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Research Article

Study of the Space Occupied by a Wheelchair User at Metro de Santiago Platforms by Laboratory Experiments

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The objective is to study the space a wheelchair passenger would use in the preferential waiting areas of an urban railway platform. For this purpose, an analysis of the variables that interfere in the space occupied by a wheelchair user was carried out at Metro de Santiago platforms, to design a preferential prototype waiting area at the Human Dynamics Laboratory of the Universidad de los Andes (Chile). The prototype has a 3.0 m long and 2.5 m wide carriage, together with a preferential waiting area on the platform of the same length as the carriage, and 2.0 m wide. With this prototype defined, a detection method was developed using PeTrack software, to accurately identify the limits of the space occupied by a wheelchair user under two scenarios of different density levels in the preferential waiting area: medium-density (1.5 passengers/m^2) and high-density (4.0 passengers/m^2). It was observed that the space occupied by a wheelchair user decreased by 33% as the density increased from medium to high. On the other hand, for a high-density level, the space occupied by a wheelchair user was found to be 61% higher than that occupied by a passenger without reduced mobility. This variation occurred mainly because passengers increased their distance from the wheelchair user, which widened their area of influence. Further experiments are proposed as future research to extend this analysis using other density situations.

1. Introduction

Currently, the metro network in Santiago is the main axis of the capital's public transportation system. It connects 26 of the 52 municipalities that make up the Metropolitan Region, thanks to the operation of its six lines. It is considered the greatest structuring power in the city, thus, the most relevant compared to other modes of transport [1]. Thus, its occupancy rate reflects that 58% of the trips made in public transport correspond to a metro system mode of transport [1]. On an average working day, it has come to register about 3 million users in normal conditions [2].

It is in this context where certain norms, regulations, and standards have had to be established for the subway system in Santiago to become a universally accessible form of transportation. The term universal accessibility has been defined in Chile as "the condition that environments, processes, goods, products, and services must meet to be understandable, usable, and practicable by all people, in conditions of safety and comfort, most autonomously and naturally possible" [3]. In this sense, passengers not only need access to public transport, but also use it [4]. Accessibility today is a very important concept focusing on the people to give them opportunities to use the environment [5, 6]. However, different types of accessible designs have been implemented in metro stations to improve quality of life [7].

The demographic data of the country taken during 2015 justifies the need to implement universal accessibility; here, it is indicated that the number of inhabitants with some type of disability corresponds to 16.7% of the total population of Chile, while in Santiago the total number of people with disabilities corresponds to 17.2%, which is equivalent to 1,188,757 people [8]. Now, as all modes of transportation must be accessible to all people, including people with disabilities, it only remains to determine who are the people who are disabled. A person with a disability is "a person who has one or more physical, mental, psychic, intellectual, or sensory impairments, of a temporary or permanent nature, and when interacting with various barriers present in the environment, is prevented or restricted from participating fully and effectively in society, on an equal footing with others" [9]. As reported by Park and Chowdhury [10], from those who are disabled, passengers using a wheelchair are perceived as one of the most vulnerable types of users due to the high interaction and physical barriers in public transport environments. In fact, D´Souza et al. [11–13] have reported that wheelchair users need more space and time to move in complex situations such as the process of boarding and alighting a public transport vehicle.

In this same manner, Metro de Santiago [2] has generated various measures to try to ensure proper universal accessibility for wheelchair users. These include the installation of elevators in its stations, guaranteeing access for all users to the platforms, delimitation of preferential spaces inside the cars, and demarcation of waiting areas on station platforms. This last measure is divided into two types of zones. The first waiting zone is the emergency waiting zone, which is constantly monitored by security cameras in case of any incident (e.g., fire or evacuation emergency). The second waiting area is preferential for wheelchair users, which is delimited with a blue line at the edge of the platform and adequate signage to ensure self-sufficient accessibility to Metro cars (see Figure 1).

Despite the measures implemented by Metro de Santiago [2], the high density of passengers on an average working day affects the occupation of such areas on station platforms, especially during rush hour at the preferential waiting areas [14]. Consequently, there is an impact on the space occupied by wheelchair users. However, it is not known exactly what this impact would be. Thus, it is proposed, experimentally, to study the space occupied by a wheelchair user in preferential waiting areas on platforms of metro stations. To this end, the specific objectives are as follows: a) to identify the study variables that interfere in the space occupied in preferential waiting areas of subway station platforms in Metro de Santiago; b) to define a method to obtain the space occupied in the defined waiting area; c) to simulate, in the Human Dynamics Laboratory of the Universidad de los Andes users waiting on the platform for the arrival of a car and entering it; d) to analyze the simulations to be able to obtain the space occupied for different passenger density configurations, in the preferential waiting area.

This article is structured in five sections, starting with the introduction. In Section 2, existing studies related to the space occupied by pedestrians are presented. In Section 3, the method is explained based on laboratory experiments. In Section 4, the results are presented followed by a discussion and conclusions in Section 5.

2. Existing Studies on Space Occupied by Pedestrians

To understand the space occupied by a person in pedestrian interaction situations in subway stations, it is first necessary to be clear about the behavior that a pedestrian assumes individually in such situations. First, a model is proposed by Rail Safety and Standards Board (RSSB) [15], which suggests that the behavior assumed by a pedestrian is subject to four criteria: (a) user density (e.g., the number of passengers boarding or alighting the train, and how many are waiting in the preferential waiting area of the platform); (b) physical design of the platform and car (e.g., the width and length of the preferential waiting area); (c) provision of information (e.g., adequate signage of the preferential waiting area); and (d) climate (e.g., protection from rain or cold). Another view, reported by Fruin [16] and Still [17], states that factors such as the age of pedestrians, their size, and the culture to which they belong must also be considered. In the case of a wheelchair user, the size should increase due to their movement disability and the use of mobility device (see Figure 2).

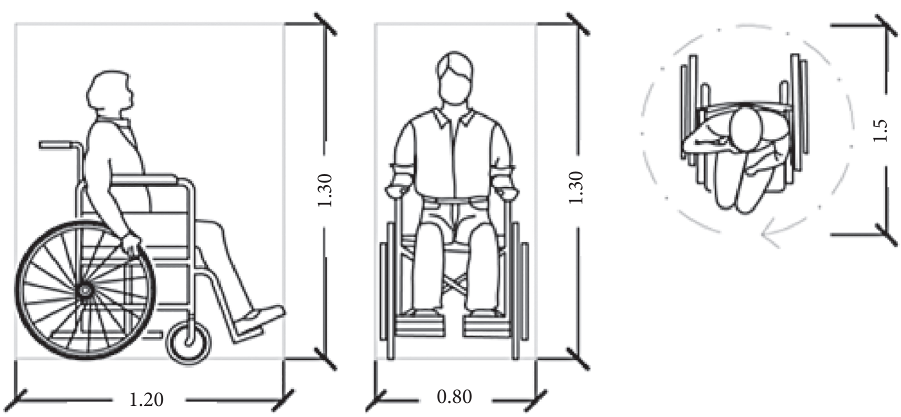
On the other hand, Webb and Weber [19] have mentioned that the behavior assumed by pedestrians in pedestrian interaction situations, such as subway stations, would also be determined by the ability to see, hear, and move, age, and gender of people. Similarly, Hoogendoorn and Daamen [20] propose that the behavior is determined by other characteristics, also specific to each user, such as the purpose of the walk, the familiarity of the route, and the luggage carried.

Another line of thought reported by Schmidt and Keating [21] determined that the factors influencing the behavior of a pedestrian, and therefore the space he/she occupies, are psychological elements. Within these, three states are described. The first is defined as a behavioral state, where the person feels crowded and has no control or freedom of movement. The second state is defined as cognitive and depends on the information given to the pedestrian before he/she is confronted with situations of pedestrian capacity collapse. The last state is decisional and corresponds to when the user has full freedom to make the desired movement.

Other types of models related to the perception of the distance between users have also been detailed by Sakuma et al. [22]. In this way, personal space has been described under two categories. The first category is based on an inner circle or ring of a small radius of influence, in which the pedestrian perceives a person or object and immediately tries to avoid it. The second category is defined as an outer ring of a larger radius of influence, where the pedestrian perceives a person or object at a certain distance and only prepares to be at a level of caution. Following this ring model, Hall [23] proposed four categories of distances between pedestrians, establishing in each of them a type of personal relationship. The first group of distances was called the intimate zone and corresponds to when distances of less than 0.5 m are established between pedestrians. Interpersonal relationships occur in this space. The second group is called the personal zone and is defined as the distance that can occur between people who are acquaintances, and its ranges are between 0.5 m and 1.2 m. The third group was called the social consultation zone and is defined as a range of distances between 1.2 m and 4.0 m. In this zone, we are facing unknown people, but it is still possible to establish

(a) (b)

Figure 1: Preferential waiting area at Tobalaba station, line 1, Metro in Santiago.



(a) (b) (c)

Figure 2: Dimensions (in m) of a wheelchair user in Chile reported by SERVIU [18].

communication if we would like to. Finally, the zone of public distance was defined, which ranges between 4 m and 10 m. Likewise, Sommer [24] states that the behavior or response of a user in pedestrian interaction situations is determined by three categories of distance. The first zone was defined as the intimate zone, which corresponds to distances of less than 0.5 m. The second category was defined as personal. The second category was defined as personal and is between 1.5 m and 1.2 m. Finally, there is the social zone, which corresponds to distances greater than 3.0 m. The models of Hall [23] and Sommer [24], although they have differences when segmenting each category according to distance, both agree that distances of less than 0.5 m correspond to the intimate zone.

