



**HAL**  
open science

## The impact of passenger non-compliance during alighting and boarding on railway stations

Mehdi Baali, Christine Buisson, Rémi Coulaud, Mehdi Moussaïd

### ► To cite this version:

Mehdi Baali, Christine Buisson, Rémi Coulaud, Mehdi Moussaïd. The impact of passenger non-compliance during alighting and boarding on railway stations. 2024. hal-04811675

**HAL Id: hal-04811675**

**<https://hal.science/hal-04811675v1>**

Preprint submitted on 29 Nov 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# The impact of passenger non-compliance during alighting and boarding on railway stations

Mehdi Baali<sup>1</sup>, Christine Buisson<sup>2</sup>, Rémi Coulaud<sup>3</sup>, and Mehdi Moussaïd<sup>4</sup>

<sup>1</sup>Ph.D. Student, Transilien SNCF-Voyageurs & LICIT-Éco7, Université Gustave Eiffel, France

<sup>2</sup>Senior researcher, LICIT-Éco7, Université Gustave Eiffel, France

<sup>3</sup>Head of DataLab' Mass Transit, Transilien SNCF-Voyageurs, France

<sup>4</sup>Senior researcher, Max Planck Institute, Germany

## Abstract

In dense train networks, the alighting and boarding process involves complex pedestrian flow dynamics. A common rule to facilitate this process is to wait until alighting is complete before boarding. However, many passengers do not adhere to this rule in real-world scenarios. Here we present an experimental study to assess the impact of such non-compliance on pedestrian flow and compare the results with field data collected from infrared sensors. Our findings indicate that pedestrian discomfort increases considerably with increasing non-compliance. However, the average alighting and boarding times are similar regardless of non-compliance levels. We show that this counter-intuitive effect is due to a compensatory mechanism between lower densities at lower degrees of non-compliance and higher densities at higher degrees of non-compliance. This research opens new perspectives in understanding and managing pedestrian flows in dense railway environments.

## 1 INTRODUCTION

In major cities, daily commuting is an essential aspect of urban life. People travel to city centers for work in the morning and return home in the evening, leading to significant crowding on suburban trains. For example, in the Paris suburban rail network (RER), over three million journeys are made daily across its five lines. In particular, the processes of boarding and alighting involve complex pedestrian dynamics that directly affect train dwell times and can contribute to delays, thus impacting the network's overall efficiency. Therefore, understanding the pedestrian flows during the alighting and boarding phases is crucial.

The collective dynamics of pedestrian flows emerge from the interactions between multiple individuals. These interactions include, among others, imitation, avoidance, and scrambling. A comprehensive overview of these interactions has been provided by Moussaïd (2010).

Collective behaviors are characterized by macroscopic variables such as pedestrian density and flow. The relationship between these variables is frequently represented using fundamental diagrams (Hankin & Wright, 1958; Carstens & Ring, 1970; Lam et al., 1995). Experimental approaches have also been employed to refine these models in various contexts (Weidmann, 1993). However, it is important to report that the fundamental diagram is formed to be highly context-dependent. For instance, stress levels have been shown to influence pedestrian behavior in non-trivial ways (Helbing et al., 2000), and the form of the relationship between density and flow can differ for bi-directional flows (Motsch et al., 2018; J. Zhang et al., 2012). In some cases, bi-directional flows are more efficient at high densities due to self-organizing patterns, such as the formation of lanes (Kretz, Grünebohm, Kaufman, et al., 2006; Moussaïd et al., 2012). Similarly, the presence of bottlenecks can significantly alter flow patterns (Helbing et al., 2005; Kretz, Grünebohm, & Schreckenberg, 2006). See Vanumu et al. (2017) for a discussion on how the fundamental diagrams change under varying contexts, including bi-directional flows, cross-flows, and bottlenecks.

48 The situation at train doors presents a unique case characterized by bi-directional pedes-  
49 trian flows in a confined space, often complicated by compliance to rules—such as alighting  
50 before boarding—that are not consistently observed.

51 Pedestrian flows at train doors have rarely been studied at the individual level, with a few  
52 exceptions, such as the study by Q. Zhang et al. (2008), which proposed a simulation based  
53 on cellular automata. More often, research has focused on more aggregated variables, such  
54 as alighting and boarding times (Wiggenraad, 2001; Daamen et al., 2008). Several models  
55 have been proposed to estimate these times. For example, Weston (1989) developed an  
56 analytical model based on the number of alighting and boarding passengers and various  
57 geometric parameters. However, this model appeared inadequate under high passenger  
58 loads (Harris, 2005). Additionally, Coulaud et al. (2023) highlighted that the dwell time  
59 of trains is related to the passenger flow data at critical door locations.

60 Seriani et al. (2019) explored the relationship between alighting and boarding times and  
61 the ratio of boarding to alighting passengers, along with the level of congestion. Their  
62 study found that the boarding time (and, similarly, the alighting time) increased when  
63 there were more alighting passengers than boarding, and vice versa. They also observed  
64 the formation of alighting lanes, which had narrower widths when the number of boarding  
65 passengers exceeded the number of alighting passengers. This observation suggests that  
66 self-organization patterns can enhance efficiency.

67 Furthermore, when platform-edge doors were present, De Ana Rodríguez et al. (2016)  
68 observed shorter alighting and boarding times. This improvement was interpreted through  
69 better positioning of passengers on either side of the door, which reduces interference  
70 between boarding and alighting passengers. Generally, operators promote compliance with  
71 the rule of waiting for alighting to be completed before boarding, assuming the alighting  
72 and boarding process to be improved. In this study, we refer to this behavior as non-  
73 compliance.

74 Despite being common in daily commuting, non-compliance with boarding and alighting  
75 rules has rarely been the subject of detailed study. Wahaballa et al. (2022) conducted  
76 observations using video footage from Cairo metro stations but found no significant rela-  
77 tionship between non-compliance and the overall alighting and boarding time. In contrast,  
78 Seriani et al. (2022) observed a slight increase—ranging from 1 to 2 seconds—in alighting  
79 and boarding times under non-compliance conditions in a controlled laboratory setting.  
80 Similarly, Li et al. (2020) investigated the effects of non-compliance using microscopic sim-  
81 ulations. Their findings indicated no significant impact on alighting and boarding times  
82 under low passenger loads; however, they noted a considerable influence under higher pas-  
83 senger loads.

84 While these studies have primarily focused on the duration of alighting and boarding  
85 processes, they have not provided strong explanations for the observed effects, nor have  
86 they explored the related flow and density patterns. Furthermore, so far, no research has  
87 evaluated the impact of non-compliance on passenger comfort.

88 There are limited tools available for studying comfort in pedestrian flows. Instead, the  
89 concept of Level of Service (LOS) is more commonly used to assess pedestrian comfort  
90 situations. Originally developed for vehicular traffic analysis (see TRB (1956) and TRB  
91 (2022) for a more recent version), LOS was adapted for pedestrian flows by Fruin (1970).  
92 LOS categorizes pedestrian environments into letter grades (from A to F), with each grade  
93 representing decreasing levels of comfort (related to increasing density). These categories  
94 also take into account different contexts, such as waiting, walking, or ascending stairs  
95 (TRB, 2022; FGSV, 2015), though they are typically defined in discrete terms.

