Pedestrian behavior experiments in and around automated revolving doors

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Abstract.
Revolving doors are a means to provide access to a building, while maintaining the interior climate. To study pedestrian behavior in and around automated revolving doors, Delft University of Technology has performed laboratory experiments. In the experimental scenarios, we varied the door rotation speed, the population, the presence of a guiding device and the walking pattern. This paper shows new insights into this behavior with respect to travel times, delays, queue characteristics, free speed distributions and the capacity of a revolving door (Tournex with diameter 3.60 m).

From our investigations, it turns out that the free travel times are nearly equal for all scenarios, although lower door rotation speeds lead to slightly higher travel times. Commuters appear to form bulk queues upstream of the entrance, leading to frequent activations of the safety sensors, and thus to numerous breakdowns and longer waiting times. A fence in front of the revolving door has a positive effect on the behavior of these hasty commuters.

In the experiments, considerable differences between the walking operations of different types of pedestrians were observed. For both commuter and shopping population, an increase in door rotation speed results in a higher mean capacity (up to 19%). Opposite flows cause a reduction in the capacity (~ 15%). When the door is loaded with commuters, the door capacity is 10.1% - 26.2% higher than with a shopping population. This is mainly due to the larger space requirements and the lack of urgency to completely fill a segment.

INTRODUCTION
Designing safe and efficient pedestrian infrastructure (shopping centers, airports, stations, offices, stadiums, etc.) is rather complicated (1-8). Reasons for this include the complicated interactions between infrastructure users (two directional flows, crossing flows, waiting pedestrians, etc.) and the infrastructure. These interactions make it nearly impossible to predict the infrastructure functioning beforehand, without using proper tools, particularly computer simulation. However, currently available computer software does generally not model entrance points (such as doors, sliding and revolving doors and turnstiles) accurately (9-13). This is remarkable, since these entrance points are usually bottlenecks in the design, both in normal and in exceptional conditions (e.g. evacuations). Moreover, new entrance concepts and technologies are developed, of which the functioning can only be correctly predicted using accurate simulation tools.

Before simulation tools can be extended with pedestrian behavior in and around entrance points in general, and specifically revolving doors, we first need to get insights into this behavior. Since a literature survey did not reveal any other contributions on this subject, we started to collect data. This paper describes a laboratory experiment involving a revolving door as well as some first analyses of the observed data.

First, a behavioral framework is derived, from which the experimental variables are derived. Secondly, the set up of the laboratory experiment is discussed, followed by some preliminary analyses. The paper ends with conclusions and an overview of future work.

BEHAVIORAL FRAMEWORK FOR REVOLVING DOORS
To identify the aspects influencing pedestrian behavior in and around revolving doors, a behavioral framework has been derived, based on the general demand – supply framework (see FIGURE 1). Such a framework is a common approach to predict the performance of a traffic system as function of demand, supply, interaction and environmental information (15).

![FIGURE 1 Behavioral framework for revolving doors (14).](image-url)
Pedestrians interact with the revolving door, where the combination of pedestrian characteristics and revolving door characteristics determines the performance of the door. Both pedestrian characteristics and revolving door characteristics are not constant, but influenced by the environment (e.g. lighting, weather, temperature, cleanliness and surface conditions).

In this framework, demand comprises all characteristics related to pedestrians and pedestrian flow. Physical size and use of space, body sway, preferred walking speed, trip purpose and grouping behavior are typical pedestrian related characteristics (3,16,17). Important pedestrian flow characteristics are flow, density and arrival patterns. Special attention should be paid to the phenomenon of self organization (causing e.g. lane formation, oscillations at bottlenecks, faster is slower effect and zipper patterns of pedestrians inside bottlenecks) (9,18,19).

The supply represents the revolving door characteristics. Examples are door size, free rotation speed, number of wings and properties of the safety sensors. Each revolving door is equipped with multiple safety sensors, which force the door to stop when someone enters the safety sensor area. This avoids people getting stuck between the revolving door and the surrounding structure, but it may have a large effect on system performance. The safety regulations differ per country, thus influencing the safety sensor tuning and the revolving door performance. To get an idea of the different types of revolving doors, FIGURE 2 gives an overview of commonly used revolving doors as well as their most important characteristics.

