



Analysis and control of the interaction between vehicular and pedestrian flows on roundabout approaches

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Abstract

This study considers the problem of estimating the reduction of roundabout entry capacity caused by pedestrian zebra crossings. An empirical procedure is developed on the basis of field observations collected at an urban four-leg roundabout located in Padova (Italy). The disturbance caused by pedestrians to approaching traffic is measured using crosswalk occupancy times, rather than pedestrian volumes like in previous studies. The proposed method leads to the determination of a capacity reduction index, which can be applied in operational analyses to obtain realistic estimates of roundabout entry capacities taking into account the impact of pedestrian crossings. Also, the possible effect of introducing pedestrian-actuated signal control on zebra crossings is evaluated, using simulation, with reference to alternative pedestrian volume and signal timing scenarios.

Keywords: road traffic; roundabouts; pedestrians; zebra crossings; pedestrian-actuated signals.

1. Introduction

In recent years there has been a considerable increase in the use of roundabouts in several countries. This may be explained by the good performance of this form of intersection design in terms of safety, capacity, vehicular delays, fuel consumption and pollutant emissions. A large number of studies dealing with this type of intersection control (and using analytical, empirical or simulation-based approaches) are available in the international traffic engineering and road design literature.

A particularly important aspect 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 empirical methods have been proposed in which entry capacity is computed as a function of circulating and exiting vehicular volumes and roundabout geometric layout. Alternatively, analytical models based on gap-acceptance theory or traffic micro-simulation models can be used to estimate roundabout entry capacity. Among the many reviews of entry capacity estimation methods see, for example, Rodegerdts et al. (2007), Gastaldi and Rossi (2008), Mauro (2010), and Sindi (2011).

A critical aspect of roundabout operation (especially in urban road networks) is the interaction between vehicular and pedestrian flows, typically taking place at zebra crossings located on roundabout approaches. Pedestrians are usually assigned the right-of-way over approaching vehicles, and therefore pedestrian crossings represent an additional source of vehicular entry capacity reduction. Since zebra crossings are commonly located some distance

upstream the yield-line, arriving vehicles have to filter through the pedestrian stream before they can try to enter the circulating lane(s). In terms of queuing theory, this means that approaching vehicles face effectively two sequential serving units (Marlow and Maycock, 1982). It is intuitively apparent that the capacity reduction impact of pedestrian flows is particularly heavy at low to medium values of circulating vehicular flow, because under these conditions the presence of crossing pedestrians may cause a considerable underutilization of the gaps available in the circulating traffic stream.

Despite the importance of the interaction between vehicles and pedestrians on roundabout approaches in terms of potential loss of entry capacity, only a few studies dealing specifically with this phenomenon can be found in the literature. Most of these studies have been aimed at developing capacity reduction factors representing the additional impedance effect caused by pedestrians to vehicles approaching the roundabout. Typically, the intensity of this impedance effect has been quantified as a function of pedestrian volumes. However, it is easy to realize that the actual reduction of entry capacity may be different, *for a given level of pedestrian volume*, depending on the *distribution of pedestrian arrivals* over time. For example, pedestrians arriving in compact bunches separated by large time gaps may have a quite different impact on arriving vehicles as compared to a stream of uniformly spaced pedestrian arrivals.

Starting from the above considerations, in this paper we propose an empirical method for the estimation of roundabout entry capacity reduction, which explicitly takes into account the pedestrian arrival distribution and the consequent temporal occupancy of the crosswalk. The main purposes of the study are:

1. to contribute to the improvement of standard methods of roundabout operational analysis;
2. to provide indications supporting the design of pedestrian flow control systems (in particular pedestrian-actuated signals) aimed at minimizing the approach capacity reduction effect caused by pedestrian crossings.

This study represents an extension of the work of Meneguzzer and Rossi (2011), in which the issue of pedestrian signal control was not considered.

The paper is organized as follows. Section 2 presents a short review of the literature on the effect of pedestrians on roundabout entry capacity. Section 3 describes the procedure used for the collection of the experimental observations. Section 4 presents the basic idea of the proposed approach and describes the statistical analyses used for characterizing the pedestrian-vehicle interactions on crosswalks, focusing in particular on the probability distribution of a random variable representing the duration of time intervals in which approaching vehicles are blocked by pedestrian crossings. In section 5 an empirically based procedure for entry capacity estimation taking into account the effect of pedestrians in terms of the above defined random variable is proposed. Section 6 presents the results of simulations performed in order to evaluate the effect of the introduction of a pedestrian-actuated signal on the entry capacity reduction caused by pedestrian crossings. Concluding remarks and suggestions for future research are presented in section 7.

2. Literature review

The number of published studies dealing with the effect of pedestrian crossings on roundabout entry capacity is relatively limited. 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 yield-line), and on the number of vehicles that can be queued between the serving units, i.e. within the space separating the crosswalk from the yield-line. Another analytical procedure based on queuing theory, known as "French method" and described in Louah (1992), uses a different formula for the determination of the capacity reduction factor to be applied to the value of entry capacity computed in the absence of pedestrians.

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.

More recently, Duran (2010) used the micro-simulation software VISSIM[®] to estimate the effect of both volume of pedestrians and distance between crosswalk and yield-line on the capacity of roundabout approaches. Sindi (2011) studied the effect of pedestrian crossings on roundabout operational performance as measured by vehicular delays. He proposed an analytical model for the estimation of delays as a function of vehicular and pedestrian volumes, and used VISSIM[®] to calibrate and validate it. It should be noted that the author assumed a distance between crosswalk and yield-line equal to zero, so that in his model vehicles approaching the roundabout simultaneously seek a gap in both the pedestrian stream and the circulating vehicular stream.

