Evaluation of streets safety environment in neighborhood streets considering the perception of road users

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Abstract

The aim of this study is to develop an evaluation method for streets' safety environment on non-arterial streets, for the purpose of street design for traffic calming. In this paper, first, a model to explain the safety perception of road users, using vehicle speed and the relative location of movers, is proposed. The model is estimated on the basis of experiments ascertaining the nature of the perception of danger by drivers, pedestrians and cyclists when they are approaching each other. Second, evaluation indices for street safety, which represent the number of movers who perceive danger, are proposed. These indices can consider simultaneously the influence on street safety environment of traffic volume, speed, the separation of road users, and parking. Finally, the evaluation method is applied to a street improvement scheme in Osaka city where traffic calming and space reallocation measures have been introduced, and its effectiveness is examined.

1 Safety Evaluation Of Neighborhood Streets Environment

Serious traffic safety problems are seen on many non-arterial streets, especially on those streets where the road space is highly occupied by a mixture of vehicle traffic, pedestrians, bicycles and on-street parking. Although the division of road space forms the core of physical safety measures, it is quite difficult to provide enough space for all road users on narrow streets in built-up areas.

Recently, measures for traffic calming have been introduced into neighborhood streets. These measures aim to make the road space shared by vehicles and other road users safer by reducing speeds and the space occupied by vehicles. It is difficult, however, to decide on designs for those streets with
mixed and heavy traffic, partly because there are no methods of analyzing traffic and roadway conditions which can effectively evaluate the improvement schemes employing speed reduction and space reallocation measures.

The number of traffic accidents is usually used as the index of road safety evaluation. In the case of neighborhood streets this index is not appropriate because the number of accidents is so small. The observation period of accidents must be so long, in order to make statistical analysis significant, that the evaluation of short-term management measures would be impossible.

The traffic conflict technique, which observes evasive action by cars, is also proposed. This method assumes that the frequency of evasive action is correlated with the possibility of accidents. By employing the conflict technique, the safety of a certain road section can be examined through observation over several hours. This method is, however, used mainly for the evaluation of intersections rather than street sections, and is not appropriate for examining planned street design because it is difficult to predict frequency of conflicts.

On the contrary, the sense of road users is an important factor in evaluating neighborhood streets where the quality of the road environment is emphasized. Certain studies have found that there are some streets with few traffic accidents, even though many road users had pointed out the streets’ degrees of danger. On the streets with mixed and heavy traffic, most road users move very carefully, but they are always under psychological pressure. This is also a reason why the sense of road users must be considered in evaluating such neighborhood streets.

Several models were developed by the correlation analysis of sense data and the physical conditions of roadways and traffic; traffic volume, road space, separation facilities, and so on. These statistical models do not consider the influence of the flow conditions of mixed traffic. To overcome these problems, the authors have developed models which can explain road users’ safety perception, using vehicle speed and the relative location of movers, and have proposed operational indices to evaluate roadways and traffic conditions.

In this study, first, revised road users’ perception models are developed which can consider the influence of the size of vehicles and the overtaking flow. Second, street evaluation indices using observed data that is, traffic volume, vehicle speed, average on-street parking and road conditions are proposed. Third, correlation analysis between the proposed indices and actual road users’ perception of various kinds of streets is carried out. Finally these street safety indices are applied to understand the street safety environment by street design for traffic calming on the non-arterial street.

2 Safety Perception Model Of Road Users

2.1 Model Description
Drivers, pedestrians and cyclists are assumed to perceive danger when they are
approaching each other and to perceive it to be difficult to avoid one another. Figure 1 shows the model for a vehicle and a pedestrian, who are approaching each other. We call this flow model "Vehicle and pedestrian model". It is assumed that the driver (or the pedestrian) perceive danger in the presence of the other, when the time between the supposed collision time and the completion time of avoidance action, which is called 'time for avoidance' in this paper, is expected to be small. If the pedestrian must take sole responsibility for avoidance action and cannot expect the driver to exhibit avoidance behavior or to reduce speed, the time for avoidance can be expressed as follows.

