly delimited door areas without connection to transition zones, whereas the structurally similar Type V has a transition area and is therefore used more intensively and more variably. Overall, the vehicle structure decisively determines the use of the door area: open, well-connected boarding zones lead to high and variable occupancy, while functional restrictions such as tip-up seats or staircases result in persistently low use.

3.1.2. Aisle Area

In the aisle area (Figure 10b), high mean densities occur in the ULF, Type T, Type X and Type V; the ULF, Type V and Type X show wide distributions at the same time. While the ULF, Type T and Type X have continuous, wide aisles, the aisle in Type V—similar to Type U—is narrow. The high use there is likely to result less from spatial openness than from the lack of alternative space. In Type X, the upper quartile is particularly wide, and the upper whisker long: the aisle area opens directly onto the door area and thus favours intensive mixing at higher passenger volumes. Type T shows a compact distribution at high occupancy, and Class 4746 lies in the upper middle range with individual upward outliers.

The lowest values are found in Type U and Type D. Type U has no transition area, and in Type D a part of the passengers is already accommodated in the upstream transition area (cf. Section 3.1.3). Citaro G and DOSTO lie in the middle to lower range with low variance; their aisles are narrow or restricted by seats and stairs, so that the aisle is used as a passage rather than as a place to stay. Here, too, structural design and connectivity determine use: continuous, open aisle zones are used more flexibly but less regularly, while narrow or functionally restricted aisles are used at a consistently low level.

3.1.3. Transition Area

In the transition area (Figure 10c), the differences between vehicles are smaller. The highest densities occur in the ULF, Type T and Type X, which have centrally located, generously dimensioned transition areas with a high quality of stay, for instance owing to leaning supports in the ULF. The ULF and Type X show wide dispersion, which indicates a situationally changing use between passage zone and fixed standing area; Type T shows—as in the aisle area—a compact distribution, corresponding to its continuous interior structure.

Low values are found in Type V and, to a lesser extent, in the Citaro G: in both vehicles, handholds are missing in the central transition, and in the Citaro G the area is located in the articulation above the turntable. In Class 4746 and the DOSTO, the transition area is partly designed as a multi-purpose space with tip-up seats, which reduces the available standing area; Class 4746 has the lowest mean transition density of all vehicle types and varies more strongly, while the DOSTO is used more evenly. Type D lies in the middle range because its transition area directly adjoins the door area and serves as the first available standing space. Type U was not included as it has no transition area. Design, location and function of the transition area thus decisively influence its occupancy.

3.1.4. Aisle Filling

Aisle filling (Figure 10d) describes the density in the door area at the moment from which passengers move on from the door area into adjoining aisle or transition areas. A high mean density means that passengers initially remain in the door area and move on only as it becomes more crowded. The highest values are shown by Type U and Type V, whose narrow aisle dimensions make early onward movement difficult. In Type T, the interquartile range is large, which indicates strongly situation-dependent transition behaviour (cf. Section 3.2.4). Type X and the ULF are at a similar level, Type X with compact dispersion and downward outliers, the ULF somewhat wider but symmetrical.

Lower values occur in Type D, DOSTO and Citaro G. In Type D and the DOSTO, defined transition or multi-purpose areas are available after boarding, so that the aisle area is used at an early stage; in the Citaro G, the less attractively designed door area is likely to favour early onward movement, which is consistent with the low median in the door area (cf. Section 3.1.1). Class 4746 disperses both upwards and downwards and thus indicates situationally variable aisle use.

Aisle filling is strongly determined by the structural characteristics of the vehicles. Vehicles with narrow aisles such as Type U and Type V show late and densified transitions, whereas open and continuous concepts such as the ULF or Type X allow earlier and more flexible onward movement. Transition or multi-purpose areas as in Type D or the DOSTO additionally relieve the aisle area and lead to more even use.

3.1.5. Cross-Area Comparison

Comparing the three areas shows a consistent ranking (Table 5, Figure 10). In every vehicle type, the door area reaches the highest mean density. Across all vehicle types, the mean aisle density amounts to 74% and the mean transition density to 72% of the mean door area density, and aisle filling begins at 1.70 P/m^2, that is, at 53% of the mean door area density. The difference between the door and aisle areas varies considerably between the vehicle types: it is largest in Type U (1.39 P/m^2) and Type D (1.14 P/m^2), intermediate in Type V (0.88 P/m^2), the DOSTO (0.81 P/m^2) and Class 4746 (0.78 P/m^2), and smallest in Type X (0.64 P/m^2), the Citaro G (0.60 P/m^2), Type T (0.59 P/m^2) and the ULF (0.56 P/m^2). In Type D and the Citaro G, the transition area reaches higher densities than the aisle area. Vehicles with continuously accessible interiors thus show the most even use of the standing area, whereas vehicles with confined door areas or upstream transition zones show the most pronounced concentration at the doors.

3.2. Regular Operation Versus Service Disruption

For the purposes of this study, service disruptions were defined as the following situations:

- Short-term disturbances of the operating process caused by external influences or by damage to vehicles or infrastructure;
- Operating processes that are changed over a longer period by disturbances, for example flooding, a metro fire or partial closures.

Service disruptions were examined separately because passengers presumably anticipate irregular operation in such situations and therefore temporarily accept personally restrictive conditions, such as a higher standing density.

3.2.1. Door Area

Figures 11a and 12a show the passenger density in the door area separately for regular operation and service disruption. In all vehicles, the mean density increases in the case of disruption. This is particularly pronounced in the ULF, Type T and Type D, where the dispersion increases at the same time—an indication of increasingly non-uniform use of the door area. In Type D, the density in regular operation is below the level of the other types with a compact distribution; only in the case of disruption does it increase markedly and become more irregular.

In the DOSTO, the distribution remains compact, whereas Class 4746 disperses more widely in the case of disruption. Citaro G, Type X and Type V show only small increases with an overall stable distribution; in the Citaro G, the median remains low. Type U and Type V hardly change, which can be attributed to their comparable, spatially restricted aisle structure—in Type U additionally reinforced by the missing transition area. Overall, service disruptions lead to higher and frequently less uniform occupancy of the door area, particularly in vehicles with openly designed door and transition areas, whereas delimited areas show more stable patterns.