A few other studies have analyzed topics that are different from, but related to, the one considered in the present paper. 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 the issue of roundabout exit blocking caused by pedestrian crossings and its effect on upstream entry capacity is considered by Rodegerdts and Blackwelder (2005) and Bergman et al. (2011). The latter may be a particularly critical aspect of roundabout operations, and neglecting it may lead to a significant overestimation of the roundabout level of service when pedestrian volumes are high. Finally, simulation has been used in other studies in order to model the interactions between pedestrians and vehicles at roundabouts for specific purposes, like the evaluation of treatments aimed at ensuring safe roundabout access to blind and low-vision pedestrians (see, for example, Roupail et al., 2005).

3. Field observations

The site chosen for the collection of the experimental data used in this study is an urban four-leg roundabout located in the central area of the city of Padova (Italy). The geometric layout of the roundabout is shown in Figure 1.

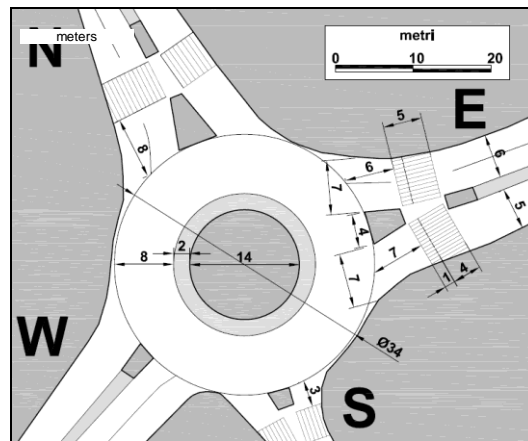


Fig. 1. Data collection site.

The data collection was carried out with reference to the East approach, which is characterized by two entry lanes and a zebra crossing used by both pedestrians and cyclists. The experimental observations were collected during peak periods of a normal working day using a video camera recorder. The following conditions were observed during the survey:

- vehicular queuing on the roundabout entry (approach saturation);
- medium to high volumes of circulating vehicles;
- a wide range of pedestrian volumes, causing significantly different levels of impedance to approaching vehicles.

The following events were recorded from the videos using a specific application software, developed at the Transportation Laboratory of the University of Padova:

- arrivals and departures of approaching vehicles at the give-way line on the roundabout entry;
- arrivals of circulating vehicles at the approach conflict points on the roundabout ring;
- arrivals of vehicles 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 using a software procedure that allows to extract, for any given time interval, information about the pedestrian/cyclist flow rates and zebra crossing occupancy times, and about circulating, exiting and entering vehicular flow rates at the approach. The observed time intervals characterized by the presence of a queue (two or more vehicles) on the studied approach have been classified according to their size, removing from the dataset 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 the empirical determination of roundabout capacities, it appears that the number of observations collected in this study is sufficient to ensure the statistical significance of the results of the analyses described in sections 4 and 5.

Tab. 1. Number of queuing intervals by size on the observed approach.

Interval size (min.)	Number of intervals
1	228
2	150
5	61
10	27
15	16

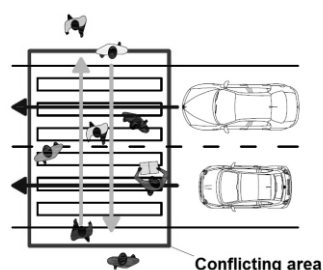
4. Using occupancy time as a measure of pedestrian impedance on crosswalks

4.1 Basic concept

Previous studies dealing with the reduction of roundabout entry capacity due to pedestrian crossings typically use pedestrian flow rate as a measure of intensity of the disturbance caused to approaching vehicles. In this paper, we introduce a different way to quantify such a disturbance, that is *crosswalk occupancy time*, or the time during which the crosswalk is completely or partially occupied by pedestrians and therefore unavailable to vehicles. In order for this measure to be meaningful, it should be expressed as a fraction (or percentage) of any assumed reference period, for example one hour. This quantity is considered here as the basic variable describing the interaction between pedestrians and vehicular streams. It is easily observed that a given rate of pedestrian flow may correspond to several different values of occupancy time depending, for example, on whether pedestrians proceed in a single line or in parallel lines. Crosswalk occupancy time is clearly related to the distribution of intervals between crossing pedestrians, and it is intuitively evident that the ability of approaching vehicles to reach the yield-line may significantly depend on such a distribution.

4.2 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. It is assumed that pedestrians have the right-of-way and that vehicles always stop whenever one or more pedestrians are present at any point on the crosswalk.

**Fig. 2.** Analysis reference area.

In order to simplify the analysis, we also assume that vehicles in both approaching lanes will wait until pedestrian crossing maneuvers are completed, before proceeding to the yield-line. Both assumptions may not always hold in reality, because of possible aggressive behavior of

some drivers not yielding to pedestrians; in addition, some vehicles may move toward the roundabout as soon as the corresponding lane becomes viable, without necessarily waiting for the entire approach to be clear. It follows that 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 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.

