Evaluating the impact of pedestrian crossings on roundabout entry capacity

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Abstract

An empirical approach to the estimation of roundabout entry capacity in the presence of significant levels of pedestrian crossing volumes is developed in this study on the basis of experimental observations. Impedance caused by pedestrians to approaching traffic is quantified using crosswalk occupancy time, rather than pedestrian volume. The analysis described in the paper leads to the estimation of a capacity reduction index, that can be used in operational analysis to obtain realistic estimates of roundabout entry capacities taking into account the impact of pedestrian crossings.

Keywords: road traffic; roundabouts; pedestrians; capacity; zebra crossings.

1. Introduction

Roundabouts are being increasingly used in many countries as a form of intersection control to promote safety and efficiency of traffic operations. One of the basic steps of the operational analysis of roundabouts is the estimation of entry capacity, that is the maximum rate at which vehicles can enter the intersection from a given approach under the prevailing traffic conditions. Several methods are available in which entry capacity is determined as a function of circulating and exiting vehicular flows, as well as of roundabout geometric layout; see, for example, Gastaldi and Rossi (2008). The presence of pedestrian crossings, however, may significantly reduce the capacity of a roundabout approach as compared to the situation in which only vehicular streams are considered. If we assume that pedestrians have the right-of-way over approaching vehicles (which is usually the case in the presence of zebra crossings), it appears evident that pedestrian flows represent an additional obstacle through which vehicles have to filter before reaching the stop-line on the roundabout approach. Intuitively, this additional impedance effect should increase with pedestrian volume, and should be especially critical for low to medium values of circulating vehicular flow, because under these conditions the presence of crossing pedestrians is likely to prevent approaching vehicles from using gaps that are otherwise available in the circulating traffic stream. Only a few studies dealing with the capacity reduction effect of pedestrian crossings can be found in the literature. These studies, based either on empirical or analytical approaches, represent this effect by applying to the values of the
capacity determined considering only vehicular flows a reduction coefficient, which, in general, is computed as a function of pedestrian and circulating traffic volumes. No consideration is given to other factors that may significantly affect entry capacity such as, for example, the distribution of the time periods during which the roundabout approach is effectively blocked by pedestrian crossings.

Starting from the above considerations, this paper addresses the problem of developing a realistic and usable procedure for the evaluation of the combined effect of both pedestrian volume and arrival distribution on roundabout entry capacity. Using experimental observations collected through video recording, we first characterize the statistical distribution of an appropriately defined random variable representing the duration of time intervals in which the flow of approaching vehicles is blocked by pedestrian crossings. Then, we analyze the relationship between this random variable and the level of pedestrian volume. Finally, we propose a procedure for the determination of roundabout entry capacity which explicitly takes into account, in addition to circulating vehicular flow, the effect of the above “time blocked” variable. The purpose of the study is to contribute to the improvement of standard methods of roundabout operational analysis, and to provide useful elements for the design of pedestrian flow control systems (such as pedestrian-actuated signals) aimed at minimizing the approach capacity reduction effect caused by pedestrian crossings.

The paper is organized as follows. In section 2 existing literature on the effect of pedestrians on roundabout entry capacity is briefly reviewed. Section 3 describes the experimental site and the data collection process. The study approach and related statistical analyses (mainly distribution fitting) characterizing the pedestrian-vehicle interactions on crosswalks are presented in section 4. In section 5 an empirically based procedure for entry capacity estimation taking into account the effect of pedestrians is proposed. Concluding comments and suggestions for future research are presented in section 6.