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter Range</th>
<th>Typical Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tournex</strong></td>
<td>d = 3.60 – 7.40 m</td>
<td>e.g. airports, hospitals, supermarkets, hotels</td>
</tr>
<tr>
<td><strong>Duotour</strong></td>
<td>d = 3.60 – 5.40 m</td>
<td>e.g. airports, hospitals, hotels, bank buildings, public buildings</td>
</tr>
<tr>
<td><strong>Tourniket</strong></td>
<td>d = 1.60 – 3.80 m</td>
<td>e.g. office buildings, hotels, supermarkets, schools, public buildings</td>
</tr>
<tr>
<td><strong>Crystal tourniket</strong></td>
<td>d = 1.60 – 3.00 m</td>
<td>e.g. hotels, office buildings</td>
</tr>
<tr>
<td><strong>Twintour</strong></td>
<td>d = 3.00 – 3.80 m</td>
<td>e.g. airports, large office buildings, supermarkets, shopping centers</td>
</tr>
</tbody>
</table>

FIGURE 2 Types and possible configurations of revolving doors. The numbers below the name of the door indicate its diameter range $d$ (in m). Below the diameter it is indicated where each type of door are typically used.

To assess the functioning of the entrance mechanism, performance indicators are introduced. Some of these factors relate to the users, while others describe the revolving doors, being important for the revolving door performance.
manipulator and the manager of the area in which the door is positioned. User related factors are travel times, incurred delays, queuing and comfort. System performance measures are e.g. capacity, level-of-service (use of the space around the revolving door) and door breakdown rate (number of stops of the revolving door induced by pedestrians activating safety sensors).

**DATA COLLECTION**

To derive a model describing pedestrian behavior in and around revolving doors accurately, detailed insights into this behavior are required. These data can be obtained by collecting real-life data or by performing controlled laboratory experiments. The chosen data collection method should fulfill the following requirements:

1. The resulting data set should contain microscopic pedestrian behavior, e.g. individual walking speeds, acceleration, interaction behavior and individual pedestrian characteristics.
2. The resulting data set should contain macroscopic flow behavior, e.g. flow, density and (average) speed.
3. Observation conditions should be stable to get the best possible results.
4. Flow conditions should be stable to have multiple observations in similar flows.
5. The observed behavior should be realistic.
6. The door should perform in conditions varying between low flows and saturated flows in which congestion is likely to occur.
7. The population should correspond to the population in different environment, e.g. transfer stations and shopping centers.

Apart from the abovementioned requirements, some practical requirements came up with respect to the observation equipment and the locations available to attach the equipment at the observed site and the time needed to perform the observations. During real-life observations, flow conditions may vary only slightly, which makes congestion hard if not impossible to observe. To observe different populations (requirement 7) different observations will have to be performed. Advantages are that the observed behavior is natural (if people do not recognize the observation equipment) and that a random population is observed. In a controlled environment the researcher is in control of all conditions, concerning not only external factors, but also composition and size of the flow, variation of the flow over time (leading to different door loads) and revolving door characteristics (such as revolving speed and safety sensor adjustment). Moreover, qualitative real-life observations had already been performed by the revolving door company. Disadvantages are the cost to build up a revolving door in the laboratory and the fact that the observations might be biased since participants do not behave naturally. The latter can be overcome by keeping the experiments on a skill-based level, that is that pedestrians will behave in a subconscious way. Since pedestrians are familiar with revolving doors, they will not expose ‘new’ behavior thus behaving as in real-life. These considerations as well as our experiences in performing experiments to observe pedestrian behavior (20,21) lead to the decision to perform a laboratory experiment.

**Experimental set up**

Two types of variables are distinguished for the experimental set up, namely experimental variables and context variables. Experimental variables are systematically changed by the researcher during the experiments to isolate and describe their influence within the system. Context variables are variables that cannot be influenced by the research, but these do influence the system performance.

