Development and application of level of safety for pedestrians on local streets

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Abstract

The small local streets of Taiwan lack adequate pedestrian sidewalks and are usually congested with parked vehicles, automobiles as well as motorcycles. The conflict between motorized vehicles and pedestrians occurs frequently on the local streets. The traffic calming countermeasures can be adopted to improve this situation; however, it is necessary to develop an assessment model to determine which of these countermeasures are most effective. This paper, therefore, develops a risk index of pedestrian-vehicle conflict consisting of both exposure and severity components. Based on this risk index, the Level of Safety (LOSafety) relating to pedestrians is defined and classified into five levels, using a fuzzy classification method. The model can then be applied in a practical way.

Keywords: traffic calming, local streets, level of safety, risk, fuzzy.

1 Introduction

The traffic safety situation for pedestrians on small local streets of Taiwan is generally not good, mainly because of the lack of pedestrian space. Many traffic calming countermeasures can be adopted to enhance the safety of coexistence for pedestrians and vehicles [1]; how to appraise their effects and choose the most appropriate countermeasures was, therefore, one of the first issues to be studied.

In the past, the traffic calming countermeasures were appraised using a ‘before and after study’ method. This research developed an assessment model based on pedestrian and vehicle conflict risk, so that it could be evaluated before implementation, thus predicting the effects in advance. The model adopts a pedestrian-vehicle conflict Risk Index to respond actual traffic safety conditions of pedestrians. The Level of Safety (LOSafety), based on Risk Index, is defined and classified into 5 levels using a fuzzy classification method. The levels of
safety are categorized from the safest level (A) to the most unsafe level (E). For practical application purposes, several locations were selected to assess levels of safety, and furthermore, the safety performances of the proposed improvement countermeasures were investigated.

2 Basic concept

In this research, a risk index based on the conflict between pedestrians and vehicles is created, consisting of two parts: an Exposure Index and a Severity Index. The exposure index measures conflict frequency when pedestrians must avoid on-coming vehicles. The kinetic force of the vehicle against the pedestrian is used to create the severity index.

3 Exposure index

The exposure index reflects the possibility of a driver being involved in an accident. A higher exposure, therefore, represents a higher probability that an accident will occur. In establishing the exposure index, either the actual conflict number, or a potential conflict concept could be used as the indicator. Because the actual conflict number is difficult to obtain, however, for convenience we adopted a concept using potential conflict. Potential conflict arises when pedestrians walk alongside the traffic and also when they cross the street at intersections. This results in two types of exposure, parallel conflict exposure, while walking along the street, and crossing conflict exposure, while crossing at intersections.

3.1 Parallel exposure along the street

Parallel conflict mainly occurs alongside the street. When pedestrians walk on the street, they are probably in conflict with all vehicles passing them on the road. The conflict number (E') will be

\[
E' = \sum_{j=1}^{2} \left\{ \sum_{i=1}^{2} U_{ij}(t_i) \right\} Q_{Pj}
\]

where \( U_{ij}(t_i) \) = expected number of conflict vehicles in direction i during the time \( t_i \) against the pedestrian going in j direction

\( t_i \) = the length of time duration a pedestrian walks on the street

\( i, j = 1,2 \), denotes two directions

\( Q_{Pj} \) = flow rate of pedestrians per time interval (5 min.)

Denoting the average speed of a vehicle as \( V \), and average walking speed as \( V_P \), the traffic flow rates of transport mode k in the two directions are \( Q_{k1} \) and \( Q_{k2} \). Pedestrian volumes, travelling in the two directions, are \( Q_{P1} \) and \( Q_{P2} \). In this paper, the time interval for estimating the exposure is 5 min. The pedestrian volume is measured in blocks of 5 minutes. The time length \( t_i \) is then \( L / V_P - L / V \),
where the street has a length of L meters and the pedestrians travel in the same
direction at the vehicles. When the pedestrians and vehicles travel in different
directions, the length of time will be \( L/V_p + L/V \). Considering all possible
situations, pedestrian conflict with mode \( k \) per unit length of the street, is then

\[
E_{r k} = \left\{ Q_{k1}(1/V_p - 1/V_k) \right\} Q_{p1} + \left\{ Q_{k2}(1/V_p + 1/V_k) \right\} Q_{p1} \\
+ \left\{ Q_{k1}(1/V_p + 1/V_k) \right\} Q_{p2} + \left\{ Q_{k2}(1/V_p - 1/V_k) \right\} Q_{p2}
\]  

(2)

\[
E = \sum_k E_{r k}
\]  

(3)

where \( E_r \) = total parallel conflict exposure with all motorized modes per time
interval.