In terms of pedestrian representation, one of the first models defined by Fruin [16] reports that a pedestrian can be spatially represented as an ellipse of area 0.3 m^2, circumscribed by the pedestrian's body depth of 0.5 m and the shoulder-to-shoulder width of 0.6 m. Subsequently, this model was complemented by Pushkarev and Zupan [25] who studied that when the pedestrian leaves the state of rest and starts walking, he/she covers a larger area due to the movement of the feet and arms and is represented as an ellipse of 0.75 m^2. The concept of sensory area was added to these studies, which is defined as the capacity of each pedestrian to perceive, evaluate, and react to a stimulus. Thus, this area corresponds to an ellipse 1.06 m wide and 1.52 m long as reported by Templer [26]. Even more detailed analyses have been specified by Gérin-Lajoie [27], in which the ellipses described by pedestrians are asymmetric and vary in size when pedestrians encounter obstacles or when accelerations in walking speed occur. More recent studies done by Seriani and Fujiyama [28] reported the space occupied by passengers alighting from the train when platform doors are used, identifying that they adjust such space to avoid collision with other users. The authors [28] used a mock-up at the UCL´s Pedestrian Accessibility Movement Environment Laboratory (PAMELA).

The behavior of a pedestrian and the representation of the occupied space are also affecting the comfort or stress in users, especially when subjected to situations of pedestrian interactions in confined areas such as subway station platforms. In turn, this perception of stress and comfort in pedestrian interaction situations is related to both psychological and physical factors [17]. Psychological factors are associated with the perception of risk and safety that each particular user has, while physical factors are correlated to the level of density users present. Therefore, a good service level measurement should encompass both variables [17]. The conception of the level of service is reported in the HCM [29], which is based primarily on physical factors for walking areas, stairways, and waiting areas. In the case of waiting areas (e.g., station platforms), Table 1 shows that density values range from the level of service *A* to the level of service *F*. It was collected and categorized into six subgroups from letter *A* (permanent circulation within the waiting area can be performed without disturbing others) to letter *F* (all persons within the waiting area are standing directly in physical contact with others, where no movement is possible, and panic is likely to be reached in large crowds at this density), with the level of service = *E* being defined as the capacity (physical contact with other users is unavoidable). While the level of service is an important indicator for determining comfort under crowding, it is only referenced or obtained under average values of densities in a given area and, thus, may not be representative for situations of high pedestrian interaction such as subway station platforms, where wheelchair users wait in front of train doors [30].

As can be seen, there are several physical variables and external environmental characteristics (pedestrian density, objects, climate, luggage, etc.), as well as those of each individual (culture, age, gender, size, sharpness of perceptual senses, physical build, the purpose of walking, mobility capacity, degree of interpersonal relationship between users, etc.), which ultimately determine the behavior, and therefore, the position that a pedestrian will adopt in space. It should be noted that the spatial characterization that a pedestrian has when combining a large part of these variables has already been studied previously. More recent studies done by Seriani et al. [31] reported in different scenarios the effect of the ratio between passengers boarding and alighting, using a mock-up of a London Underground train at a laboratory facility. Using also experiments, Geoerg et al. [32] studied the movement of passengers in a bottleneck and a corridor. The authors found that passengers changed their behavior by keeping greater distances and renounce to overtaking actions when they interacted with wheelchair users.

Although important advances have been made in this research, it is still necessary to study this space with more precision for wheelchair users in different conditions of platform density in subway stations. Thus, for this study, we seek to determine the space occupied by a wheelchair user in the preferential waiting area of platforms, being a space of high pedestrian interaction. For this purpose, a heterogeneous group of people surrounding the wheelchair user should be considered, so that the external variables are similar to those found in subway stations in Santiago.

3. Methodology

3.1. Observation at Tobalaba Station. Before establishing a method to determine the space occupied by a wheelchair user, a registry of subway stations with preferential waiting areas on their platforms was obtained. Tobalaba is the only station on line 1 of the metro system in Santiago that has this type of area, which is about 3.0 m long by 2.0 m wide. In addition, the platform includes a yellow line, which is located 60 cm from the edge of the platform to prevent passengers from falling into the train lines.

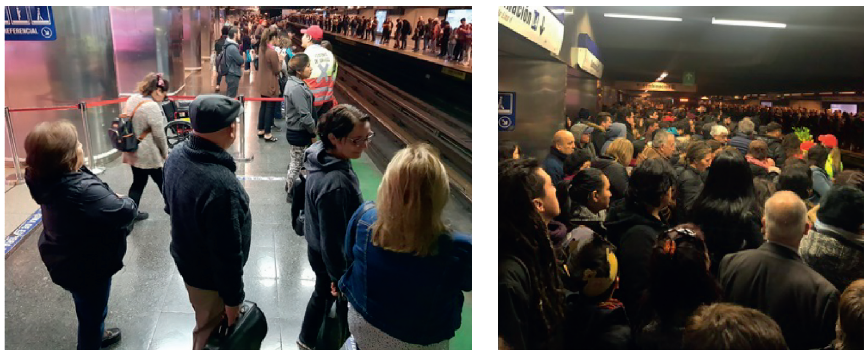
Two variables were observed. The first variable was the density of passengers using the preferential waiting areas. Density was defined as the ratio between the number of users (wheelchair users, elderly, pregnant women, people with babies, among others) and the area of that zone. The number of users making use of this area was counted in each cycle of boarding and alighting of the car. The second variable determined was the composition of the passenger flow. In other words, the type of user who made use of this zone was identified, which was obtained by counting in each cycle how many people corresponded to wheelchair users.

It was observed that the density of these zones varies between 1.5 passengers/m^2 and more than 4.0 passengers/m^2, depending on the hour of measurement (see Figure 3). The highest density is obtained for the morning rush hour, where passengers wait for the train in the direction of the east of the capital (towards Los Dominicos). In addition, it is reported that the preferential waiting areas were not always occupied by wheelchair users, being occupied by passengers without reduced mobility.

3.2. Experimental Design. Once the flow density and composition variables were obtained in the field, the preferential waiting area was defined at the Human Dynamics Laboratory of the Universidad de los Andes (Chile). The laboratory was created with the objective of providing guidelines for the design of public transport vehicles, the design of bus/metro stations, and the management of passengers in public transport systems. It consists of a full-scale model of a public transport vehicle and its adjacent platform. Video cameras and image processing are used for study the behavior of passengers. This laboratory is the only one of its kind in Chile and one of the few that exist in the world. The total area of the laboratory is 77 m^2, of which approximately 47 m^2 are used for the tests of 1:1 models of the public transport vehicles.

Table 1: Density values and available space in waiting areas reported in [29].

Level of service	Density of users (passengers/m^2)	Space available per user (m^2/passenger)
A	≤0.83	≥1.21
B	0.83–1.11	1.21–0.93
C	1.11–1.67	0.93–0.65
D	1.67–3.33	0.65–0.28
E	3.33–5.00	0.28–0.19
F	≥5.00	≤0.19



(a) (b)

Figure 3: Densities observed in preferential waiting areas at the Tobalaba station in the Metro of Santiago.

The scenario studied had a preferential waiting area similar to the Tobalaba subway station in Santiago, with a length of 3.0 m and a width of 2.0 m. The platform at the experiments has the same length as this area, but a width of 2.6 m since it includes a yellow line 0.6 m from the edge of the platform. The car in the laboratory has similar dimensions to the cars used in the Santiago metro, representing only the entrance hall (3.0 m long by 2.5 m wide).

The number of people studied (experiments done in 2019) was divided into two different density scenarios. In the first scenario (Figure 4(a)), 10 people participated, achieving a density of approximately 1.5 passengers/m^2, while the second scenario (Figure 4(b)) included 23 participants, obtaining a density close to 4.0 passengers/m^2. Both scenarios included the same wheelchair user, who has been using a wheelchair for 24 years. The wheelchair user is a young person (between 18 and 24 years old) whose weight is 70 kg, and the wheelchair model is an Activa Light (front wheels of 12.7 cm diameter, rear wheels of 61 cm diameter, total width of 60 cm, and total depth of 42 cm). In the first scenario, 80% of the participants were young people between 18 and 24 years of age, while 10% were adults between 24 and 36 years of age. In the case of the second scenario, 80% were also young people between 18 and 24 years of age, but 17% presented mobility difficulties, in which three of them had over 60 years old and one of them simulated to have a baby carriage.

For each of these scenarios, 11 repetitions were carried out, in which the users entered the carriage from the preferential waiting area and then descended from the carriage once the doors were opened. In this way, each of these repetitions or cycles of getting on and off the car consisted of three phases. The first phase consisted of users randomly entering the preferential waiting area from the platform, which simulated waiting for the arrival of a train. In addition, at this stage, three random users were told that they were in a hurry to board the car, to better represent a situation more similar to that observed in stations. Then, in the second phase, the doors were opened, and all the users entered the carriage, culminating with the closing of the doors. Finally, in the third phase, the doors were opened, and the users descended from the car, and the cycle ended with the closing of the doors.

3.3. Detection Method in the HDL. The PeTrack software elaborated by researchers Boltes and Seyfried [33] from Research Centre Julich was used to process the videos recorded at the moment when the users made the platform-car transition, which with the proper calibration was able to deliver the relative position of the users in the preferential waiting zone for each scenario defined in the laboratory. Such calibration was performed in two phases. The first phase, called intrinsic calibration, corrected the curvature of the camera lens to eliminate any distortion. The second phase, called extrinsic calibration, allowed associating the real Cartesian coordinates of the physical model with the digital reference system used by the software (pixel positions in the video). With these two calibrations performed, the software was able to deliver .txt files with the Cartesian positions or coordinates of the users marked in the program.