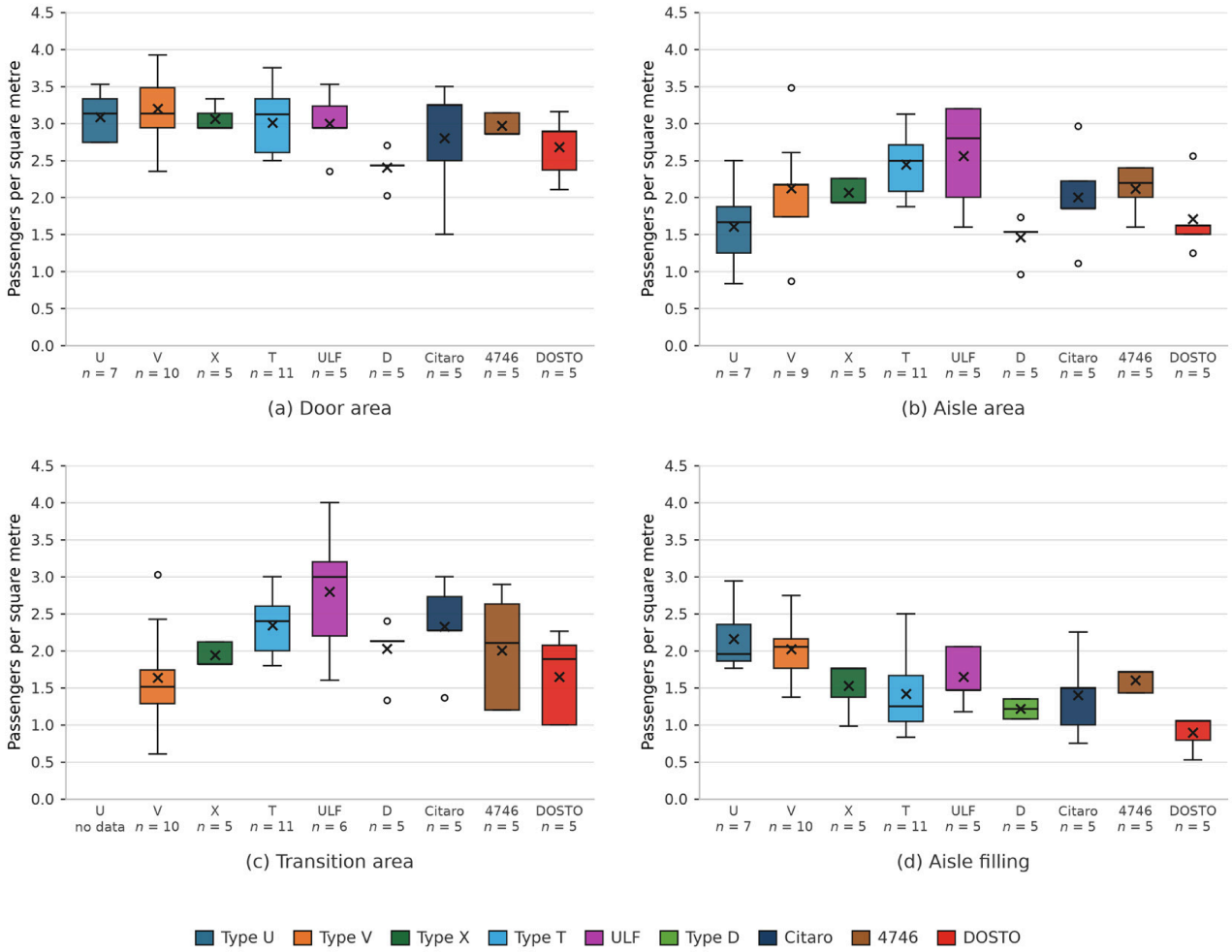


Figure 11. Passenger density at limit capacity in regular operation—(**a**) door area, (**b**) aisle area, (**c**) transition area, (**d**) aisle filling (own illustration; $n = 58/57/52/58$ cases).

3.2.2. Aisle Area

In the aisle area (Figures 11b and 12b), the mean density likewise increases in all vehicles, particularly clearly in Type V, Type T and the DOSTO. The highest values under disruption are reached by Type T and the ULF: in the ULF, dispersion increases and use becomes more irregular, whereas in Type T the distribution remains compact despite a higher mean. In both vehicles, the aisle area serves as the central alternative space under disruption, albeit in different ways.

Type D is used with a delay: in regular operation, the aisle density is low because of the upstream transition area (cf. Section 3.1.2), and only under disruption does it increase. In Type U the distribution becomes more compact, and in Type V the entire distribution shifts upwards, while Type X disperses more widely. In Class 4746 and the Citaro G, the median remains stable with slightly increasing dispersion; in the DOSTO, median and dispersion increase together. Vehicles with continuous, openly designed aisles are used more intensively and more variably in the case of disruption, whereas delimited or restricted aisle zones are used more stably.

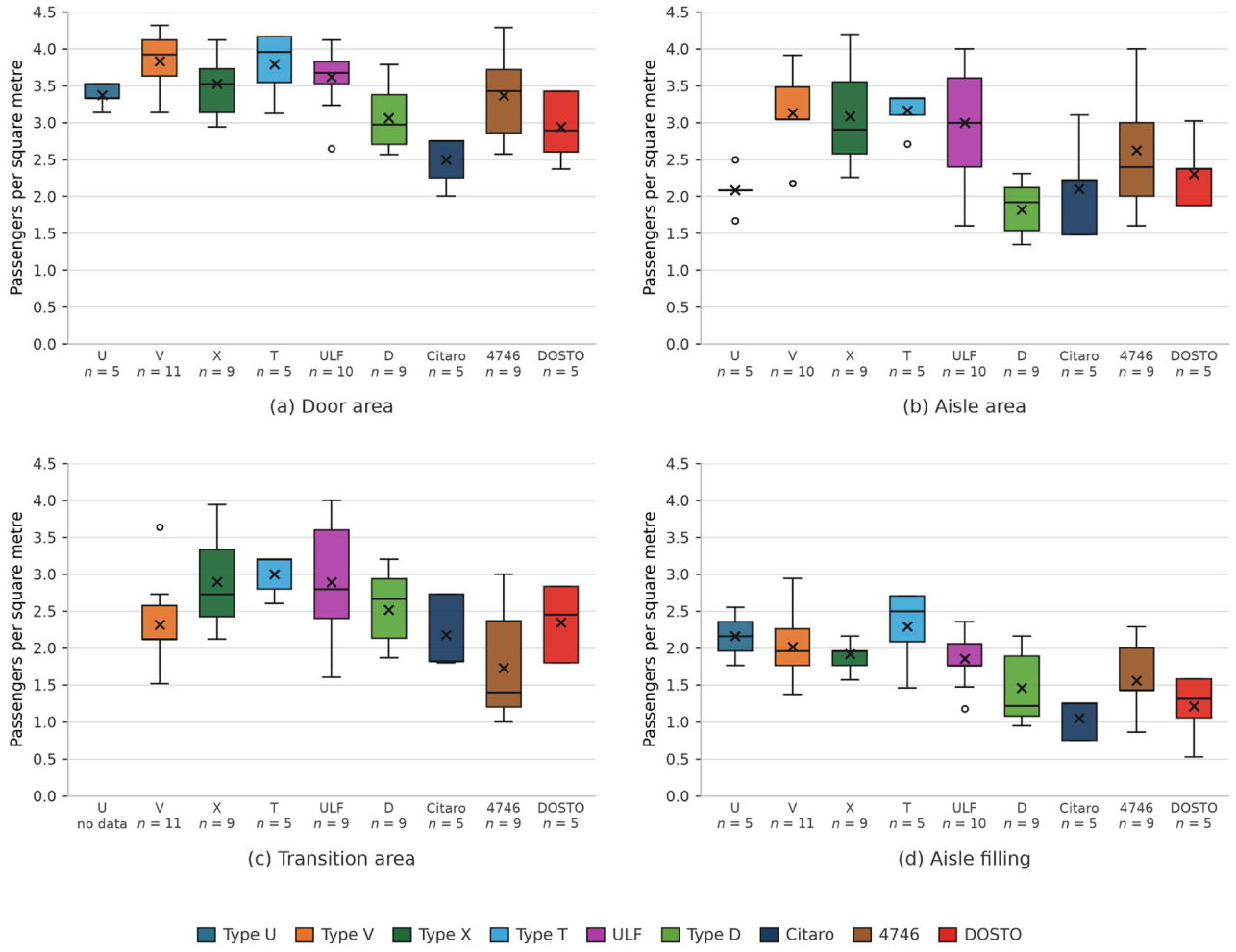


Figure 12. Passenger density at limit capacity under service disruption—(**a**) door area, (**b**) aisle area, (**c**) transition area, (**d**) aisle filling (own illustration; n = 68/67/62/68 cases).

