BASIC CAPACITY FORMULATION FOR PEDESTRIANS AT UNSIGNALIZED CROSSWALKS ON TWO-WAY ROADWAYS

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Abstract: This study proposes a basic pedestrian capacity that plays a critical role in the installation of pedestrian signal at the crosswalks. This methodology determining the pedestrian capacity is based on the pattern of vehicle arrived at the crosswalks. This paper has studied on determining the basic capacity for pedestrians that can cover a variety of levels of flow rate using Erlang distributions for headway distributions that Erlang parameter (K) of 1, 2, or 3 at 2-, 4-, or 6-lane roadway in both directions. This study considered two types of road with and without a pedestrian refuge area. Results show that the pedestrian capacity decreases as flow rate increases and Erlang parameter decreases for the road with the pedestrian refuge. For the road without the pedestrian refuge area, the pedestrian capacity shows the same trends like the road with pedestrian refuge area. However, the values of capacity of the road without the refuge are much lower than those of the road with the refuge. This study has the meaning of developing the models to determine the pedestrian capacity under a variety of flow rates and the outcomes of this study could be used as the criteria for the determination of the installation of pedestrian signal or for the provision of pedestrian refuge in the median of road.

Key Words: Pedestrian Capacity, Erlang Distribution, Pedestrian Signal, Refuge Area

1. INTRODUCTION

Crosswalks are provided to facilitate safely as pedestrians can cross to the other part of road. If the pedestrians crossing the road become increased continuously, it is very important to determine when a pedestrian signal would be implemented to protect the crossing pedestrians at the crosswalks. It is well known that the criteria in which the pedestrian signal operates at the crosswalks is dependent on the pedestrian demand. Recently a US study proposed a model.
for the pedestrian capacity using a negative exponential distribution for the arrival pattern of vehicles. However, this model has some limitations not to reflect a variety of flow levels, especially high level of flow rate.

This study considers two types of road with pedestrian refuge and without pedestrian refuge. In case of the road with the pedestrian refuge it is assumed that the pedestrians at the refuge could wait for the next acceptable gap provided by the traffic flow of opposite direction. In addition, in case of the road without the pedestrian refuge the pedestrians must cross the road in both directions at a time using two gaps that are provided by the traffic flow of each direction.

Oh and Sisiopiku (2000) presented an analytical approach for calculation of pedestrian crossing capacity and pedestrian delay at roundabouts. Comparisons between pedestrian capacity and delays at roundabouts and signalized intersections were also provided. The maximum pedestrian crossing rate (MPCR) was based on a probabilistic gap acceptance model. The results indicated that roundabouts provided more capacity than signalized intersections for approaching traffic of up to 1000 veh/h/direction. In their paper, the MPCR model for calculation of pedestrian capacity and delay at roundabouts were suggested and experimental results from model application were presented and discussed.

Lam et al. (2002) investigated the bi-directional flow characteristics at signalized crosswalk facilities in Hong Kong and in their study the pedestrian speed-flow functions for the crosswalk facilities of two types were calibrated and the relationships between the walking speed at capacity and directional distribution of pedestrian flow are determined.

This study proposes a basic pedestrian capacity model that plays a critical role in the operation of pedestrian signal at the crosswalks and the methodology used to determine the pedestrian capacity is based on the pattern of vehicles arrived at the crosswalks. In addition, this paper focuses on the determination of capacity value for pedestrians that can cover the various levels of flow rate using Erlang distribution as the headway distribution for Erlang parameter (K) of 1, 2, or 3 with 2-, 4-, or 6-lane roadway in both directions.

2. PEDESTRIAN CHARACTERISTICS AND HEADWAY DISTRIBUTION
2.1 Pedestrian Crossing Characteristics

In general, it is known that there are three crossing behaviors based on the following decisions
when pedestrians cross the bi-directional road.

O The pedestrians cross in judging if there is an ample acceptable gap for both directional traffic flows.
O The pedestrians cross against the approaching flow in anticipating the gap to be provided in sequence in the traffic stream of opposing direction.
O In the case of the road with a refuge area for pedestrians, the pedestrians begin crossing the road if the gap of the first directional road is provided and then try to cross again after waiting at the refuge area in the median of road until the gap provided by the traffic stream of opposing direction can be allowed.