The experimental variables are free door rotation speed, population and pedestrian flow composition, flow and walking pattern. The free door rotation speed is the speed with which the tips of the door wing travel over the circumference of the entrance. At low rotation speed, pedestrians have much time to fill a segment, but their travel time through the door will be higher. At high rotation speed, the opposite occurs: pedestrians have less time to fill the segment, but they are able to pass the door faster. Populations are combinations of different types of pedestrians that form the load of the revolving door. Multiple variables of interest are brought together in this experimental variable, such as pedestrian type (gender, trip motive), free speed indication and aggressiveness. Aggressiveness relates to the degree in which pedestrians want to maintain their free or desired speed: if someone has to catch a train, he will put more effort into keeping a high speed than when he is strolling along a shopping street. The size of the pedestrian flow determines the load upon the revolving door. The aim is to gradually load the entrance to and beyond its capacity and then gradually decrease the load again. The walking pattern indicates the predefined routes that pedestrians follow during the experiments. Changing those routes will lead to loads from different directions, thus distinguishing between unidirectional flows, bidirectional flows and crossing flows. When the door is only loaded from one direction, pedestrians have a longer time to fill the segment than when an opposite flow is present that first has to empty the segment. In case of opposite flows,
strict separation of the two flows might decrease the hindrance and thus optimize the throughput of the revolving door. This separation might be induced by a fence next to the door (see FIGURE 3, top right).

As indicated before, the above described experimental variables are systematically changed during the experiments to identify their influence on the system performance and pedestrian behavior. In an ideal situation, all combinations of variables should be tested. Due to the time restrictions, a selection needs to be made in which all mentioned experimental variables and their values are observed.

After filtering all impossible and irrelevant combinations, the following questions were leading while defining the final experiments:

- What is the influence of the free door rotation speed on both pedestrian behavior and system performance?
- What is the influence of different populations?
- What types of conflicts are observed when pedestrians cross the ingoing flow?
- What is the influence of a fence that separates the in and outgoing flow?

This process has lead to the nine scenarios shown in TABLE 1.

### TABLE 1 Overview Experimental Scenarios

<table>
<thead>
<tr>
<th>Pedestrian flow</th>
<th>Revolving door</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>Rotation speed</td>
<td>Obstacle</td>
</tr>
<tr>
<td>50% N, 50% F</td>
<td>0.50 m/s</td>
<td>Free</td>
</tr>
<tr>
<td>50% N, 40% C, 10% T</td>
<td>0.75 m/s</td>
<td>Fence</td>
</tr>
<tr>
<td>50% N, 40% C, 10% T</td>
<td>1.00 m/s</td>
<td>Crossing flows</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Pedestrian flow</th>
<th>Revolving door</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

N = normal walking speed; F = fast walking speed; C = walking in couples; T = walking with shopping trolley.

The first four scenarios concern commuter flows, while scenarios five to nine consider a shopping population. The category ‘commuters’ consists of pedestrians in a hurry and pedestrians walking with their normal speed. ‘Shoppers’ are pedestrians walking in their normal speed, couples and pedestrians with shopping charts. For both flows, we considered three rotation speeds (slow, normal and fast). Also, for each type of flow a single scenario is performed with opposite flows using a fence for separation (see FIGURE 3, top right). The scenarios with commuter flows (1-3) consider unidirectional flows, while the scenarios with a shopping population consider opposite flows and as well as a scenario with crossing flows.

**Performing the experiments**

The experiments have been performed in the Stevin Laboratory of the Delft University of Technology. The walking area was 10 meters wide and 20 meters long. Two video cameras have been mounted perpendicular above the pedestrian flow at a height of 10 meters. The revolving door (three wings Tournex with a diameter of 3.6 m) was located in the middle of the walking area. The digital camera observed the walking area upstream of the revolving door, while the analogue camera observed the revolving door. A second analogue camera next to the door was used to register the characteristics of pedestrians entering the door.
Eighty persons participated in the experiment, whose age varied between 14 and 80 years. Participants have been recruited by advertisements in local journal, in university journals and on our internet site. Each participant was given a white T-shirt and a colored cap, the color of which depended on the role of the participant (normal walking pedestrian, fast walking pedestrian, walking as a couple or walking with a shopping trolley). The participants were subdivided into 8 groups of 10 people. Acquaintances were separated as much as possible to stimulate individual behavior. ‘Real’ couples were grouped together to form realistic couples in the scenarios five to nine. All group compositions were heterogeneous, indicating that groups consisted of men and women of different age.

Each experiment lasted around fifteen minutes. During this time period, participants walked through the revolving door, walked back around the observation area and joined the experiment again. After one or two minutes, depending on the scenario, an extra group was added to the experiment, thus increasing density and hoping to load the revolving door until capacity.