3.2.3. Transition Area

In the transition area (Figures 11c and 12c), the mean density increases in all vehicles except Class 4746, particularly in Type V, the ULF, Type T and the DOSTO. As in the aisle area, Type T and the ULF reach the highest values, the ULF with wide dispersion and Type T with even use. In Type D, occupancy and dispersion increase, which underlines the function of this area as an alternative zone used early, before the aisle area proper (cf. Section 3.1.2).

In Type V, the transition area is used only weakly in regular operation; under disruption, the median increases with only slightly rising dispersion. As central handholds are missing (cf. Section 3.1.3), the increased use results from a lack of space in the remaining areas rather than from attractive design. In Type X and the Citaro G, the distribution widens visibly under disruption; in the DOSTO, the values converge while the median rises, since the area designed as a multi-purpose zone with tip-up seats is used deliberately as soon as the adjoining areas are fully occupied. In Class 4746, the median decreases slightly while dispersion increases, which likewise indicates the restricted availability of this area. Transition areas are thus used more intensively under disruption, but their usability varies strongly with the structural design.

3.2.4. Aisle Filling

Aisle filling (Figures 11d and 12d) changes non-uniformly under disruption. The largest difference is shown by Type T, in which the entire distribution shifts upwards: the transition from the door area starts later and less uniformly, which can be explained by the wide, continuous aisle areas without spatial separations. Type U and Type V remain almost unchanged; the consistently late aisle filling indicates that it is not passenger behaviour but the structural conditions that govern use. In Class 4746 the mean remains unchanged while dispersion increases.

In Type X and the ULF, the distribution, which is wide in regular operation, becomes more compact under disruption, and the median rises; the open, continuous aisle areas allow early onward movement in regular operation but are occupied more quickly under disruption. In Type D, use becomes more irregular because the upstream transition area fills up faster. In the Citaro G, the distribution becomes more compact with a slightly rising median; the DOSTO shows the lowest aisle filling overall and remains early and comparatively constant under disruption as well. The structural conditions thus directly affect the temporal and spatial evasion behaviour of the passengers.

3.2.5. Comparison of the Vehicle Areas

A comparison of the mean values across all vehicle areas confirms the pattern described above. Figure 13 shows that the passenger density increases in all standing areas under service disruption and that the door area remains the most heavily used zone. In the door area, the mean density rises from 2.91 P/m^2 in regular operation to 3.33 P/m^2 under service disruption. The increase is of a similar magnitude in all areas, so that no targeted shift of passengers is discernible but rather a uniform densification across all zones.

3.2.6. Comparison of the Peak Periods

A comparison of the two peak periods reveals a difference in passenger behaviour. In the morning peak (06:30–09:00), the densities under service disruption exceed those in regular operation, particularly in the aisle and transition areas (Figure 14). This suggests that in the morning passengers are more willing to board despite high occupancy, for example because of time pressure on the way to work or education. In the afternoon peak (16:00–19:00), by contrast, the differences between regular operation and disruption are smaller. This is because the densities under disruption are lower in the afternoon than in the morning, whereas those in regular operation are slightly higher. Under disruption, the willingness to board at high occupancy thus appears to be lower in the afternoon than in the morning; in regular operation, by contrast, the limit of accepted occupancy is reached at a slightly higher density in the afternoon.

3.3. Special Cases and Event Traffic

For special operating situations such as football matches and the Vienna City Marathon, the analysis focuses on Type V and Type X, since these vehicles are frequently deployed at events with high passenger volumes.

3.3.1. Type V

The comparison of passenger densities in Type V (Figure 15a) shows that the limit-capacity values during football matches and during the Vienna City Marathon differ clearly from regular operation. In both cases, the passenger density increases noticeably in all areas and reaches about four passengers per square metre in the door area. The aisle and transition areas are also used more intensively, which indicates an even and complete penetration of the interior. It is notable that hardly any differences are discernible between the two event

types—the mean values are almost identical, so that no event-specific passenger behaviour can be derived. This suggests that well-attended sports events generally lead to similar patterns of use.

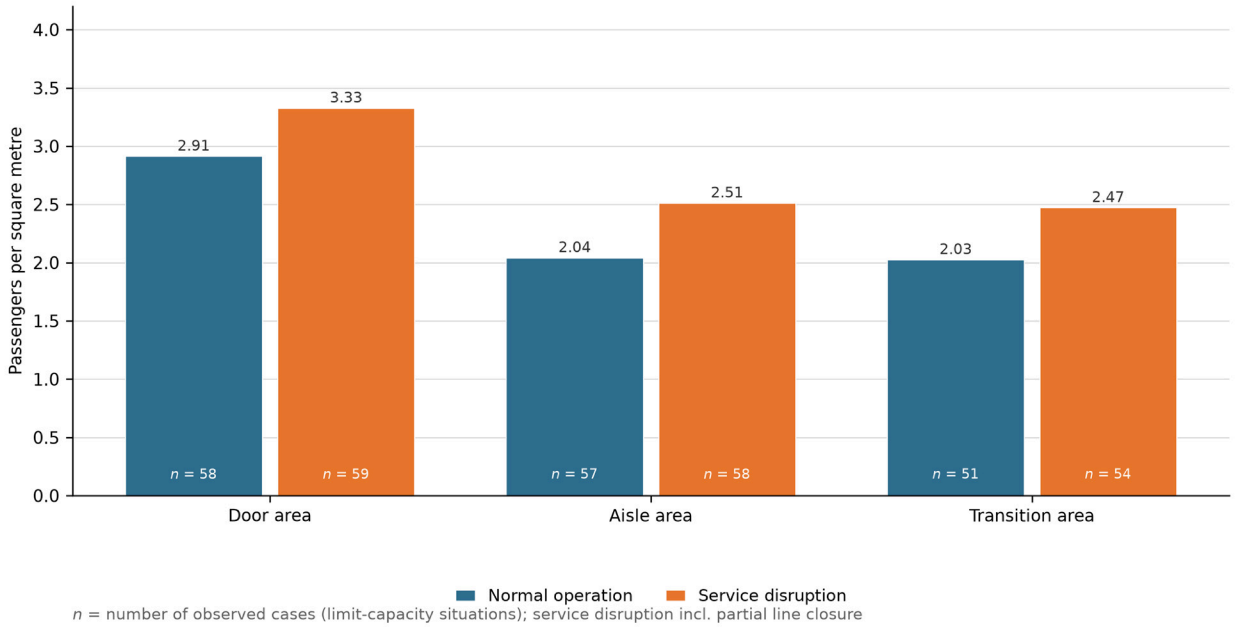


Figure 13. Comparison of the mean passenger densities in the different standing areas in regular operation and under service disruption (own illustration; numbers of cases per bar shown in the figure).

