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Lessons regarding the combination of survey and monitoring data

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Studying the Pedestrian Level-of-Service (PLoS): Lessons regarding the combination of survey and monitoring data

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Abstract

Crowding is often analyzed using crowd dynamics variables. Yet, it is questionable whether quantitative variables fully describe the perception of crowdedness. This paper presents four case studies into the Pedestrian Level-of-Service (PLoS), featuring a 1) mass event, 2) shopping environment, 3) festival, and 4) touristic hotspot. The relation between the PLoS and the crowds' movement dynamics is studied using a combination of survey and monitoring data. This study establishes that the perception of LoS is partly related to the crowds' dynamics, and that the combination of in-situ surveys and monitoring data provides more comprehensive insights w.r.t. pedestrians' perceptions of space.

Keywords: Crowd management, Survey, Crowd monitoring, Pedestrian Level-of-Service, Safety, Crowd dynamics

1. Introduction

In recent years, city streets and event spaces have become increasingly crowded. Population levels in metropolitan areas are growing at an incredible speed. The UN forecasts that 80% of EU inhabitants will live in an urban area by 2050 (United Nations, 2015). Also the EU tourism sector is growing steadily, with an increase of 9% in 2018 (World Tourism Organization, 2019). COVID-19 has temporarily curbed the growth in 2020 and 2021. Yet, similar growth numbers are expected in coming years, when tourists are able to travel again. People's continuous search for

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entertainment ensures that inhabitants, tourists, and event visitors will also in the future experience high levels of crowding in pedestrian spaces, which can potentially lead to annoying and dangerous situations.

Currently, crowding in these densely populated spaces is mainly analyzed and managed using quantifiable objectives, such as density, flow rate, and walking speed. Yet, citizens and mass event visitors report very variable experiences when exposed to the same level of crowding. Thus, the question arises whether quantitative objectives represent the perception of crowdedness of citizens, tourists and mass event visitors, and which factors, besides the density, influence their perception of the service level of pedestrian spaces.

Since 2016, one of the authors has been studying this question, the results of which have been published in various theses (i.e., Hoskam (2018), Grolle (2017), and Zuurbier (2019)). Though they present interesting perspectives on the topic at hand, these three theses failed to study and discuss the suitability of the adopted research methodology to study this complex relation. This while the adopted research methodology severely influences the extent to which the relationship can be captured. This paper aims to bridge this gap and identifies key lessons regarding the methodological improvements needed in the design of future surveys into the (Pedestrian) Level-of-Service (PLoS).

This study features four case studies of the Pedestrian Level-of-Service in a variety of Dutch crowding scenarios. In all cases, the relationship between the perceived Pedestrian Level-of-Service and objective measurements of crowd's dynamics is investigated. The context of these four case studies are 1) visitors of a mass event in an urban environment, 2) pedestrians in a shopping environment, 3) visitors of a public festival, and 4) tourists in a city center. This study compares the findings of all four case studies and draws overarching conclusions considering the relation between the perceived and measured crowd dynamics. Besides that, this study derives several lessons regarding the methodology to survey pedestrians in-situ at crowded spaces are discussed.

The paper continues as follows. Section 2 presents a summary of the state-of-the-art on the pedestrian Level-of-Service, with a focus on empirical research methodologies. Accordingly, section 3 discusses the research methodology and introduces the four case studies. Sections 4 – 7 discuss the results of the four case studies. Accordingly, sections 8 and 9 provide an overview of the key lessons regarding Pedestrian Level-of-Service and the combination of in-situ surveys and crowd monitoring data. Section 10 indicates several directions for future research.

2. State-of-the-art Level-of-Service

Greenshields (1933) presented the first parameterization of traffic behavior in one dimension (along a road stretch). This, so-called fundamental relation of traffic flow (i.e. flow rate is a product of speed and density) states that there is a limit to the number of vehicles that can travel a cross-section per time period. He was the first to identify that there is a natural limit to the traffic flow in a the traffic corridor.

In 1971, Fruin (1971) was the first to present a parameterized description of this fundamental relation for pedestrians, which relates the flow rate to the number of pedestrians in a restricted two-dimensional area. In addition, he developed the Pedestrian Level-of-Service (PLoS) concept. This PLoS translated quantitative measurements on crowd movement dynamics into a qualitative assessment of the perceived Level-of-Service of pedestrian infrastructures, such as the London Underground. To do so, Fruin analyzed time-lapse videos of pedestrian crowds and developed a crowding scale based on the average spatial area available to each individual in the crowd. Even though widely adopted, this first PLoS is limited by the fact that it does not take into account the temporal dimension and contextual dynamics of pedestrian traffic.