To understand the limits of the space occupied by the wheelchair user, where a detection method was established that indicated which users could be considered around the wheelchair user to be marked in the software, the first criterion used was that, to consider a user as a boundary, he/

Figure 4: Preferential waiting zone scenarios simulated in the laboratory.

she must have a direct field of view to the wheelchair user without obstacles or interference (e.g., persons 1 and 3 in Figure 5 are considered as the boundary, not person 2 who is not observed by the wheelchair user). The second criterion used establishes that, between two users close to the wheelchair user, there must be an angle greater than 5 degrees to consider both as the boundary of the occupied space (e.g., between persons 1 and 2 there are no more than 5 degrees and therefore person 2 is not marked). Both criteria were previously defined by other authors [28] who conducted similar research using a mock-up of a London Underground train, in which the area of passengers was measured on the platform for different scenarios of the ratio between passengers boarding and alighting.

The detection method defined also considered the edges of the preferential waiting area as the limits of the space occupied by the wheelchair-bound. For this purpose, three conditions had to be met simultaneously (see Figure 6):

(i) The first condition stated that when the distance between two users close to the wheelchair user was greater than 75 cm, the space between them would be considered free, and thus, an edge of the waiting area could be taken as the boundary of the occupied space. This was derived from Hall [23] and Sommer [24], who deduced that, at distances equal to or less than 50 cm, this space is considered to be the pedestrian's intimate zone. If this distance is added to the average body depth of a person, which is 25 cm [34], then free space is generated for distances greater than 75 cm.

(ii) Once the previous condition was met, a second condition was needed, which depended on the field of view of the wheelchair user. The first condition was to extend a line from the user who was close to the wheelchair user perpendicularly to the edge of the preferential waiting area. Subsequently, if the intersection of this line with the edge of the preferential waiting zone was within the field of view of the wheelchair user, then this intersection was considered as the limit of the perceived free space.

(iii) If a vertex of the preferential waiting zone was directly visible to the wheelchair user, it was to be considered as the boundary of the perceived space (third condition). In addition, in cases where the intersection of the line projected from the user to the edge of the preferential waiting zone was not visible to the wheelchair user, that intersection could not be taken as the boundary of the perceived free space.

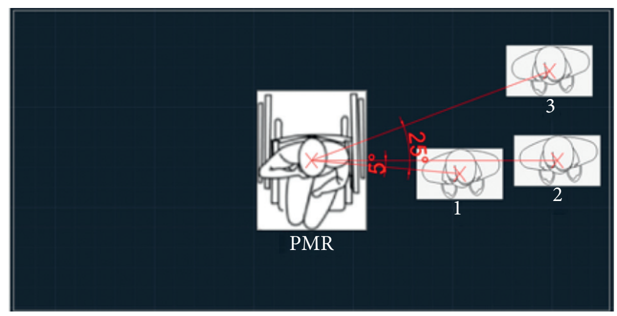
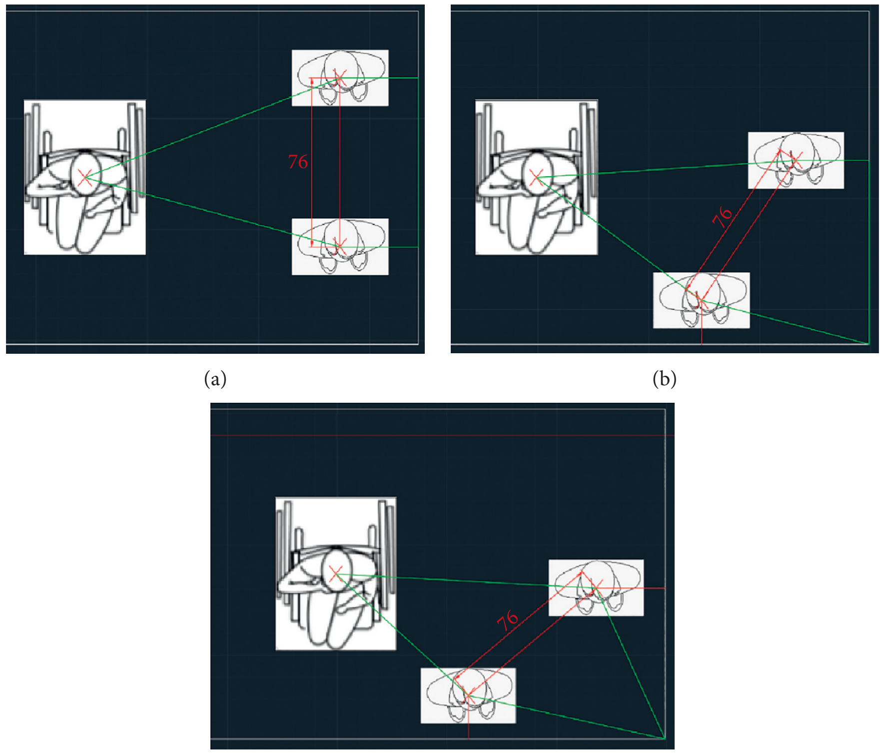


Figure 5: Marking of users outside the wheelchair-bound.

Once the limits around a wheelchair user had been parameterized, five variables associated with the polygon formed by delimiting the space occupied by a wheelchair user in each repetition for each scenario were studied. The first three variables studied were the space occupied, the distance to the wheelchair user, and the distance between users. These three variables determined whether the number of square meters of occupied space increased or decreased in each scenario. The other two remaining variables were the average lateral distance and the average frontal distance, which determined whether the distribution of the occupied space could be parameterized to obtain a regular polygon common to all the scenarios studied.

To obtain each variable, it was first established that the first ordered pair extracted as data in coordinates (x, y) in cm was the wheelchair user (see Figure 7). Subsequently, the following ordered pairs (x, y) in cm were extracted clockwise, marking the users with red numbers and the edges of the preferential waiting area with a green letter B. The first pair was the wheelchair user (see Figure 7). With this assignment of Cartesian coordinates, it was possible to apply the following mathematical formulations and obtain the desired results (Table 2).

3.4. Statistical Analysis. Once all the variables calculated for each repetition of each experiment were obtained (area of the space occupied by a wheelchair user by the sum of the



(a) (b) (c)

Figure 6: Preferential waiting area as a boundary of the space occupied by a wheelchair-bound. (a) Condition 1. (b) Condition 2. (c) Condition 3.

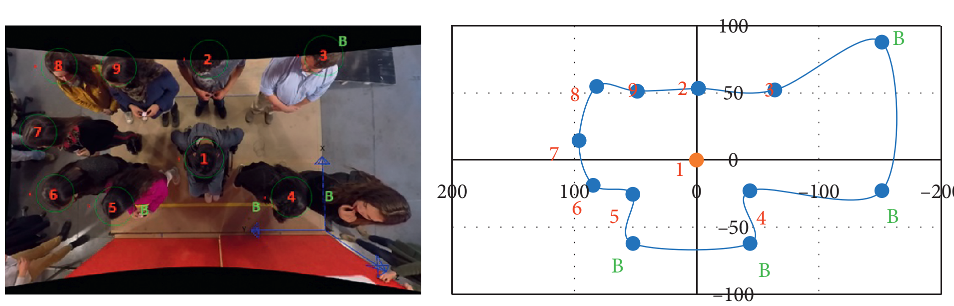


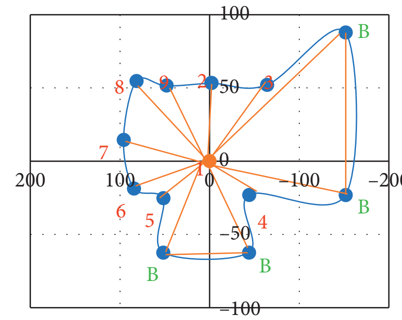
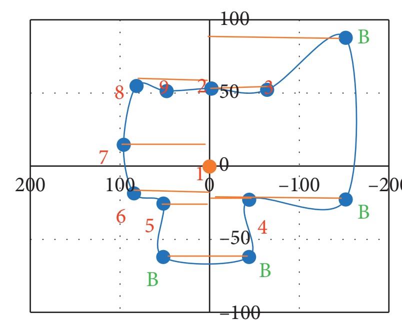
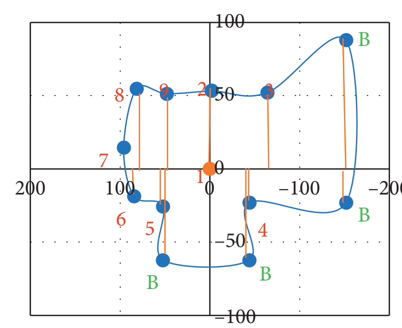
Figure 7: Sequence of detections using the PeTrack software.

triangles, the average distance between users, average right lateral distance, average left lateral distance, average rear vertical distance, average front vertical distance, and the average distance between users to the wheelchair user), a statistical analysis was performed to verify if these parameters changed when the density in the preferential waiting area was modified. In this way, we sought to quantify whether the means of these variables were different from each other.

All these variables mentioned above were assumed to behave as nonparametric variables since they were obtained through the position of the users in the space in front of a wheelchair user. This does not necessarily follow a normal distribution behavior when performing only between 10 and 11 repetitions of these experiments, where the users were randomly ordered in the preferential waiting area of the platform analyzed in the laboratory. So, to perform statistical analysis with sensitivity and lack of error, the Mann–Whitney U test was chosen, since it fulfilled all the assumptions necessary for its application. In the first place, it was a nonparametric test, and the parameters obtained were ordinal or continuous variables collected from experiments that were independent of each other.