96 Kretz (2011) proposed a formula to unify various pedestrian scenarios and calculate LOS  
97 on a continuous scale. This continuous LOS measurement offers a more nuanced tool  
98 for evaluating complex pedestrian flows, such as those occurring during the alighting and  
99 boarding processes.

100 The goal of the present study is to quantitatively assess the impact of varying degrees

101 of non-compliance on flow and density patterns in pedestrian traffic, where the degree of  
102 non-compliance refers to the number of passengers who begin boarding before alighting is  
103 complete. We design an experiment to measure these effects under controlled conditions,  
104 and the experimental findings are validated using field data. Additionally, we provide a  
105 quantitative evaluation of the LOS for each level of non-compliance based on the experi-  
106 mental results.

107 This paper is organized as follows: Section 2 details the experimental setup, including  
108 data collection and preprocessing methods for both experimental and field data. Section  
109 3 presents the effects of non-compliance on cumulative profiles, as well as on alighting and  
110 boarding times, followed by an analysis of the flow and density patterns. This section  
111 concludes with an estimation of the LOS for different levels of non-compliance. Finally,  
112 Section 4 provides a discussion of the results and offers concluding remarks.

## 113 2 METHOD

114 In this section, we present the experimental setup and the data collection framework.  
115 We also present field data and how they were pre-processed to be compared with the  
116 experimental data.

### 117 *Two kind of data; experimental data and field data*

#### 118 **Experiment**

119 We designed an experiment to quantitatively measure the impact of passenger non-compliance  
120 during the alighting and boarding process. We used a real train (called Z20500) dwelling  
121 at a dedicated platform at *Gare de Lyon* (Paris) available during the whole morning. This  
122 rolling stock was chosen for its small doors (1,3m wide). We wanted to make sure enough  
123 hindrance would occur with a small number of participants as there was uncertainty on  
124 the number of participants we would reach. We called on colleagues to participate in the  
125 experiment to play "passengers". To do so, we spread a form in the company to register  
126 interested people to participate. Despite the no-shows, we reached 32 participants.

127 The experiment has been divided into scenarios ( $S$ ) of non-compliance to extract the  
128 influence of increasing non-compliance, and scenarios were replicated ( $R$ ). In each scenario  
129 replication ( $S,R$ ), half of the participants (16 people) were positioned inside the train (to  
130 alight), the other half (16 people) outside the train (to board) in a designated waiting zone  
131 marked by chalk. The zone was divided into two (both sides of the door) and the same  
132 number of participants had to stand on both sides. After a signal to the train driver, the  
133 door was unlocked and one participant inside pressed the button to open the door. An  
134 alighting and boarding process then occurred.

135 We evaluated five different scenarios of non-compliance. A scenario of non-compliance  
136 corresponds to a given number of boarding passengers trying to board as soon as the door  
137 is open before the alighting is complete. The five scenarios match five different numbers  
138 of non-compliant boarding passengers, see Table 1. For each scenario, we performed 12  
139 replications. The sequence of scenarios and replications is sorted by replication and for each  
140 replication, the five scenarios are performed in randomized order, for example, the sequence  
141 for the two first replications was: ( $S1, R1$ ), ( $S5, R1$ ), ( $S4, R1$ ), ( $S2, R1$ ), ( $S3, R1$ ), ( $S2,$   
142  $R2$ ), ( $S4, R2$ ), ( $S3, R2$ ), ( $S5, R2$ ), ( $S1, R2$ ). Randomising enabled mitigating the impact  
143 of fatigue perceived by the participants during the experiment. We did 45 minutes of  
144 experiment followed by a 15-minute break followed by 30 minutes of experiment for a total  
145 duration of 90 minutes.

146 Before starting the experiment, participants had to sign an informed consent form and were  
147 briefed on the experiment's functioning and some security information. Each participant  
148 was given a colored chasuble (red or blue) and a number (from 1 to 16). At each replication,

Scenario ( $S$ )	Number of non-compliant passengers
$S1$	0
$S2$	3
$S3$	6
$S4$	9
$S5$	12

Table 1: Presentation of the five scenarios assessed in the experiment. Twelve replications ( $R$ ) were performed for each scenario ( $S$ ).

149 the non-compliant passengers were designated by their number.

150 Finally, each replication follows this sequence:

- 151 1. Indication of the scenario and call for non-compliant passengers,
- 152 2. Signal to the train driver and closing of the door,
- 153 3. Unlocking of the door by the train driver and opening of the door (one alighting  
154 participant had to push a button),
- 155 4. Alighting and boarding process,
- 156 5. Repositioning of participants (alighting participants becoming boarding participants  
157 and vice-versa).

158 The whole experiment was captured by a camera fixed above the train door.

159 Two kinds of data have been extracted from the video of the experiment:

- 160 • The passenger flow (number of people alighting and boarding at each second),
- 161 • The passenger density (number of people in one square meter).

162 For both of these variables, two steps were followed. First, the videos were subsampled  
163 into pictures every second. Second, manual counting was done on each picture to get flow  
164 and density data. For the passenger flow, the counting was validated by comparing the  
165 total number of counted people to the known number of participants. In other words, if  
166 we did not count 16 people alighting and 16 people boarding, the counting had to be done  
167 again. For the density, a surface was fixed, in which the counting was done. The surface  
168 was 1.5m<sup>2</sup> included in the camera view where all participants were fully viewable. The  
169 density was obtained by dividing the counted number by this surface. Flows and density  
170 are time-dependent with data extracted every second. For each ( $S,R$ ) time 0 corresponds  
171 to the door's opening.

## 172 **Field data**

173 Some new-generation trains (called Regio2N) are equipped with infrared sensors that count  
174 the number of people alighting and the number of people boarding every several seconds  
175 at each door and each stop of a train. The time separating two counting events is truly  
176 random, having a standard deviation of 3s for an average of 3s. The data has been collected  
177 over six months (September 2022 to February 2023) on line N which is the main line  
178 operated by this rolling stock. Unfortunately, it is rare to see important bi-directional  
179 flows on this line. There are 205 observations for ten people alighting and ten people  
180 boarding (see Table 2) which is the studied case. Considering more alighting and boarding  
181 people leads to an excessively small sample. On line N, the platforms are all at the same  
182 height (except for two excluded stations) which leads to negligible differences in flows for  
183 different stations or doors and all the doors are 1.6m wide.

	Degree of non-compliance	Number of observation
ten alighting	0	34
and	3	4
ten boarding	6	4
people	Others (excluded)	163

Table 2: Number of observations for the different studied cases from field data.