Over the years, many other researchers have been studying the way in which pedestrians experience pedestrian infrastructures. Here, pedestrian infrastructures are defined as any type of infrastructure that is specifically designed to host any type of individual that walks from A to B, including pedestrian pathways in neighborhoods, shopping malls, train stations and event terrains. Most often, the studies on the infrastructure appraisal of pedestrian spaces featured roadway scenarios, in which the pedestrian is a walking individual on route through an urban environment while frequently interacting with other modes of transport, such as cars, mopeds, busses, and trucks. These so-called 'Walkability' studies explicitly include trip and built environment characteristics such as distance, crossing opportunities, light conditions, pavement conditions and social safety (e.g. Frank et al. (2010), Ewing & Handy (2009), Fonseca et al. (2022), and Arellana et al. (2020)). The crowd density is generally low in these studies, i.e. pedestrians are not hampered in their operational movements, information gathering processes and decision making by the presence of other individuals. As a result, it is very difficult to adopt 'walkability' as a framework to study the

Pedestrian Level-of-Service of more crowded spaces where the crowding levels might influence people's experiences of the space severely.

These crowded pedestrian spaces are special in the fact that interactions between modalities are limited and the densities are relatively high, for instance train stations, shopping areas and event terrains. Several researchers have further elaborated the PLoS for more crowded scenarios. Landis et al. (2001) for example studied the perception of safety and comfort of pedestrians on a designed roadway course with varying traffic conditions. Similarly, Bian et al. (2007) interviewed pedestrians on sidewalks in China regarding their real-time perceptions concerning the site layout. In 2008, Dowling et al. (2008) reviewed the PLoS models developed up to that moment. They find that most of the resulting adaptations of Fruin's PLoS model are not generalizable and depend heavily on the context for which the PLoS framework was originally calibrated.

Reviews by Raad et al. (2017) and Banjeree et al. (2018) of PLoS models show that little has changed since 2008. The macroscopic flow variables density and flow are still at the basis of most PLoS models. New PLoS models predominantly added geometric infrastructure characteristics (e.g. the width of the walkway, the distance to the nearest crosswalk, the gradient of the road), traffic characteristics (e.g. traffic volume, pedestrian walking speed, and travel time delay), or user characteristics (e.g., age, gender, and non-compliance rate) to the model formulation.

In the last few years, researchers started studying the impact of time and specific pedestrian contexts on the PLoS. For instance, Finch (2010) provides a variety of assessment frameworks that are dependent on the context. Van Gelder (2018) researched the impact of crowding on the experience of train travelers in the Netherlands by a combination of survey and monitoring data. The reported experience on the platform was related to the number of people present within a demarcated area on the platform. Compared to Fruin's original PLoS model, these more recent PLoS frameworks are better equipped to handle the complexity of urban traffic.

Yet, until now, most PLoS studies have predominantly focussed on generic pedestrian traffic on streets. These PLoS frameworks predominantly feature pedestrian-only facilities, such as pedestrian sidewalks, intersections, and unsignalized crossings. Moreover, the flow rates are low and limited interactions between pedestrians arise. Also mixed traffic spaces, for example, spaces shared between pedestrians and bicycles, have not been studied. Therefore, the question is whether existing PLoS frameworks hold for these more crowded, more chaotic, and often more spacious, conditions.

3. Methodology

The literature identifies that most often Pedestrian Level-of-Service is determined using personal space analyses, workshops, and small surveys. Often a wide variety of spatial factors is identified to determine one global Pedestrian Level-of-Service for a location or street, which often does not take into account the crowd's dynamics at the location. Yet, we hypothesize that for crowded pedestrian spaces (density larger than 1 P/m^2), the crowd's dynamics are a major influencing factor on the perceived Pedestrian Level-of-Service. Therefore, this study aims to relate the objective crowd's state to the crowd's perceived Level-of-Service.

Given that we are predominantly interested in highly trafficked pedestrian spaces where most people are continuously on the move, the crowd movement dynamics are operationalized by means of the flow rate. Here, the flow rate refers to the total amount of pedestrians that pass through an area in a given unit of time. Please note, as a result of this definition of flow rate, the crowd's movement dynamics at the studied locations can be uni-directional, bi-directional, or quite random.

In addition, we have operationalized the Pedestrian Level-of-Service using two concepts, namely 'Crowding' and 'Safety'. Here, crowding refers to the perceived density of the crowd at a given location. Please note, this is the respondent's assessment of the level of crowding at a location. Similarly, safety refers to the self-reported perceived safety of the respondents. We did not distinguish between social and physical safety, as we experienced in a pilot study that respondents find it rather difficult to distinguish these two concepts. Moreover, respondents were selected on first come, first serve basis at the moment the interviewer was finished with the previous respondent. Response rate was not recorded, as this was almost impossible to track non-response in the dense crowd. Each interview lasted 5 minutes at maximum, often less time was spend with each respondent.

Over the course of several years, four case studies were performed in varying contexts, i.e., 1) mass event visitors in an urban environment, 2) pedestrians in a shopping environment, 3) mass event visitors at a festival and 4) tourists in a densely populated city centre. All four case study locations have been performed in pedestrian spaces where high densities frequently occur because of activities at or near the location. The respective case studies and general characteristics of the data are introduced in the following 4 sections. In addition, the main results and lessons per case study are presented.

4. Case study 1: Shopping environment

The first case study featured the perception of safety and crowding in a shared space shopping street in Delft, The Netherlands (see Figure 1). The street is approximately 7.5 meters wide and features shops on both sides. Twice a week, a large farmers market is organized close to this pedestrian street. Most shops have placed small billboards on the street just in front of the store. The street is paved with a smooth surface of paving stones without any significant directive markings (white striped, etc.) and features a pedestrian area where cyclists are allowed.