**DATA ANALYSES AND EXPERIMENTAL FACTS**

Before the gathered data can be analyzed, the raw video images need to be processed. For this, dedicated software has been developed at the department of Transport & Planning to identify and track pedestrians. The software results in a data set containing for each pedestrian his or her location over time (each 0.04 second), thus allowing to draw trajectories and perform detailed analyses. Some examples of these trajectories in experiment 1 are shown in FIGURE 4. We can see that during low and medium flows, pedestrians walk directly to the entrance of the door, while in higher flows pedestrians occupy a wider area upstream of the door in order to use the complete opening of the door.
FIGURE 4 Trajectories of pedestrians in experiment 1 (unidirectional flow with 50% normal and 50% fast walkers with a low door rotation speed).

Deriving cumulative curves
To obtain data on pedestrian travel times and door capacity, we use cumulative curves. A cumulative curve describes the time moments that passengers pass a given cross-section. To determine travel times, we have determined two cross-sections: one at the start of the walking area and a second one downstream of the revolving door (see FIGURE 5). Since the revolving door is considered to be the bottleneck, the departure curve can also be used to determine the capacity of the revolving door.

a. Location of arrival ($X_1, A(t)$) and departure curve ($X_2, D(t)$).
b. Arrival curve (blue) and departure curve (red) in scenario 2. The green line indicates the departure curve when pedestrians would not have experienced hinder.

c. Detail of the arrival and departure curve for scenario 2. Different traffic characteristics, such as free travel time, delay and number of pedestrians in the observed area, have been indicated.

d. Detail of the departure curve, downstream of the revolving door. The step wise function is clear, caused by emptying a segment.

FIGURE 5 Cumulative curves: location of arrival and departure curves (a), arrival and departure curve of scenario 2 (b), zoom of arrival and departure curve of scenario 2 (c), explanation of steps in departure curve during saturation (d).
The use of cumulative curves implies a first-in-first-out order of pedestrians. Since the system is empty at the start of each scenario, the travel time \( w \) of the \( N^{th} \) pedestrian corresponds to the horizontal distance between the departure curve \( D^{-1}(N) \) and the arrival curve \( A^{-1}(N) \) and can be calculated by

\[
w(N) = A^{-1}(N) - D^{-1}(N)
\]  

(1)

Pedestrian travel times, delays and queue characteristics

To calculate the delay of an individual pedestrian, a ‘free’ departure curve has been drawn, which is similar to the arrival time, but shifted over the free walking time to the right. This free walking time is obtained by calculating the travel time at low flows, since the delay due to the door is still included, while a pedestrian does not have waiting time due to congestion. When the realized departure curve is on top of the ‘free’ departure curve, pedestrians encounter no delays. The horizontal distance between the realized departure curve and the ‘free’ departure curve indicates the delay of each pedestrian. The total delay is then the cumulative delay of all pedestrians that arrived at \( X_2 \) during the considered time period, while the average delay is the total delay divided by the number of pedestrians.

While the arrival curve is rather smooth, the departure curve consists of steps. The varying step sizes show the varying capacity of the door over time. During oversaturation (queuing time) full segments empty quickly, but because of the door breakdowns it takes time before the next segment opens again. Hence, the higher the load upon the door, the more distinctive the steps become. The height of the steps indicates the number of pedestrians inside a segment, while the duration of a step (so-called clearing time) indicates the time it takes to empty the segment.

TABLE 2 gives an overview of travel times, delays and queue characteristics for each scenario. The free travel times are similar for all scenarios, except for scenarios 1 and 5 that have higher travel times due to the low peripheral speed of the door wings. Both the revolving door speed and the fence appear to influence pedestrian behavior. In scenario 1 and 5 the door speed is very low (comparable to revolving doors in hospitals), which gives pedestrians much time to completely fill the segments. This leads to frequent breakdowns, even at relatively low flows, and thus to longer delays. In the scenarios with one-directional commuter flow (1-4), pedestrians in congestion formed a bulk queue upstream of the entrance that completely occupied the opening. Their pushy behavior while entering the segments frequently activated the safety sensors. The fence appears to have a positive effect on the behavior of these hasty commuters, which are forced to stay in line and form a linear queue. The entrance can only be accessed for the right side of the fence, leading to less frequently activated sensors. Shopping pedestrians formed a linear queue, in which situation the fence might have negative influences, since it only reduces entrance width. The maximum number of pedestrians in the system is significantly higher in the scenarios where bulk queues are formed, since these queues have much higher densities than linear ordered queues.