184 We defined the number of non-compliant passengers slightly differently than in the experi-  
185 ment: the degree of non-compliance will be the number of passengers boarding before 90%  
186 of the alighting passengers have got off. A more strict definition considering the number of  
187 passengers boarding before alighting is complete (as for the experiment) is not appropri-  
188 ate. Indeed, in real-world scenarios, some passengers may alight lately. For example, if the  
189 latest alighting passengers are not standing close to the door they may not be seen by the  
190 boarding passengers right away. Then, the passengers boarding after 90% of the alighting  
191 flow and before the 10% remaining may not necessarily hinder the alighting flow.  
192 Notice that these sensors only capture the flow and do not capture the density. Then, we  
193 are studying only cumulative profiles and flows from this field data for three degrees of  
194 non-compliance (0, 3, and 6 non-compliant passengers).

### 195 *Variables of interest*

196 In Section 3, we analyse the results through several variables:

- 197 • The cumulative profiles (cumulative alighting, cumulative boarding, and total) over  
198 time;
- 199 • The alighting and boarding times computed as the time of the last alighting or  
200 boarding;
- 201 • The alighting, boarding, and total flows (number of people crossing the door each  
202 second);
- 203 • The alighting, boarding, and total densities (number of people in the vicinity of the  
204 door by square meter).

205 From flows and densities, we plot the fundamental diagrams (flow versus density). Then, we  
206 compute the capacity (maximal flow) and the critical density (density where the maximal  
207 flow is obtained). Two methods were used to estimate them. First, we used a raw method:  
208 we compute the maximum of the flow and the density where this maximum is obtained.  
209 Second, we fitted a parabola (using the polyfit function from the numpy library in Python)  
210 over the data of the fundamental diagram and took capacities and critical densities from  
211 this parabola.

212 Finally, we studied the comfort during the alighting and boarding process through the  
213 notion of level of service (LOS). To do so, we use the formula proposed by Kretz (2011). The  
214 formula needs to be calibrated with two speed parameters ( $c_1$  and  $c_2$ ). The chosen values  
215 correspond to existing categories (Fruin, 1970; TRB, 2022; FGSV, 2015), for example, A  
216 being from 0 to 1, B being from 1 to 2, and so on. This formula is the following:

$$217 \quad LOS = \rho \left( 1 + \frac{\bar{v}}{c_1} + \frac{Var(\mathbf{v})}{c_2^2} \right), \quad (1)$$

218 where  $\rho$  is the density,

$$219 \quad \bar{v} = \frac{1}{N} \sum_i^N \|\mathbf{v}_i\|,$$

220

221

$$Var(\mathbf{v}) = \frac{1}{N} \sum_i^N \left( \mathbf{v}_i - \frac{1}{N} \sum_i^N \mathbf{v}_i \right) \cdot \left( \mathbf{v}_i - \frac{1}{N} \sum_i^N \mathbf{v}_i \right),$$

222  $\mathbf{v}_i$  being the speed vector of passenger  $i$ . The term proportional to the mean speed illus-  
 223 trates that the faster is the crowd the less comfortable it is. The term proportional to the  
 224 variance captures how messy the flow is. Taking  $c_1 = 0.67$  m/s and  $c_2 = 3.06$  m/s, we get  
 225 a LOS corresponding to Fruin categories (according to Kretz (2011)).

### 226 *Preprocessing of the data*

227 Experimental and field data were then processed to compare the average profile by degree  
 228 of non-compliance. For experimental data, for each couple  $(S,R)$ , the profiles of variables  
 229 of interest against time are smoothed by a sliding mean (using a 4s window). We then  
 230 took the average and standard deviation of the variable of interest over a given number of  
 231 non-compliant passengers. For field data, the same treatment is performed over the three  
 232 scenarios referenced in Table 2.

## 233 3 RESULTS

234 In this section, the above-mentioned variables of interest from both experimental and field  
 235 data are plotted and interpreted.

### 236 *Cumulative profile: differences that compensate*

237 First, the cumulative profile of alighting, boarding, and total (i.e. the sum of alighting  
 238 and boarding) are plotted in Figure 1 with their confidence intervals (at 95% threshold)  
 239 from experimental data (left) and field data (right). For alighting only and boarding only  
 240 respectively, the small intersection between the confidence intervals shows good distinction  
 241 between the profiles for different degrees of non-compliance. Both the alighting process  
 242 duration and the boarding process duration are longer with increasing non-compliance. As  
 243 expected, for lower non-compliance boarding starts later and alighting ends sooner, both  
 244 suffering less hindrance. What is more interesting is the width of the confidence interval  
 245 which also increases with non-compliance for both alighting and boarding (meaning more  
 246 variability). If we focus on the total, the average profile is very similar for all the degrees  
 247 of non-compliance with particularly little differences at the end of the process, meaning  
 248 very close alighting and boarding times. Table 3 confirms this observation. Such little  
 249 differences in alighting and boarding times, although already observed in the literature  
 250 (Wahaballa et al., 2022; Seriani et al., 2022; Li et al., 2020), are counter-intuitive and  
 251 suggest compensation somewhere in the process. The profiles from field data are similar to  
 252 the experimental ones, this disproves an experimental bias as the origin of the pattern.  
 253 The study of flows and densities helps to understand this compensation.

### 254 *Flows: uneven transitions between alighting and boarding processes*

255 Figure 2 shows the alighting, boarding and total passenger flows for the different degrees  
 256 of non-compliance from both experimental and field data. On experimental data (left of  
 257 Figure 2), for lower non-compliance, the alighting flow reaches a sharp and high peak at  
 258 the beginning while the boarding flow reaches one at the end. As the non-compliance  
 259 increases, both peaks in alighting and boarding flows flatten and widen meaning two more  
 260 simultaneous but less effective flows. The total flow illustrates the compensation. For  
 261 lower non-compliance, we see two peaks separated by a gap: both alighting and boarding  
 262 flows are very effective but a latency is observed in between. By contrast, the total flow  
 263 is roughly constant for higher non-compliance, lower at the beginning and the end but