The application of this test involved the average hierarchy of each variable analyzed in each repetition for the two scenarios being evaluated (i.e., comparison between pairs of results) had to be obtained. This means that the relative position, or rank, occupied by each data item for the total of all repetitions should be obtained, considering both scenarios being compared. Subsequently, the hierarchies of

Table 2: Variables of the space occupied in the HDL

Variables	Formula	Illustrative graphics
Area of space occupied using each of the triangles	$(1/2) - \mathrm{Det}\begin{bmatrix} x_1 & y_1 & 1 \\ x_i & y_i & 1 \\ x_{i+1} & y_{i+1} & 1 \end{bmatrix}$	
Average distance between users	$\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$	
Average distance between users and the wheelchair user	$\sqrt{(x_i - x_1)^2 + (y_i - y_1)^2}$	
Average right lateral distance	$\sum_{i=2}^{n} x_i \ (\forall x_i > 0)$	
Average left lateral distance	$\sum_{i=2}^{n} x_i \ (\forall x_i < 0)$	
Average rear vertical distance	$\sum_{i=2}^{n} y_i \ (\forall y_i > 0)$	
Average front vertical distance	$\sum_{i=2}^{n} y_i \ (\forall y_i < 0)$	

each variable in each repetition for each scenario had to be added up, and this means two sums of ranks were obtained for each variable analyzed. The first corresponds to the sum of the ranks for the first scenario, and the second to the sum of the ranks for the second scenario. Next, the U statistics had to be calculated and compared with the critical values. The comparison of these values finally determined whether the null hypothesis (H_0) was accepted, where it was established that the means were equal. Regarding the calculation of the minimum critical values for the application of this statistical analysis, the data was obtained from a table of coefficients specific to this test, and for the maximum value using a formula. In the case of the minimum value, the minimum critical value associated with the size of the samples compared and the percentage of confidence with which the test would be performed were sought. In the particular case of this report, the experiences would be analyzed and contrasted with a confidence level of 95%. The maximum critical value was obtained. Finally, for the null hypothesis to be true, this means that, for the average of the variables to be equal in both scenarios compared, two conditions had to be met. The first was that the minimum value of the U statistics had to be greater than the minimum critical value. In addition, the largest U-statistic had to be less than the maximum critical value. When both conditions were not met, then it could be said that there was not enough evidence to accept the null hypothesis, and therefore, the average of the variables is not equal; that is, there would be significant differences between the two scenarios compared.

4. Results

Through the above methodology, the results of the variables mentioned above were obtained for each of the repetitions, in which a wheelchair user was studied, in both the 1.5 passenger/m^2 (10 passengers) and 4 passenger/m^2 (23 passengers) density scenarios (see Tables 3 and 4).

For illustrative purposes, the polygons formed (measured in cm) can be seen, for the space occupied by a wheelchair user in each scenario, for each repetition (see Figure 8), which can be seen in detail and separately by repetition in Figures 9 and 10. The coordinate (0, 0)

Table 3: Results of the variables for the 1.5 passenger/m^2 scenario in the experiments

Run	Area occupied (m^2/pass)	Distance between users (cm)	Distance to wheelchair user (cm)	Rear distance (cm)	Right distance (cm)	Left distance (cm)	Front distance (cm)
1	2.35	53.85	74.49	52.36	76.18	35.74	69.04
2	2.04	69.18	72.06	22.81	80.90	51.43	66.01
3	2.31	56.02	78.73	40.29	75.36	49.23	85.29
4	2.46	75.34	71.63	37.89	79.37	59.52	73.86
5	2.61	74.40	81.78	24.48	88.94	64.31	82.91
6	1.97	72.04	71.31	41.07	58.44	52.85	75.38
7	1.98	73.99	79.86	65.81	43.37	29.09	95.35
8	2.13	62.24	81.33	43.09	96.54	33.18	74.64
9	1.85	65.42	70.38	43.40	63.45	50.62	55.10
10	2.20	74.39	59.79	72.46	56.03	41.79	76.52
11	1.38	57.05	64.22	35.75	49.39	44.52	62.22
Average	2.12	66.72	73.23	43.58	69.82	46.57	74.21
Std dev.	0.33	8.21	7.02	15.21	16.86	10.95	11.20

Table 4: Results of the variables for the 4 passenger/m^2 scenario in the experiments

Run	Area occupied (m^2/pass)	Distance between users (cm)	Distance to wheelchair user (cm)	Rear distance (cm)	Right distance (cm)	Left distance (cm)	Front distance (cm)
1	1.65	49.58	78.94	59.52	43.69	34.31	57.68
2	1.65	56.08	66.97	78.02	48.82	19.01	55.29
3	1.67	66.95	64.61	89.81	45.94	24.16	48.92
4	1.47	56.69	75.77	62.70	53.61	15.73	53.33
5	1.03	60.87	67.17	42.02	46.39	27.96	52.52
6	1.55	66.97	67.59	68.14	37.86	45.18	43.79
7	1.50	57.07	75.81	53.30	46.56	46.69	45.55
8	1.70	65.21	77.65	84.68	31.89	23.46	60.54
9	1.27	56.88	73.19	53.26	36.37	36.18	52.19
10	1.08	57.92	73.24	57.26	61.66	14.32	41.52
11	1.09	51.48	68.56	57.16	29.87	23.60	56.32
Average	1.42	58.70	71.77	64.17	43.88	28.23	51.60
Std dev.	0.26	5.80	4.96	14.61	9.41	11.06	6.03

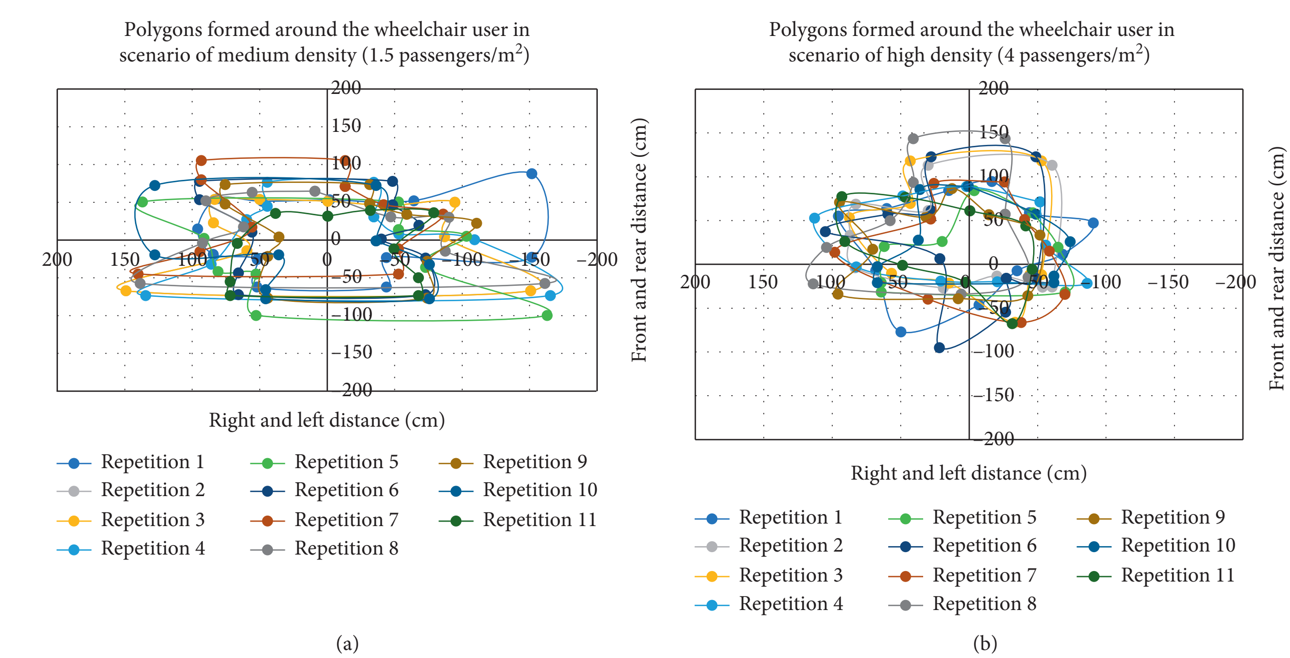
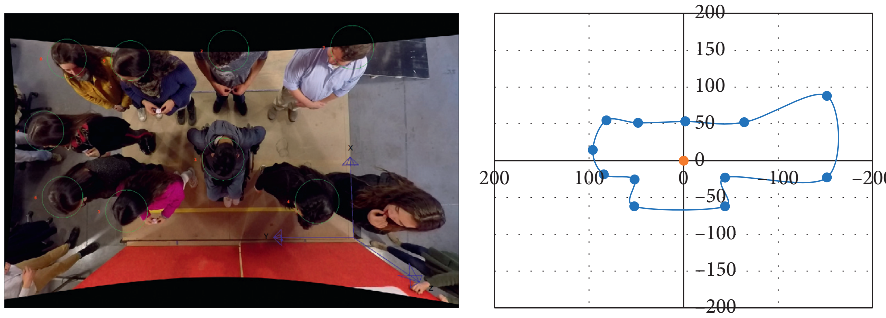


Figure 8: Graphical representation as polygons (measured in cm) of the space occupied by a wheelchair user in each scenario considering the total number of repetitions.