4.3 Probability distributions of crosswalk occupancy times

Since percent crosswalk occupancy is adopted in this study as the basic variable for the quantification of pedestrian impedance, and since it is clear that occupancy times (also called *blocked periods* or *blocked intervals*) may be represented using a random variable, it is of primary importance to investigate the form of its probability distribution based on the experimental data. 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. This is because the shape of the distribution of occupancy times may be expected to be sensitive to the level of pedestrian volume. 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 observed blocked intervals. 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.

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

Flow (ped/h)	N. of five-minute intervals	N. of observed blocked periods
200-300	9	118
300-400	18	401
400-500	16	323
500-600	5	92
600-700	11	308
200-700	59	1242

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

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

where τ represents the minimum value of the random variable under consideration, α is a positive shape parameter, and β is a positive scale parameter. The mean value of this distribution is equal to the product of α and β . 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 α and β , 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 ($\tau = 1$ s.) 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). The mean values vary approximately between 3.6 and 4 seconds, showing, as expected, a moderately increasing trend for growing pedestrian volume.

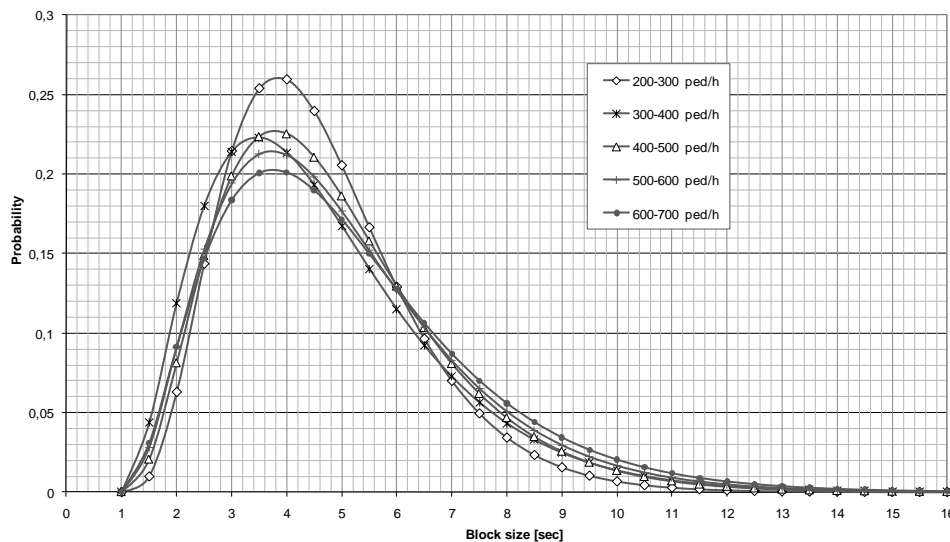


Fig. 3. Gamma probability density functions of occupancy times fitted to the observed data.

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

Flow (ped/h)	τ (s.)	α	β (s.)	σ (s.)
200-300	1	4.60	0.79	2.72
300-400	1	3.05	1.20	1.45
400-500	1	3.68	1.04	1.84
500-600	1	3.31	1.18	1.54
600-700	1	3.12	1.30	1.36

5. A procedure for the estimation of the effect of pedestrians on entry capacity

In this section, an empirically based procedure for estimating roundabout entry capacity reduction due to pedestrian crossings 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 measured in terms of crosswalk percent occupancy rather than in terms of pedestrian volume.

The first step of the analysis consisted of estimating a relationship between crosswalk percent occupancy and pedestrian volume based on 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:

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

where p_{occ} represents percent occupancy and v_p represents pedestrian volume (expressed in *pedestrians/hour*). 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*. Additional data collection is needed in order to extend the range of observed pedestrian flows. The characteristic shape of the curve is explained by the fact that pedestrians tend to proceed in parallel lines when the crosswalk becomes crowded, so that percent occupancy may increase less than proportionally with respect to pedestrian volume.

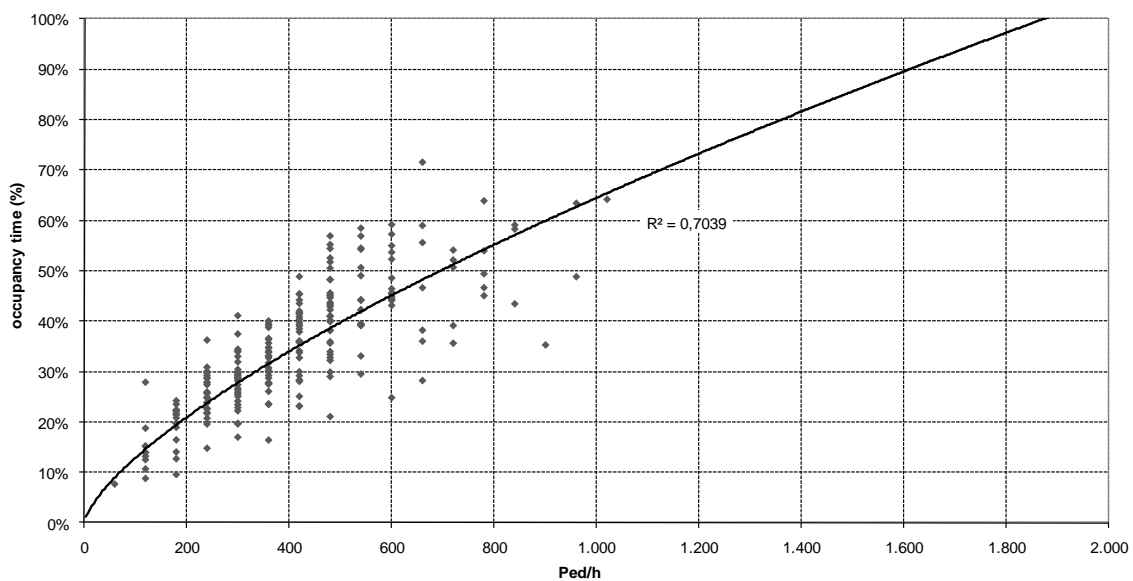


Fig. 4. Empirical relationship between crosswalk percent occupancy and pedestrian volume.