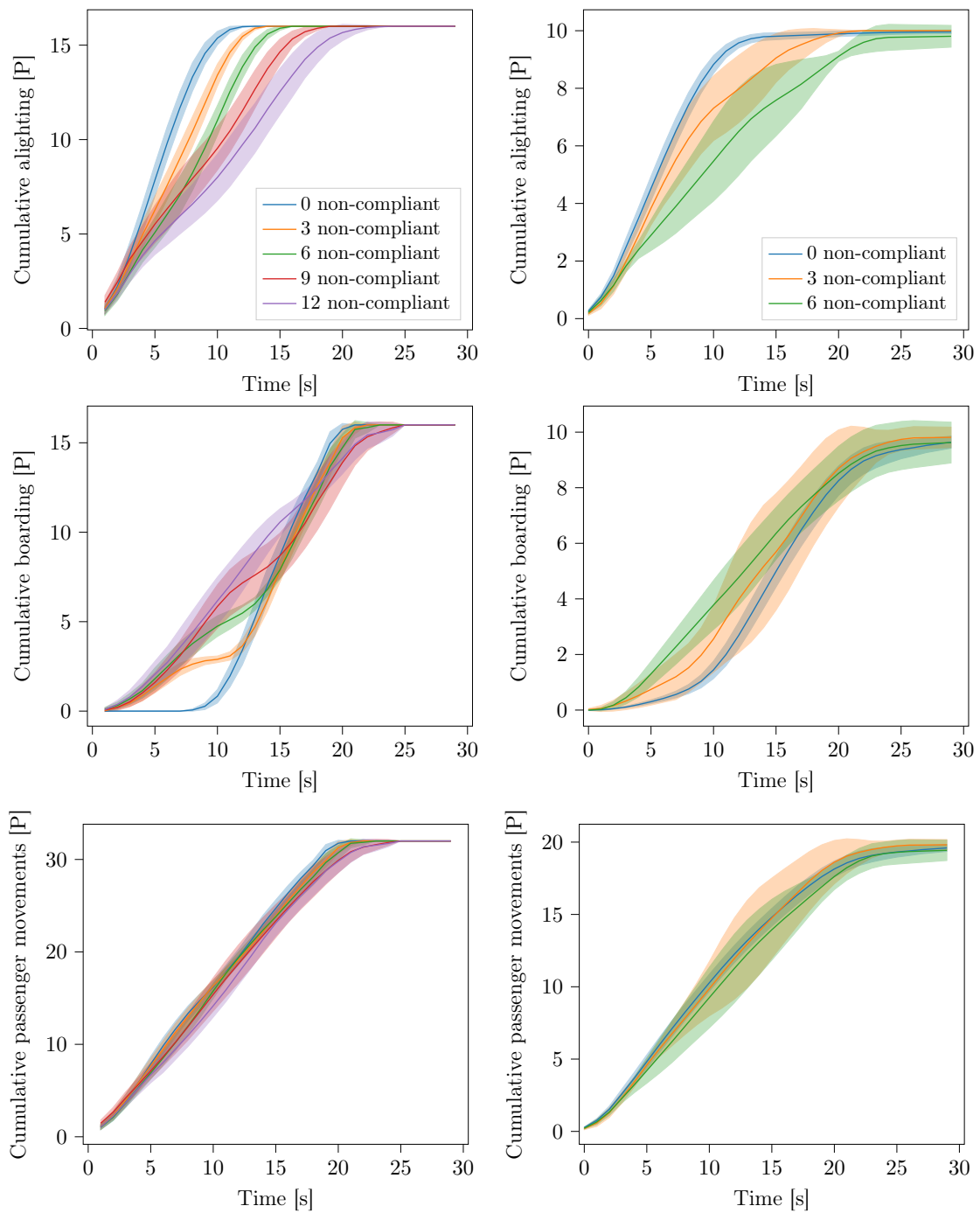


Figure 1: Cumulative alighting (top), boarding (center), and total (bottom) average profiles versus time from experimental data with confidence intervals at 95% (left) and field data (right). A good distinction between degrees of non-compliance is possible for the alighting and the boarding while there is little difference in the total profile.



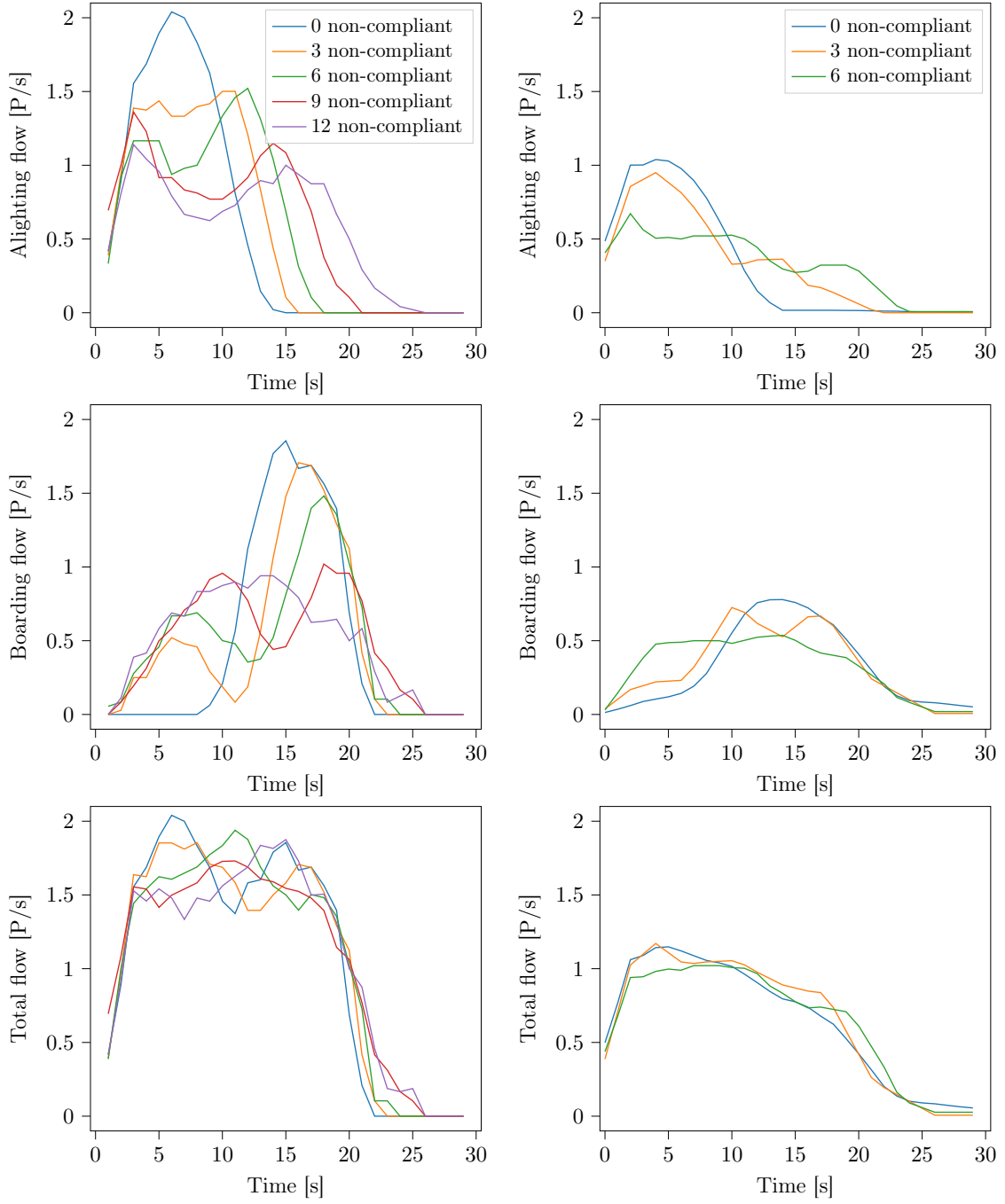


Figure 2: Alighting (top), boarding (center), and total (bottom) average flows versus time from experimental data (left) and field data (right). Alighting flows and boarding flows flatten as non-compliance increases. In the total flow, the observed drop in experimental data corresponds to a transition between the alighting and the boarding. Such drop is not observed for field data.