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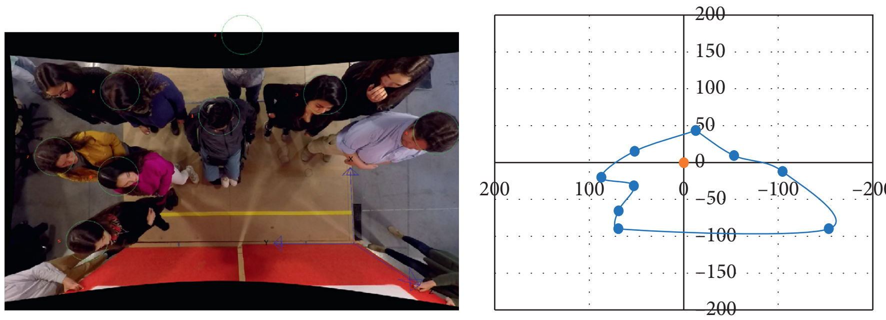

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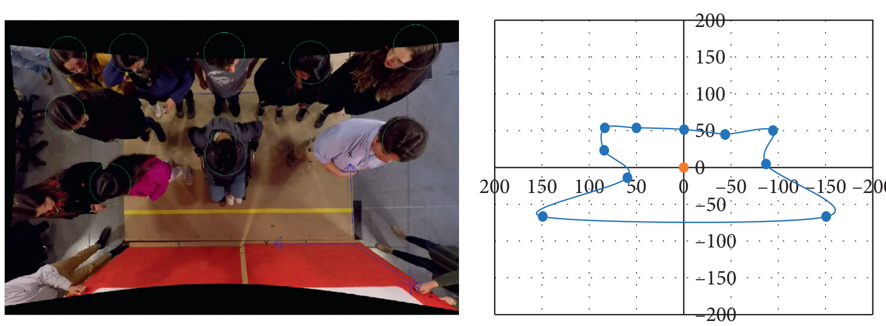

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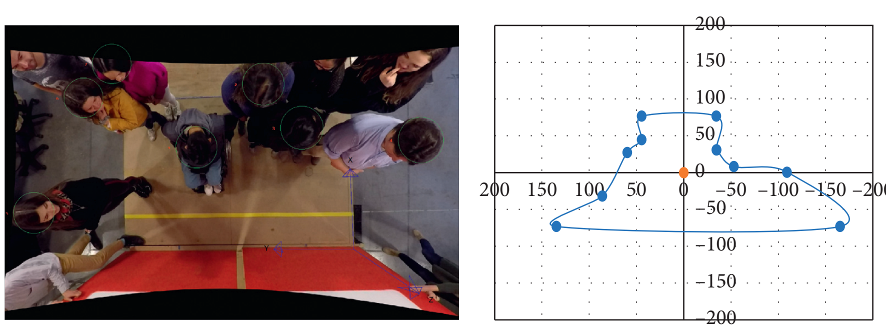

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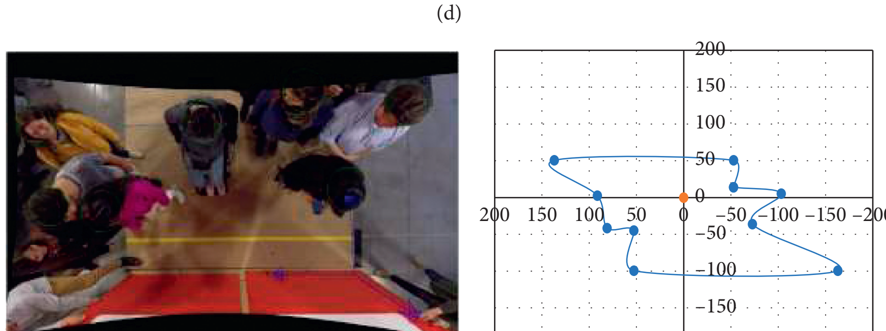

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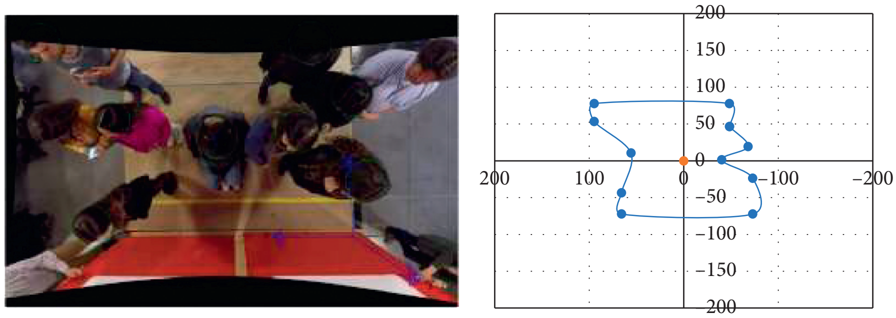
Figure 9: Continued.



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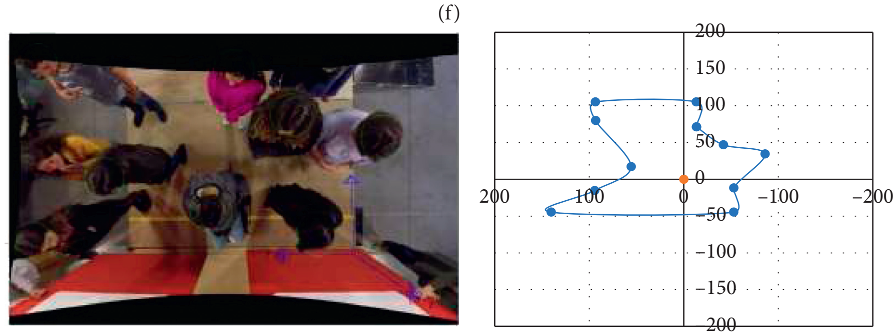

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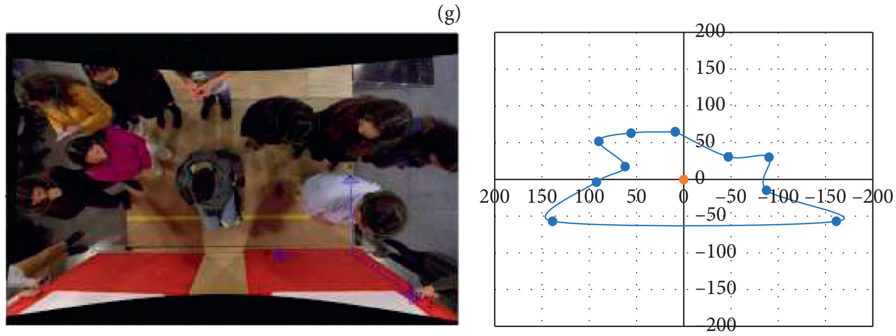

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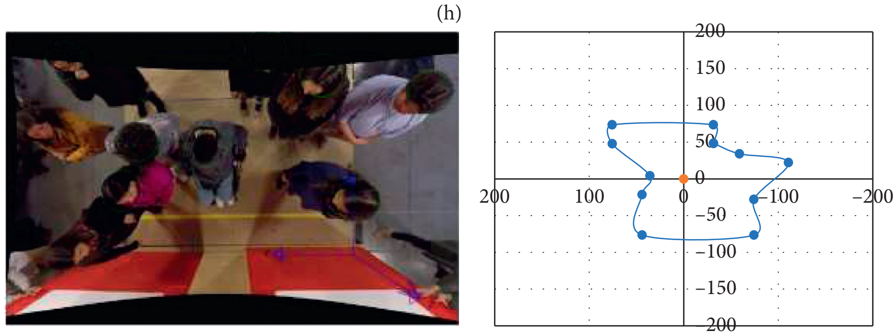

(i)

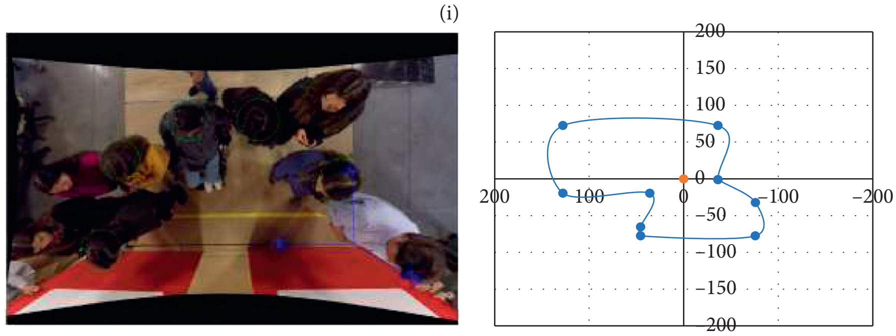

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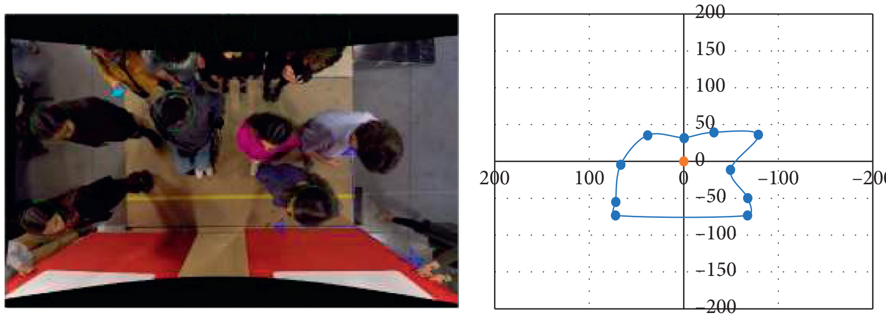
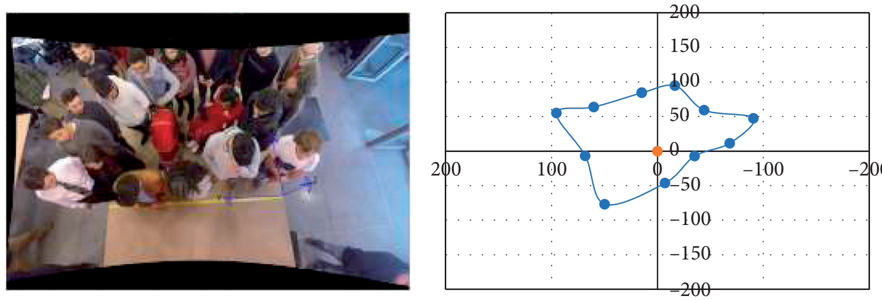
Figure 9: Continued.