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

$$C_e = \sqrt{C_m^2 - \frac{C_m}{b} p_{occ}} \tag{3}$$

where, for any given class of circulating flow, C_e represents entry capacity (pce/h), p_{occ} represents percent occupancy, C_m is the maximum entry capacity at zero pedestrian volume (pce/h), and b is a positive shape parameter. Note that the values of C_e used for the estimation of (3) are those observed in the field. Also 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. Applying this condition to equation (3) we obtain:

$$C_e = C_m \sqrt{1 - p_{occ}} \tag{4}$$

The full set of estimated relationships is illustrated in Figure 5; as shown in Table 4, satisfactory values of R^2 were obtained in most cases.

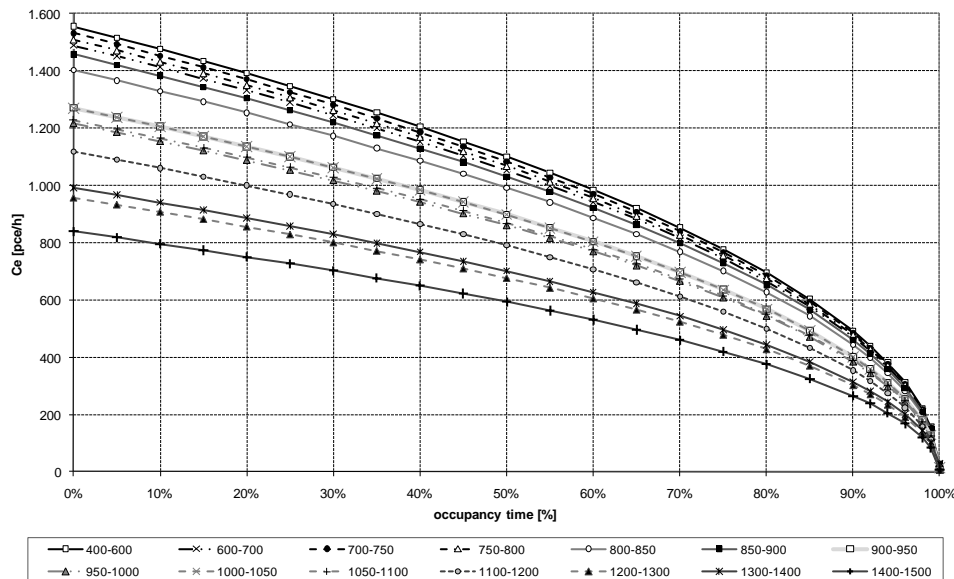


Fig. 5. Entry capacity vs. percent occupancy for various values of vehicular circulating flow.

Tab. 4. Empirical relationships between entry capacity and percent occupancy for various classes of vehicular circulating flow: R^2 values.

Circulating flow (pce/h)	R^2	Circulating flow (pce/h)	R^2	Circulating flow (pce/h)	R^2	Circulating flow (pce/h)	R^2
400-600	0.972	800-850	0.616	1,000-1,050	0.830	1,300-1,400	0.536
600-700	0.688	850-900	0.810	1,050-1,100	0.551	1,400-1,500	0.825
700-750	0.826	900-950	0.709	1,100-1,200	0.503		
750-800	0.909	950-1,000	0.705	1,200-1,300	0.299		

Next, the above relationships were 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 applied 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; the resulting lines are shown in Figure 6. In the estimation process, all the lines were forced to converge to the point corresponding approximately to $Q_c = 1,700 \text{ pce/h}$ and $C_e = 500 \text{ pce/h}$, which represents the conditions of highest vehicular congestion observed in the study site. 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 $1,600 \text{ pce/h}$. This result is in agreement with previous studies (see section 2), considering that the roundabout under examination is characterized by two-lane approaches.

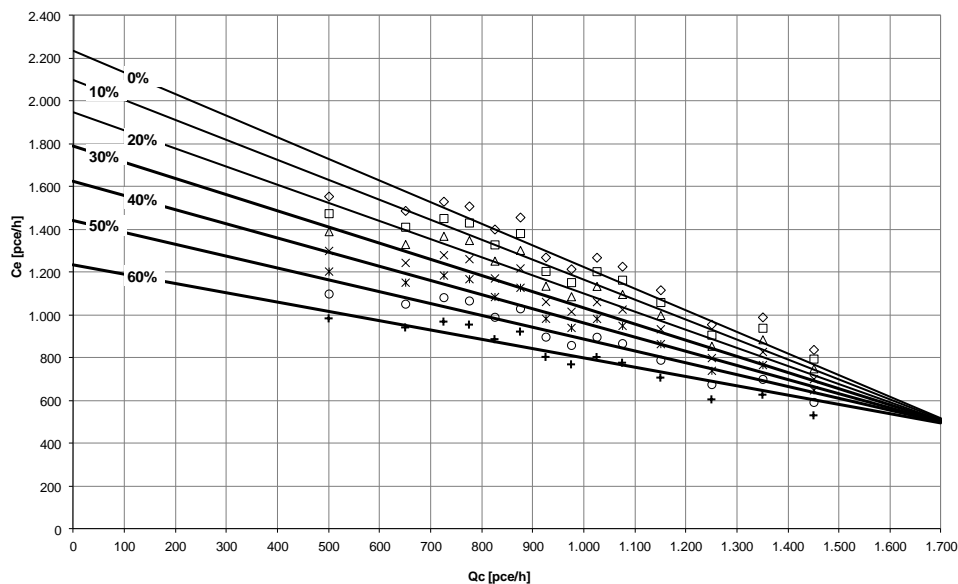


Fig. 6. Entry capacity as a function of vehicular circulating flow for various levels of percent occupancy.