2. Previous studies on the effect of pedestrians on roundabout entry capacity

Only a few studies dealing with the effect of pedestrians on roundabout entry capacity can be found in the literature. Marlow and Maycock (1982) proposed an analytical method based on queuing theory to determine the capacity reduction of an approach to a major/minor junction or to a roundabout in the presence of zebra crossings. They considered the junction entry as a queuing system with two sequential serving units through which the approaching vehicles have to move before entering the intersection. Under the assumption of pedestrian priority on the crosswalk, they determined the vehicular capacity of the zebra crossing using a formula due to Griffiths (1981), and then introduced a reduction coefficient to be applied to the entry capacity computed considering only vehicular flows. This coefficient depends on the ratio of the capacities of the two serving units (crosswalk and stop-line), and on the number of vehicles that can be queued between the serving units. Brilon et al. (1993) used an empirical approach to develop a capacity reduction coefficient as a function of the volume of circulating vehicles in front of the subject entry and the volume of crossing pedestrians. Based on data collected at roundabouts in Germany, different expressions were developed for the cases of single-lane and two-lane approaches. According to these expressions, the effect of capacity reduction caused by pedestrians increases with pedestrian volume (for given circulating flow) and decreases for increasing circulating flow (for given pedestrian volume). Pedestrian crossings do not affect entry capacity at all for circulating volumes over 900 pcu/h and 1600 pcu/h, respectively for single-lane and two-lane approaches.

A few other papers have analyzed situations that are similar, but not the same, to that considered in this study, and therefore are only mentioned here. Among them, a study by de Leeuw et al. (1999) deals with the impact of slow-moving traffic (in particular cyclists) on roundabout entry capacity and delay, while Rodegerdts and Blackwelder (2005) analyze the case of roundabout exit blocking caused by pedestrian crossings and its effect on upstream entry capacity. Finally, simulation has been used in other studies in order to quantify the interactions between pedestrians and vehicles at roundabouts (see, for example, Chae 2005).
3. Data collection

The field data used in this study have been collected at an urban four-leg roundabout located in the central area of Padova (Italy). The geometric layout of the roundabout is shown in figure 1.

Figure 1 Data collection site.

The East approach has been chosen for the analysis; it has two entry lanes and a zebra crossing used both by pedestrians and cyclists. The experimental observations have been collected during peak periods using a video camera recorder. During the survey the following conditions have been observed:

- vehicular queuing on the approach (approach saturation);
- medium to high circulating vehicular flows;
- different levels of impedance due to pedestrians crossings.

The videos have been processed using an application software that allows the user to record:

- entering vehicles’ arrivals and departures at the give-way line of the approach;
- circulating vehicles’ arrivals at the approach conflict points on the roundabout ring;
- vehicles’ arrivals at the approach exit lane;
- vehicle category (car, van, truck, etc.);
- pedestrian/cyclist entry into the zebra crossing area;
- pedestrian/cyclist exit from the zebra crossing area.

The data were organized in a database and then processed through a software procedure that allows to extract, for any given time interval, information about the pedestrian/cyclist zebra crossing occupancy time and about circulating, exiting and entering vehicular flow rates at the approach. The observed time intervals characterized by the presence of a queue on the studied approach have been classified according to their size, removing from the data set those of less than one minute; see table 1. Consistent with the urban location of the roundabout, low percentages of heavy vehicles were observed during data collection. All values of vehicular flows were converted into pce/h (passenger car equivalents per hour) for the purpose of the subsequent analyses. Based on the available literature regarding empirical estimation of roundabout capacities, it appears that the size of the dataset collected in this study is adequate for deriving statistically significant estimates.
Table 1 Number of queuing intervals by size on the observed approach.

<table>
<thead>
<tr>
<th>Interval size (min.)</th>
<th>Number of intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>228</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>61</td>
</tr>
<tr>
<td>10</td>
<td>27</td>
</tr>
<tr>
<td>15</td>
<td>16</td>
</tr>
</tbody>
</table>

4. Analysis of pedestrian-vehicle interactions on crosswalks

The main feature of our study approach is to take the time during which the crosswalk is occupied by pedestrians as a basic variable describing the interaction between pedestrians and vehicular streams. This is considered as an alternative to using just the pedestrian flow rate as a measure of impedance to approaching vehicles, which is the method adopted in the studies cited in section 2. Indeed, a given level of pedestrian flow may correspond to several different values of occupancy depending, for example, on whether pedestrians proceed in a single line or in parallel lines. Crosswalk occupancy time is related to the distribution of intervals between crossing pedestrians, and it is intuitively evident that the ability of approaching vehicles to reach the stop-line may significantly depend on such a distribution.