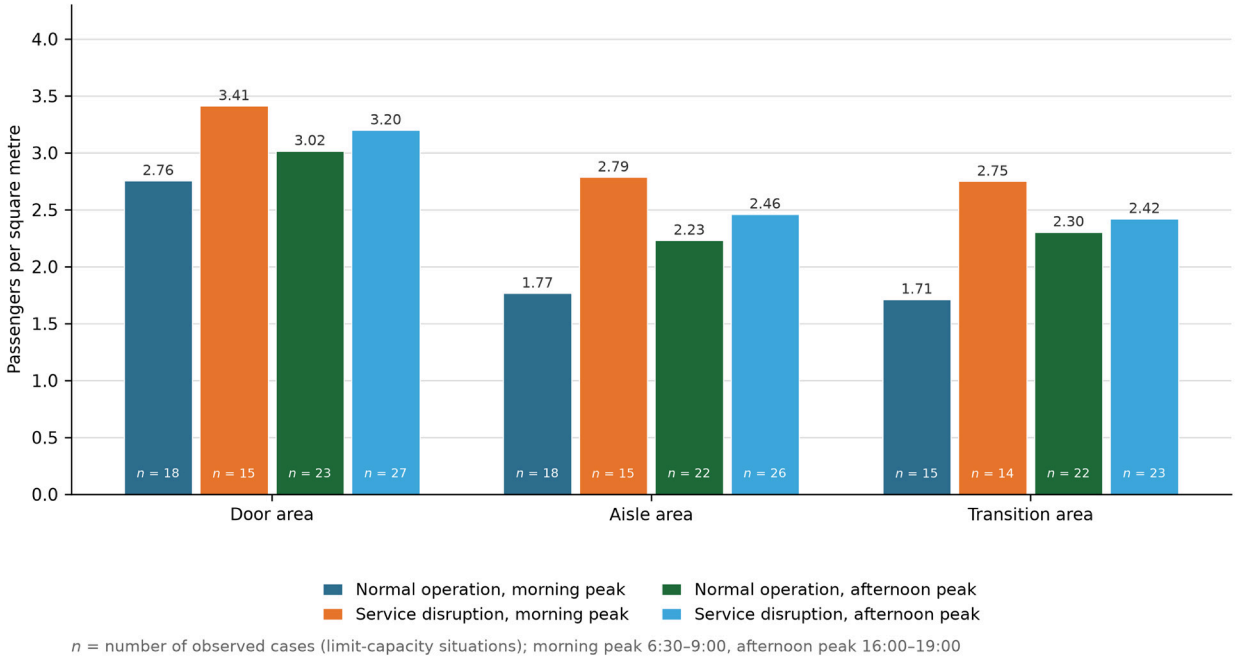


Figure 14. Comparison of the mean values for the peak periods between 06:30 and 09:00 and between 16:00 and 19:00 (own illustration; numbers of cases per bar shown in the figure).

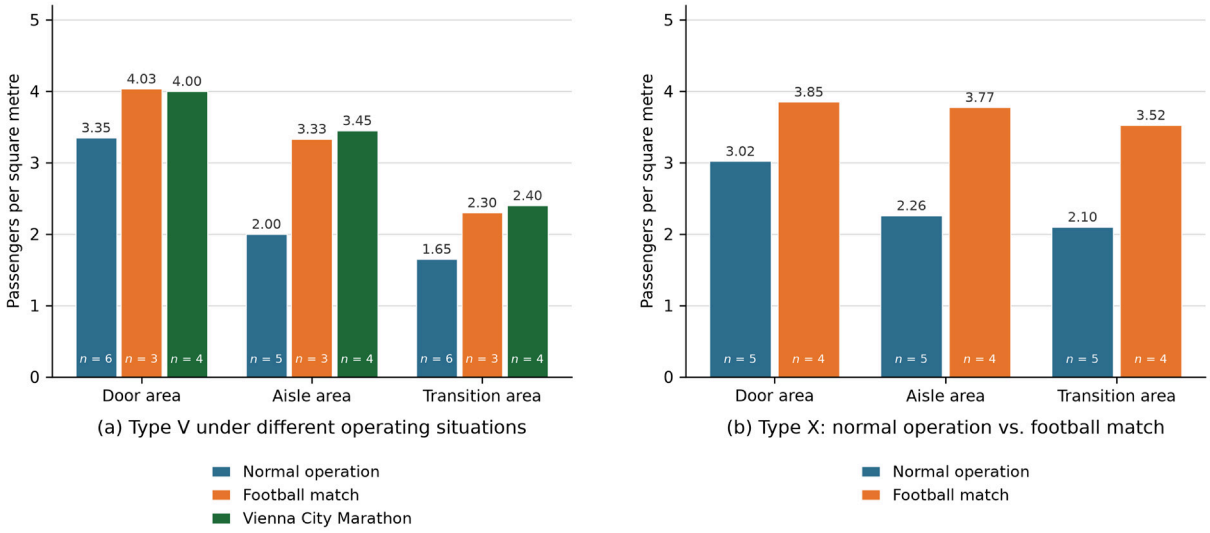


Figure 15. Mean passenger densities in event traffic—(**a**) Type V in different situations, (**b**) Type X in regular operation and during football matches (own illustration; numbers of cases per bar shown in the figure).

3.3.2. Type X: Regular Operation Versus Football Matches

The comparison of passenger densities in Type X between regular operation and journeys to football matches (Figure 15b) shows an increase in all areas. The aisle and transition areas are particularly striking, as the density almost doubles in event traffic. The door area also shows higher occupancy but remains more moderate by comparison. The even growth across all zones indicates that passengers travelling to football matches do not concentrate only in the boarding area but increasingly move into the depth of the vehicle.

3.3.3. Journeys to Football Matches: Type V Versus Type X

Comparing the passenger densities in event traffic between Type V and Type X (cf. Figure 15a,b) shows that Type X reaches higher values in the aisle and particularly in the transition area, while the door areas of both vehicles are similarly heavily occupied. One possible reason lies in the structural design of the transition area: in Type V, central handholds are missing because holding elements are only available laterally in the area of the bogie (cf. Section 3.1.3). In addition, the articulation section of Type X is more compact, which improves usability. Moreover, the transition from the door area to the transition area is wider in Type X, so that passengers tend to distribute themselves further into the interior.

Across both vehicle types, the densities observed in event traffic exceed those in regular operation, particularly in the areas located further away from the doors.