Providing that people can avoid collision at constant speed after some delay, the function of time to avoid can be assumed to be a linear function of $x$ as $f(W+B/2-x)=\alpha (W+B/2-X)+\beta$ where $\alpha$ and $\beta$ are parameters. We have assumed that people perceive danger when their estimated $TA$ is negative. The estimated value of $TA$ should have an error item. If the error depends on independent Gamma distribution, the probability of danger perception can be obtained from the following logit model.

$$Pr(x,y,V) = \frac{1}{\exp(\theta \, TA) + 1} \quad (\text{if } x < W)$$

where $\theta, \alpha, \beta$: parameters

If the relative position ($x$) is larger than the avoidance width $W$, the second term of the function $TA$ should be negative but this is impossible. The probability of the perception of danger in this case is assumed to depend on the supplement avoidance width that is $x-W$, and can be obtained from the following logit model:

$$Pr(x,y) = \frac{1}{\exp(\theta \, y/V) - \theta \, \alpha (W-x) - \beta} + 1 \quad (\text{if } x < W)$$

where $Pr(x,y,V)$: probability of the perception of danger on the position ($x,y$)
model.

\[
Pr(x) = \frac{1}{\exp(\theta(x-W))+1} \quad (if \quad x > W) \tag{3}
\]

where \( Pr(x) \) : probability of the perception of danger on the position \( x \)

\( \theta \) : parameters

It is predictable that the avoidance width \( W \) depends on the vehicle speed and the width of vehicle.

\[
W = \gamma V + B/2 + \epsilon \tag{4}
\]

where \( B \) : width of vehicle

\( \gamma, \epsilon \) : parameters

The sign of all parameters should be positive from the assumptions of the model. The same model can be formed in the case of the driver's sense if the function \( f(x) \) means the time to avoid pedestrians for vehicles by steering and so on. The same models are also formed for a vehicle and a cyclist approaching model, if the pedestrian is replaced by a cyclist. The model under this flow condition is called a "Vehicle and bicycle model".

Overtaking models, that is, where a vehicle is overtaking a pedestrian or a cyclist, are also able to be formed as the same equations, in which the relative speed \( V \) should be defined as the difference between the vehicle speed and pedestrian (cyclist) speed.

2.2 Experiments

Parameters of the proposed model are estimated on the basis of experiments, which were carried out to ascertain the nature of the perception of danger by drivers, pedestrians and cyclists when they were approaching each other and when the vehicle was overtaking. As Figure 2 shows, a vehicle approaches a pedestrian walking at a certain position (or cyclist riding in a certain lane) at indicated speed, and drivers and pedestrians turn on the light to indicate to the tester the point of which they feel danger before an avoidance action is initiated. Each subject cannot see the others' light. An 8mm video system is used to measure the position of danger perception and accurate car speed. The experiments were carried out on the conditions of \( x \) and \( V \) shown in Table 1.

![Figure 2 Experiments on Perception of Danger](image-url)
Table 1 Experimental Conditions

<table>
<thead>
<tr>
<th>Model</th>
<th>Flow type</th>
<th>Car speed</th>
<th>Position X</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle-and-Pedestrian</td>
<td>Approaching</td>
<td>15</td>
<td>25,75,125,175,225</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>25,75,125,175,225</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Overtaking</td>
<td>15</td>
<td>25,75,125,175,225</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>25,75,125,175,225</td>
<td>30</td>
</tr>
<tr>
<td>Vehicle-and-bicycle</td>
<td>Approaching</td>
<td>15</td>
<td>25,75,125,175,225</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>25,75,125,175,225</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Overtaking</td>
<td>15</td>
<td>25,75,125,175,225</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>25,75,125,175,225</td>
<td>60</td>
</tr>
</tbody>
</table>

2.3 Estimation of Avoidance Width Function

It is, however, a complicated problem to estimate simultaneously all the parameters of the model, defined in equations of (2),(3) and (4). The avoidance width function (4) is estimated independently in this study.