Figure 1. Photo of the shopping street in Delft, The Netherlands

For 6 days in October 2017, cyclists and pedestrians alike were asked to fill in a short survey after passing through the street between 12 a.m. and 07 p.m. Most questionnaires were distributed during daytime. An anonymous survey recorded some socio-demographic information, their recent experiences, and several questions related to collision incidents. For example, ‘How crowded did the street feel when you passed through it? Provide a rating between 1 (very quiet) and 10 (very busy)’. Besides that, a camera was mounted orthogonally from a second-floor office in the street. The video recordings were used to manually determine the flow rate per type of visitor (i.e., pedestrian, cyclist, other).

4.1. Summary of data collected for case study 1

In total, 115 respondents filled in the survey, on average 15 per timeslot for which the camera was analyzed. The gender of the respondents was quite balanced, 47.8% male and 52.2% female. The age of the respondents ranged from 16 to 80 years, a large portion of the respondents was between 45 and 65 years old (33.9%). The group size of the respondents varied, with 43.5% traveling alone and 45.2% traveling in pairs. Most of the respondents (51.3%) had the objective ‘to shop’. During the moments that the surveys were deducted flow rates varied heavily from 116 to 448 pedestrians and cyclists per 15 minutes. At maximum, 63 cyclists and 404 pedestrians were present per 15 minutes. In general, the number of cyclists in the street decreased when pedestrian densities increased.

4.2. Results of case study 1

The answers of all respondents to the two questions regarding the perceived level of crowding and the perceived level of safety are depicted in Figure 2. As one can see, the answers to both questions are highly scattered, which suggests that the flow rate is not the only factor influencing the respondent’s perception of crowding and safety. We hypothesize that also other factors, such as socio-demographics and experience, might have played an important role in their perception with respect to crowding and safety.

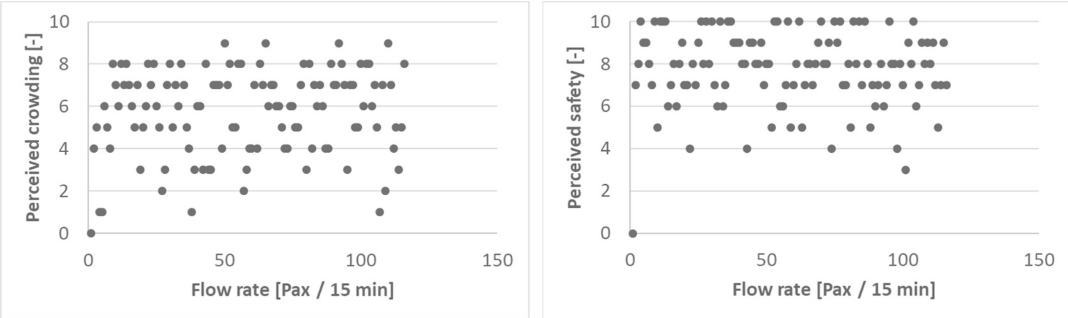

Figure 2. The perceived level of crowding (left) and the perceived safety (right) in relation to the total flow rate in the shopping street.

For both questions, linear regression models have been estimated (see Table 1). These models feature models with a relatively low fit. The models show that especially the characteristics of the pedestrian determine their assessment of crowding and safety levels. In particular, males and frequent visitors provide lower estimates of the level of crowding. At the same time, people that are travelling through the area without a destination in the area ('transit') and live in smaller towns have a more negative perception of the level of safety.

Table 1. Linear regression models featuring the perception of crowding and safety

Variable name	**Perception of crowding ($\rho^2 = 0.092$)**			**Perception of safety ($\rho^2 = 0.129$)**		
	Beta	**t-stat**	**Sign.**	**Beta**	**t-stat**	**Sign.**
Gender (1 = male)	-0.226	-2.343	**	0.207	2.187	**
Visit Frequency (3 times per week or more)	-0.208	-2.159	**			
Resident = small town				-0.207	-2.179	**
Purpose = transit				-0.799	-2.092	**

Where ** = 95%, * = 90%

5. Case study 2: Traffic to and from a large public event

The second case study features the perception of the level of crowding and safety in a pedestrian corridor between a train station (Station Amsterdam Zuid – see Figure 3) and two ticketed events nearby named Nassau Festival and Kingsland. The first festival hosted 15,000 visitors for one day, while the latter festival hosted 35,000 visitors. Both festivals drew a young crowd to the city of Amsterdam, most of which were no resident of Amsterdam. Both events started at approximately the same moment in time and ended at 20:00h. Consequently, most visitors walked through the station area in a relatively short period. During one day, 27 April 2017, surveys were conducted on Zuidplein between 10 a.m. and 11 p.m. Questionnaires were distributed during daytime and after sunset. The anonymous survey recorded aggregated socio-demographic information, such as age category, gender, and place of origin (Amsterdam, NL, outside NL). Accordingly, the pedestrians were asked to rate their perception of crowding and safety (e.g. 'On a scale of 1 to 10, how crowded do you think it is right now?'). Lastly, a question was asked about their substance use, as we hypothesized this might be an important influential factor of respondents' perception of their environment during these events.