Figure 1 illustrates that pedestrians cross against the traffic streams at a 4-lane street and q1 and q2 are the first directional flow rates that the pedestrians meet first and q3 and q4 are the opposing directional flow rates that the pedestrians must cross subsequently.

![Figure 1. Crossing Process for Pedestrians](image)

2.2 Headway Distribution

In general, time headway distribution is an important factor to be defined when crossing and merging into the road. It is known that the time headway distribution and its shape vary for different volume states because of the increasing headway interaction within traffic flow. For instance, in low traffic flow levels there is very little interaction between vehicles so that the time headways are somewhat random. As the traffic flow level increases, the headway interactions between vehicles also increases and the time headway becomes constant. When
the traffic flow level approaches to capacity, vehicles are in car following state.

As given in Equation (1), the Pearson type III distribution is one of the generalized mathematical models that can be used to define the time headway distribution, which actually is a family of distribution models consisting of simpler distribution models. This model becomes a simple Erlang distribution as given in Equation (2) if the shift parameter, a, takes zero value and the shape parameter, K, takes on any positive integer value. The K value can take any integer value from 0 to $\infty$. If K is selected to be 1, the form of this distribution is a negative exponential (or random) distribution. As the K value approaches to infinity, the resulting distribution becomes a constant headway distribution. In this paper the shift parameter, K, is called Erlang parameter.

$$f(t) = \frac{\lambda}{\Gamma(K)} \lambda(t-a)^{K-1} e^{-\lambda(t-a)}$$  \hspace{1cm} (1)

where  
- $f(t)$ = probability density function
- $\lambda$ = parameter that is a function of the mean time headway and the two user specified parameters, K and a
- K = user-selected parameter between 0 and $\infty$ that affects the shape of the distribution
- a = user-selected parameter greater than or equal to zero that affects the shift of the distribution (seconds)
- t = time headway being investigated (seconds)
- e = constant parameter, 2.71828
- $\Gamma(K)$ = gamma function, equivalent to $(K-1)!$

$$f(t) = \frac{\lambda}{(K-1)} (\lambda t)^{K-1} e^{-\lambda t}$$  \hspace{1cm} (2)

In this paper, it is assumed that the time headway distribution of approaching traffic flow is represented by Erlang distribution model. This is because Erlang distribution can represents overall traffic flow by changing Erlang parameter (K) and only Erlang distribution can have a solution as the formulation of pedestrian capacity is derived. In addition, the shape parameter, K, used in Erlang distribution should be selected and it is known that this parameter is affected by road alignments, grade, and other environmental factors; however, the most influential factor is the volume level. An approximate K value can be determined using the following equation. In this study it is assumed that Erlang parameter, K, is 1, 2, or 3 that can cover up to the high range of volume.
\[ K = \frac{\bar{t}}{s} \] (3)

where

\( K \) = Erlang parameter

\( \bar{t} \) = the mean time headway

\( s \) = the standard deviation of the measured time headway distribution

3. DERIVATION OF PEDESTRIAN CAPACITY EQUATIONS

3.1 Basic Concept and Assumptions

The model being developed is made possible with the following practical assumptions: (a) priority can not be given to the pedestrian at the crosswalk and (b) arrival rate of approaching vehicles follows the probabilistic distribution. In addition, this study assumes the followings to formulate the model of pedestrian capacity at crosswalks.

1) Unsignalized crosswalk
2) Each lane width is 4 meters.
3) Pedestrian walking speed is 1.0m/sec and the interval between pedestrians is 2 seconds.
4) Headway distribution of arrival vehicles is Erlang distribution.
5) There are single, inexhaustible queue of pedestrians waiting to cross the road.
6) Refuge area in the median of road is wide enough to accommodate lots of pedestrians.
7) Road that pedestrians could cross without signal is the maximum 6-lane roadway in both directions.

To calculate pedestrian capacity using equations being developed, it is necessary to define the value of variables as above. The critical gap (T) can be calculated from the width of roadway in one direction and the walking speed of pedestrian. The interval between two pedestrians is using for another gap (H). Because each lane width is defined as 4 meters, the width of roadway with two lanes in one direction is used as 8 meters in this study.