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. It is observed that the curves are rather flat for low values of occupancy, meaning that in such conditions the *percent* reduction of entry capacity caused by pedestrians is essentially independent of the vehicular circulating flow. The value of *CRI*, instead, tends to be quite sensitive to Q_c under heavy pedestrian occupancy, indicating in particular that the negative impact of pedestrian crossings becomes much less important, in relative terms, when the impedance to entering vehicles is already high as a consequence of large circulating flows.

We can conclude that, in an operational analysis of a roundabout with pedestrian crossings, the actual entry capacity of an approach can be estimated by multiplying the vehicular-only capacity (measured directly in the field or computed using one of the available methods) 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 derived from observed pedestrian volumes using the relationship of Figure 4.

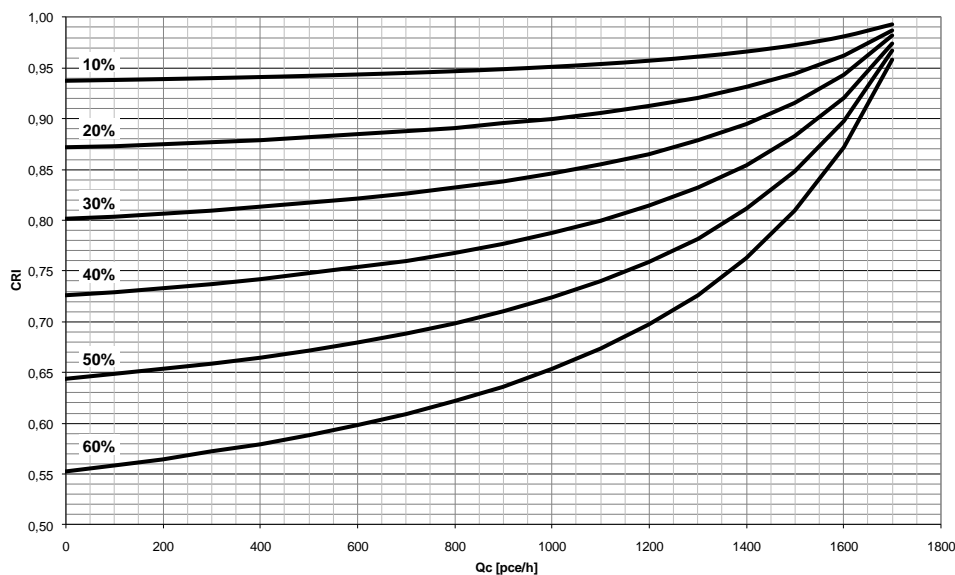


Fig. 7. Capacity Reduction Index versus vehicular circulating flow for various levels of percent occupancy.

6. Evaluating the impact of a pedestrian-actuated signal on crosswalk occupancy

The analysis described in the previous sections has shown that pedestrian crossings may considerably decrease roundabout entry capacity. It is, therefore, interesting to examine how such a negative effect may be diminished through intersection design and/or control measures. Essentially, a reduction of the impact of pedestrian crossings on roundabout entry capacity can be achieved in two different ways: 1) by locating the crosswalks sufficiently far away from the yield-line. This type of solution, however, may cause inconvenience to pedestrians by excessively increasing the length of their path; 2) by introducing pedestrian-actuated signal control on crosswalks. In order to maximize intersection level of service, this type of solution should be carefully designed by seeking the best possible compromise between vehicular and pedestrian delays, both being obviously affected by this form of signal control. In the present study we focus on the second solution, and we evaluate its impact using simulations based on the results of the previous analyses.

6.1 Probability distributions of crosswalk available times

In order to simulate the arrival of a pedestrian stream at a pedestrian-actuated signal it is necessary to determine, in addition to the probability distribution of crosswalk occupancy times (see section 4.3), the probability distribution of crosswalk available times. As defined in section 4.2, these are the intervals between two successive occupancy times. If large enough, these intervals can be used by approaching drivers to filter through the pedestrian stream and move towards the yield-line. Therefore, the simulation consisted in generating a random sequence of *blocked* and *unblocked intervals* drawn from the respective probability density functions.

The probability distribution of unblocked intervals was obtained from the experimental data following the same procedure used for blocked intervals (section 4.3); in particular, the total numbers of observed elementary unblocked periods are, as expected, the same as those shown in Table 2 for the various classes of pedestrian volume. In this case, the statistical software StatFit 2[®] indicated that the *negative exponential* probability density function provided the best overall fit to the field observations considering all classes of pedestrian volume. Figure 8 shows the full set of distributions fitted to the observed data (one curve for each class of pedestrian flow), and Table 5 shows the corresponding mean values and

standard deviations. Note that, as expected, both parameters decrease with increasing pedestrian volume.