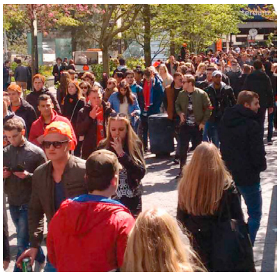

Figure 3. Photo of the pedestrian crowd moving towards the event terrain

5.1. Summary of data collected for case study 2

In total 251 respondents answered the survey, of which 55.4% were male and 44.6% were female. The respondents were between 15 and 70 years old, with an average age of 25 years old. 47.4% of the visitors attended the Kingsland festival, and 17.5% the Nassau festival. The objective of the remaining respondents was to visit the city, go to work or go on another social activity in the city. In addition, roughly 48.2% of the visitors mentioned that they drank an alcoholic substance and 11.1% identified that they had taken one or more medicinal substances. During the time the surveys were conducted, flow rates varied from 0 to 625 people per minute.

5.2. Results of case study 2

The relations between the flow rate and the perceived level of crowding, and the flow rate and perceived level of safety, are depicted in Figure 4. In this case, the scores are highly scattered. Yet, a log-like trend is visible in the crowding data. Small changes in the flow rate at low flow rates lead to large differences in the perception of crowding, while small changes in flow rate at high flow rates lead to almost no difference in crowding and safety scores. However, given the magnitude of the scatter, we expect that also in this case study other socio-demographic and experience-related factors are influencing the respondent's perception of crowding and safety.

The survey and counting data is used to develop two regression models, one featuring the perceived level of crowding and the second the perceived level of safety (see Table 2). In this case, we find that the flow rate influences the perception of crowding (i.e. a 7.14 points difference between an empty corridor and the maximum recorded flow rate). Besides that, the goal-orientation of the respondents impacted pedestrians' perception as well, where the respondents that had to travel to work perceived the location as less crowded than all other respondents. Similarly, respondents of the Nassau festival reported lower crowding levels. Interestingly, also substance use is also found to impact the perception of crowding. Respondents that indicated they had used XTC that day experienced the same crowding conditions as more crowded.

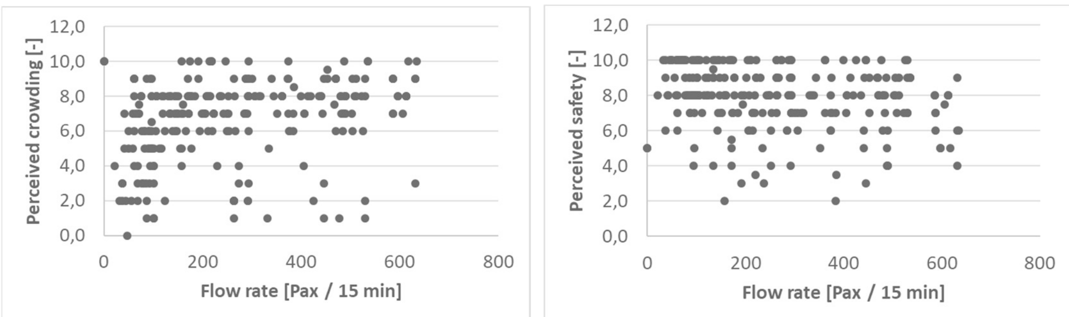

Figure 4. The perceived level of crowding (left) and the perceived safety (right) in relation to the flow rate in the pedestrian corridor in front of Station Zuid, Amsterdam, The Netherlands.

Table 2. Linear regression models featuring the perceived level of crowding and safety for case study 2

	Perception of crowding ($\rho^2 = 0.26$)			Perception of safety ($\rho^2 = 0.15$)		
	Beta	**t-stat**	**Sign.**	**Beta**	**t-stat**	**Sign.**
Ln(Total intensity)	1.111	6.40	**	-0.489	-3.30	**
Objective = Kingsland				-0.998	-4.34	**
Objective = Nassau festival	-1.509	-4.03	**			
Objective = Work	-1.895	-4.32	**			
Substances = Sober				-0.479	-2.20	**
Substances = XTC	2.488	4.89	**			

Where ** = 95%, * = 90%

Concerning safety, an inverse trend is visible, where the perception of safety decreases with the flow rate. Besides that, also here respondents that visited the Kingsland festival experienced the location as less safe. Similarly, respondents that reported to be sober also gave lower safety scores.

This second case study teaches us three things. First, the flow rate is influencing the perception of crowding. Second, the goal orientation of pedestrians does matter, which is a potential proxy for the expectations that pedestrians have regarding the scenario they are going to encounter. Third, substance use can both negatively and positively influence perceptions of crowding. The direction of this relationship depends on the exact substance that is used. Therefore, understanding what substances the crowd use is essential to understand their perception of and reaction to dense crowd scenarios.

6. Case study 3: Festival crowd

The third case study features a large festival in the East of The Netherlands. The TT Festival is an annual festival that comprises four days of music, motor fun, carnival, and parties. According to estimates of the organizer, yearly 160.000 visitors take part in the festivities for one or more days. During the TT Festival, the city center of Assen is turned into a non-motorized festival terrain, with eight music stages, a fair, a motor fun corner, and a parade (see Figure 5). The TT Festival is visited by a wide variety of visitors, amongst others, groups of youngsters, families, adult groups of friends, and the elderly.