(k)

Figure 9: Graphical representation of space (measured in cm) occupied by a wheelchair user in the case of 1.50 passengers/m^2 (11 runs).



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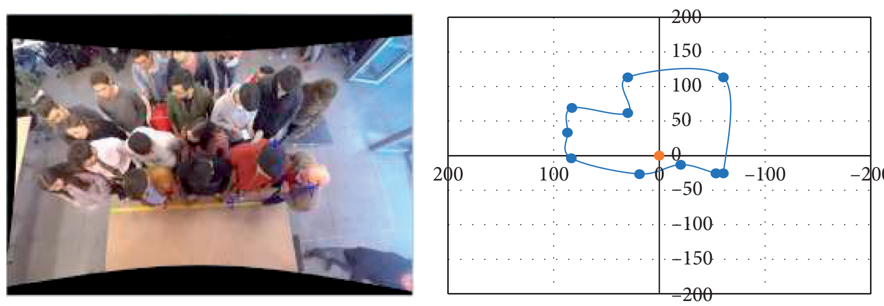

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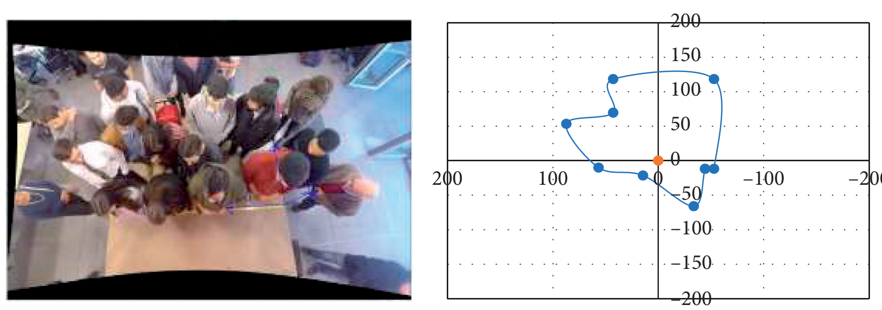

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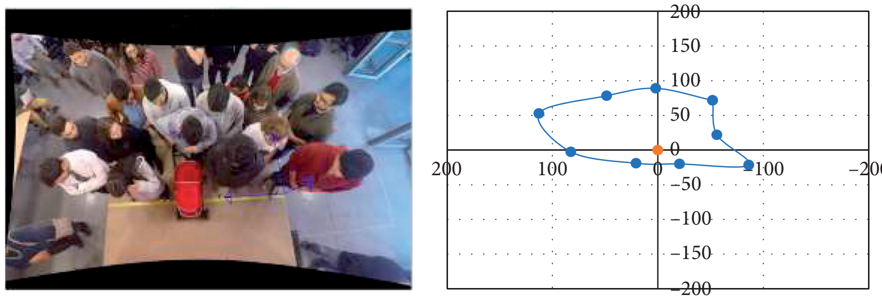

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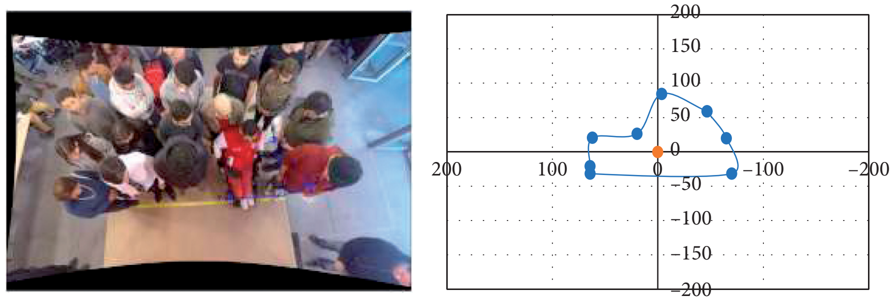

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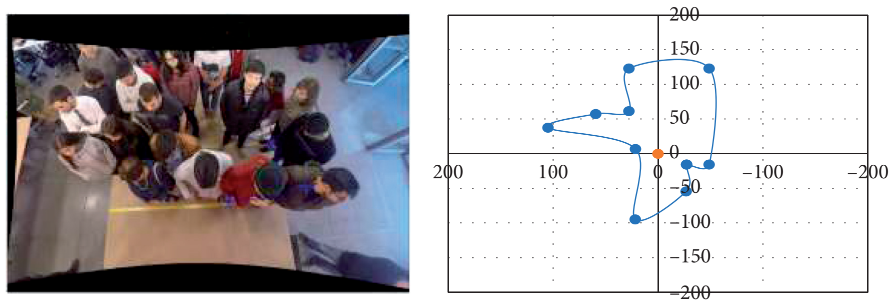

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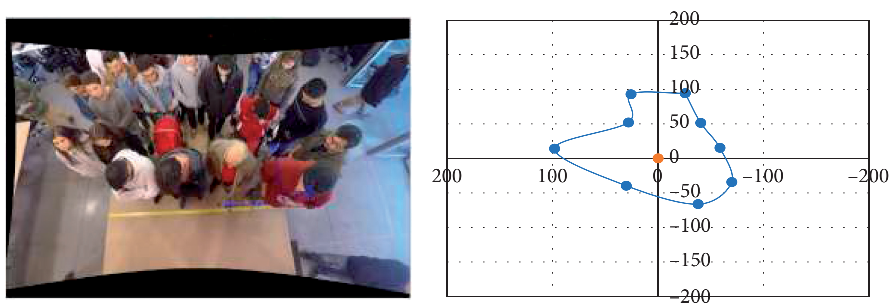

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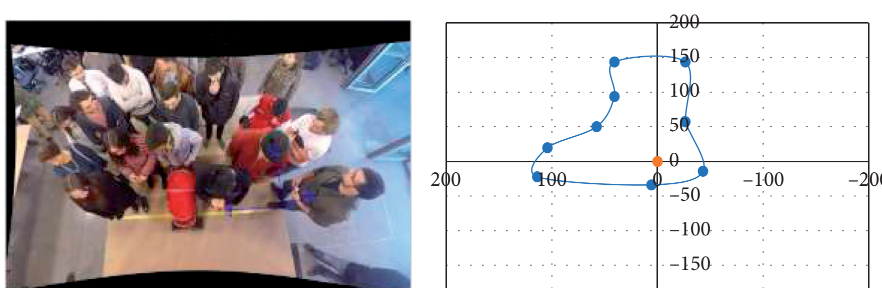

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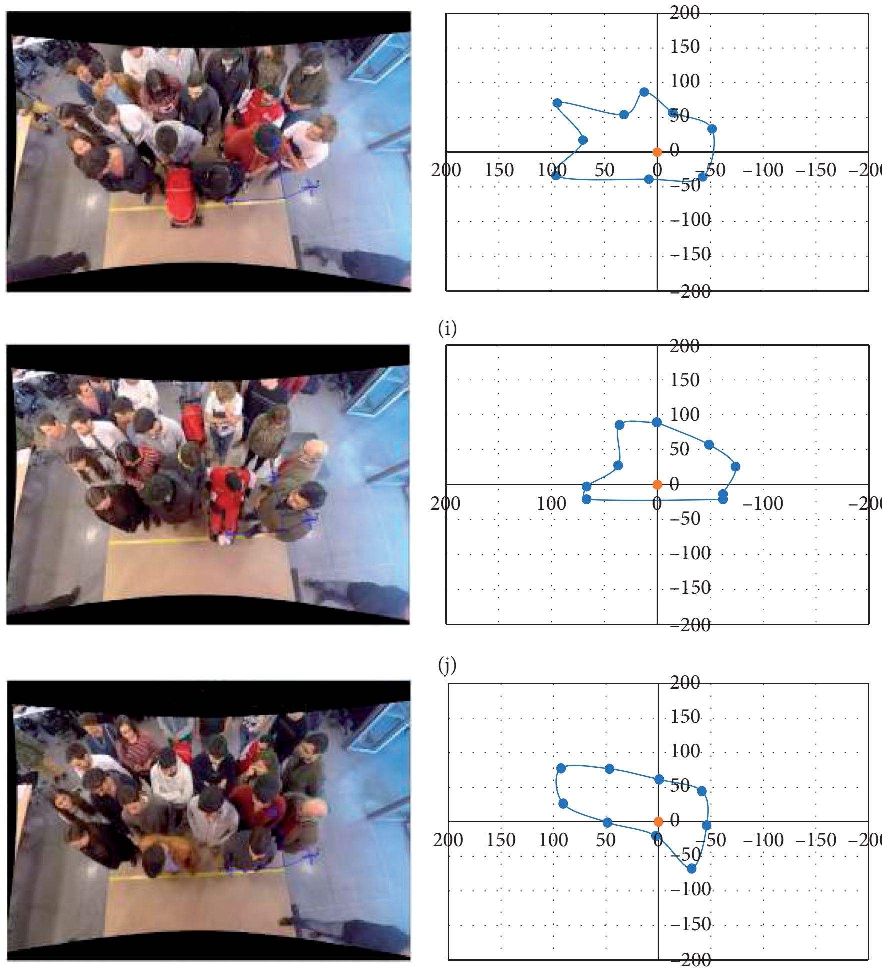


(i) (j) (k)

Figure 10: Graphical representation of space (measured in cm) occupied by a wheelchair user in the case of 4.0 passengers/m^2 (11 runs).

Table 5: Results of the variables for the 4 passengers/m^2 scenario in passenger without disability.