The avoidance width can be regarded as the relative position from where people perceive no danger in passing each other. The parameters of the equation were estimated by discriminant analysis. The discriminant groups were defined as follows in the cases of the above experiments. One group consisted of the cases when people felt no danger in passing, and the other, when people felt danger.

The discriminant functions can be obtained as F=aV+bx+c where x is the relative position of pedestrians, and a,b,c are estimated parameters. The diverging point for grouping cases (CF) can also be estimated from the analysis using the means of discriminant scores. The avoidance width is obtained from the equation of F=CF as the equation (5).

Table 2 shows the result of analysis. Discriminant functions are significant considering the values of Wilks’ lambda and the percentage of correct grouped samples.

\[
aV + b(W+B/2) + c = CF
\]
\[
W= (-a/b)V + (CF-c)/b + B/2 = \gamma V + \varepsilon + B/2
\]  

Table 2 Estimation Results of Avoidance Width Function (Discriminant Analysis)
In the case of the approaching flow, the parameter $\varepsilon$, which means the avoidance width when the vehicle speed is zero, is smaller, and the parameter $\gamma$, which means the sensibility of the avoidance width to the vehicle speed, is larger in the pedestrian model than the bicycle model. This is a reasonable result considering that cyclists need wider lanes for moving than pedestrians, even when the vehicle speed is low.

On the other hand, in the case of the overtaking flow, the parameter $\varepsilon$ is larger, and the parameter $\gamma$ is smaller in the pedestrian model than the bicycle model. This seems due to the adoption of the relative speed to explain the avoidance width, which is small in the overtaking flow and in the bicycle model.

2.4 Model Calibration

From the video analysis of experiments, indices of danger perception (0 or 1 value), location (x,y), and car speed (V) were measured at every 0.2 seconds.

The maximum likelihood estimation method is applied to calibrate the safety perception models by using this database. Table 4 shows the estimated parameters. These results are also significant according to the t values of each parameter and the value of $\rho^2$.

Table 3 Estimation Results of Safety Perception Model (Logit Model Analysis)

<table>
<thead>
<tr>
<th>Model</th>
<th>Vehicle and Pedestrian</th>
<th>Vehicle and Bicycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow type</td>
<td>Approaching</td>
<td>Overtaking</td>
</tr>
<tr>
<td>Subject</td>
<td>Driver</td>
<td>Pedest.</td>
</tr>
<tr>
<td>W&gt;X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>1.72522 (24.1)</td>
<td>1.84354 (23.5)</td>
</tr>
<tr>
<td>$Y/V$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1.62643 (11.5)</td>
<td>3.04842 (17.3)</td>
</tr>
<tr>
<td>(W-X)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta$ constant</td>
<td>3.00590 (19.4)</td>
<td>2.38983 (16.7)</td>
</tr>
<tr>
<td>$\chi^2$ significance</td>
<td>1833.3 (19.4)</td>
<td>1962.8 (16.7)</td>
</tr>
<tr>
<td>$\rho^2$</td>
<td>0.529</td>
<td>0.564</td>
</tr>
<tr>
<td>% correct</td>
<td>86.424</td>
<td>86.747</td>
</tr>
<tr>
<td>W&lt;X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>3.3976 (9.5)</td>
<td>5.1573 (9.5)</td>
</tr>
<tr>
<td>(X-W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi^2$ significance</td>
<td>208.9</td>
<td>288.8</td>
</tr>
<tr>
<td>$\rho^2$</td>
<td>0.402</td>
<td>0.555</td>
</tr>
<tr>
<td>% correct</td>
<td>81.818</td>
<td>86.631</td>
</tr>
</tbody>
</table>

2.5 Vehicle Front Dangerous Area Perceived By Road Users

Figure 3 shows the space perceived as the dangerous zone in front of moving vehicles. These areas are calculated by the estimated models providing that the probability of danger perception equals 0.5, that is, the time for avoidance (TA) is zero or the relative position x is the same as the avoidance width W.