3.4. Comparison of the Data Sets

Three data sets are compared: the structured test scenarios conducted within the research project TrainOptimizer2.0 at TU Wien, which explore the possible limits under defined conditions, and the measurements in regular service and at major events such as football matches, which represent real passenger behaviour under everyday and exceptional loads respectively.

3.4.1. Without Luggage

Figure 16 compares the passenger densities in the three vehicle areas under the different conditions—test run, real operation and mass event—in each case without luggage, and

additionally for the door area with a 50% share of luggage. In all areas, the values of the test run are clearly above those of real operation, which points to the deliberate guidance of the test persons and to optimal use of the area; this difference is particularly striking in the transition area. The values for the mass event lie in-between in the aisle and transition areas, but in the door area they are almost at the level of the test run, which indicates consistently dense use of this area at high passenger volumes. Aisle and transition areas, by contrast, remain below their potential in everyday operation.

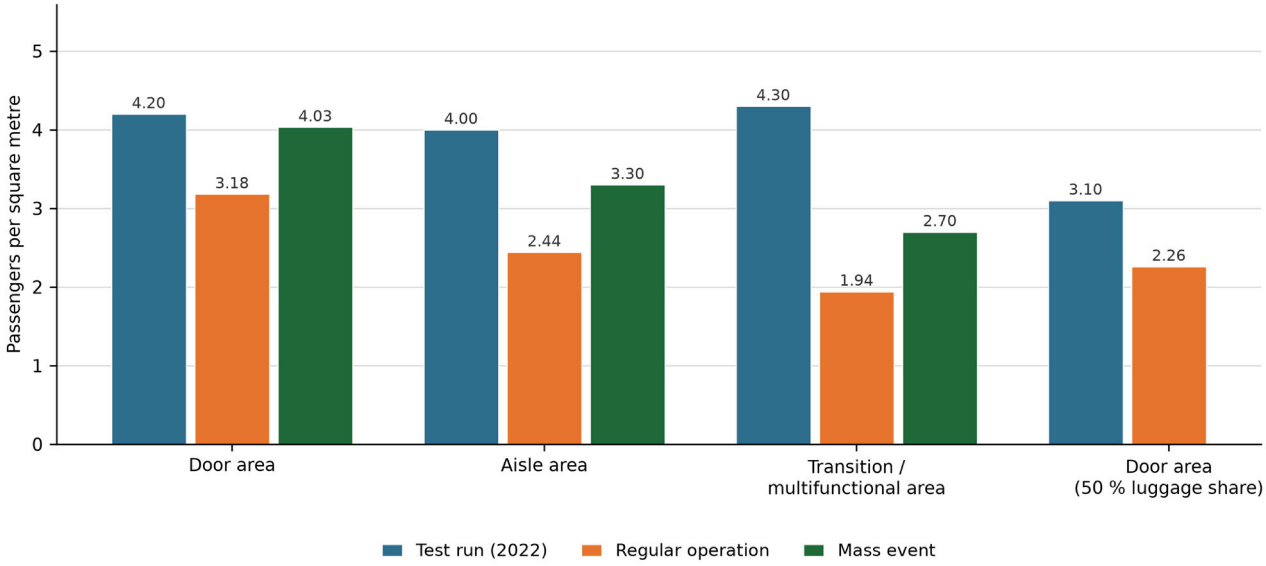


Figure 16. Comparison of the mean values from the test run, real operation and mass event by vehicle area and in the door area with a 50% share of luggage.

3.4.2. With Luggage

Comparing the values with a 50% share of luggage in the door area with those without luggage (Figure 16, right-hand versus left-hand category) shows consistently lower mean densities. The difference between the respective scenarios remains roughly the same, but the overall level shifts downwards. The additional volume of the luggage thus reduces the usable area per person, and the subjective occupancy limit is reached earlier. Not only the number of persons but also the luggage carried therefore plays an essential role for the perceived occupancy—even in the test run with a high initial density, no level comparable to that without luggage is reached.

3.5. Door Area Occupancy and Use of the Standing Areas

3.5.1. Data Basis

This section includes all recorded data, that is, also those situations in which boarding was still possible. The aim is to examine the correlation between the occupancy of the door area and that of the adjoining aisle and transition areas. On the basis of this complete data set, it can be analysed how occupancy is distributed spatially and how the individual vehicle areas relate to one another.

3.5.2. Aisle Area

The plot in Figure 17a shows a positive relationship between the occupancy of the door area and the use of the aisle area. The Pearson correlation coefficient is $r = 0.565$ ($p < 0.001$) and thus indicates a moderate positive association: as the passenger density in the door

area increases, the use of the aisle area also increases. The fitted curve underlines this trend and points to a functional coupling of the two areas.