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
<th>Scenario 6</th>
<th>Scenario 7</th>
<th>Scenario 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_r = 0.5 \text{ m/s} )</td>
<td>( v_r = 0.75 \text{ m/s} )</td>
<td>( v_r = 1.0 \text{ m/s} )</td>
<td>( v_r = 0.75 \text{ m/s} )</td>
<td>( v_r = 0.5 \text{ m/s} )</td>
<td>( v_r = 0.75 \text{ m/s} )</td>
<td>( v_r = 1.0 \text{ m/s} )</td>
<td>( v_r = 0.75 \text{ m/s} )</td>
</tr>
<tr>
<td>Free travel time [sec.]</td>
<td>14.50</td>
<td>13.63</td>
<td>13.05</td>
<td>13.22</td>
<td>14.50</td>
<td>14.08</td>
<td>13.86</td>
</tr>
<tr>
<td>Mean travel time [sec.]</td>
<td>50.96</td>
<td>43.86</td>
<td>32.27</td>
<td>29.90</td>
<td>35.05</td>
<td>27.70</td>
<td>26.16</td>
</tr>
<tr>
<td>Maximum delay [sec.]</td>
<td>101.50</td>
<td>103.38</td>
<td>79.95</td>
<td>70.78</td>
<td>48.50</td>
<td>48.91</td>
<td>43.14</td>
</tr>
<tr>
<td>Total delay [min.]</td>
<td>258.83</td>
<td>320.00</td>
<td>220.42</td>
<td>156.54</td>
<td>130.49</td>
<td>79.65</td>
<td>70.95</td>
</tr>
<tr>
<td>Max. queue length [ped]</td>
<td>54</td>
<td>53</td>
<td>58</td>
<td>37</td>
<td>30</td>
<td>28</td>
<td>25</td>
</tr>
<tr>
<td>Queuing time [sec]</td>
<td>500</td>
<td>600</td>
<td>450</td>
<td>800</td>
<td>700</td>
<td>375</td>
<td>400</td>
</tr>
</tbody>
</table>

TABLE 2 Travel Times, Delays and Queue Characteristics for each Scenario
Free speed distribution
To derive a free speed distribution, only those pedestrians are considered that clearly walk free. That is, they fulfill one out of the following conditions:

- The pedestrian faces an empty walking area.
- The pedestrian has a distance of at least 3 meters or 3 seconds to his predecessor.
- The predecessor is walking away, that is the distance between the pedestrians is increasing.

The trajectories are only analyzed in the middle of the walking area to avoid influences of both the revolving door and the turning point. For each pedestrian type different distributions have been estimated (normal, lognormal, Gamma and Weibull). All distributions appeared to fit rather well (see FIGURE 6). TABLE 3 shows free speed characteristics for all pedestrian types as well as results of a fit normal distribution.

![Different free speed PDF of normal individuals](image1)

![Normal free speed CDF of observed pedestrian types](image2)

a. Different probability distribution functions of the free speed. The histogram shows the observed free speed, while four distributions have been fit to the data set.

b. Cumulative distribution functions of the free speed for different pedestrian types.

**FIGURE 6** Free speeds; Probability density functions for free speeds with different fits (left) and cumulative density functions for all pedestrian types.

As can be expected, fast individuals have a higher walking speed than normal walking pedestrians, which have again a higher walking speed than slow walking pedestrians. The difference in median speed is 15.1% and 23.5% respectively. The median speed of normal walking pedestrians equals 1.34 m/s, being similar to values...
found in literature (e.g. 17). Although the maximum speed of both couples and trolleys is over 2.0 m/s, their median speed is significantly lower. Couples have a median speed of 1.23 m/s, in between slow and normal walking pedestrians, while pedestrians with trolleys have a median speed comparable to slow walking pedestrians.