The shapes of the dangerous spaces are different between the flow conditions; approaching and overtaking. In the case of approaching flow, the spaces of the vehicle and pedestrian model are smaller than the spaces of
vehicle and bicycle model. This seems to be due to the fact that bicycles need more space than pedestrians and the relative speed between car and bicycle is larger than the speed between car and pedestrians.

In the case of the vehicle and pedestrian model, the dangerous space perceived by drivers is shorter in length than the space perceived by pedestrians. This indicates there is a possibility of a certain condition when pedestrians feel danger, but drivers do not. This means that vehicles tend to invade the street safety environment because of their lack of perception of peoples’ safety perception.

In the case of overtaking flow, the pentagonal shape of the dangerous space are clear except in the pedestrians’ model. It indicates the avoiding speed of road movers (α) is high. This seems due to the relative speed, which tends to have a small value in the overtaking flow.

Figure 3 Vehicle Front Dangerous Space

3 Street Safety Index Using The Safety Perception Model

3.1 Assumptions
The safety perception model can be employed for the purpose of the evaluation of street safety, if detailed traffic flow is able to be observed by the video survey and so on. It is quite laborious, however, to carry out such a survey. The
operational index, which can be calculated from the average traffic volume, speed, number of parking, and traffic lane distribution, is proposed by adopting the following assumptions.

1) The speed of all vehicles is the same as the average of observed samples.
2) The speeds of all pedestrians and cyclists are the same as their respective averages.
3) Lane distributions of vehicles, pedestrians and cyclists can be obtained or estimated. All road movers are behaving independently according to these distributions.

3.2 Index Description

Figure 4 shows the concept of the street safety index on a certain cross-section of street. Now pedestrians and cyclists are assumed to be moving according to the lane distribution function $D^p(x)$ or $D^b(x)$ (persons/m) at speed $V_p$ and $V_b$ (m/s). Traffic density of pedestrians and cyclists can be obtained from the equation; density $K(x)$ (persons/m²) equals $QD(x)/V$, where $Q$ is the ratio of flow per second. When a vehicle's front is just at $x_c$ on the cross-section, the probability of road users perceiving danger can be estimated by employing the safety perception models. The total number of road users perceiving danger can be calculated as equations of (6) and (7).

The hourly average of index would be calculated from the equation of (8).

![Figure 4 Street Safety Index on Cross-section](image)

\[
S^{xz}_i = \int_x \int_y Pr^{xz}(x-x_c,y,V_i,B_i) \frac{Q^z D^z(x)}{V_p} dxdy \\
S_z^{xz} = \int_x \int_y Pr^{xz}(x-x_c,y,V_i,B_i) \frac{Q^z D^z(x)}{V_p} dxdy
\]

where $S^{xz}_i$ : Safety index of cross section for road user $u$ ( pedestrian for approaching vehicle ; $z=p$, $u=c$ / cyclist; $z=b$, $u=c$ / driver for approaching pedestrian; $z=c$, $u=p$ / for bicycle; $z=c$, $u=b$ ) against a vehicle (i)

$Pr^{xz}(x-x_c,y,V_i,B_i)$ : probability of danger perception for road user $z$ at the position $(x-x_c,y)$, vehicle speed is $V_i$, vehicle width is $B_i$

$x_c$ : the position of vehicle

$Q^z$ : traffic ratio of flow of road user $z'$ (/s) pedestrians; $z' = p$
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cyclists; \( z' = b \)
drivers; \( z' = c \)

\[ D'(x) : \text{lane distribution function at lane position } x \text{ of road user } z' \]

\[ V_{z'} : \text{velocity of road user } z' \]

\[ Sh^z = \sum_{1(Q_c S^z_i)} \]

where \( Q_c : \text{Traffic volume of vehicle (/hour)} \)