\( E_{r k} \) = parallel exposure of motorized mode \( k \), including large vehicles,
automobiles and motorcycles.

\( V_k \) = average speed of mode \( k \) (m/sec).

\( V_p \) = average speed of pedestrians (m/sec).

\( Q_{kj} \) = traffic flow rate of mode \( k \) in direction \( j \); \( Q_{k1} \) and \( Q_{k2} \) are the traffic
flows in the two directions (veh/sec).

\( Q_{pj} \) = pedestrian flow rate in \( j \) direction, \( j=1, 2 \); \( Q_{k1} \) and \( Q_{p1} \) are travelling in
the same direction; \( Q_{k1} \) and \( Q_{p2} \) are travelling in opposite directions
(person/time interval).

3.2 Crossing conflict exposure at intersection

Crossing conflict mostly occurs at intersections. Waiting to cross, the pedestrian
stands at the side of a street and looks to see whether a vehicle is approaching or
not. The number of possible conflicts is the number of vehicles passing the
intersection during the time the pedestrian has to wait to cross the street. During
pedestrian crossing the street, the approaching vehicles will be counted also as
the possible conflict to the pedestrian. The total time duration \( (t_c) \), when the
possible conflict occurs, is then the total waiting time \( (t_2) \) plus the pedestrian
time needs to cross the street \( (t_1) \). Total possible conflict number \( (E_{c'}) \) is thus:

\[
E_{c'} = \left\{ \Sigma_{i=1,2} U_i(t_c) \right\} Q_p
\]  

(4)

where \( U_i(t_c) \) is the expected number of vehicles travelling in direction \( i \) during \( t_c \),
and \( Q_p \) is the total number of pedestrians per time interval; \( t_c \) is the total length of
time.

Then \( t_1 = W/V_p \), where \( W \) is the street width and \( V_p \) is the speed of
pedestrian. \( t_2 \) can be estimated according to whether the gap is longer than the \( t_1 \),
which is the crossing time the pedestrian requires to cross the intersection. From
observation in the field, the arrival of vehicles is assumed to follow Poisson
distribution. The probability of the vehicle headway \( T \) being less than \( t_1 \) is

\[
P(T \leq t_1) = 1 - e^{-\lambda t_1}
\]

where \( \lambda \) is the vehicle’s average arrival rate. When the
vehicle headway is longer than \( t_1 \), (when the pedestrian can cross the intersection
during this gap), the probability is then \( P(T \geq t_1) = e^{-\lambda t_1} \). The average time
headway of the vehicles, whose arrival headways are less than \( t_1 \), can be
calculated using the equation

\[
\int_0^{t_1} T \lambda e^{-\lambda T} dT
\]

. The expected length of time \( t_2 \) is then
t_2 = P(T \geq t_1) \times 0 + P(T \geq t_1) \times P(T \leq t_1) \times \int_0^{t_1} T \lambda e^{-\lambda t} dT

+ P(T \geq t_1) \times P(T \leq t_1)^2 \times 2 \int_0^{t_1} T \lambda e^{-\lambda t} dT + \ldots

+ P(T \geq t_1) \times P(T \leq t_1)^n \times n \int_0^{t_1} T \lambda e^{-\lambda t} dT + \ldots

= t_1 e^{-\lambda t_1} + e^{-\lambda t_1}/\lambda + e^{\lambda t_1}/\lambda - 2/\lambda - t_1 \quad (5)

t_c = t_1 + t_2 = t_1 e^{-\lambda t_1} + e^{-\lambda t_1}/\lambda + e^{\lambda t_1}/\lambda - 2/\lambda \quad (6)

All the vehicles arriving during t_c have a potential conflict with pedestrians. The total crossing conflict number (E_c) of all transport modes is as follows:

E_c = \sum_k E_{ck} \quad (7)

E_{ck} = [Q_k(t_1 e^{-\lambda t_1} + e^{-\lambda t_1}/\lambda + e^{\lambda t_1}/\lambda - 2/\lambda)] Q_p \quad (8)

in which

t_1 = W/V_p

where E_c = total crossing conflict exposure (person-vehicle/time interval).
E_{ck} = crossing conflict exposure of mode k.
V_p = average speed of pedestrian (m/sec).
\lambda = total traffic flow rate of vehicles in two directions (veh/sec).
Q_k = traffic flow rate of mode k, (large vehicle, automobile or motorcycle).
Q_p = flow rate of crossing pedestrians (person/time interval).
W = width of street (m).