Degree of non-compliance [P]	Average alighting and boarding time [s]	Standard deviation [s]
0	19.1	0.89
3	20.1	0.94
6	20.6	1.03
9	21.3	1.92
12	21.3	2.11

Table 3: Means alighting and boarding time and their standard deviations measured for each studied degree of non-compliance from experimental data. Little difference is observed in the mean values while the standard deviation increases with non-compliance.

264 higher in between. In other words, the transition between the alighting and the boarding  
265 for lower non-compliance leads to a loss in flow overall, explaining such small differences  
266 in alighting and boarding times across degrees of non-compliance.

267 Concerning the field flows (right of Figure 2), the pattern is not fully the same. On  
268 the one hand, the alighting flows and the boarding flows follow a similar pattern as for  
269 the experiment. On the other hand, the total flow does not undergo two clear peaks  
270 for lower non-compliance contrary to experimental flows. The total flow profile is more  
271 similar between degrees of non-compliance. One explanation could be the granularity of  
272 the field data where observations are reported with an interval often greater than one  
273 second, leading to an excessively smoothed curve. Another explanation comes from the  
274 definition of non-compliance chosen for field data: for lower non-compliance, a slightly  
275 better transition between the alighting and the boarding should be observed as boarding  
276 starts as soon as 90% of the alighting is complete. Yet, some compensation is still observed  
277 with a higher flow at the beginning and at the end for lower non-compliance while the flow  
278 is maximal at the middle of the exchange for higher non-compliance.

279 Besides, one may notice that the total flow is on average less for field data than for ex-  
280 perimental ones while the door is larger for field data. This might be explained by flows  
281 lower than the capacity resulting from insufficient densities (more details in the sequel).  
282 These insufficient densities can be due to fewer people overall, or a propensity to keep more  
283 distance between each other in real-world scenarios compared to the experiment (where the  
284 participants generally know each other). Unfortunately, density data are not available from  
285 field alighting and boarding processes. Then, in the sequel, we only focus on experimental  
286 data to study density and its implications.

### 287 *Density: higher non-compliance means higher density*

288 Figure 3 shows the density in the vicinity of the door from experimental data, for only  
289 alighting people, only boarding people, and the total. Similar to flows, for lower non-  
290 compliance, the alighting density reaches a peak at the beginning and the boarding density  
291 at the end, coherent with the two phases of the scenario. When non-compliance increases,  
292 the alighting density is high for a longer duration whereas the emergence of a second  
293 peak at the beginning of the process is observed for boarding. The height of this second  
294 peak increases with non-compliance while the height of the original peak decreases. This  
295 pattern is coherent with the principle of the experiment: a given number of participants  
296 have to board as soon as possible which generates high densities at the beginning; after non-  
297 compliant participant have boarded, the density decreases until alighting is complete and  
298 boarding may resume. If we focus on the total density, higher non-compliance corresponds  
299 to higher density overall but does not necessarily lead to much lower flows as seen in Figure  
300 2.

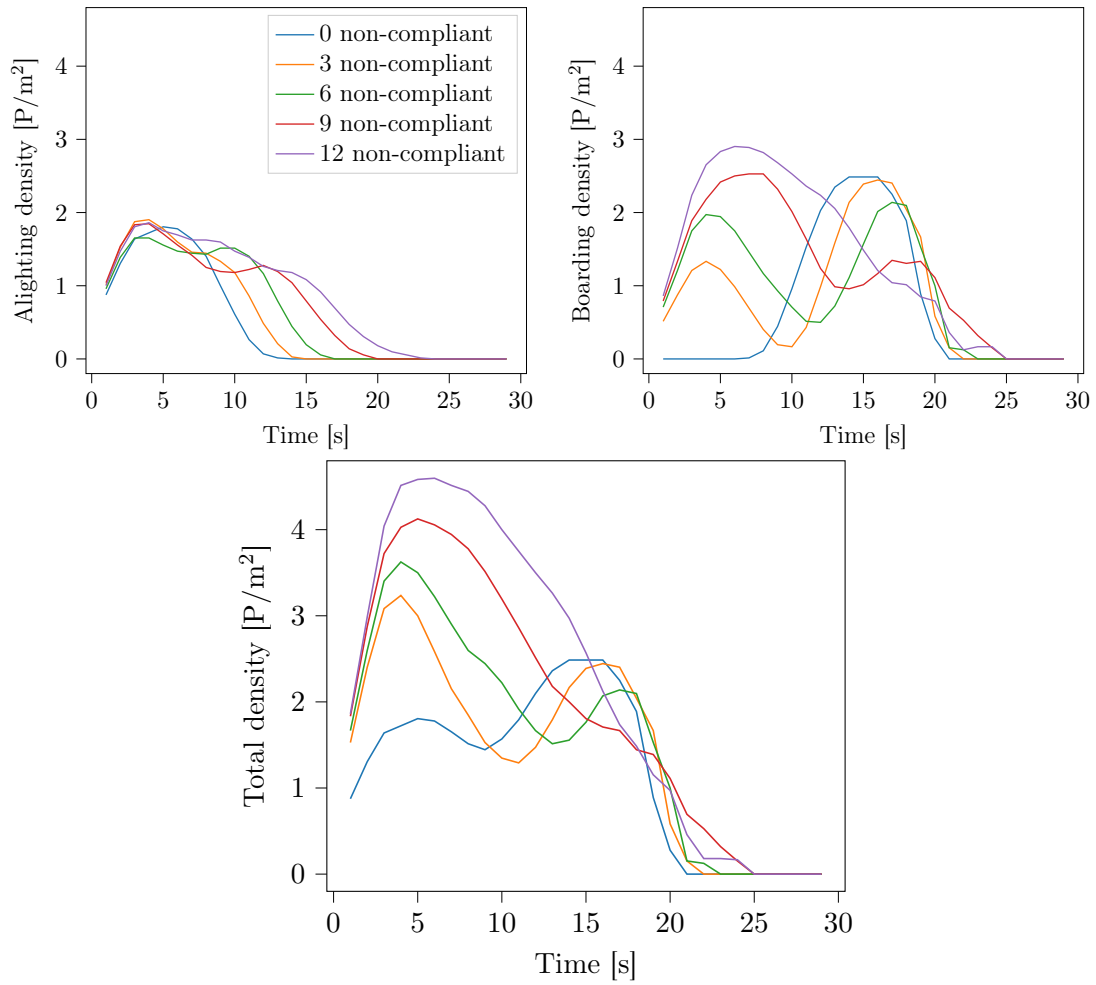


Figure 3: Alighting (top left), boarding (top right), and total (bottom) average density versus time from experimental data. The density is higher for boarding and for higher non-compliance.