4.1. Assumptions and definitions

The analysis described in this section focuses on the interactions between pedestrians and vehicles entering the roundabout, and therefore on the potential conflicts taking place within the rectangular area illustrated in figure 2.

In order to simplify the analysis, we assume that vehicles in both approaching lanes will wait until pedestrian crossing maneuvers are completed, before proceeding to the stop-line. This may not always be a fully realistic description of actual behavior, because in some cases a vehicle may move toward the roundabout as soon as the corresponding lane becomes viable, without necessarily waiting for the entire approach to be clear. In this sense, our simplified approach should lead to conservative estimates of the vehicular capacities of roundabout entries.

We define crosswalk occupancy time (or briefly occupancy time) the duration of a generic interval in which the crosswalk is continuously occupied by one or more crossing pedestrians. In the case of a single pedestrian, this is simply the time needed to execute the individual crossing maneuver. In the case of several pedestrians walking in bunches (not necessarily in the same direction), it can be defined as the time between the beginning of the crossing by the first member of the group and the completion of the crossing by the last member of the group. The identification of several pedestrians as a “group” implies that the intervals between successive individuals are not
sufficient to allow vehicles to pass between them. For a given period of observation, the ratio of the total occupancy time to the length of the observation period will be defined as percent occupancy. We call available time the duration of a generic interval between two successive occupancy times. Clearly, the sum of occupancy times and available times should always be equal to the total duration of the observation period.

4.2. Analysis of the distribution of occupancy times

Since both occupancy times and available times may be represented as random variables, it is interesting to investigate the form of their probability distributions based on the experimental data. In this study, we focus in particular on the distribution of occupancy times, since percent occupancy is later adopted as the key variable for the quantification of pedestrian impedance. In order to perform this analysis, the available observations have been categorized into five classes, according to the value of the equivalent hourly pedestrian flow; see table 2. Observation periods of five minutes have been considered, so that hourly pedestrian flows are obtained multiplying measured flows by a factor of twelve. Table 2 shows, for each class of pedestrian flow, the number of 5-minute periods used for the determination of the probability density functions of occupancy times, and the number of elementary occupancy intervals that have been observed. The statistical software StatFit 2® (Geer Mountain Software Corp. 2001) has been used for distribution fitting. This program provides a list of probability density functions, ranked according to their fit to the experimental observations, which is evaluated mainly on the basis of the one-sample Kolmogorov-Smirnov test.

Table 2 Sample sizes for distribution fitting by class of pedestrian flow.

<table>
<thead>
<tr>
<th>Flow (ped/h)</th>
<th>Number of five-minute intervals</th>
<th>N. of elementary blocked periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-300</td>
<td>9</td>
<td>118</td>
</tr>
<tr>
<td>300-400</td>
<td>18</td>
<td>401</td>
</tr>
<tr>
<td>400-500</td>
<td>16</td>
<td>323</td>
</tr>
<tr>
<td>500-600</td>
<td>5</td>
<td>92</td>
</tr>
<tr>
<td>600-700</td>
<td>11</td>
<td>308</td>
</tr>
<tr>
<td>200-700</td>
<td>59</td>
<td>2052</td>
</tr>
</tbody>
</table>

Overall, the best fit to the experimental data was provided by the Gamma probability density function, whose equation is:

\[
f(x) = \frac{(x-\tau)^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)} \exp\left(-\frac{x-\tau}{\beta}\right)
\]