**TABLE 3 Free Speeds for all Pedestrian Types including Estimation Results for the Normal Distribution (in m/s)**

<table>
<thead>
<tr>
<th>Data</th>
<th>Slow individuals</th>
<th>Normal individuals</th>
<th>Fast Individuals</th>
<th>Couples</th>
<th>Trolleys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.4300</td>
<td>0.5159</td>
<td>0.6269</td>
<td>0.5169</td>
<td>0.1011</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.0050</td>
<td>2.0159</td>
<td>2.9134</td>
<td>2.5421</td>
<td>2.0097</td>
</tr>
<tr>
<td>Median</td>
<td>1.1387</td>
<td>1.3409</td>
<td>1.6558</td>
<td>1.2257</td>
<td>1.1508</td>
</tr>
<tr>
<td>Mean</td>
<td>1.1331</td>
<td>1.2870</td>
<td>1.5204</td>
<td>1.3173</td>
<td>0.7283</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>0.2059</td>
<td>0.2018</td>
<td>0.3552</td>
<td>0.2604</td>
<td>0.4454</td>
</tr>
</tbody>
</table>

**Fit results normal**

| Mean         | 1.13         | 1.29         | 1.74         | 1.32     | 1.17     |
| Variance     | 0.21         | 0.20         | 0.26         | 0.26     | 0.27     |
| K-S Test     | 0.0224       | 0.0329       | 0.0355       | 0.0429   | 0.0191   |
| Chi-Square   | 0.0197       | 0.0157       | 0.0278       | 0.0390   | 0.0181   |

**Revolving door capacity**

Capacity is defined as the maximum number of passengers passing a cross-section during a given time period. Capacity is stochastic, with a certain mean and standard deviation. We can distinguish between two capacities: the pre queue capacity (= outflow from bottleneck just before congestion sets in) and the queue discharge rate (= outflow from bottleneck during congestion). Although often the pre queue capacity is somewhat higher than the queue discharge rate, the latter lasts longer. In this paper, we will focus at the queue discharge capacity.

Because of the nature of a revolving door (stepwise release of pedestrians each time a segment opens) limits the number of useful observations to determine the capacity. To overcome this problem, we will apply slanted cumulative curves. The slope of a cumulative curve (in this case the departure curve) describes the throughput and capacity of the revolving door. However, it is hard to determine variations in the slope. A slanted curve is a cumulative curve in which the variations are shown with respect to a specific flow \( q_0 \) (see FIGURE 7):

\[
D_{slanted}(t) = D(t) - q_0(t - t_0)
\]  

Where \( D_{slanted}(t) \) is the slanted cumulative curve, \( D(t) \) is the departure curve, \( q_0 \) is the flow to be compared and \( t_0 \) is the time the observations started.
Slanted curve of scenario 1

Cum. ped. count-q*(t1-t0)

Time (s)

Slanted curve scenario 1

Cum. ped. count-q*(t1-t0)

Time (s)

a. Slanted cumulative curve of scenario 1, with different phases (capacity versus through put).

b. Slanted cumulative curve of scenario 1 with the three capacity trends during congestion upstream of the door.

FIGURE 7 Slanted curves of scenario 1 to determine the capacity of the revolving door.

The interaction between pedestrians and revolving door results in a varying system performance. The fluctuating capacity is indicated by the trends in the slanted departure curve during queuing time (see the right figure in FIGURE 7). The total capacity is here determined as the total number of pedestrians passing the door during oversaturation:

\[
C = \frac{D_{\text{cumul}}(t_q) - D_{\text{cumul}}(t_p)}{t_q - t_p} + q_{\max}
\]  

TABLE 4 shows an overview of the capacity trends and the global capacity of each scenario. For each scenario at least three trends can be distinguished. The first and the last trend are usually highest, while the trends in between are lower, suggesting that when the queue is building up or reducing, the capacities are higher than when the queue length remains more or less constant (flow equals the capacity of the door).
For both commuter and shopping population, an increase in door rotation speed results in a higher mean capacity (up to 19%). The opposite flow in scenario 4 clearly shows a reduction in the capacity (~15%). Also the population has a large effect on the door capacity: with commuters the capacity is 10.1% - 26.2% higher than with a shopping population. Shoppers are strolling and less aggressive than commuters, which benefits the use of the entrance. However, couples and individuals with a trolley require more space and do not feel the urgency of completely filling a segment. The occupancy inside the door is therefore far from optimal, which has a negative influence on the capacity.