The average index of the street section should be the same as the index of cross-section \( (Sh^z) \), if the roadway and traffic conditions, traffic volumes, traffic speeds, and lane distributions of traffic, are constant for the street section. The lane distribution, however, depends on the existence of on-street parking. The average index considering parking condition is to be defined as the average weighted by the street length and parking time of the indices estimated without parking and with one parked vehicle respectively. When the total parking time (vehicle seconds) is observed, the average index, which can consider simultaneously the influence on street safety of traffic volume, speed, separation of road users, and parking is as follows.

\[ SS^z = \left\{ \frac{Sh^z_n (3600 L - L_p H_p) + Sh^z_p L_p H_p}{3600 L} \right\} / (3600 L) \]

where

\[ SS^z : \text{Safety index of street section for road users } z \]

\[ Sh^z_n : \text{Safety index of cross-section in non-parking condition} \]

\[ Sh^z_p : \text{Safety index of cross-section where there is one parked vehicle} \]

\[ L : \text{Length of the street section} \]

\[ L_p : \text{Length where the lane distribution is influenced by one parked vehicle (assumed to be 10m)} \]

\[ H_p : \text{Total Parking time (vehicles seconds) in the section of street} \]

4 Analysis Of Street Safety Indices And Residents’ Safety Perception

4.1 Sample Streets and Sense Surveying

In order to make clear the evaluation criteria for the proposed street safety indices, the correlation between the safety perception of residents living along the streets and the proposed indices are analyzed. Table 5 shows the characteristics of sample streets. The width of sample street are 4m, 6m and 8m, which are popular in residential areas recently developed in Japan. Among the 8 m wide streets, 4 streets of "Community Street" are included, which are designed for traffic calming by introducing chicane shaped carriageway.

**Table 4 Characteristics of Sample Streets for Correlation Analysis**

<table>
<thead>
<tr>
<th>Road width</th>
<th>Traffic</th>
<th>Sidewalk</th>
<th>N. of Samples</th>
<th>Traffic volume (range/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wide vehicle</td>
</tr>
<tr>
<td>4m</td>
<td>one-way</td>
<td>none</td>
<td>3</td>
<td>4~72</td>
</tr>
<tr>
<td></td>
<td>dual-way</td>
<td>none</td>
<td>2</td>
<td>0~6</td>
</tr>
<tr>
<td>6m</td>
<td>one-way</td>
<td>none</td>
<td>8</td>
<td>0~28</td>
</tr>
<tr>
<td></td>
<td>dual-way</td>
<td>none</td>
<td>9</td>
<td>4~180</td>
</tr>
<tr>
<td>8m</td>
<td>one-way</td>
<td>equipped</td>
<td>6</td>
<td>8~68</td>
</tr>
<tr>
<td></td>
<td>one-way</td>
<td>with cicane</td>
<td>4</td>
<td>2~16</td>
</tr>
</tbody>
</table>
The sense of safety in walking, cycling and in total street environment, of those resident in each street, is surveyed by questionnaire. The numbers of samples in each street are from 10 and 15, and the total number is 383 for 32 streets. The safety perception was measured by the rating scales method using 5 categories; 1) very dangerous, 2) dangerous, 3) a little dangerous, 4) normal and 5) safe. The questionnaire results are converted to the sense score values by employing the following equation which is estimated by the scale construction method of successive categories.

\[ S_j = \sum_{i} c_j \cdot 1.00 \cdot \delta_{1ij} + 0.67 \cdot \delta_{2ij} + 0.38 \cdot \delta_{3ij} + 0.18 \cdot \delta_{4ij} \]

where
\[ c_j \cdot \delta_{kij} = 1 \text{ if the answer of resident } i \text{ living along street } j \text{ is } k \]
\[ = 0 \text{ if other (k=1: very dangerous, =2: dangerous, =3: a little dangerous, = 4 normal)} \]
\[ C_j : \text{ set of samples of street } j \]