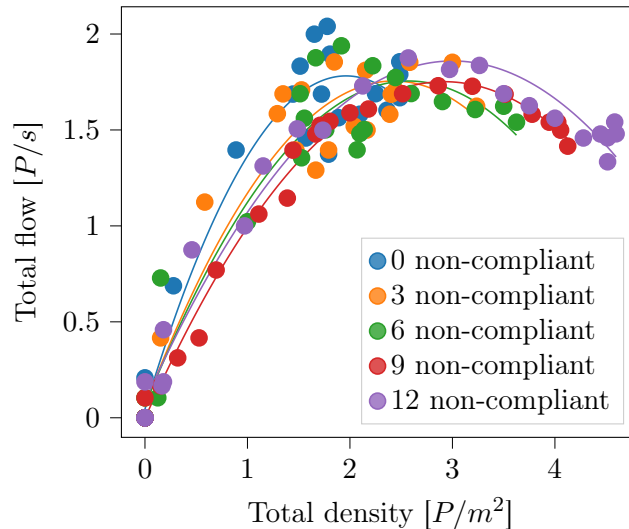


Figure 4: Pedestrian fundamental diagrams in this experiment (dots) and parabolic fit (line) for the five studied degrees of non-compliance. The five profiles are similar.

Degree of non-compliance [P]	Critical density (raw) [P/m <sup>2</sup> ]	Critical density (fitted) [P/m <sup>2</sup> ]	Capacity (raw) [P/s]	Capacity (fitted) [P/s]	$R^2$ (fit)
0	1.8	2.0	2.0	1.8	0.96
3	1.8	2.4	1.9	1.8	0.95
6	1.9	2.6	1.9	1.8	0.95
9	2.9	2.9	1.7	1.8	0.99
12	2.6	3.0	1.9	1.9	0.97

Table 4: Critical densities and capacities for each studied degree of non-compliance extracted from the fundamental diagrams with the two methods presented in Section 2. The critical density seems to increase with non-compliance but the capacity is stable.

### 301 *Capacity & compensation pattern explanation*

302 From the flows and densities, we plot the fundamental diagrams for the studied degrees  
 303 of non-compliance (see Figure 4). As commonly observed in the literature, all the flow-  
 304 density curves are concave parabolas. The observed profiles for the different degrees of  
 305 non-compliance are quite similar but the data might be insufficient to spot differences. In  
 306 particular, the observed densities are not high enough to study properly the decrease in  
 307 flow at high density, and the measurement of the capacity (the maximal flow) and the  
 308 critical density is quite imprecise.

309 Table 4 presents the obtained critical densities and capacities for the different degrees of  
 310 non-compliance along with the coefficients of determination of the fit (that show decent  
 311 correspondence). The capacity does not vary with method and degree of non-compliance.  
 312 By contrast, the estimated critical density might differ with the method (in particular for  
 313 3, 6, and 12 non-compliant people). Besides, the critical density slightly increases with  
 314 non-compliance (no matter the method) which could be explained by self-organization in  
 315 the flow. Lanes formation is a commonly observed example where the bi-directional flow  
 316 is made more efficient (see Section 4 for further discussion).

317 The study of the fundamental diagram helps to explain the compensation observed in  
 318 alighting and boarding times (see Section 3). For lower non-compliance, the total density  
 319 drops (until 1-1.5 P/m<sup>2</sup>) at the transition between the alighting process and the boarding  
 320 process. It leads to sub-maximal flows (between 1 P/s and 1.5 P/s), as seen in Figure 4.  
 321 For higher non-compliance, the flow (around 1.5 P/s) remains close to maximum despite

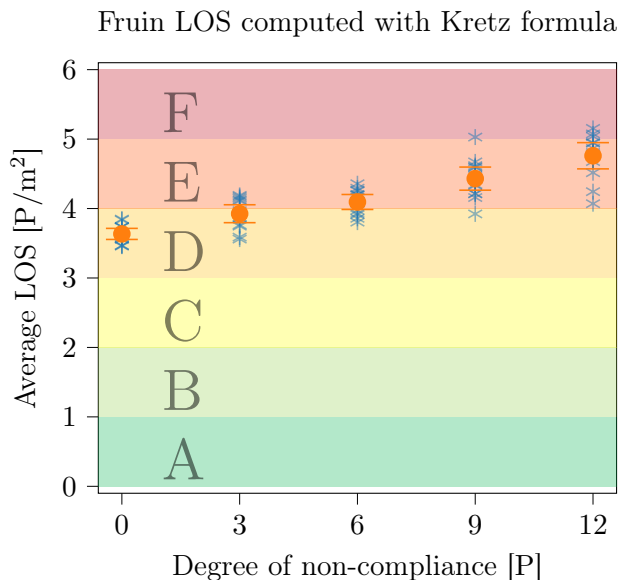


Figure 5: Average level of services (LOS) versus degree of non-compliance. Colors correspond to Fruin LOS. The discomfort increases with non-compliance.

322 higher densities. Then, in the studied context, non-compliance does not significantly affect  
 323 the duration of the alighting and boarding process. Nevertheless, higher non-compliance  
 324 increases the uncertainty in the alighting and boarding time and might decrease comfort.

#### 325 *A quantitative assessment of comfort loss due to non-compliance*

326 In this section, we estimate the level of service (LOS) during the alighting and boarding  
 327 process. The average LOS in the vicinity of the door is presented for each degree of  
 328 non-compliance in Figure 5. We see that despite important spread, the average LOS  
 329 increases with non-compliance. The size of the confidence interval also increases with  
 330 non-compliance.

331 From these experimental results, although the alighting and boarding time is relatively in-  
 332 dependent of non-compliance, the LOS significantly increases with non-compliance. How-  
 333 ever, the LOS is not measurable with the field data available for this study.

## 334 4 DISCUSSION AND CONCLUSION

335 In this study, we designed an experiment to evaluate the influence of non-compliance on  
 336 pedestrian flows in alighting and boarding processes. The experiment showed no significant  
 337 impact on the alighting and boarding time, which is coherent with existing literature  
 338 (Wahaballa et al., 2022; Seriani et al., 2022; Li et al., 2020). However, flows and densities  
 339 over time had different profiles and this observation was confirmed by field data. This  
 340 phenomenon was interpreted thanks to the fundamental diagram: a decrease in density  
 341 during the transition between alighting and boarding for lower non-compliance extends the  
 342 alighting and boarding time as much as the hindrance at higher non-compliance.

343 Some processes at the microscopic level may explain this result but are not captured by  
 344 the fundamental diagram. A well-documented example is the formation of lanes (Moussaïd  
 345 et al., 2012). People from both directions (alighting and boarding) cross the door using a  
 346 fraction of its width without hindering each other. Figure 6 shows an illustration from our  
 347 experiment. Existing works show efficient bidirectional flows when lanes appear. Kretz,  
 348 Grünebohm, Kaufman, et al. (2006) see such an example in a corridor. Helbing & Vicsek  
 349 (1999) shows that the formation of lanes enhances the flow by decreasing the friction



Figure 6: Pictures showing the formation of lanes: an example of self-organization leading to a more efficient process. Pictures captured from the experiment.

350 between pedestrians from both directions. This concurs in explaining the relatively high  
 351 flows for higher densities in the fundamental diagrams no matter the non-compliance.