4 Severity index

The severity of traffic accidents is determined by the amount of energy transmitted by the collision. Transmission of energy is normally calculated using the square value of collision speed [2]. The probability and the energy of the collision can also reflect the safety measures taken and the degree of possible injury to the pedestrian [3]. This paper will, therefore, take the product of vehicle mass and the square value of vehicle speed as a severity indicator and define the probability of collision in order to obtain a statistic expectation value for the Severity Index. When a vehicle is moving towards a pedestrian, the vehicle headway (T) is defined as the time allowed for this on-coming vehicle to react to the presence of a pedestrian, preventing a collision. As this is an assessment model, the assumption is that all vehicles will attempt to avoid pedestrians; when the vehicle can not stop before meeting the pedestrians, it is assumed that an accident will probably occur and using the end speed when meeting the pedestrian to calculate the severity. The severity of the accidents can be looked at as a statistical expectation. With a beginning speed of V, the end speed of the vehicle, V_i as it collides with the pedestrian, is shown in table 1; t_i is the time required to stop the vehicle.
Table 1: The probability and expected collision speed of vehicle at impact.

<table>
<thead>
<tr>
<th>case</th>
<th>speed by collision $V_i$</th>
<th>probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; T \leq t_p$</td>
<td>$V_i = V$</td>
<td>$f(T) = \lambda e^{-\lambda T}$</td>
</tr>
<tr>
<td>$t_p &lt; T \leq t_s$</td>
<td>$V_i = (t_s - T)a$</td>
<td></td>
</tr>
<tr>
<td>$t_s &lt; T$</td>
<td>$V_i = 0$</td>
<td>No severity</td>
</tr>
</tbody>
</table>

where $f(T)$ is the vehicle headway probability density function, which is treated as exponential distribution; $t_p$ is the reaction time; $t_s$ is the stopping time; and $t_s = t_p + V/a$, $\lambda$ is the average traffic flow rate.

The expected value of $V_i$ at the point of impact can be calculated using the weighted average of $V_i$, with different vehicle headways. Therefore:

$$S' = M \times (V_i)^2$$

$$= M \left\{ \int_0^{t_p} f(T)V^2dT + \int_{t_p}^{t_s} f(T)[(ts - T)a]^2dT \right\} \left/ \int_0^{t_s} f(T)dT \right\}$$

Assuming vehicle headway follows an exponential distribution, with arrival rate $\lambda$, then:

$$S' = M \left\{ V^2 + P(T \geq t_s)(-2a^2/\lambda^2) + P(T \geq t_p)(t_s^2a^2 + t_p^2a^2 + 2t_pa^2/\lambda$$

$$-2t_sa^2/\lambda - 2t_pt_a^2 + 2a^2/\lambda^2 - V^2) \right/ \left[ 1-P(T \geq t_s) \right]$$

where $P(T \geq t_s) = e^{-\lambda t_s}$

$P(T \geq t_p) = e^{-\lambda t_p}$

$\lambda$ = the sum of vehicle traffic flow rates in both directions.

The Severity Index of mode $k$ is then calculated as follows:

$$S_k = M_k \left\{ V_k^2 + (e^{-\lambda t_s})(-2a_k^2/\lambda^2) + (e^{-\lambda t_p})(t_s^2a_k^2 + t_p^2a_k^2 + 2t_da_k^2/\lambda$$

$$-2t_sa_k^2/\lambda - 2t_pt_a_k^2 + 2a_k^2/\lambda^2 - V_k^2) \right/ \left[ 1-(e^{-\lambda t_s}) \right]$$

where $S_k = \text{severity index of mode } k \text{ (ton-m}^2/\text{sec}^2)$

$M_k = \text{vehicle mass of mode } k \text{ (ton)}$

$V_k = \text{vehicle speed of mode } k \text{ (m/sec)}$

$t_p = \text{driver reaction time to pedestrian (sec), set as 1 sec.}$

$t_s = \text{time to stop the vehicle (sec)}$

$\lambda = \text{total flow rate of vehicle in both directions (veh/sec)}$

$a_k = \text{vehicle maximum deceleration rate of mode } k \text{ (m/sec}^2)$

The total Severity Index, including all vehicles, is then:

$$S = \sum_k S_k$$

(11)

5 Risk index

Risk index is defined as:

$$R_r = \sum_k (S_k \times E_{rk})$$

(12)
where \( R_r \) is the risk of a pedestrian suffering collateral conflict on the road, and \( R_c \) is the risk to a pedestrian when crossing at an intersection.