where \(\tau\) represents the minimum value of the random variable under consideration, \(\alpha\) is a positive shape parameter, and \(\beta\) is a positive scale parameter. The mean value of this distribution is equal to the product of \(\alpha\) and \(\beta\). For \(\alpha > 1\), which is the range of interest in our experimental application, the distribution is characterized by \(f(\tau) = 0\), peaks at a value that depends on \(\alpha\) and \(\beta\), and decreases monotonically thereafter. Figure 3 shows the full set of Gamma probability density functions fitted to the observed data (one curve for each class of pedestrian flow), and table 3 shows the corresponding parameter values and standard deviations. Note that the minimum value of occupancy time \((\tau = 1\ \text{sec.})\) is explained by the fact that a limited number of bicycles using the pedestrian crosswalk were included in the sample of observations. Also note that the distributions corresponding to the various classes of pedestrian flow are fairly similar, with the only exception of the lowest volume class (200-300 ped/h).
Figure 3 Gamma probability density functions fitted to the observed data.

Table 3 Parameter values and standard deviations of the Gamma distributions of occupancy times.

<table>
<thead>
<tr>
<th>Flow (ped/h)</th>
<th>$\tau$ (sec)</th>
<th>$\alpha$</th>
<th>$\beta$ (sec)</th>
<th>$\sigma$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-300 ped/h</td>
<td>1</td>
<td>4.60</td>
<td>0.79</td>
<td>2.72</td>
</tr>
<tr>
<td>300-400 ped/h</td>
<td>1</td>
<td>3.05</td>
<td>1.20</td>
<td>1.45</td>
</tr>
<tr>
<td>400-500 ped/h</td>
<td>1</td>
<td>3.68</td>
<td>1.04</td>
<td>1.84</td>
</tr>
<tr>
<td>500-600 ped/h</td>
<td>1</td>
<td>3.31</td>
<td>1.18</td>
<td>1.54</td>
</tr>
<tr>
<td>600-700 ped/h</td>
<td>1</td>
<td>3.12</td>
<td>1.30</td>
<td>1.36</td>
</tr>
</tbody>
</table>

5. Estimation of entry capacity reduction due to pedestrian crossings

In this section, an empirically based procedure for entry capacity estimation taking into account the effect of pedestrians is described. This procedure represents an alternative to the methods available in the literature (see section 2), since the impedance effect caused by pedestrians to the stream of vehicles approaching the roundabout is quantified in terms of crosswalk percent occupancy rather than in terms of pedestrian volume.

The first step of the analysis consisted of developing a relationship between crosswalk percent occupancy and pedestrian volume, on the basis of the available experimental data. This relationship is important because it allows one to apply the procedure without direct knowledge of pedestrian occupancy, which is usually less easily observed in the field as compared to pedestrian volume. Using nonlinear regression on the set of observations represented by one-minute time intervals, the following equation was estimated:

$$p_{occ} = 0.0052 \, v_p^{0.699}$$  (2)

where $p_{occ}$ represents percent occupancy and $v_p$ represents pedestrian volume. Figure 4 shows the curve representing the above equation, together with the experimental observations used for curve fitting. The value of the $R^2$ coefficient is also shown in the figure. It should be noted that the range of validity of the estimated relationship in terms of pedestrian volumes is approximately 100 to 1000 ped/h (pedestrians per hour). Additional data collection is being conducted in order to extend the range of observed pedestrian flows. The nonlinear form of the equation is
explained by the fact that pedestrians tend to proceed in parallel lines when the crosswalk becomes crowded, so that pedestrian volume may increase more than proportionally with respect to occupancy.

Next, a set of empirical relationships between entry capacity and percent occupancy for various values of vehicular circulating flow has been developed. The latter variable has been categorized into 14 classes, and for each class a nonlinear curve fitting the one-minute experimental observations has been estimated. The general form of the equation for these curves is:

\[ C_e = \sqrt{C_m^2 - \frac{C_m}{b} p_{occ}} \]  

where, for any given class of circulating flow, \( C_e \) represents entry capacity (observed in the field), \( p_{occ} \) represents percent occupancy, \( C_m \) is the maximum entry capacity in the absence of pedestrians, and \( b \) is a positive shape parameter. Note that the condition \( C_e (p_{occ}=100\%) = 0 \) was imposed in the estimation of the above equation, meaning that entry capacity should be zero when an uninterrupted stream of pedestrians occupies the crosswalk. The full set of estimated relationships is shown in figure 5; the values of parameter \( b \) were found to be fairly homogeneous for low to medium levels of circulating flow, and satisfactory values of \( R^2 \) were obtained in most cases (Tab. 4).