In 2018, a study was conducted at the TT Festival, both during daytime and nighttime between 4 p.m. and 1 a.m. This study combined an in-situ survey on the perception of crowding with real-time monitoring of the crowd dynamics. Besides that, also sound, light, and weather conditions on the grounds were recorded at regular intervals. The in-situ survey comprised of questions related to socio-demographics, the state of the visitors (i.e. emotion, substance use, type of visitor), and the visitors' perception of crowding and safety (i.e. 'How do you rate the level of crowding at this location? 1 (very quiet) – 5 (very busy)'). In addition, 8 Wi-Fi and 4 smart camera sensors were installed to record the crowding levels at various locations in the city center.

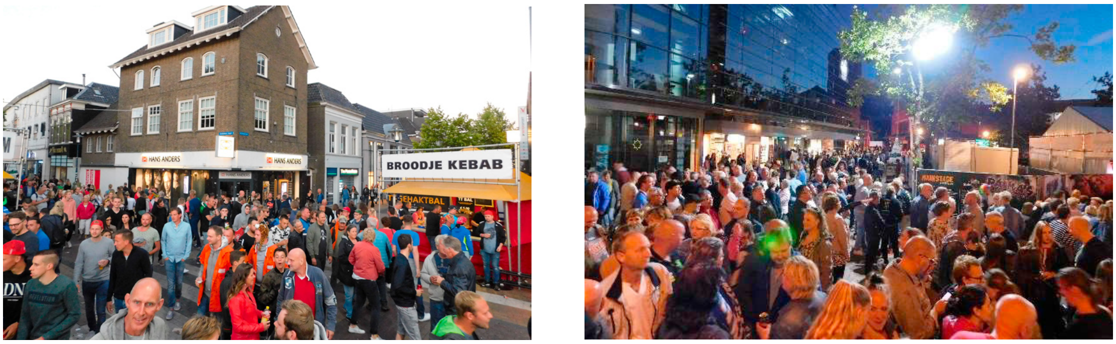

Figure 5. Photos of the crowd movements on the TT Festival during the day (left) and night (right).

6.1. Summary of data collected for case study 3

Of the 242 respondents of the survey, 50.4% were males and 49.2% were females. Most of them visited the city of Assen daily (51.7%). Only 13% of the respondents had never been to Assen before the day of the survey. Similarly, most respondents had visited the TT Festival at least one time before (74%). Most respondents traveled in mixed groups of males and females (71.7%). The age of the respondents of the survey ranged from 18 to 75+, most of which are between 45 and 64 years old (35.1%). At the moment of the survey, most respondents had already spent more than 1 hour on the TT Festival terrain, with outliers of up to 8 hours. At the locations where the survey was performed, between 361 and 1905 Wi-Fi traces per 15 minutes were found, with an average of 1126 unique Wi-Fi traces per 15 minutes.

6.2. Results of case study 3

The relations between the number of enabled Wi-Fi devices and the reported level of crowding and level of safety are visualized in figure 6. The crowding graph is quite scattered but shows a clear upwards trend. The safety graph also features a lot of scatter and no discernable trends. This suggests that there is no relation between the number of Wi-Fi devices (a proxy for the crowds' density) and the perceived safety of a location.

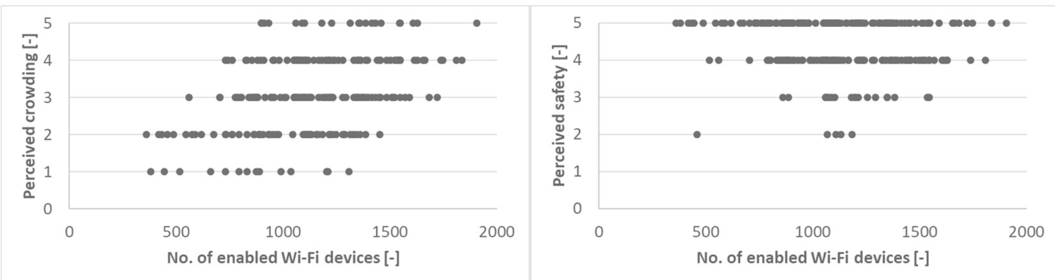

Figure 6. The perceived level of crowding (left) and the perceived safety (right) in relation to the number of Wi-Fi devices at the TT Festival

Even so, two linear regression models have been developed to study these findings more elaborately (see Table 3). Similar to case study 2, also in case study 3 several factors related to the person have been identified that influence their perceptions with respect to the level of crowding and safety. Adult respondents and respondents who smoked marihuana systematically report lower crowding levels than youngsters and respondents that had never been to Assen before. The perceived crowding is positively related to the time of day. A trend that is also identified in the crowd monitoring data.

As already expected based on the scatter plot in figure 6 (right), the relation between the measured crowding levels and the perception of safety cannot be established. Instead, only the age of the respondents, the level of darkness, and whether they are foreign have a slight impact on the respondent's perception of safety.