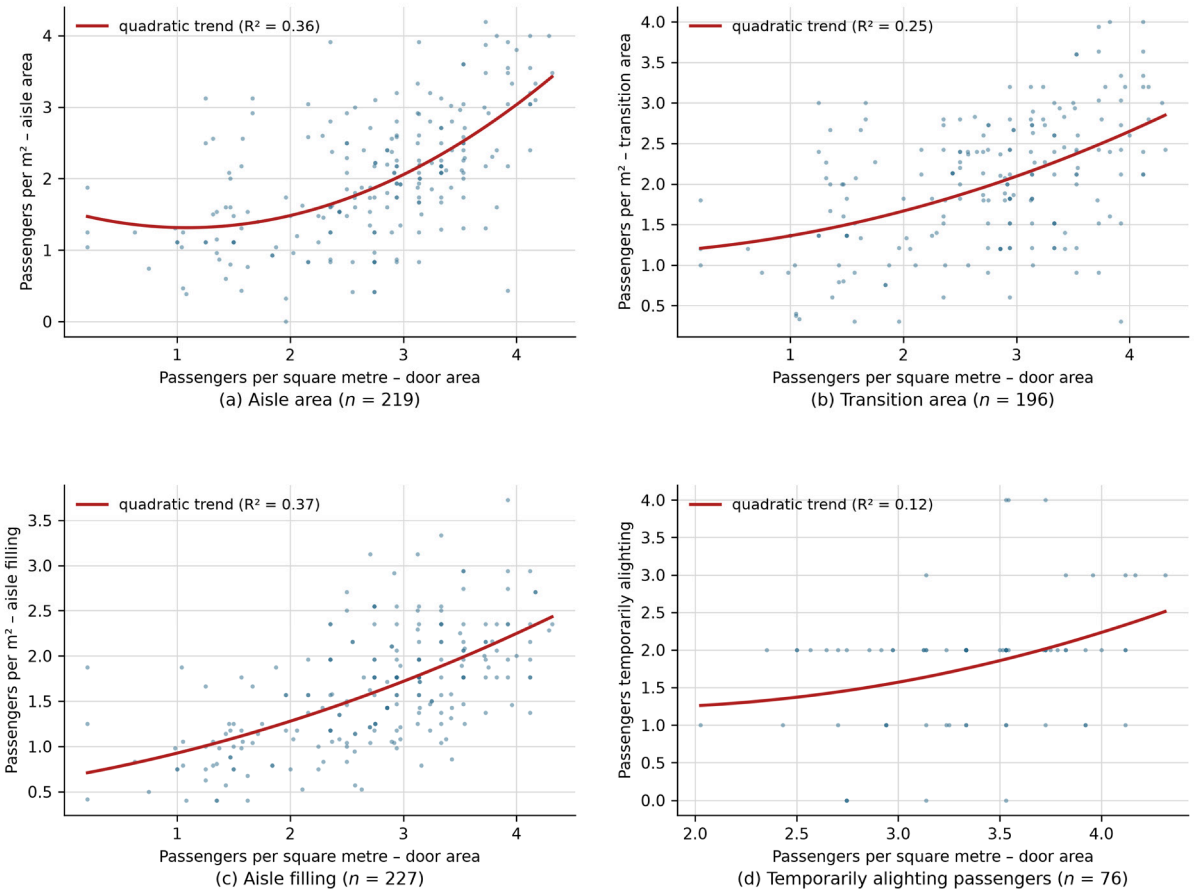


Figure 17. Relationship between the passenger density in the door area and (**a**) the aisle area, (**b**) the transition area, (**c**) aisle filling and (**d**) the number of temporarily alighting passengers (own illustration; n = 219/196/227/76 observation cases).

3.5.3. Transition Area

The relationship between the occupancy of the door area and the transition area is shown in Figure 17b. With r = 0.492 ($p < 0.001$), a moderate positive association is found: as the passenger density in the door area rises, the density in the transition area also tends to increase. The correlation is, however, weaker than that with the aisle area (r = 0.492 compared with r = 0.565), since in most vehicle types the transition area is located further from the door area, and its use depends more strongly on vehicle-specific structures such as articulation turntables or tip-up seats.

3.5.4. Aisle Filling

Figure 17c shows a positive relationship between the passenger density in the door area and the subsequent aisle filling. With r = 0.607 ($p < 0.001$), a moderate positive association is obtained: the higher the occupancy in the door area, the more strongly passengers move into the adjoining areas. The effect is somewhat stronger than for the aisle or transition area alone, which underlines the combined character of aisle filling as a transition reaction.

3.5.5. Temporarily Alighting Passengers

The relationship between the passenger density in the door area and the number of passengers who briefly alight at a stop in order to allow others to alight and then board again is shown in Figure 17d. As the density in the door area increases, the number of these temporarily alighting passengers rises. At high occupancy, the necessary movement space inside the vehicle is therefore lacking, and passengers are forced to create space for alighting outside the vehicle; this briefly relieves the door area and facilitates passenger exchange.

The evaluation of this relationship is based exclusively on those 76 stopping events for which the number of temporarily alighting passengers is actually documented. Stopping events without a documented value were excluded; the relationship remains positive, but the explained variance is low, with a coefficient of determination of 0.12.

4. Discussion

This study set out to determine the standing densities actually reached at the behaviour-based capacity limit in regular service (RQ1), to explain their differences between vehicle types (RQ2), to assess the influence of operating states and luggage (RQ3) and to quantify the gap to experimental and normative values (RQ4). Its main novelty lies in tying area-differentiated density values to an observable behavioural criterion—waiting passengers being left behind—instead of averaging over runs and vehicles or relying on laboratory conditions. Three findings stand out: the usable capacity is limited by behaviour well before the area assumed in planning is filled; this limit differs systematically between door, aisle and transition areas depending on their accessibility; and the acceptance threshold shifts upwards under disrupted and event conditions while remaining below the experimental maximum occupancy. The following subsections discuss these findings along the research questions, relate them to the international literature and address their transferability and limitations.

4.1. Behaviour-Based Limit Capacity Versus Normative Design Values (RQ1, RQ4)

The analysis of standing area use shows that the passenger densities actually reached are, as a rule, below those values that serve as a planning basis in technical regulations and in the relevant literature. Of particular relevance is the reference value of four passengers per square metre, which is widely used across Europe, for example in the guidelines of the German Association of Transport Companies and in numerous capacity models. In addition, normative load assumptions of 5000 N per square metre imply a theoretical density of about 6.67 passengers per square metre. Even at limit capacity, neither value is reached on average in any vehicle area, and only rarely and only locally did individual zones exceed the mark of four passengers per square metre. The deviation is therefore not an artefact of weakly occupied runs but a property of the behaviour-based limit itself: passengers stop boarding before the area assumed in planning is used. This difference is directly relevant for capacity-related assessments, since the actual usability of many vehicle areas lies below the values assumed in planning.

4.2. Influence of Vehicle Design and Operating Conditions (RQ2, RQ3)

The real utilisation of standing areas is influenced on the one hand by technical and behavioural factors and on the other by operational and temporal ones. The empirical data show that the interior design in particular plays a central role. Vehicles with a continuous interior, such as Type T or Type X, allow a more even distribution of passengers and thus a higher effective capacity. Interrupted vehicle segments and narrow aisles, as found for example in Type U, by contrast lead to uneven use of the area.

A central behavioural factor is the use of the door area. Passengers prefer this area, and in most cases it shows the highest density. The observations show, however, that a high density in this area does not automatically lead to an even shift into the adjoining aisle or transition areas. Only above a certain threshold of door area occupancy does aisle filling begin, in which passengers actively move into the interior of the vehicle. This shift does not proceed continuously but depends strongly on the vehicle type and the interior structure. Narrow aisles or missing handholds can delay this process.

Beyond this, external operating conditions also affect the use of the standing areas. While regular operation tends to show more stable patterns of use, deviating behaviour appears during service disruptions. In vehicles such as Type U and Type V, aisle filling remains almost unchanged even in disruption situations, which indicates structurally limited possibilities of redistribution. In other vehicle types, the operational exception leads to greater dispersion in evasion behaviour. The higher willingness to board under disruption in the morning peak than in the afternoon peak suggests that, besides the operating state, trip purpose and time pressure also shape the acceptance threshold.

The difference between theoretical standing place assumptions and real vehicle occupancy therefore does not consist merely in numerical values but in fundamentally different logics. Calculation models frequently assume an even, area-based use. The empirical analysis shows that this assumption does not correspond to actual use in operation. Vehicle areas are frequented very differently depending on structure, equipment and accessibility. Door zones reach high densities early, while transition areas or narrow aisle sections remain permanently underused. In addition, passengers are not distributed passively but make active decisions shaped by time pressure, comfort needs, orientation or group size. Real capacity therefore does not consist of square metres alone but of a multitude of situational and structural conditions that only in combination determine how much space is actually used—and how much remains unused.

In event traffic, two effects presumably act together. First, a higher passenger density is accepted because the overall passenger volume is exceptionally high, and crowding is perceived as situationally normal. Second, passengers expect most of the other passengers to alight at the same station. This reduces the concern about not being able to alight in time from positions further away from the boarding door, and it correspondingly increases the willingness to use areas that are otherwise occupied to a below-average extent. Since passengers' motives were not surveyed, this interpretation remains a hypothesis to be tested in further research.