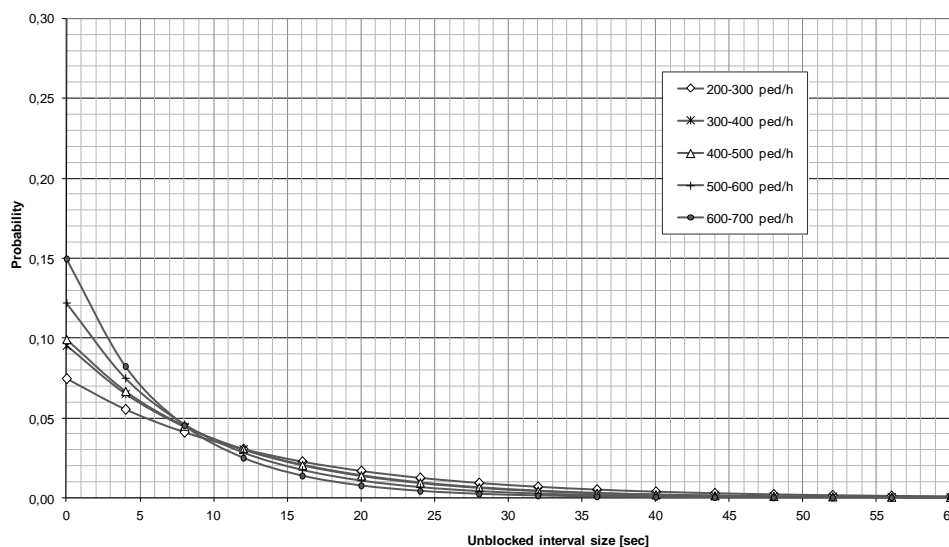


Fig. 8. Negative exponential probability density functions of unblocked intervals fitted to the observed data.

Tab. 5. Mean values and standard deviations of the negative exponential distributions of unblocked intervals.

Flow (ped/h)	μ (s.)	σ (s.)
200-300	13.4	13.4
300-400	10.5	10.5
400-500	10.1	10.1
500-600	8.2	8.2
600-700	6.7	6.7

6.2 Simulation of the effect of pedestrian-actuated signal control

The effect of the introduction of a pedestrian-actuated signal was simulated under different pedestrian volume and signal timing conditions, with the purpose of estimating crosswalk percent occupancy and allowing a comparison with the base case (without signal). In particular, the simulations were carried out with reference to the previously defined classes of pedestrian flow, and with the following durations of effective pedestrian green time G (including the amber interval) and pedestrian waiting time W (time from the push-button request until the start of pedestrian green):

$$G = 10, 15, 20 \text{ s.} \quad W = 30, 40, 50, 60 \text{ s.} \quad (5)$$

For each of the classes of pedestrian volume, a random sequence of blocked and unblocked intervals was generated using StatFit 2[®] for a total duration of one hour. For this purpose, the previously estimated distribution parameters (see sections 4.3 and 6.1) were adopted. The generated sequences were used to determine crosswalk occupancy times, first without signal control and then with signal control for each of the 12 combinations of the timing parameters G and W . Thus, a total of 65 scenarios was simulated. In all simulations it was assumed that

all pedestrians arriving at the crosswalk during the waiting period W and during the effective green period G are able to complete the crossing within the corresponding signal cycle.

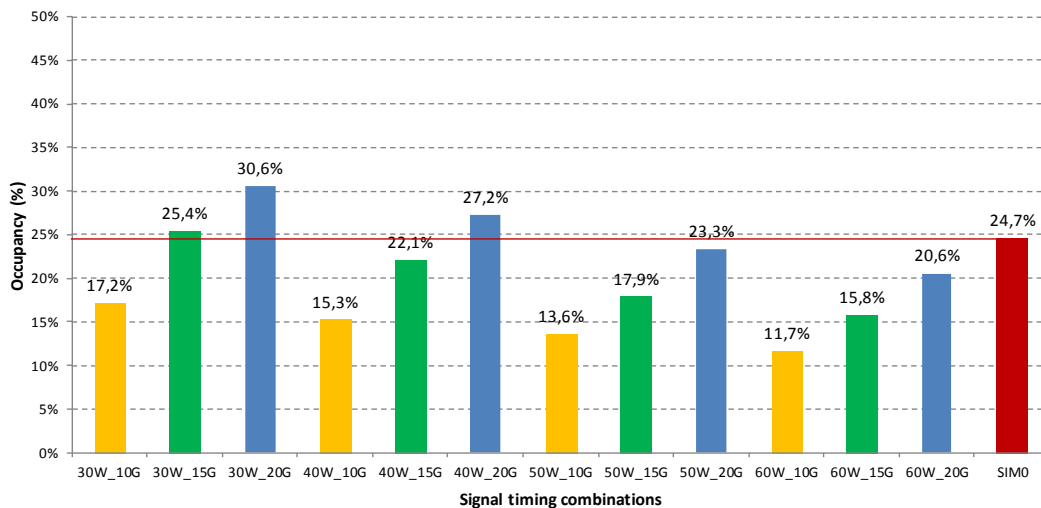
The *maximum* number of pedestrian requests that can be served in one hour is easily computed as:

$$N_{\max} = \frac{3600}{G + W} \quad (6)$$

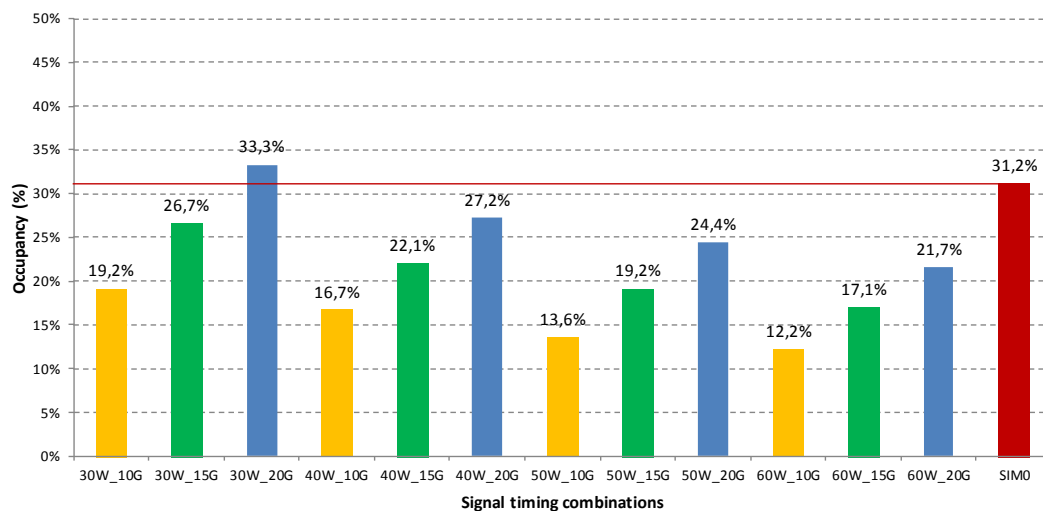
where G and W are measured in seconds. Introducing the assumed values (5) into (6), we can see that N_{\max} varies from a minimum of 45 to a maximum of 90 calls per hour.

The results of the simulations are shown in Figure 9, in which each histogram refers to a specific class of pedestrian volume. The following observations can be made on these results. First, introducing a pedestrian signal always reduces crosswalk percent occupancy as compared to the base case (no signal), except for four signal timing combinations which, as expected, occur in the two lower classes of pedestrian flow (200-300 and 300-400 *ped/h*) and for medium and long pedestrian green times (15 and 20 *s.*). As pedestrian volume increases, the benefit to approaching vehicles of introducing crosswalk signalization becomes more and more evident, especially when the shortest green time (10 *s.*) is used. In particular, when pedestrian volume is in the 600-700 *ped/h* range, implementing a signal plan with a 10 *s.* green and a 60 *s.* wait for pedestrians would reduce crosswalk occupancy from 48.1% to 12.5%. Of course, this large benefit to vehicles is obtained at the expense of a high delay to pedestrians. As previously noted, in an overall evaluation of roundabout operation both vehicular and pedestrian delays should be carefully taken into account.

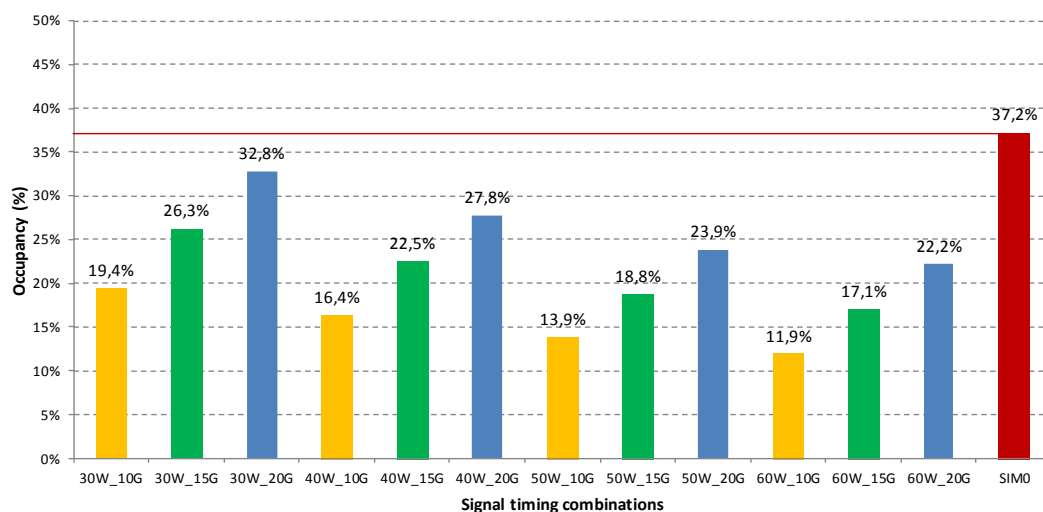
In addition, for any given class of pedestrian volume the effect of the signal timing combinations can be clearly seen in the histograms: for fixed pedestrian waiting time, crosswalk occupancy increases with pedestrian green time; on the other hand, for fixed pedestrian green time, crosswalk occupancy decreases as waiting time gets larger.