<table>
<thead>
<tr>
<th>Circulating flow (pce/h)</th>
<th>( R^2 )</th>
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<th>( R^2 )</th>
<th>Circulating flow (pce/h)</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-600</td>
<td>0.972</td>
<td>800-850</td>
<td>0.616</td>
<td>1,000-1,050</td>
<td>0.830</td>
<td>1,300-1,400</td>
<td>0.536</td>
</tr>
<tr>
<td>600-700</td>
<td>0.688</td>
<td>850-900</td>
<td>0.810</td>
<td>1,050-1,100</td>
<td>0.551</td>
<td>1,400-1,500</td>
<td>0.825</td>
</tr>
<tr>
<td>700-750</td>
<td>0.826</td>
<td>900-950</td>
<td>0.799</td>
<td>1,100-1,200</td>
<td>0.503</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750-800</td>
<td>0.909</td>
<td>950-1,000</td>
<td>0.705</td>
<td>1,200-1,300</td>
<td>0.299</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The above relationships may be used to estimate, for any given level of percent occupancy, the value of entry capacity as a function of vehicular circulating flow. Linear regression was then used to interpolate, for each level of percent occupancy ranging from 0 to 60% with 10% increments, the 14 points corresponding to the previously defined classes of circulating flow; see figure 6. In the estimation process, the set of resulting lines was forced to converge to the point corresponding approximately to $Q_c = 1,700$ pce/h and $C_e = 500$ pce/h, which represents the conditions of highest vehicular congestion observed in the field. Note that, as expected, the capacity reduction effect caused by pedestrians decreases with increasing circulating flow, and becomes negligible for values of $Q_c$ over 1,600 pce/h. This result is in agreement with previous studies (see section 2), given that the roundabout under examination is characterized by two-lane approaches.
Finally, the above described linear relationships were used to derive the values of the Capacity Reduction Index (CRI), computed, for any specified level of $Q_c$, as the ratio of the capacity at a given level of pedestrian occupancy to the corresponding capacity at 0% occupancy. A family of curves representing CRI versus $Q_c$ for various values of $p_{occ}$ is shown in figure 7. Therefore, in an operational analysis of a roundabout with pedestrian crossings, the actual capacity of an approach can be estimated by multiplying the vehicular-only capacity by the value of CRI corresponding to the observed conditions. If data on pedestrian occupancy are not available, the values of this variable may be inferred from observed pedestrian volumes using the relationship of figure 4.

6. Conclusions

In this paper, the interaction between vehicular traffic and pedestrians on roundabout approaches has been analyzed by considering crosswalk occupancy time as the key variable to quantify the impedance caused by pedestrians to vehicles entering the intersection. Previous studies had used the pedestrian flow rate as the only measure of such impedance. The probabilistic distribution of occupancy time has been estimated on the basis of experimental observations at an urban roundabout, and has been found to be adequately described by a Gamma density function over a rather wide range of pedestrian flow levels. Linear relationships between entry capacity and circulating flow for various levels of crosswalk occupancy have been developed, leading finally to the definition of a capacity reduction index to be applied to calculated vehicular-only approach capacities. An empirical curve relating percent occupancy to pedestrian volume allows the application of the method even when direct observations of occupancy times are not available.

A larger set of experimental data is needed to validate the proposed approach and to allow a comparative evaluation versus alternative methods available in the literature. Other aspects of the problem could be investigated in future research, such as, for example, the effect of the vehicular storage length between crosswalk and stop-line on the capacity reduction caused by pedestrians, and the impact of aggressive behavior of drivers on two-lane roundabout approaches.

![Figure 7 Capacity Reduction Index as a function of vehicular circulating flow for various levels of percent occupancy.](image-url)
Acknowledgements

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References