Based on the third case, we conclude that the perceived level of crowding is related to the observed level of crowding. in addition, the composition of the crowd also has a large impact on the crowd's perception of safety.

7. Case study 4: Tourism

The last case study features the perceived level of crowding and safety of tourists on a crowded tourist spot in the city center of Amsterdam, namely the Red Light District (RLD). The RLD consists of four parallel streets alongside 2 channels. Several bridges and narrow streets (<2.5 m) connect the four streets (see Figure 7). Even though this location

Table 3. Linear regression models featuring the perceived level of crowding and safety at the TT Festival

	Perception of crowding ($\rho^2 = 0.328$)			**Perception of safety ($\rho^2 = 0.068$)**		
	Beta	**t-stat**	**Sign.**	**Beta**	**t-stat**	**Sign.**
No. of Wi-Fi enabled devices per 15 min	0.001	4.507	**			
Hour of the day	0.519	4.609	**			
Daytime (1 = yes)	0.675	2.846	**	0.200	2.167	**
Age (25 – 65 yr)	-0.439	-3.157	**	-0.230	-2.041	**
Residency(Foreign)				0.431	2.700	**
Frequency (Never visited Assen before)	0.730	2.844	**			
Substances (Sober)	0.366	2.883	**			
Substances (Marihuana)	-1.039	-2.300	**			

Figure 7. Photos of the crowd movements on the Red Light District during the night.

still partly has the same function as before, it is also one of the main tourist attractions in Amsterdam. Especially during weekend nights, large crowds will gather in this neighborhood for a stroll and some sightseeing.

In 2018, a survey was conducted amongst the tourists, especially during nighttime between 7 p.m. and 11 p.m. and . The questions were similar to case study 3. Tourists were asked to rate the level of crowding and safety on a scale between 1 (very quiet / very unsafe) and 5 (very busy / very safe). Besides that, smart cameras counted throughput (flow rate) at three strategic locations in the area.

7.1. Summary of data collected for case study 4

In total, 182 respondents took part in the survey distributed over the course of 3 evenings (19:00 – 22:00) in October 2018. 40.7 % of the respondents had never visited Amsterdam, and 49.5% had never visited the RLD before. 18.1%

visited Amsterdam regularly and 9.3% visited the RLD regularly. Most respondents walked around in small groups of 2 and 3 (71.4%) and most of them were foreigners (84.1%). Before going to the RDL, a large portion of the visitors drank some alcohol (41.8%). Some respondents reported the use of other medicinal substances (i.e. MDMA – 0.5%, Marihuana – 25.3%, Mushrooms – 1.6%).

During the time the questionnaires were distributed at RLD, the smart cameras in the narrow streets recorded flow rates between 28 and 81 P/s. Similarly, the Wi-Fi sensors recorded between 24 and 89 unique Wi-Fi traces per minute. During the day, both the flow rate and density steadily increased during the survey period.

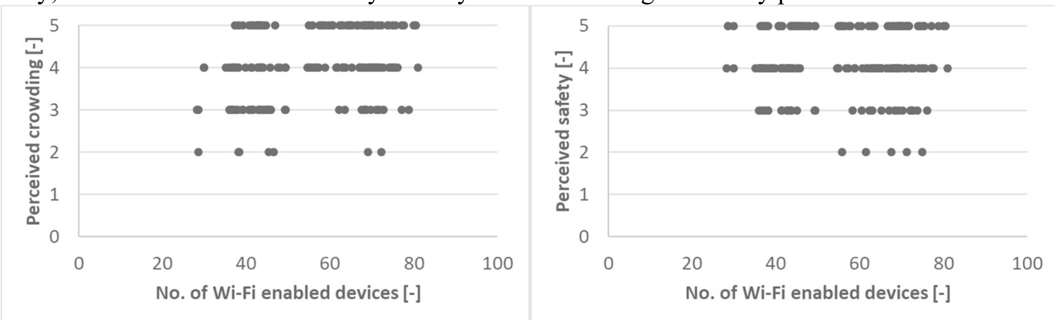

Figure 8. The perceived level of crowding (left) and the perceived safety (right) in relation to the number of Wi-Fi devices at the Red Light District

Table 4. Linear regression models featuring the perceived level of crowding and safety at the Red Light District

	Perception of crowding ($\rho^2 = 0.186$)			Perception of safety ($\rho^2 = 0.076$)		
	Beta	**t-stat**	**Sign.**	**Beta**	**t-stat**	**Sign.**
No. of Wi-Fi enabled devices per 15 min	0.017	4.077	**			
Colleagues	-0.790	-3.803	**			
Groupsize (Alone)	-0.487	-2.433	**			
Visit Amsterdam frequently				-0.344	-2.343	**
Gender (Male = 1)				0.286	2.508	**
Substances (Mushrooms)				-0.916	-2.049	**

7.2. Results of case study 4

Scatterplots of the perceived crowding and safety levels in relation to the number of Wi-Fi-enabled devices are depicted in Figure 8. In both graphs, it is difficult to discern a trend. This suggests that the measured crowding levels are not the only thing influencing the perception of the respondents.