6 Validation of the model

The aforementioned model is theoretical. The risk is a potential risk, arising from potential conflict. Therefore, validation of the relationship between the model’s estimates and observation in the field is necessary to ensure the estimation is unbiased when compared to the real conflict situation. On the other hand, consistency between the estimated risk level and the actual local traffic situation should also be checked from the pedestrian’s perspective.

6.1 Conflict exposure value

A survey using video was taken. Using the video, the number of actual conflict occurrences is counted, and traffic flow rates, the speed of vehicles and pedestrians are observed. Totally, 30 cases are sampled, situated on 11 locations in the capital city of Taipei. A comparison between the number of conflicts estimated by the model and actual number of conflicts was carried out. The correlation between real and estimated conflict was proved positive by the Spearmann rank correlation coefficient (rs) test, since \( rs = 0.860 \) of parallel traffic was much greater than the critical value \( r_{crit} = 0.305 \); and \( rs = 0.882 \) of crossing traffic was much greater than the critical value \( r_{crit} = 0.305 \). It was confirmed, therefore, that the estimated conflict exposure value reflects the real conflict situation, making the theoretical model, developed in this paper, applicable.

6.2 Validation of risk index

Theoretically, the higher the estimated risk, the more dangerous the situation is. In order to validate this statement, a survey was conducted through an interview process asking participants to gauge how safe they felt in various situations. The method is the successive categories methods by psychological feeling scaling interview [4]. Risk index values were collected from 11 local streets, containing altogether 290 min. of data; a video, showing these traffic situations, was shown to 34 interview participants. Based on the traffic situation, these interviewees were asked to choose, from 5 categories, whether they felt the situation was very safe, safe, fair, unsafe or very unsafe. The correlation, positive or not, between the estimated values and the perceived values, according to the participants, was then tested using the Spearmann rank correlation coefficient (rs) test. Since the \( rs=0.745 \) of parallel risk was greater than the critical value \( c_{crit}=0.368 \) and the \( rs=0.810 \) of crossing risk was greater than the critical value \( c_{crit}=0.343 \), the correlation was proved to be positive. This indicates that the perception of the
road users is consistent with the estimated results, which were calculated using the model developed in this study.

7 Level of safety

In order to apply this model in the assessment of pedestrian safety levels and to further evaluate the efficacy of proposed traffic calming countermeasures, a Level of Service concept, similar to that of the American Highway Capacity Manual was adopted. The Level of Safety is based on the Risk Index and classified it into 5 levels, from the best (level A) to the worst (level E). Through this evaluation process, all of the local streets will have their own pedestrian Level of Safety. In this study, to determine these classification levels, a Fuzzy classification process was applied. Through the Fuzzy classification process, the Level of Safety can be based on the perception of the road users. The range of risk on the risk index is identified according to the perception of safety, using the Fuzzy membership function, as shown in fig. 1.

To create the Fuzzy membership function, the first step is to conduct a survey of road users to determine their perception of the safety of various traffic situations and then to compare these results to the estimated Risk Index value. Based on this Fuzzy membership function, the classification threshold of each Level of Safety is identified. The boundary of the Fuzzy membership degree of each Level of Safety is illustrated in table 2. The Level of Safety classifications and their safety ranking can be seen in table 3, showing how it can be applied to analyze the traffic conditions at intersections of local streets.

![Figure 1: Illustration of Fuzzy classification membership function.](image-url)
Table 2: Fuzzy membership degree boundary of Level of Safety for pedestrian traffic.