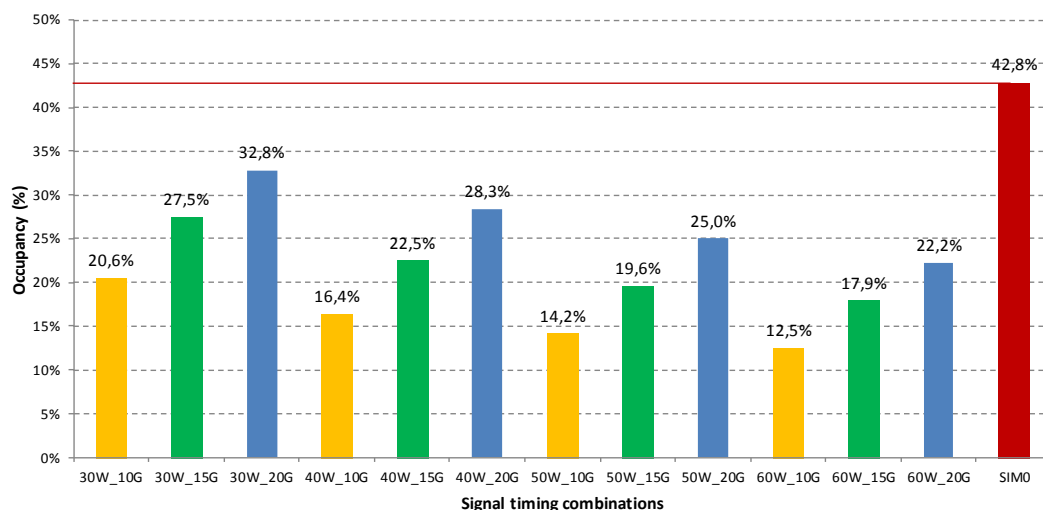
[a]



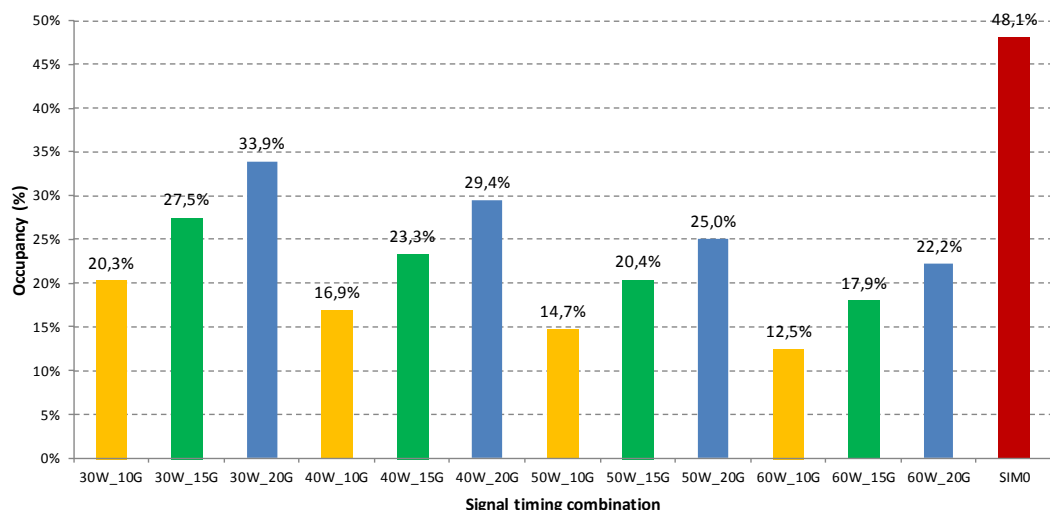
[b]



[c]



[d]



[e]

Fig. 9. Crosswalk percent occupancy for the base case (SIM0) and for various signal timing combinations by class of pedestrian volume (*a*: 200-300 *ped/h*; *b*: 300-400 *ped/h*; *c*: 400-500 *ped/h*; *d*: 500-600 *ped/h*; *e*: 600-700 *ped/h*).

7. Conclusions

The problem of estimating the capacity reduction of roundabout entries caused by pedestrian crossings has been studied in this paper using an empirical approach. In particular, the interaction between vehicular traffic and pedestrians on roundabout approaches has been analyzed focusing on crosswalk occupancy time, instead of pedestrian flow rate, as the basic variable representing the impedance caused to vehicles entering the intersection.

The probability distributions of occupancy times and intervals between pedestrian blocks have been identified based on field observations collected at an urban four-leg roundabout characterized by a sufficiently wide range of pedestrian volumes. The Gamma and negative exponential probability density functions have been found to provide the best fit to the experimental values of occupancy times and unblocked intervals, respectively. Linear relationships between entry capacity and circulating vehicular flow for various levels of crosswalk occupancy have been estimated, and a capacity reduction index to be applied to calculated vehicular-only approach capacities has been developed. An empirical curve relating crosswalk percent occupancy to pedestrian volume has been determined. This allows the application of the method in the absence of direct observations of occupancy times.

The possible benefit to vehicles of introducing pedestrian-actuated signal control on crosswalks has been evaluated using simulation. Generally, the results show that crosswalk occupancy can be considerably reduced (and therefore vehicular capacity can be increased) by implementing pedestrian signalization, and that the amount of such a reduction depends on both pedestrian volume and signal timing. While in the present study only the effect of the signal on vehicular capacity has been considered, the delay imposed to pedestrians should be included in a more comprehensive evaluation of roundabout level of service.

In future studies, the proposed procedure should be validated using experimental data collected at other roundabouts, and a comparative evaluation versus alternative methods available in the literature should be carried out. Other aspects of the problem under analysis could be investigated in future research, such as, for example, the impact of aggressive driving behavior on entry capacity in the presence of pedestrian crossings. Finally, the proposed approach should be extended in order to deal with the problem of roundabout capacity reduction caused by pedestrian crossings on exit lanes.

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