3.2 Formulation of Basic Capacity Model

The basic concept for pedestrian capacity is that the pedestrians cross the road making use of
the gaps provided when vehicles arrive the crosswalk and that the maximum number of possible pedestrians that can cross the road for a hour is the same as the total summation in which pedestrians can cross using time headway distributions at a certain period. When the pedestrians cross against the traffic stream of road, the primary parameter to be estimated is the critical gap.

The critical gap is the time in seconds below which a pedestrian will not attempt to begin crossing the street. Pedestrians use their own judgment to determine if the available gap is long enough for a safe crossing. If the available gap is greater than the critical gap, it is assumed that the pedestrian will cross, but if the available gap is less than the critical gap, it is assumed that the pedestrian will not cross.

Consider a single, inexhaustible queue waiting to cross a roadway of traffic stream where T is the critical gap for a pedestrian to cross the roadway and H is another critical gap which is a gap for entry of additional pedestrians that consecutively follow the first pedestrian as shown in Figure 2.

Based on the time headway of approaching traffic and the critical gap, the possibility of pedestrians to cross the roadway is as follows:

- If the passing time headway, t, is less than the critical gap, T, no pedestrian crosses.
- If t is between T and T+H, only one pedestrian crosses.
- If t is between T+H and T+2H, two pedestrians cross, etc.

Hence, the possible pedestrians crossing the one directional roadway per unit time becomes:

$$C_p = q \sum_{i=0}^{\infty} (i+1) \cdot P[T+iH \leq t < T+(i+1)H]$$  \hspace{1cm} (4)$$

where

- $C_p$ = the maximum on-ramp flow (ped/sec)
- q = the approaching flow rate (ped/sec)
T = Critical Gap (sec)
H = Another critical gap for entry of additional pedestrians (sec)

\[ P[T + iH \leq t < T + (i + 1)H] = \text{the probability of the time headway (t) taking a value between T + iH and T + (i + 1)H} \]

Considering that the negative exponential distribution for \( K=1 \) represents the distribution of headways in the stream of approaching traffic, the probability density function, \( f(t) \), and the cumulative distribution function, \( P(h \leq t) \), are given as below.

\[
f(t) = qe^{-qt} \\
P(h \leq t) = 1 - e^{-qt}
\]

Merging Equations (4) and (6), the possible pedestrians crossing the one directional roadway per unit time for \( K=1 \) becomes:

\[
C_p = q[e^{-qT} - e^{-q(T+H)}] + 2q[e^{-q(T+H)} - e^{-q(T+2H)}] + \ldots \\
= qe^{-qT} + qe^{-q(T+H)} + qe^{-q(T+2H)} + \ldots \\
= qe^{-qT} (1 + e^{-qH} + e^{-2qH} + \ldots) \\
= \frac{qe^{-qT}}{1 - e^{-qH}} \tag{7}
\]

For \( K=2 \), the probability density function, \( f(t) \), and the cumulative distribution function, \( P(h \leq t) \), are:

\[
f(t) = 4q^2te^{-2qt} \\
P(h \leq t) = 1 - e^{-2qt}[1 + 2qt] \tag{8}
\]

In same manners, the possible pedestrians crossing the roadway per unit time for \( K=2 \) can be derived as shown by the following equation.

\[
C_p = -\frac{qe^{-2qT}}{(1-e^{-2qH})}[(1+2qT)+\frac{2qHe^{2qH}}{(1-e^{-2qH})}] \tag{9}
\]

Finally, for \( K=3 \), the probability density function, \( f(t) \), and the cumulative distribution function, \( P(h \leq t) \), are given as follows:
\[ f(t) = \frac{27q^3 t^2 e^{-3qt}}{2} \]

\[ P(h \leq t) = 1 - e^{-3qt} [1 + 3qt + \frac{(3qt)^2}{2}] \]  

(10)

And if this cumulative distribution function merges equation (4) as the same process like equations (7) and (9), the pedestrians capacity crossing the traffic stream per unit time for \( K = 3 \) can be expressed as shown by the equation

\[ C_p = \frac{qe^{-3qT}}{[1 - e^{-3qH}]} [1 + 3qT + 4.5q^2T^2 + \frac{3qH(1 + 6qT)e^{-3qH}}{(1 - e^{-3qH})} + \frac{9q^2H^2(1 + e^{-3qH})e^{-3qH}}{(1 - e^{-3qH})^2}] \]  

(11)

Equations (7), (9), and (11) define the pedestrians capacities for different range of flow rate \( (q) \) based on Erlang parameter \( (K) \) values. For calculating the pedestrian capacities, it should be defined that the critical gap \( (T) \) is calculated by the width of roadway and another critical gap \( (H) \) for additional vehicles is assumed to be 2 seconds in this study.