<table>
<thead>
<tr>
<th>Level of safety on local street</th>
<th>Parallel conflict risk index value</th>
<th>Crossing conflict risk index value</th>
<th>Necessity of improvement</th>
<th>Safety ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$0 \leq R_t &lt; 0.48$</td>
<td>$0 \leq R_c &lt; 2.86$</td>
<td>Unnecessary</td>
<td>Very safe</td>
</tr>
<tr>
<td>B</td>
<td>$0.48 \leq R_t &lt; 16.90$</td>
<td>$2.86 \leq R_c &lt; 138.05$</td>
<td>Unnecessary</td>
<td>Safe</td>
</tr>
<tr>
<td>C</td>
<td>$16.90 \leq R_t &lt; 53.03$</td>
<td>$138.05 \leq R_c &lt; 478.59$</td>
<td>fare</td>
<td>fare</td>
</tr>
<tr>
<td>D</td>
<td>$53.03 \leq R_t &lt; 158.49$</td>
<td>$478.59 \leq R_c \leq 666.55$</td>
<td>necessary</td>
<td>Unsafe</td>
</tr>
<tr>
<td>E</td>
<td>$158.49 \leq R_t$</td>
<td>$666.55 \leq R_c$</td>
<td>prior</td>
<td>Very unsafe</td>
</tr>
</tbody>
</table>

Table 3: Classification of pedestrian Levels of Safety on local streets.

<table>
<thead>
<tr>
<th>Level of safety on local street</th>
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<th>Necessity of improvement</th>
<th>Safety ranking</th>
</tr>
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</tr>
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<td>$666.55 \leq R_c$</td>
<td>prior</td>
<td>Very unsafe</td>
</tr>
</tbody>
</table>

8 Application

To apply this model, the first step is to collect traffic flow rates and the average speed of vehicles and pedestrians in order to calculate the Risk Index value, using eqn. (1) - (13). The Level of Safety can then be identified by using table 3. The expected effects of traffic calming countermeasures are estimated using the same procedures mentioned above, by calculating the new risk index value. If the resulting Level of Safety is higher than level C, then the traffic calming countermeasures are decided. This procedure can be used as a decision making tool in choosing traffic calming countermeasures.

A typical local street in Taipei city centre was selected as an example to test the model. Frequent conflicts and dangerous situations had occurred along this particular section of road, due to the narrow sidewalk. The sidewalk is only 1m wide and inadequate for pedestrians, in particular, during rush hour; many pedestrians were therefore walking in the vehicle lanes, as can be seen in the
picture of fig.2. The parallel Risk Index value on this section of road is rated as 141.96 and classified as Level of Safety D, as illustrated in table 4.

Note: The pedestrian traffic problem is related to sidewalk width, which is too narrow, while the vehicle speed is too high. The after case shows widened the sidewalk and installation of a speed bump to reduce the speed of vehicles.

Figure 2: Case study: Local street with narrow sidewalk.

Table 4: A case study of pedestrian Level of Safety in a local street in Taipei.

<table>
<thead>
<tr>
<th>Case study of road section</th>
<th>Before (exiting)</th>
<th>After (traffic calming)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Large vehicle</td>
<td>Car</td>
</tr>
<tr>
<td>V(m / s)</td>
<td>-</td>
<td>5.26</td>
</tr>
<tr>
<td>Q_{p1} or Q_{k1}</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Q_{p2} or Q_{k2}</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>R_{r} (Parallel)</td>
<td>141.96</td>
<td></td>
</tr>
<tr>
<td>LOSafety</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

The countermeasure selected to counteract this situation was to widen the sidewalk from the 1m to 1.5m. Thus, the number of pedestrians in conflict, walking in the road, will be reduced. It was then proposed that the lane width for vehicle traffic be narrowed to 3.5m wide. A speed bump would also be installed to reduce vehicle speed. The volume of pedestrians walking in the vehicle lanes will be proportionately reduced by about 20%. According to previous experience in traffic calming countermeasures [1], a rough estimate for the expected
reduction in the speed of vehicles is about 35%, with traffic flow rates being reduced by about 20%. After the data was entered into the model, the results for the evaluation of the situation, after implementation of the proposed countermeasures, showed an improved Level of Safety of parallel pedestrian traffic in the road section, as illustrated in table 4.

9 Conclusion

This study uses a Fuzzy classification method to classify the Level of Safety from the perspective of road users. The Level of Safety assessment and classification, therefore, can reflect the exiting feelings pedestrians have towards the safety situation on local streets. This method can be applied to identify both the need for and the effects of taking traffic calming countermeasures. The model developed in this paper was proved useful in practice. In the future, it can be adopted to generate a comprehensive guideline of traffic calming countermeasures.

Reference