Run	Area occupied (m^2/pass)	Distance between users (cm)	Distance to passenger without disability (cm)	Rear distance (cm)	Right distance (cm)	Left distance (cm)	Front distance (cm)
1	0.98	58.89	68.98	62.46	42.08	18.73	47.48
2	0.73	51.72	58.78	39.90	48.24	31.84	19.34
3	0.49	53.58	57.09	41.29	39.48	0.00	43.15
4	1.19	56.19	64.23	51.28	43.36	31.39	58.11
5	1.20	46.76	68.12	57.30	53.02	29.21	36.49
6	0.97	46.82	55.88	47.31	26.66	31.36	56.36
7	0.84	53.38	61.83	39.39	48.32	36.72	31.64
8	0.77	53.55	66.65	44.14	69.32	4.25	37.51
9	0.80	56.35	55.40	42.43	40.21	21.80	42.29
10	0.77	63.82	60.15	42.27	38.37	12.73	60.75
11	0.68	57.79	61.17	46.26	43.87	12.46	39.78
Average	0.86	54.44	61.66	46.73	44.81	20.95	42.99
Std dev.	0.21	5.03	4.81	7.45	10.60	12.31	12.31

represents the wheelchair user, which is surrounded by other passengers at the preferential waiting area.

Statistical analysis was performed by collecting all the results of each repetition, for each scenario, using the Mann–Whitney U test. There is not enough evidence to assert that the means are equal for all the variables, which would imply that a change in density could have a significant impact on those analyzed variables. However, the only case, in which it can be statistically asserted that the means for both scenarios are equal, was the distance to wheelchair user.

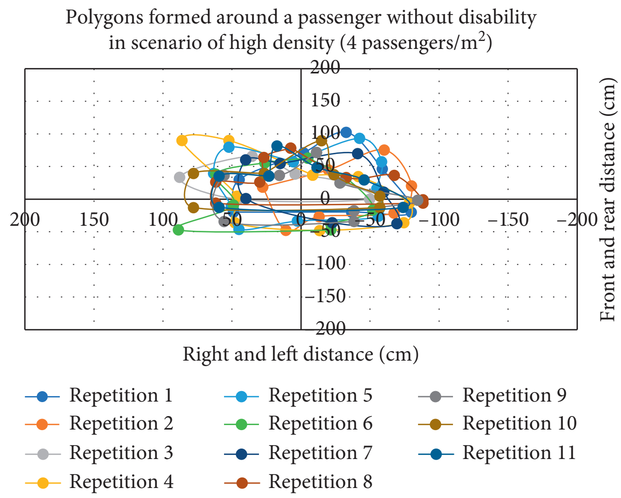
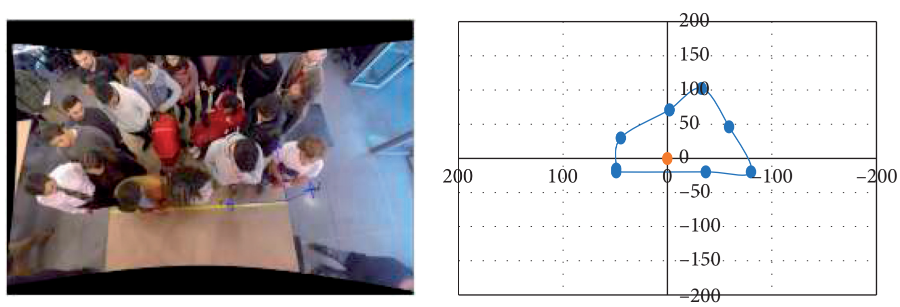


Figure 11: Graphical representation as polygons (measured in cm) of the space occupied by a passenger without disability in each scenario considering the total number of repetitions.



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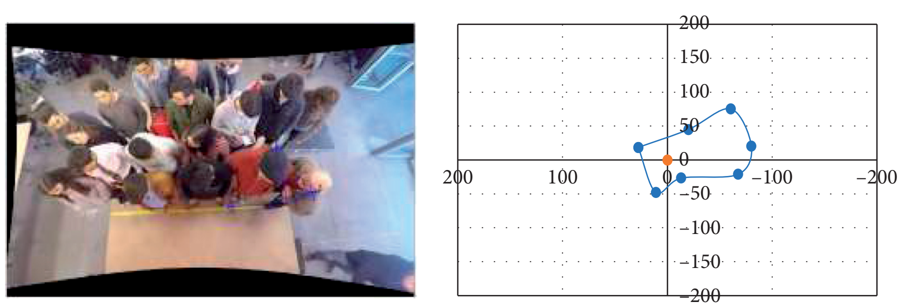

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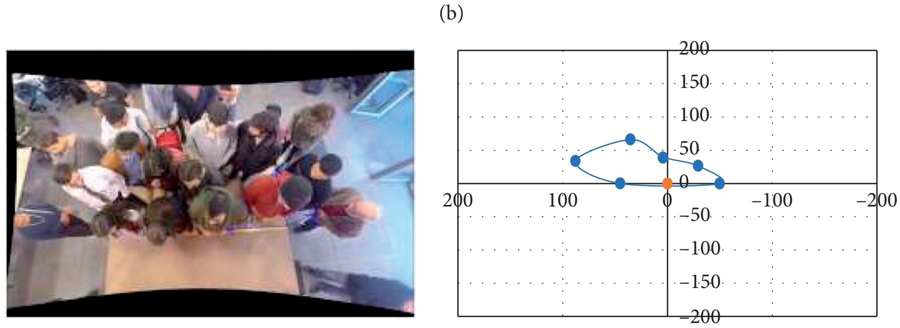

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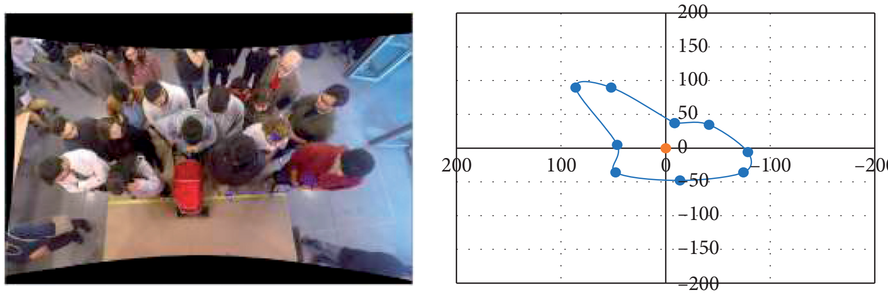

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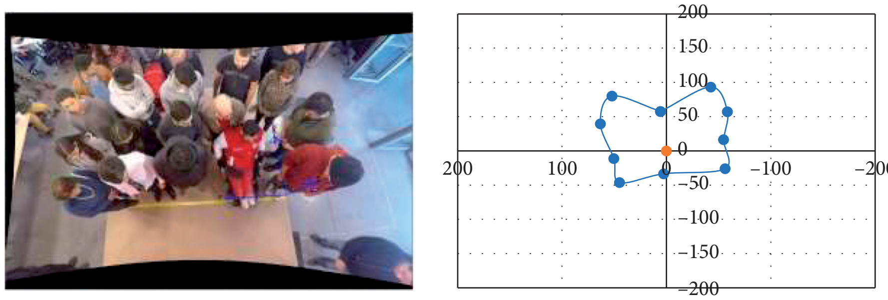

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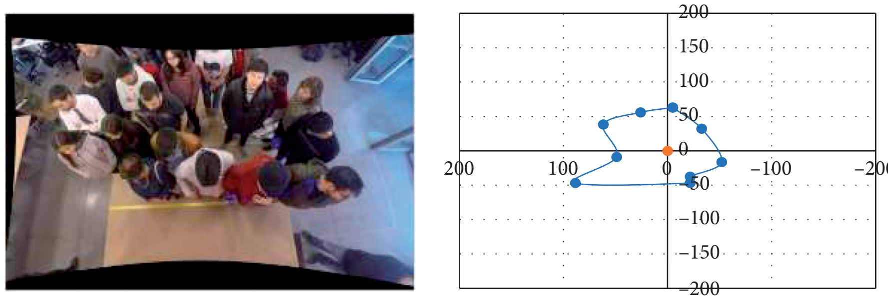

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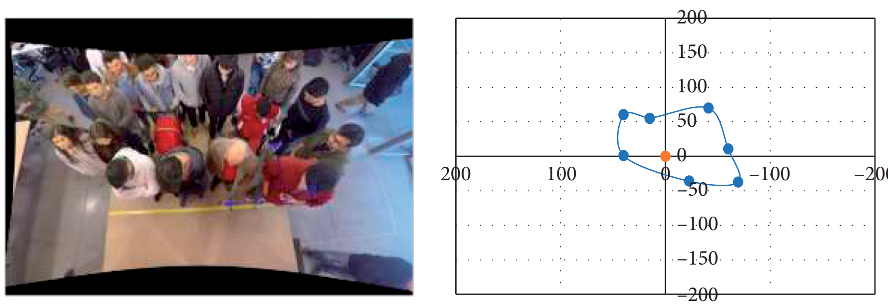