352 Besides, for lower non-compliance, alighting flows drop at the end of the alighting process.  
 353 Such a drop has already been discussed in the literature (Heinz, 2003). Two potential  
 354 explanations were raised: either people in the main flow undergo stress within the crowd  
 355 that leads them to hurry, or the several lanes during the process break down into one  
 356 single lane at the end, reducing the density. These two potential explanations are not  
 357 incompatible and could be true simultaneously.

358 Concerning flow management, a common rule of thumb is to ask boarding passengers to  
 359 wait for the alighting to be complete before boarding. Surprisingly, our results contradict  
 360 this usage (as already mentioned). Nevertheless, this rule may be relevant to cases other  
 361 than the one studied here. In this sense, notice that we considered:

- 362 • A balanced flow (as many alighting people as boarding people),
- 363 • Little to medium demand (16 alightings and 16 boardings in the experiment, 8 alight-  
 364 ings and 8 boardings for field data),
- 365 • An initial position where boarding passengers wait at both sides on the edge of the  
 366 door (with no additional order).

367 Although the studied case represents most situations in the Paris suburban railway net-  
368 work, our conclusions are obtained in this specific context. Our conclusion should hold for  
369 lower demand or a more significant number of alighting (compared to boarding) since the  
370 non-compliance dynamic is not expected to change. By contrast, we cannot extend our  
371 conclusions for higher demand, more boarding compared to alighting, more load inside the  
372 train (see the results of Li et al. (2020)), or a more organized initial position (in organized  
373 lanes, for example).

374 The studied initial position is known to be sub-optimal (Heinz, 2003). Yang et al. (2019)  
375 shows, for example, an improvement in alighting and boarding time by having all the  
376 boarding people waiting at one side of the door. Yet, several works observed the initial  
377 position in real-world scenarios (Wu & Ma, 2013; Dell’Asin & Hool, 2018) where people  
378 wait at both sides of the door, similarly to our experimental instructions. Our experimental  
379 protocol was adapted to fit real-world scenarios as well as possible.

380 In conclusion, this study shows that, with a symmetric moderate total flow, the passengers’  
381 compliance with the rule “alighting before boarding” does not impact the alighting and  
382 boarding duration. By contrast, we showed significant improvement in comfort with lower  
383 non-compliance, which advocates for such a rule.

384 Our future research includes designing another experiment to investigate cases where the  
385 alighting and boarding time could be increased by higher non-compliance. Given the  
386 above-discussed results, alighting and boarding time could be increased by a density that  
387 is high enough to decrease the total flow significantly (cf fundamental diagram). There is  
388 uncertainty on whether such a density is reachable in an alighting and boarding process:  
389 people could self-organize to avoid an excessively high density. Future work will aim to  
390 design an experiment that produces an appropriate environment for high enough densities  
391 to be observed. Besides, we faced two challenges in creating the experiment presented  
392 in this paper. The first was to assess only a few scenarios to perform enough replication  
393 for each scenario in a restricted time (including some margin). The second was to en-  
394 roll enough colleagues to participate in a non-paid experiment on a Saturday morning.  
395 Designing another experiment should meet these constraints while assessing the case for  
396 more participants overall or higher degrees of non-compliance. Such an experiment will be  
397 realized in future work.

## 398 REFERENCES

- 399 Carstens, R., & Ring, S. (1970). Pedestrian capacities of shelter entrances. *Traffic Engineering,*  
400 *Inst Traffic Engr.*
- 401 Coulaud, R., Keribin, C., & Stoltz, G. (2023). Modeling dwell time in a data-rich railway envi-  
402 ronment: with operations and passenger flows data. *Transportation Research Part C: Emerging*  
403 *Technologies, 146*, 103980. doi: 10.1016/j.trc.2022.103980
- 404 Daamen, W., Lee, Y.-c., & Wiggendaad, P. (2008). Boarding and alighting experiments: Overview  
405 of setup and performance and some preliminary results. *Transportation Research Record: Journal*  
406 *of the Transportation Research Board, 2042*(1), 71–81. Retrieved 2024-03-18, from [http://](http://journals.sagepub.com/doi/10.3141/2042-08)  
407 [journals.sagepub.com/doi/10.3141/2042-08](http://journals.sagepub.com/doi/10.3141/2042-08) doi: 10.3141/2042-08
- 408 De Ana Rodríguez, G., Seriani, S., & Holloway, C. (2016). Impact of platform edge doors on  
409 passengers’ boarding and alighting time and platform behavior. *Transportation Research Record:*  
410 *Journal of the Transportation Research Board, 2540*(1), 102–110. Retrieved 2024-03-18, from  
411 <http://journals.sagepub.com/doi/10.3141/2540-12> doi: 10.3141/2540-12
- 412 Dell’Asin, G., & Hool, J. (2018). Pedestrian Patterns at Railway Platforms during Boarding:  
413 Evidence from a Case Study in Switzerland. *Journal of Advanced Transportation, 2018*, 1–11.  
414 Retrieved 2024-04-24, from <https://www.hindawi.com/journals/jat/2018/4079230/> doi:  
415 10.1155/2018/4079230
- 416 FGSV. (2015). *Handbuch für die bemessung von straßenverkehrsanlagen.*