4. DETERMINATION OF PEDESTRIAN CAPACITY

This chapter describes to determine the pedestrian capacity for two types of roads with and without a refuge area in the median using equations developed above. For the road with a refuge area, since the pedestrians can wait for more acceptable gap than the critical gap at the refuge area the pedestrian capacity is the same as the result that only one direction flow is considered. In case of the road without a refuge area, both directional flows should be considered to determine the pedestrian capacity.

4.1 Road with a Refuge Area

This study formulated pedestrian capacity models that represented for Erlang parameter \( (K) \) of 1, 2, or 3. The results in Figures 3, 4, and 5 show that the pedestrian capacity decrease as flow rates increase and Erlang parameters decrease for the road with the pedestrian refuge area. For the road without the refuge area, the pedestrian capacity shows the same trends like the road with the refuge area. However, the values of capacity of the road without the refuge area are much lower than those of the road with the refuge area. This is because the crossing pedestrians are not in sequence easy to meet the two acceptable gaps to cross the roadway in
both directions at a time. The case that a pedestrian can cross the road without the refuge area at a time is the only when two acceptable gaps are in sequence provided.

![Figure 3. Pedestrian Capacity with a Refuge Area (for 2-Lane Roadway)](image1)

As the number of lanes increases, the pedestrian capacity becomes decreased under same conditions of flow rate and Erlang parameter. This is because the critical gap is greater as the width of road becomes increased in accordance with increase of the number of lanes.

![Figure 4. Pedestrian Capacity with a Refuge Area (for 4-Lane Roadway)](image2)
Figure 5. Pedestrian Capacity with a Refuge Area (for 6-Lane Roadway)

Table 1 shows the pedestrian capacity with the refuge area by Erlang parameter and the number of lanes. With the help of the refuge area in the median of road, the capacity is high flow rate, respectively. The pedestrian capacity decreases very greatly in proportion to the increase of the number of lanes. In case of 6-lane roadway, there is few pedestrian if flow rate is higher than 1,200 vph and Erlang parameter (K) is 2.

Table 1. Pedestrian Capacity with a Refuge Area

<table>
<thead>
<tr>
<th>Flow Rate (veh/h/direction)</th>
<th>Pedestrian Capacity (ped/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-lane</td>
</tr>
<tr>
<td>400</td>
<td></td>
</tr>
<tr>
<td>K = 1</td>
<td>1,287</td>
</tr>
<tr>
<td>K = 2</td>
<td>1,099</td>
</tr>
<tr>
<td>K = 3</td>
<td>1,359</td>
</tr>
<tr>
<td>1,200</td>
<td></td>
</tr>
<tr>
<td>K = 1</td>
<td>650</td>
</tr>
<tr>
<td>K = 2</td>
<td>429</td>
</tr>
<tr>
<td>K = 3</td>
<td>418</td>
</tr>
<tr>
<td>2,000</td>
<td></td>
</tr>
<tr>
<td>K = 1</td>
<td>323</td>
</tr>
<tr>
<td>K = 2</td>
<td>144</td>
</tr>
<tr>
<td>K = 3</td>
<td>85</td>
</tr>
</tbody>
</table>

In general, Erlang parameter is related to flow rate level and the low Erlang parameter like K=1 can explain the low flow rate only because Erlang parameter of K=1 is the negative exponential distribution that represents a random arrival pattern. As Erlang parameter has a great value, the headway distribution changes to constant distributions like the normal
distribution. Therefore, Erlang distribution like $K=3$ cannot represent low flow rate like 400 vph in Table 1. Some boundaries for Erlang parameter are presented in Table 2 and the ranges of flow rate in this table were made with some field data collected in Korea.