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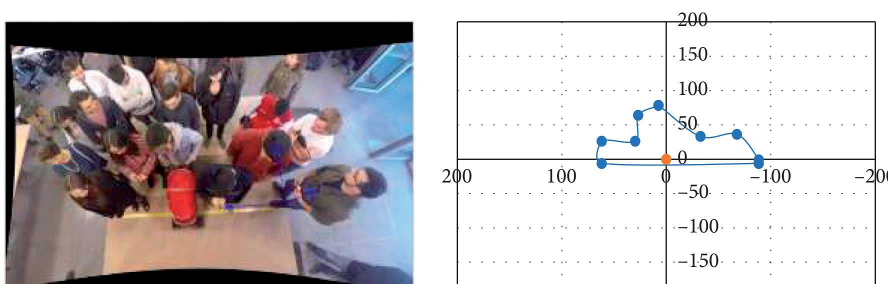
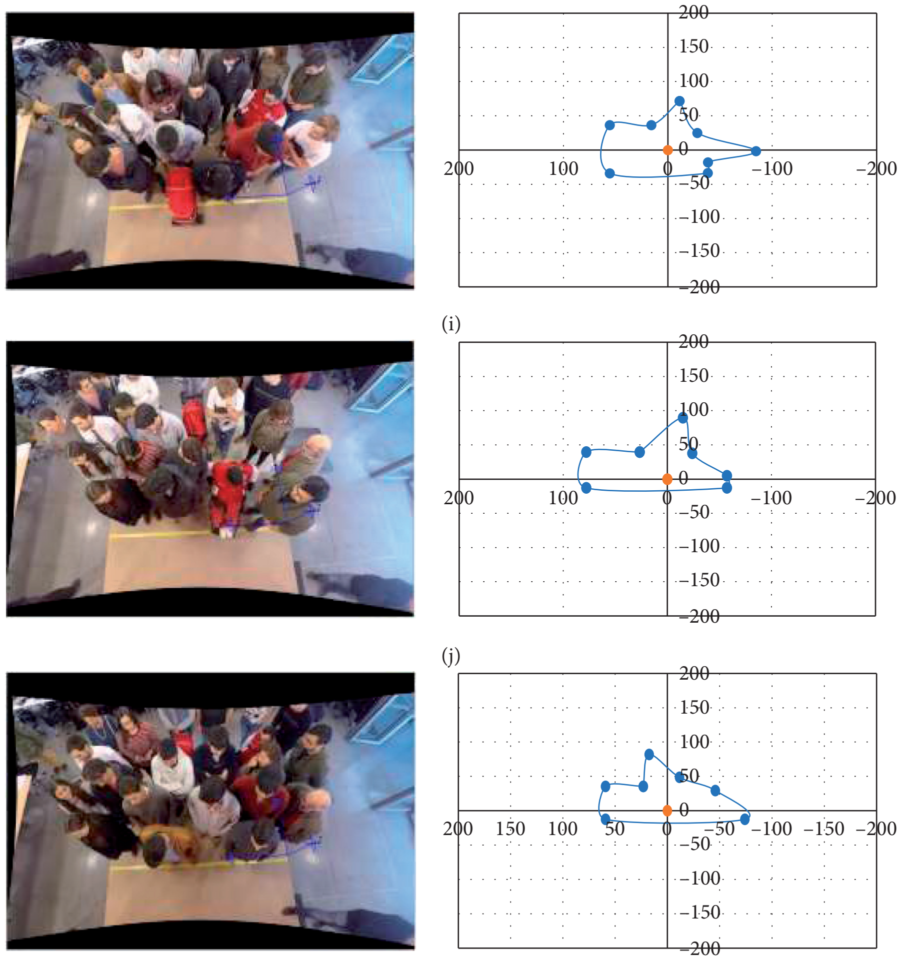


(h)

Figure 12: Continued.



(i)

(j)

(k)

Figure 12: Graphical representation of space (measured in cm) occupied by a passenger without disability in the case of 4.0 passengers/m^2 (11 runs).

This could be caused because in all cases passengers keep more distance from the wheelchair user, as the wheelchair user would need more space to move. Maybe this is something related to the behavior of passengers as reported by Geoerg et al. [32], which should be considered as further research.

Analyzing these data, it can be deduced that the 1.5 passengers/m^2 scenario had an average occupied space of 0.6 m^2/passenger (using the inverse of the average density of 1.5 passengers/m^2 in the entire preferential waiting area). While using the method defined in this research, the space occupied by a wheelchair user was 2.12 m^2 (almost 4 times the average occupied space). In the 4 passengers/m^2 scenario, the average space occupied by users was 0.25 m^2/passenger (using the inverse of the average density of 4 passengers/m^2 in the entire preferential waiting area), while the result of the space occupied by a wheelchair user using the method defined in this study was 1.42 m^2/passenger (almost 5 times the average space occupied).

When contrasting the density scenarios, it can be verified that, by increasing the occupational density (from 1.5 passengers/m^2 to 4 passengers/m^2), the space occupied by a wheelchair user decreased by 33%. This percentage variation was statistically significant enough to be able to reject the null hypothesis, which asserted that the mean space occupied by a wheelchair user for both scenarios was not the same. The reason why the space occupied by a wheelchair user decreased is because more passengers were surrounding the wheelchair user, and therefore the minimum criteria for including the platform edges (distance between users greater than 75 cm) were not met to a greater extent for the 4 passengers/m^2 scenario.

Furthermore, under this same contrast, it could also be observed that the distribution of the space occupied by a wheelchair user underwent a statistically significant change, since all the means of the distances (rear, front, right lateral, and left lateral) were different under the Mann–Whitney *U* test. Thus, since there is no total equivalence of these means, we can agree with the idea proposed by Gérin-Lajoie [27], who mentioned that the occupied space is not fully parameterized as an ellipse.

Equivalently, and as additional research, a contrast was made between the space occupied by a wheelchair user and the space occupied by a person without disability, both under a density scenario of 4 passengers/m^2 (see Table 5). In the 4 passenger/m^2 scenario a passenger without disability obtained, the average occupied space using the method defined in this research was 0.86 m^2/passenger, which is almost half of that used by a wheelchair user (1.42 m^2/passenger). This again verifies that a wheelchair user requires more occupied space than a passenger without disability, which has significant differences. In other words, regarding the distribution of the space occupied, it is not possible to state that it is similar between a wheelchair user and a passenger without disability. There is a significant variation in the area, and there is also a variation in the posterior distance that users maintain for the wheelchair users. However, there is not enough evidence to assert that the means are equal for the distance between passengers, the lateral (right and left) distances, and the front vertical distance. This could be caused by the comparison between the wheelchair user and the passenger without disability under the same scenario of density.

In addition, the polygons formed in each of the repetitions to identify the space occupied by a passenger without disability are shown in Figure 11, which can be seen in detail and separately by repetition in Figure 12. The coordinate (0, 0) represents the passenger without disability, which is surrounded by other passengers at the preferential waiting area.

5. Conclusions

The study and analysis were carried out under two different scenarios, to quantitatively measure the impact on the space occupied by a wheelchair user under different densities. In addition, this research also contrasted the space occupied by a passenger without disability under constant external conditions.

Regarding the variations in user density, it was observed that the space occupied by a passenger without disability decreased by 33% when increasing the density from 1.5 passengers/m^2 to 4 passengers/m^2 as expected. This decrease in space is explained by the fact that users with higher density decrease their separation distance to a range of less than 75 cm, so that the edges of the preferential waiting area are no longer considered as limits of the perceived free space. On the other hand, when the 4 passenger/m^2 scenario was analyzed for different study subjects, it was found that the space occupied by a wheelchair user is 61% larger than that occupied by a passenger without disability. This increase was mainly because users increased their distance from the wheelchair user, which expanded their area of influence.

Under different density scenarios, the results show that the space occupied using the method defined in this research was between 4 and 5 times greater for a wheelchair user than the average density in the entire preferential waiting area. This implies that a wheelchair user needs and occupies more space than the average of all users. This result reinforces the criticism made by Evans and Wener [30] to the density used by Fruin [16] and reported in HCM [29] through the level of service, which is composed of an average in the study area and, therefore, may not be representative of wheelchair users.

With the completion of these two scenarios, it can be noted that the occupied space can increase or decrease for two reasons. The first reason is that users increase or decrease the distance between them, which results in counting or not counting the edges of the preferential waiting area as the limits of the occupied area. The second reason why the occupied space could vary is related to the fact that users decrease or increase the distance between the wheelchair user and each of them, thus generating a contraction or expansion of the area of influence.

Finally, for each of these experiments, an analysis was made of the distribution of the space occupied by the wheelchair user, using the variables of frontal distance, rear distance, right lateral distance, and left lateral distance (in addition to those mentioned above, as are the distance between users and the distance to the wheelchair user). Under this analysis, it was obtained that, by modifying external variables such as density (1.5 passengers/m^2 and 4 passengers/m^2), there was a statistically significant difference in terms of space distribution, which would affirm the argument put forward in the literature, which mentions that the space occupied is not entirely parameterizable as an ellipse and would depend on external conditions as reported by Gérin-Lajoie [27].

As a contribution to Metro de Santiago operators, it is important to notice that preferential waiting areas should be designed from the point of view of passengers with disabilities such as wheelchair users, who need more space than passengers without disabilities. Therefore, practitioners could find in this research a method not only to obtain the space occupied by a passenger, but also to understand the need of an adequate space to improve accessibility at the platform-train interface.

Given the results obtained, a research line is left open to define a methodology or mathematical argumentation that manages these polygons of areas, under the same conditions of waiting areas, since it was not observed that there was a statistically significant difference between them.

Another way that can be a source of future research is to test scenarios with other density conditions, in order to establish a mathematical relationship between the occupied space and the density through some regression. The methodology used to understand the behavior of other users could also be extended, for example, those who have other disabilities that do not necessarily imply the use of a wheelchair. In this sense, new experiments are needed to expand the current level of service [16, 29] for passengers with disabilities in waiting areas.

The main limitation of this study is that the waiting areas were based only in the case of Tobalaba metro station, and therefore, it was not possible to expand the analysis to other metro systems in Chile due to the pandemic (COVID-19), which is affecting the whole world. Future research will consider different types of special waiting area tested in laboratory and in existing stations.

Data Availability

The data are available at https://www.uandes.cl/get-eng/research/

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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