4.3. Contribution Relative to the International Literature

The densities determined here of 3.19 P/m^2 in the door area and 2.37 P/m^2 and 2.30 P/m^2 in the aisle and transition areas lie in the upper range of the values reported internationally without reaching the normative design figures. On the basis of smart card and vehicle location data, a mean standing density of 0.73 P/m^2 is reported for an MTR line [26], a quarter-hour maximum of 3 P/m^2 for Amsterdam trams and buses [27], likewise a maximum of 3 P/m^2 for the Singapore metro [28] and 2.3 P/m^2 for the Paris metro from direct counts compared with 1.7 P/m^2 from operator data [29]. Computational evaluations for Warsaw yield real densities of 2.0 to 3.8 P/m^2 [6]. The difference from the values presented here is methodological and substantively central: while the studies mentioned average over runs, vehicles and cross-sections, the present investigation records exclusively the state of limit capacity and differentiates by vehicle area.

The study thus confirms and quantifies a limitation that the aggregated works formulate themselves: the actual density may be considerably higher in parts of the vehicle, particularly near the doors [26], and average densities are not a suitable indicator of the

distribution of passengers inside the vehicle [38]. The difference measured here between the door and aisle areas of 0.8 P/m^2 on average—and up to 1.4 P/m^2 in Type U with its confined door areas and 1.1 P/m^2 in Type D with its pronounced seating orientation—corresponds to the order of magnitude known from laboratory experiments and from individual observations in operation: 8.6 of 20 persons concentrated in the door vestibule in the experiment compared with 1.0 person in the side aisles [7], and in an Australian analysis door areas were observed with 2.5 P/m^2 while the density in the seating aisles is stated as "perhaps 0.5 passengers per square metre" [8]. The present work provides a systematic, vehicle-type-related database from regular service for this unequal distribution, which so far has been documented only selectively.

The finding on the behaviour-based capacity limit is equally consistent. Despite being designed for 6 P/m^2, the Hong Kong MTR reaches only about 4 P/m^2 in practice because passengers avoid a vehicle that appears full [51]; the boarding rate increases only up to about 2.5 to 3 P/m^2 [12,40], and above 4 P/m^2 the door flow decreases [41]. The maximum values of the door area observed here of up to 4.3 P/m^2 lie precisely in this range. With 4.0 to 4.4 P/m^2 without luggage, the field experiments with test persons yielded values that correspond to the laboratory findings [38,39] but lie about 25% to 38% above the mean limit capacity observed in regular service. The difference between the experimental maximum occupancy and the voluntarily accepted occupancy is thus about 1 P/m^2. This explains why capacity values derived from structural, payload or evacuation assumptions [3,4,9] are unsuitable for operational planning; the physical upper limit of 6.6 to 9 P/m^2 [25] is not remotely reached in everyday operation. Even in pedestrian flows, stopping pedestrians appear at densities above about 3 P/m^2 [47].

The influence of luggage likewise fits into the state of research. In the experiments, the maximum achievable density fell to 2.6 to 3.1 P/m^2 at a luggage share of 50% to 100%, that is, by up to 40%. This corresponds to the order of magnitude that follows from the increased area demand of 0.35 to 0.55 m^2 per person with travel luggage [18] and agrees with findings on extended passenger exchange times and reduced door capacities with luggage [42,43] as well as with the evidence that insufficient luggage storage markedly reduces area and seat utilisation [44,45]. With mobility aids and prams, the effect is even more pronounced [18,46]. For vehicles in regional service with a high share of luggage, flat design values of 4 P/m^2 must therefore be regarded as particularly critical.

The higher densities during service disruptions (about 3.3 P/m^2 in the door area) and major events (around 4 P/m^2) can be interpreted as a shift of the acceptance threshold: when the expected waiting time for the next vehicle increases or when passengers share a common destination, they are prepared to accept a higher density. Comparable effects are found in networks with structurally high occupancy, for instance in Tokyo with peak loads of around 160% of the nominal capacity [65,66]. It is remarkable that even under these conditions the values of 6.7 P/m^2 and above stated in regulations are not reached.

4.4. Transferability and Application to Other Networks

The absolute density values are bound to the Vienna network, its level of service and its passenger population. Accepted densities are shaped by cultural factors and by the service frequency, and in networks with structurally higher occupancy they are considerably higher [65,66]. Three groups of local factors are likely to govern transferability. Passenger behaviour—norms of personal space, the mix of commuters and occasional travellers, and the amount of luggage carried—determines which density is still accepted. Vehicle configuration—the number and width of doors, the seat layout, continuous gangways and handholds—determines how far passengers can distribute themselves into the vehicle. Local operating practices—above all the service frequency, which defines the expected

waiting time for the next vehicle, but also platform management and boarding rules—determine whether waiting passengers decide to stay behind. In a densely served network such as Vienna, the short expected waiting time is likely to lower the acceptance threshold; in networks with longer headways or without alternative routes, higher limit densities are to be expected. The service disruptions in the present data support this interpretation (Section 3.2): during disruptions and the partial closure of line U1, passengers could expect that the replacement services offer less capacity than the metro and that the following vehicle would therefore also be crowded. Accordingly, they accepted higher densities, which rose to about 3.3 P/m^2 on average in the door area (Section 3.2.5). What can be transferred is therefore primarily the structure of the results rather than the absolute values: the ranking of the areas, the ratio of the aisle and transition densities to the door area density of about 0.7 to 0.75, and the dependence of this ratio on the accessibility of the areas. For application in other networks, it is recommended to calibrate the door area density locally with a limited number of limit-capacity observations following the protocol described in Sections 2.5 and 2.6, and to derive the values for the other areas from the area ratios, taking into account vehicle-specific features such as continuous gangways, multi-purpose areas and handholds. Where the share of luggage differs markedly, as in airport, regional or long-distance services, the luggage-related reductions from the experiments (Section 3.4.2) should be applied in addition. The limit-capacity criterion itself—waiting passengers left behind although space is still geometrically available—is independent of the network and can be observed with little effort, which makes the approach suitable for comparative studies in further cities.

4.5. Implementation in Capacity Estimation and Simulation Models

The area-differentiated values can be integrated directly into capacity estimation. Instead of multiplying the total standing area by a flat value such as 4 P/m^2, the usable standing capacity of a vehicle section is calculated as an area-weighted sum: $C = A_{\text{door}} \cdot \rho_{\text{door}} + A_{\text{aisle}} \cdot \rho_{\text{aisle}} + A_{\text{transition}} \cdot \rho_{\text{transition}}$. The reference areas A follow the delimitation in Section 2.4, and the densities ρ are taken from Table 5 for the respective vehicle type. For new vehicles, the values of an existing type with a comparable interior can be used. For vehicles with a high share of luggage, the reductions of up to 40% (Section 3.4.2) should be applied to the affected areas.

In service planning, the usable capacity calculated in this way replaces the nominal capacity when headways and train lengths are dimensioned; the required number of vehicles per hour follows from the peak demand divided by the usable capacity per vehicle. The values observed under disruption (about 3.3 P/m^2) and in event traffic (around 4 P/m^2) can serve as upper bounds for contingency planning. The experimental maximum occupancy, by contrast, is an absolute ceiling and should not be used for scheduled capacity.