<table>
<thead>
<tr>
<th>Erlang Parameter (K)</th>
<th>Volume Range (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K = 1</td>
</tr>
<tr>
<td></td>
<td>$0 &lt; q &lt; 1,306$</td>
</tr>
</tbody>
</table>

For the roadway with a refuge area, the pedestrian capacity is dependable on the stream of left side traffic because the pedestrians crossing one directional road can wait for the gap to cross the opposite direction at the refuge area. The number of pedestrians to wait at the refuge area decreases because the flow rate of the first direction is greater than that of the second direction so that the probability of acceptable gap becomes high in the opposite direction and vice versa. Therefore, the total of pedestrian capacity ($C_p$) in both directions can be defined by comparing the first capacity ($C_{p1}$) to the second capacity ($C_{p2}$) as follows.

1) If $C_{p1} > C_{p2}$, the capacity ($C_p$) is the same as $C_{p2}$
2) If $C_{p1} < C_{p2}$, the capacity ($C_p$) is the same as $C_{p1}$
3) If $C_{p1} = C_{p2}$, the capacity ($C_p$) is the same as $C_{p1} = C_{p2}$

### 4.2 Road without a Refuge Area

Now that pedestrians should meet two gaps in turn that are greater than the critical gap, the probability to cross is very low comparing to the road with a refuge area so that the pedestrian capacity is fewer respectively.

In the case of the roadway without a refuge area, the pedestrian capacity can be obtained by multiplying the crossing probabilities of each direction using Equation (4) as below.

$$C_p = q \sum_{n=1}^{\infty} n \cdot P_1[T + (n - 1)H \leq t < T + nH] \times P_2[t \geq T + (n - 1)H]$$

(12)

where

- $q =$ the flow rate of the first traffic stream that the pedestrians must cross first (veh/sec)
- $n =$ the number of pedestrians to cross together when an acceptable gap is provided (ped)
- $P_1 =$ the probability of the time headway ($t$) of the first traffic stream that pedestrians must cross first
$P_2$ = the probability of the time headway (t) of the opposing traffic stream

The second probability that a pedestrian should cross against the opposing traffic is always greater than the lower limit of the gap in the first traffic stream.

### 4.2.1 K=1 for both directions

In case n pedestrians can cross using a gap, merging Equations (12) and (6) for K=1, the pedestrian capacity is given by the following equation and Figure 6 is shown how the capacity varies by flow rate and the number of lanes.

$$C_p^n = q \times n \times P_t [T + (n - 1)H \leq t < T + nH] \times P_2 [t \geq T + (n - 1)H]$$

$$= q \times n \times [e^{-q(T+(n-1)H)} - e^{-q(T+nH)}] \times e^{-q(T+(n-1)H)}$$

$$= q \times n \times [e^{-q(T+(n-1)H)} - e^{-q(2T+(2n-1)H)}]$$

(13)

![Figure 6. Pedestrian Capacity without a Refuge Area (Both K=1)](image)

### 4.2.2 K=1 for the first direction and K=2 for the second direction

With same manners as described above, the pedestrian capacity is derived as the following formulation.

$$C_p^n = q \times n \times P_t [T + (n - 1)H \leq t < T + nH] \times P_2 [t \geq T + (n - 1)H]$$

$$= q \times n \times [e^{-q(T+(n-1)H)} - e^{-q(T+nH)}] \times e^{-2q(T+(n-1)H)} [1 + 2q(T + (n - 1)H)]$$

$$= q \times n \times [1 + 2q(T + (n - 1)H)] \times [e^{-3q(T+(n-1)H)} - e^{-q(3T+(3n-2)H)}]$$

(14)
4.2.3 K=2 for the first direction and K=1 for the second direction

In this case, because the time headway distribution of the first traffic stream is Erlang parameter of 2, the probability to cross the first traffic is lower than the case of K=1 and K=2. As seen in Figure 8, the pedestrian capacity decreases very rapidly as flow rate increases and it looks like there is no meaning under low or high range of flow rate.

$$C_p^n = q \times n \times P_1[T + (n - 1)H \leq t < T + nH] \times P_2[t \geq T + (n - 1)H]$$
$$= q \times n \times [e^{-2q(T+(n-1)H)}(1+2q(T+(n-1)H)) - e^{-2q(T+nH)}(1+2q(T+nH))] \times e^{-q(T+(n-1)H)}$$

(15)

$$= q \times n \times [e^{-3q(T+(n-1)H)}(1+2q(T+(n-1)H)) - e^{-q(3T+(n-1)H)}(1+2q(T+nH))]$$
As shown in Table 2, as the flow rate is 1,200 vph and the road has 4 lanes in both directions, only 5 pedestrians can cross the road without the refuge. If the crossing pedestrian demand is greater than the capacity calculated by this study, the pedestrian signal will be needed for the pedestrian safety and the higher crossing of pedestrians.