**TABLE 4 Capacity Trends and Global Capacity of each Scenario**

<table>
<thead>
<tr>
<th>Capacity [peds/min]</th>
<th>Scenario 1 (v_r = 0.5) m/s</th>
<th>Scenario 2 (v_r = 0.75) m/s</th>
<th>Scenario 3 (v_r = 1.0) m/s</th>
<th>Scenario 4 (v_r = 0.75) m/s</th>
<th>Scenario 5 (v_r = 0.75) m/s</th>
<th>Scenario 6 (v_r = 1.0) m/s</th>
<th>Scenario 7 (v_r = 0.75) m/s</th>
<th>Scenario 8 (v_r = 0.75) m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trend 1</td>
<td>33</td>
<td>44.2</td>
<td>48.5</td>
<td>35.2</td>
<td>25.9</td>
<td>25.2</td>
<td>15.0</td>
<td>25.6</td>
</tr>
<tr>
<td>Trend 2</td>
<td>30.6</td>
<td>35.3</td>
<td>37.8</td>
<td>16.7</td>
<td>25.6</td>
<td>25.0</td>
<td>32.2</td>
<td>30.9</td>
</tr>
<tr>
<td>Trend 3</td>
<td>34.1</td>
<td>25.1</td>
<td>39.5</td>
<td>27.2</td>
<td>--</td>
<td>30.0</td>
<td>24.5</td>
<td>27.5</td>
</tr>
<tr>
<td>Trend 4</td>
<td>--</td>
<td>36.8</td>
<td>--</td>
<td>33.8</td>
<td>--</td>
<td>45.8</td>
<td>--</td>
<td>25.3</td>
</tr>
<tr>
<td>Trend 5</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>26.7</td>
<td>--</td>
<td>25.6</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Global mean</td>
<td>32.7</td>
<td>36.3</td>
<td>38.9</td>
<td>30.6</td>
<td>25.3</td>
<td>26.8</td>
<td>28.8</td>
<td>27.5</td>
</tr>
</tbody>
</table>

**CONCLUSIONS AND FUTURE WORK**

Revolving doors are a means to provide access to a building, while maintaining the interior climate. Although these objects are frequently used in designs of pedestrian facilities, their behaviors are not included in pedestrian simulation tools, used to assess these designs. As a first step, this paper shows some first insights into the behavior of pedestrians in and around revolving doors. To study this behavior, Delft University of Technology has performed laboratory experiments with a revolving door and 80 participants. After automatically tracking the pedestrians on the collected video images, we derived pedestrian trajectories and cumulative curves. These form the basis for further analyses with respect to travel times, delays, queue characteristics, free speed distributions and the capacity of revolving doors.

The free travel times are similar for all scenarios, although scenarios 1 and 5 have higher travel times due to the low peripheral speed of the door wings. The revolving door rotation speed has a positive effect: the higher the revolving door speed, the lower the travel times. However, the rotation speed is limited due to safety restrictions: the maximum speed of the wing tip is required to be lower than 1.0 m/s. Commuters appear to form bulk queue upstream of the entrance, which leads to frequent activations of the safety sensors, and thus to numerous breakdowns and longer waiting times. A fence in front of the revolving door appears to have a positive effect on the behavior of these hasty commuters, which are forced to stay in line and form a linear queue.

As can be expected, fast individuals have a higher walking speed than normal walking pedestrians, which have again a higher walking speed than slow walking pedestrians. The difference in median speed is 15.1% and 23.5% respectively. The median speed of normal walking pedestrians equals 1.34 m/s, being similar to values found in literature (e.g. 17). Couples have a median speed of 1.23 m/s, in between slow and normal walking pedestrians, while pedestrians with trolleys have a median speed comparable to slow walking pedestrians.

For both commuter and shopping population, an increase in door rotation speed results in a higher mean capacity (up to 19%). Opposite flows cause a reduction in the capacity (~15%). When the door is loaded with commuters, the door capacity is 10.1% - 26.2% higher than with a shopping population. This is mainly due to the larger space requirements and the lack of urgency to completely fill a segment.

Future work will consist of further elaboration of data analyses and theory and model formulation for pedestrian behavior in and revolving doors. However, we will start with further analyses of the available data, e.g. with respect to self organization phenomena, pre queue capacity, and level-of-service measures. Based on the results of the data analyses we will derive theories describing this pedestrian behavior. These theories will then be translated into models, each describing different aspects of the pedestrian behavior. Our final aim is to include these models in our pedestrian simulation tool Nomad.

In order to extrapolate the findings presented in this paper to other configurations, we will perform real-life observations for different configurations and compare these to the results. This way, we can consider the value of our laboratory results, study behavior in real-life conditions and study different types of revolving doors.
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