In passenger and pedestrian simulation, the results can be used in three ways. First, the type-specific door area density at limit capacity (on average 3.19 P/m^2) can serve as the criterion at which waiting agents refuse to board. Second, the aisle filling value (on average 1.70 P/m^2) can serve as the threshold at which agents start to move from the door area into the aisle. Third, the standard deviations in Table 5 can be used to vary these thresholds stochastically between stopping events. Calibrated in this way, simulation models reproduce the uneven distribution inside the vehicle instead of filling the standing area evenly.

For vehicle design and procurement, the same calculation allows interior layouts to be compared by their usable rather than their nominal capacity. An interior concept that improves the accessibility of aisle and transition areas, for example through continuous gangways, wider transitions or additional handholds, raises the area-weighted capacity without additional floor area.

4.6. Limitations

The results are subject to several limitations. First, they refer to a single, densely served urban network, so that the absolute values cannot be transferred directly (Section 4.4), and an independent verification in other networks is still outstanding. Accepted densities are shaped by cultural factors and by the level of service; in networks with structurally higher occupancy, the values are considerably higher [65,66]. Second, the sample is not drawn at random but deliberately directed at peak periods, service disruptions and major events because limit capacity occurs almost exclusively in such situations; the results therefore describe the behaviour-based limit under high demand and not the typical occupancy over the operating day. The 126 limit-capacity situations are distributed unevenly across the vehicle types with 10 to 21 cases each (Table 4). Since the project has been completed, neither an extension of the sample nor an independent validation data set is available. The evaluation is therefore exploratory, and significance tests were deliberately omitted (Section 2.8).

Third, observation itself is error-prone: at high density, the view of individual areas is restricted. Video or sensor recording was not used for data protection reasons; automatic counting systems in turn show considerable losses of accuracy in the relevant density range [52]. In addition, the motives for not boarding were not surveyed, so that individual cases of non-boarding unrelated to crowding cannot be excluded (Section 2.6). Fourth, the delimitation of areas is not standardised normatively [6,24]; the reported densities are bound to the definition set out in Section 2.4 and are comparable with other studies only if this delimitation is taken into account. Fifth, every observation is a snapshot immediately before the doors close, without the temporal course within the journey.

Sixth, the experimental values are based on two vehicle types and a simulated situation. The realism of the behaviour was assessed and confirmed by experts mixed in with the test persons but could not be validated independently by measurement. Seventh, seasonal effects, in particular the additional area demand caused by winter clothing [25], as well as the composition of passengers by age, luggage and mobility restriction, were not modelled as control variables but only recorded descriptively.

A further limitation concerns the number of cases. The reported distributions are based on 126 observation cases distributed across nine vehicle types with 10 to 21 cases each; for the Citaro G and the DOSTO, only ten cases each are available. At group sizes of this order, quartiles and in particular the whiskers of the box plots react sensitively to individual observations, which is why the dispersions shown are to be read as an orientation about the bandwidth of use and not as a precise estimate of the distribution. For the transition area, the data basis is reduced to 114 cases because Type U has no continuously accessible car-to-car gangway; in the separate consideration of regular operation and service disruption, the numbers of cases per vehicle type fall to between five and eleven. For this reason, inferential statistical tests and the derivation of significance statements were omitted—the reported differences are to be interpreted as descriptive findings that are supported by the consistency of the patterns across areas, vehicle types and operating states. Mixed-effects models that account for the clustering by line, vehicle type and time of day would be the appropriate inferential approach for larger samples and are recommended for future surveys. The numbers of cases are therefore stated in all figures and in Table 5 in order to make the robustness of the individual groups transparent.

The group definitions are also not uniform throughout. The comparison of regular operation and service disruption is not carried out with an identical group delimitation in all figures: the box plots (Figures 11 and 12) combine all situations deviating from regular operation, that is, service disruptions in the narrower sense, the partial closure of line U1 and event traffic ($n = 68$ cases in the door area), whereas the mean value comparisons in

Figures 13 and 14 exclude event traffic and consider it separately in Figure 15 ($n = 59$ cases in the door area). The numbers of cases of the individual figures can therefore not be converted directly into one another; the applicable delimitation is stated in each figure. In addition, the values of the 2022 test run shown in Figure 16 are single measurements of a defined reference loading and not means of an observation series. This comparison is therefore to be read as a plausibility check of the order of magnitude and not as a statistical comparison.

Finally, the explanatory power of the relationships shown in Figure 17 is limited. The fitted quadratic curves describe the coupling between the vehicle areas only partly: the coefficient of determination is 0.36 for the relationship between the door and aisle areas, 0.25 for the door and transition areas, 0.37 for the door area and aisle filling, and 0.12 for the relationship with the temporarily alighting passengers. The curves thus reproduce the direction and the order of magnitude of the coupling but do not allow any prediction of individual stopping events.

5. Conclusions

For the Vienna network, the results show that flat area-based calculation methods systematically overestimate the standing capacity that can actually be used. At limit capacity—the state in which waiting passengers are left behind although space is still geometrically available—mean densities of 3.19 P/m^2 were reached in the door area and 2.37 and 2.30 P/m^2 in the aisle and transition areas (RQ1), compared with 4 P/m^2 in VDV practice and 6.7 P/m^2 and more in manufacturer specifications. The area is not used evenly: depending on the accessibility of the areas, the difference between the door and aisle areas ranges from about 0.6 to 1.4 P/m^2 between the vehicle types (RQ2). Service disruptions raise the door area densities to about 3.3 P/m^2 and major events to around 4 P/m^2, and luggage reduces the experimental maximum occupancy of 4.0 to 4.4 P/m^2 by up to 40% (RQ3). The limit capacity in everyday operation thus lies about 1 P/m^2 below the experimental maximum occupancy, about 20% below the design value of 4 P/m^2 and by a factor of about two below manufacturer specifications and structural load assumptions (RQ4). For vehicle procurement and tenders, capacity figures should therefore be stated in an area-differentiated, empirically calibrated form instead of by a single area figure, which empirically supports the criticism of the lack of uniform calculation methods [6] and of payload-based manufacturer figures [9]. In service planning, the usable rather than the nominal capacity should be applied, since occupancy close to the nominal capacity leads to denied boardings, extended dwell times and missed connections [12,13], and the benefit of lower densities can be quantified with crowding multipliers [10] and documented utility gains [67]. In vehicle design, continuous interiors, wide transitions, standing-oriented multi-purpose areas, sufficient luggage racks and door areas that allow two flow lanes increase the usable capacity without additional vehicle area [7,39,44,45]. For capacity estimation and simulation, the area- and type-related values provide calibration parameters (Section 4.5), with about 3.3 P/m^2 for disruption and about 4 P/m^2 for event planning as reserve values. Since the study is limited to one network, further research should extend the survey to other cities, vehicle types and seasons with larger samples, link area-related densities with passenger exchange and dwell times, and develop data-protection-compliant automated survey methods.

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Informed Consent Statement: Because of the exclusively anonymous observation, consent of the observed passengers was not required. The test persons of the field experiments participated voluntarily after prior information.

Data Availability Statement: The anonymous observation protocols and the evaluation data set derived from them can be made available by the authors upon reasonable request.

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