- 417 Fruin, J. J. (1970). *Designing for pedestrians a level of service concept*. Polytechnic University.
- 418 Hankin, B., & Wright, R. A. (1958). Passenger flow in subways. *Journal of the Operational*  
419 *Research Society*, 9(2), 81–88.
- 420 Harris, N. (2005). Train boarding and alighting rates at high passenger loads. *Journal of Advanced*  
421 *Transportation*, 40(3), 249–263. doi: 10.1002/atr.5670400302
- 422 Heinz, W. (2003). *Passenger service times on trains. theory, measurement, and models*. (Licentiate  
423 thesis).
- 424 Helbing, D., Buzna, L., Johansson, A., & Werner, T. (2005, February). Self-organized pedes-  
425 trian crowd dynamics: Experiments, simulations, and design solutions. *Transportation Science*,  
426 39(1), 1–24. Retrieved 2024-03-18, from [https://pubsonline.informs.org/doi/10.1287/](https://pubsonline.informs.org/doi/10.1287/trsc.1040.0108)  
427 [trsc.1040.0108](https://pubsonline.informs.org/doi/10.1287/trsc.1040.0108) doi: 10.1287/trsc.1040.0108
- 428 Helbing, D., Farkas, I., & Vicsek, T. (2000). Simulating dynamical features of escape panic.  
429 *Nature*, 407(6803), 487–490.
- 430 Helbing, D., & Vicsek, T. (1999). Optimal self-organization. *New journal of physics*, 1(1), 13.
- 431 Kretz, T. (2011). A level of service scheme for microscopic simulation of pedestrians that integrates  
432 queuing, uni-and multi-directional flow situations. *European Transport Research Review*, 3, 211–  
433 220.
- 434 Kretz, T., Grünebohm, A., Kaufman, M., Mazur, F., & Schreckenberg, M. (2006). Experimen-  
435 tal study of pedestrian counterflow in a corridor. *Journal of Statistical Mechanics: Theory*  
436 *and Experiment*, 2006(10), P10001–P10001. Retrieved 2024-03-18, from [https://iopscience](https://iopscience.iop.org/article/10.1088/1742-5468/2006/10/P10001)  
437 [.iop.org/article/10.1088/1742-5468/2006/10/P10001](https://iopscience.iop.org/article/10.1088/1742-5468/2006/10/P10001) doi: 10.1088/1742-5468/2006/10/  
438 P10001
- 439 Kretz, T., Grünebohm, A., & Schreckenberg, M. (2006). Experimental study of pedes-  
440 trian flow through a bottleneck. *Journal of Statistical Mechanics: Theory and Experiment*,  
441 2006(10), P10014–P10014. Retrieved 2024-03-18, from [http://arxiv.org/abs/physics/](http://arxiv.org/abs/physics/0610077)  
442 [0610077](http://arxiv.org/abs/physics/0610077) (arXiv:physics/0610077) doi: 10.1088/1742-5468/2006/10/P10014
- 443 Lam, W. H., Morrall, J. F., & Ho, H. (1995). Pedestrian flow characteristics in hong kong.  
444 *Transportation research record*, 1487, 56–62.
- 445 Li, Z., Lo, S., Ma, J., & Luo, X. (2020). A study on passengers’ alighting and boarding process at  
446 metro platform by computer simulation. *Transportation Research Part A: Policy and Practice*,  
447 132, 840–854. Retrieved 2024-03-18, from [https://linkinghub.elsevier.com/retrieve/](https://linkinghub.elsevier.com/retrieve/pii/S0965856419304884)  
448 [pii/S0965856419304884](https://linkinghub.elsevier.com/retrieve/pii/S0965856419304884) doi: 10.1016/j.tra.2019.12.017
- 449 Motsch, S., Moussaïd, M., G. Guillot, E., Moreau, M., Pettré, J., Theraulaz, G., ... ,Department  
450 of Mathematics, Imperial College London, London SW7 2AZ, UK (2018). Modeling crowd  
451 dynamics through coarse-grained data analysis. *Mathematical Biosciences & Engineering*, 15(6),  
452 1271–1290. Retrieved 2024-03-18, from [http://aimsciences.org//article/doi/10.3934/mbe](http://aimsciences.org//article/doi/10.3934/mbe.2018059)  
453 [.2018059](http://aimsciences.org//article/doi/10.3934/mbe.2018059) doi: 10.3934/mbe.2018059
- 454 Moussaïd, M. (2010). *Étude expérimentale et modélisation des déplacements collectifs de piétons*  
455 (Unpublished doctoral dissertation). Université de Toulouse III - Paul Sabatier.
- 456 Moussaïd, M., Guillot, E. G., Moreau, M., Fehrenbach, J., Chabiron, O., Lemerrier, S., ... Ther-  
457 aulaz, G. (2012). Traffic instabilities in self-organized pedestrian crowds. *PLoS Computa-*  
458 *tional Biology*, 8(3), e1002442. Retrieved 2024-03-18, from [https://dx.plos.org/10.1371/](https://dx.plos.org/10.1371/journal.pcbi.1002442)  
459 [journal.pcbi.1002442](https://dx.plos.org/10.1371/journal.pcbi.1002442) doi: 10.1371/journal.pcbi.1002442
- 460 Seriani, S., Barriga, J. M., Peña, A., Valencia, A., Aprigliano, V., Jorquera, L., ... Fujiyama,  
461 T. (2022). Analyzing the effect of crowds on passenger behavior inside urban trains through  
462 laboratory experiments — a pilot study. *Sustainability*, 14(22), 14882. Retrieved 2024-03-18,  
463 from <https://www.mdpi.com/2071-1050/14/22/14882> doi: 10.3390/su142214882



- 464 Seriani, S., Fernandez, R., Luangboriboon, N., & Fujiyama, T. (2019, May). Exploring the  
465 effect of boarding and alighting ratio on passengers' behaviour at metro stations by laboratory  
466 experiments. *Journal of Advanced Transportation*, 2019, 1–12. Retrieved 2024-03-18, from  
467 <https://www.hindawi.com/journals/jat/2019/6530897/> doi: 10.1155/2019/6530897
- 468 TRB. (1956). *Highway capacity manual*.
- 469 TRB. (2022). *Highway capacity manual, sixth edition: A guide for multimodal mobility analysis*.
- 470 Vanumu, L. D., Ramachandra Rao, K., & Tiwari, G. (2017). Fundamental diagrams of pedestrian  
471 flow characteristics: A review. *European Transport Research Review*, 9(4), 49. Retrieved 2024-  
472 03-18, from <http://link.springer.com/10.1007/s12544-017-0264-6> doi: 10.1007/s12544-  
473 -017-0264-6
- 474 Wahaballa, A. M., Abdelhaleem, M., Saeed, K., & Othman, A. (2022). Experimental analysis of  
475 boarding and alighting behavior in urban public transport network: A case study. *Transportation  
476 Research Procedia*, 62, 25–34.
- 477 Weidmann, U. (1993). Transporttechnik der fußgänger: transporttechnische eigenschaften des  
478 fußgängerverkehrs, literaturauswertung. *IVT Schriftenreihe*, 90.
- 479 Weston, J. (1989). Train service model-technical guide. *London underground operational research  
480 note*, 89, 18.
- 481 Wigenraad, I. P. B. (2001). *Alighting and boarding times of passengers at dutch railway stations*  
482 (Doctoral thesis).
- 483 Wu, J., & Ma, S. (2013). Division method for waiting areas on island platforms at metro stations.  
484 *Journal of transportation engineering*, 139(4), 339–349.
- 485 Yang, X., Yang, X., Xue, S., Zhang, J., Pan, F., Kang, Y., & Wang, Q. (2019). The effect  
486 of waiting area design at the metro platform on passengers' alighting and boarding behaviors.  
487 *Applied Mathematics and Computation*, 358, 177–193.
- 488 Zhang, J., Klingsch, W., Schadschneider, A., & Seyfried, A. (2012). Ordering in bidirectional  
489 pedestrian flows and its influence on the fundamental diagram. *Journal of Statistical Mechanics:  
490 Theory and Experiment*, 2012(02), P02002. Retrieved 2024-03-18, from [https://iopscience  
491 .iop.org/article/10.1088/1742-5468/2012/02/P02002](https://iopscience.iop.org/article/10.1088/1742-5468/2012/02/P02002) doi: 10.1088/1742-5468/2012/02/  
492 P02002
- 493 Zhang, Q., Han, B., & Li, D. (2008). Modeling and simulation of passenger alighting and boarding  
494 movement in beijing metro stations. *Transportation Research Part C: Emerging Technologies*,  
495 16(5), 635–649. Retrieved 2024-03-18, from [https://linkinghub.elsevier.com/retrieve/  
496 pii/S0968090X07000927](https://linkinghub.elsevier.com/retrieve/pii/S0968090X07000927) doi: 10.1016/j.trc.2007.12.001