Table 3. Pedestrian Capacity without a Refuge Area

<table>
<thead>
<tr>
<th>Flow Rate (veh/hr/direction)</th>
<th>Pedestrian Capacity (ped/hr/both)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-lane</td>
</tr>
<tr>
<td>400 K=1 for Both Directions</td>
<td>255</td>
</tr>
<tr>
<td>First K=1, Second K=2</td>
<td>251</td>
</tr>
<tr>
<td>First K=2, Second K=1</td>
<td>522</td>
</tr>
<tr>
<td>1,200 K=1 for Both Directions</td>
<td>75</td>
</tr>
<tr>
<td>First K=1, Second K=2</td>
<td>58</td>
</tr>
<tr>
<td>First K=2, Second K=1</td>
<td>85</td>
</tr>
<tr>
<td>2,000 K=1 for Both Directions</td>
<td>20</td>
</tr>
<tr>
<td>First K=1, Second K=2</td>
<td>10</td>
</tr>
<tr>
<td>First K=2, Second K=1</td>
<td>13</td>
</tr>
</tbody>
</table>

4.3 Comparison of Capacity between Two Types

Figure 9 shows the comparison of pedestrian capacity between both directional 4-lane roadways with and without a refuge area.

Figure 9. Comparison of Pedestrian Capacity with and without a Refuge Area (K=1)
The pedestrian capacity with the refuge area is much greater than that without the refuge area. This is because the pedestrian capacity without the refuge area comes out of two acceptable gaps in both directions that are greater than the critical gap at the same time.

5. CONCLUSIONS

This paper has studied on determining the basic capacity for pedestrians at unsignalized crosswalks that can cover the various levels of flow rate using Erlang distribution as a headway distribution at 2-, 4-, or 6-lane roadway in both directions. In addition, this study considered two types of road with and without a refuge area for pedestrians.

Some capacity models are developed for Erlang parameter (K) of 1, 2, or 3 that represented the level of approaching flow rate. Results showed that the pedestrian capacity decreases as flow rates increased and Erlang parameters decreased in the case of the road with the pedestrian refuge area. For the road without the pedestrian refuge area, the pedestrian capacity showed the same trends like the road with pedestrian refuge. However, the values of capacity of the road without the refuge area are much lower than those of the road with the refuge area.

Though pedestrian flow is two ways, each flow is independent at the unsignalized crosswalk because two flows do not affect each other. Each capacity for one way direction can be calculated using developed equations in this study and the crossing capacities presented in this paper apply to one direction.

In reality, when the pedestrians cross the crosswalk the crossing behaviors are very various and complex. For instance, crossing pedestrians often group or walk side by side and artificial gaps by the traffic flow upstream of a signalized intersection could be provided. Though it is difficult to exactly consider these various behaviors, in this study a group of pedestrians can be reflected as including the variable of another critical gap (H). In addition, pedestrians who walk side by side are dependent of crosswalk width and could be considered by multiplying calculated capacity by the number of side pedestrians. Because artificial gaps are related to the arrival pattern of traffic flow, this is concerned with the selection of Erlang parameter.

This study has the meaning of formulating the models to determine the pedestrian capacity at unsignalized crosswalks under a variety of flow rates and the result could be used as a basis to install a pedestrian signal or to provide a pedestrian refuge area in the median of road.
This paper has not undertaken the validation of pedestrian capacity using observed field data. It is not easy to observe pedestrian capacity at the unsignalized crosswalk because the ample pedestrian demand is generally not guaranteed at the unsignalized crosswalk. In other words, the crosswalks with high pedestrian demand usually have the signal system for pedestrians. In future studies, it should be necessary to calibrate some variables assumed in this study to determine exact crossing pedestrian capacity.

REFERENCES