Linear regression models of both independent variables are provided in Table 4. Concerning crowding, the measured level of crowding is found to impact the perception of crowding. In addition, groups consisting of colleagues reported lower crowding levels, as did respondents that were traveling through the area alone.

Concerning safety, we find that the measured level of crowding did not influence the scores. Experience with the city of Amsterdam, and the use of Mushrooms did negatively influence the perception of safety. Unsurprisingly, male respondents recorded higher safety scores.

At the same time, the fit of both models is limited (i.e. $\rho^2 = 0.186$ / $\rho^2 = 0.076$). Thus, we also conclude that there are many other factors that influence the perception of crowding and safety. Moreover, the feeling of safety is not impacted by the crowd dynamics at the RLD.

8. Lessons regarding the perception of crowdedness and safety

By combining these four pilots, four lessons regarding the perception of crowding and safety can be distilled. These are briefly discussed underneath.

1. *Perception of crowding is related to the crowd size* **-** Three out of four case studies confirmed that the perception of crowding is related to the number of people that simultaneously walk through a pedestrian space. The case studies also confirm that people do not only perceive the crowding at one moment in time, but take into account a period of time in their evaluation of the crowding and safety of pedestrian spaces.

2. *At high crowding levels, changes in flow rate have limited effect* – The findings of case study 2 indicate that the relationship between the measured crowdedness and the perceived level of crowdedness can be non-linear. Our research is inconclusive regarding the extent to which this occurs in practice. Especially for high-density scenarios this can potentially create dangerous crowd situations, as our finding suggests that pedestrians do not perceive changes in crowd density anymore and are thus not always able to distinguish between 'safe' and 'unsafe' crowd densities.

3. *Personal characteristics impact the perceived level of crowdedness* – All four studies confirm that personal characteristics impact respondents' perceptions with respect to crowding and safety. Socio-demographic characteristics, such as age and gender, can influence the perception of crowding. Yet, which socio-demographic characteristics are significant dependents heavily on the context. In addition, previous experiences with respect to similar pedestrian spaces are found to be influential to the current evaluation of the PLoS in a pedestrian space.

4. *Context-related factors are strong determinants for perceived crowdedness* – Lastly, these studies show that context-related factors are strong determinants of both people's perception of crowding as well as safety. Group composition matters, as does the time of day, and goal-orientation (i.e. work, shop, entertainment). Interestingly, also substance use is found to impact people's perception.

9. Lessons regarding the combination of in-situ and crowd monitoring data

Next to the conclusions regarding the topic of study, also seven essential lessons were distilled from the case studies regarding connecting survey data, in particular related to the perception of individuals, and crowd monitoring data.

1. *Combination of data sources allows for more comprehensive insights* – The explicit combination of 'objective' crowd monitoring data with subjective survey data considering perceptions allows researchers to relate subjective concepts like the Pedestrian Level-of-Service to actual movement behavior. This allows researchers a more comprehensive insight into pedestrians' experiences, how they perceive reality, and which factors influence their perceptions.

2. *In-situ questionnaire are essential to get valid answers* - While performing the survey, pedestrians would provide informal insights regarding how they rate crowdedness. The 'small talk' illustrated that they react to a lot of information that is very difficult to recreate in SP surveys or VR environments. Examples of the missing information in SP and VR studies are the behavior of groups, the social dynamics, the crowd's interaction dynamics, the soundscape, and the light conditions. Thus, we conclude that it is essential to ask the questions about pedestrians' perception in-situ to establish a valid PLoS model for these more complex crowded scenarios.

3. *Perceptions are rooted in history* – Respondents in all four studies indicate that they find it difficult to score their perceptions, as they do not know what part of their experience they are taking into account. At the same time, case studies 3 and 4 also show that the perception scores of pedestrians are correlated with the global

crowding levels in the entire area over a longer period, instead of the flow rate ate a particular location at which they were questioned. We learned that when one asks people to evaluate a crowd scenario (w.r.t. crowding, safety, comfort), it is essential to record seemingly superfluous information regarding the local crowd dynamics in other neighboring locations, as well as the average crowd dynamics in the area.

4. *Perceived PLoS is very context and population-dependent* - The influential factors differ greatly between the four cases. This leads us to conclude that PLoS models are very context-dependent. Thus, PLoS models need to be developed for each context separately, such as generic city travel, shopping, tourism, and mass event scenarios. Moreover, one needs to ensure that all subgroups of the population are accounted for in the research to establish valid PLoS models.

5. *A large number of data points is required to determine PLoS relationships* - The in-situ nature of the study illustrated that pedestrian perceptions are highly variable in time and space due to the highly variability of pedestrian dynamics in crowded pedestrian spaces, as well as the high variability in pedestrians' characteristics and previous experiences. As a result, a large number of data points is required to determine the relationship between the measured and perceived Pedestrian Level-of-Service. Additionally, the high variance in responses regarding the perceived level of crowdedness of seemingly similar individuals (i.e. male adults) illustrates that a large heterogeneous population should be included in data collection before one can develop a PLoS model for a particular context.

6. *RP surveys in crowded, chaotic scenarios are difficult to distribute and only record the bare minimum amount of information.* In contrast to most previous studies into the perception of crowding and safety, these four case studies were conducted in very densely populated areas. Consequently, there is little time and space to conduct the interviews and record the respondents' answers. Moreover, respondents are often distracted by third parties if the interview takes too long. Therefore, we learned to design RP surveys that only record the bare minimum information required to get an answer to the main research question. Moreover, the questions needed to be phrased in a way that respondents could answer without requiring a lot of spoken contact with the interviewer, as this was very difficult to achieve in these often loud environments.

7. *Combining monitoring data and RP surveys requires the active involvement of the local authorities and lots of flexibility of the researchers and their research design.* Advanced crowd monitoring systems take lots of time, money and effort to design, install and validate. As a result, most static crowd monitoring systems are owned by local authorities. Thus, a solid and pro-active collaboration with the local authorities is essential to work with crowd monitoring data. Besides that, additional systems are often installed at events for short durations of time. Their location is often guided by the availability of power supplies and internet connectivity. The setup of the system is often only finalized after installation. This requires a versatile setup of the research design as well to link the crowd monitoring data to RP surveys.

10. Suggestions for future work

Currently, crowding in these densely populated spaces is mainly analyzed and managed using quantifiable objectives, such as density, throughput, and walking speeds. The question arises whether quantitative objectives represent the perception of crowdedness of citizens, tourists and mass event visitors, and which factors, besides the physically experienced crowdedness, influence their perception thereof. This research showcased 4 preliminary studies into the perception of crowding and safety at crowded pedestrian spaces. The conclusions above provide various suggestions regarding an improved empirical design for PLoS studies. Besides that, this study developed linear regression models for relatively small data samples. More research into PLoS models for crowded pedestrian spaces is required to develop comprehensive, trustworthy PLoS models for these complex scenarios. In addition, the use of choice modelling techniques, such as latent class analysis, could potentially further model development and be used to capture the various subgroups that experience crowded pedestrian spaces differently.

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References

Arellana, J., Saltarín, M., Larrañaga, A. M., Alvarez, V., & Henao, C. A. (2020). Urban walkability considering pedestrians' perceptions of the built environment: a 10-year review and a case study in a medium-sized city in Latin America. Transport reviews, 40(2), 183-203.

Banjeree, A., Maurya, A.K., Lammel, G., 2018. A review of pedestrian flow characteristics and level of service over different pedestrian facilities. Collective Dynamics, 3.A17, 1-52.

Bian, Y., Wang, W., Lu, J., Ma, J. Tan, D., 2007. Pedestrian level of service for sidewalks in China. Proceedings of the 86th Annual meeting of the Transportation Research Board (TRB), #07-1185.

Dowling, R., Reinke, D., Flannery, A., Ryus, P., Vandehey, M., Petritsch, T., Landis, B., Rouphail, N. Bonneson, J., 2008. Multimodal Level of Service Analysis for Urban streets. NCHRP report, 616. Transportation Research Board.

Ewing, R., & Handy, S. (2009). Measuring the unmeasurable: Urban design qualities related to walkability. Journal of Urban design, 14(1), 65-84.

Finch, E., 2010. Pedestrian comfort level guidance. Transport for London.

Fonseca, F., Ribeiro, P. J., Conticelli, E., Jabbari, M., Papageorgiou, G., Tondelli, S., & Ramos, R. A. (2022). Built environment attributes and their influence on walkability. International Journal of Sustainable Transportation, 16(7), 660-679.

Frank, L. D., Sallis, J. F., Saelens, B. E., Leary, L., Cain, K., Conway, T. L., & Hess, P. M. (2010). The development of a walkability index: application to the Neighborhood Quality of Life Study. British journal of sports medicine, 44(13), 924-933.

Fruin, J., 1971. Designing for pedestrians: A level-of-service concept. Highway Research Record, 355, 1-15.

Greenshields, B., 1993. The photographic Method of studying Traffic Behaviour, Proceedings of the 13th Annual meeting of the Highway Research Board.

Grolle, J., 2017. Perception of crowdedness, safety and atmosphere in large groups of people, Delft University of Technology, The Netherlands, BSc. thesis.

Hoskam, S., 2018, The experience of safety of cyclists and pedestrians in shared spaces, Delft University of Technology, The Netherlands, BSc. thesis.

Landis, B., Vattikuti, V., Ottenberg, R., McLeod, D., Guttenplan, M., 2001. Modeling the roadside walking environment: pedestrian level of service. Transportation Research Record, 1773, 82-88.

Raad, N. Burke, M., 2017. Pedestrian Level-of-Service tools: problems of conception, measurement and usefulness. 39th Australasia Transport Research Forum (ATRF), #01700836.

United Nations, Department of Economic and Social Affairs, Population Division, 2015. World Urbanization Prospects: The 2014 Revision, (ST/ESA/SER.A/366).

Van Gelder, A. 2018. Drukte op het perron en impact op reizigersbeleving. Technical report, NS Stations.

World Tourism Organization, 2019. World Tourism Barometer, 17.1, Madrid, Spain.

Zuurbier, E., 2019. Pedestrian perception on Level of Service measures at mass events, Delft University of Technology, The Netherlands, MSc. thesis.