4.2 Estimation of Lane Distribution
The lane distributions of bicycles and pedestrians were not surveyed for the sample street. We developed estimation models from observed sample by employing the following Gumbel distribution function.

\[ F_z(x) = \exp \left( - \exp \left( - \omega_z \left( x - \eta_z \right) \right) \right) \]

where
\[ F_z(x) : \text{ probability distribution function of lane distribution of road user } z \]
\[ x : \text{ position (m) from the edge of road if } z = \text{ pedestrians} \]
\[ \text{position (m) from the edge of carriageway if } z = \text{ bicycles} \]
\[ \omega_z, \eta_z : \text{ parameters (the following values are estimated from the video survey)} \]
\[ \omega_z = 4.24, \eta_z = 0.886 \text{ for pedestrians on the road without sidewalks} \]
\[ \omega_z = 5.92, \eta_z = 0.756 \text{ for pedestrians on the road with sidewalks} \]
\[ \omega_z = 4.36, \eta_z = 1.455 \text{ for bicycles on the carriageway with sidewalks} \]

4.3 Correlation Analysis
Figure 5 shows the correlation between the proposed street safety indices and safety perception scores of residents. Figure a) shows the relationship between the pedestrians street safety index and residents’ safety perception in walking along the street, figure b) shows the cyclists street safety index and residents’ sense in cycling along it. In figure c), the vertical axis means the average value of 4 kinds of street safety indices; 1) drivers’ safety perception for pedestrians, 2) pedestrians’ safety perception, 3) drivers’ safety perception for bicycles and 4) cyclists’ safety perception. In all figures, the correlation coefficient (single R) shows a value between 0.73 and 0.77.
Figure 5 Correlation Analysis of Street Safety Indices and Residents' Perception
5 The effect of street design considering safety perception

The developed street safety indices are applied to understand the street safety environment by street design for space reallocation at "Oimatsu Street". This street is located in the central area of Osaka City. Before improvement, the width of the street is only 7.3m, the daytime traffic volumes were over 2000 vehicles, 6000 pedestrians and 1000 cyclists, including over 500 cases of on-street parking in 360m. According to an interview survey, 75% of visitors complained of the danger of the street.

Figure 6 shows a street design of "Oimatsu Street" improvement. Sidewalks of 1.65m wide are provided, are narrow for daytime 6000 walkers. Carriageway narrowing is introduced at the approaches of the intersections to reduce the vehicles' speed and secure additional pedestrian space.

![Figure 6 Introduced design of Oimatsu Street](image)

We made an inspection using a video camera to assess traffic conditions before and after implementation to get the traffic. And the safety indices were calculated on the traffic and roadway conditions for Oimatsu street. Figure 7 shows scores of residents' perception. The index of pedestrians decreased from the "a little dangerous" level to the middle, and that of drivers for pedestrians also decreased. On the contrary, the indices for cyclists and that of drivers for bicycles show values of "a little dangerous". These results conform to the peoples' evaluation shown in Figure 8.

![Figure 7 Street Safety Environment for Residents](image)
6 Conclusion

The conclusions can be summarized as follows.
1) The models to explain road users’ perception could be developed by employing the concept of time for avoidance. From the estimation of these models, the perception zones between road users could be clarified.
2) The proposed safety indices can be calculate simply from average traffic indices.
3) These safety indices conformed with the residents’ safety perception according to the correlation analysis of 32 sample streets in Osaka city.
4) By employing proposed street safety index, the effect on street environment by street design considering safety perception of the road user could be shown.

The following problems should be considered in further studies.
1) Detailed experiments would be necessary to examine the effects of traffic and roadway conditions, for example, space for avoidance, personal attributes of age and safety perception etc., which were not considered in this paper.
2) To ascertain the assumptions for straightforward calculation of proposed indices, it is necessary to closely analyze application of the safety perception model to the traffic flows investigated by video observation.

Acknowledgment

This work has been carried out by authors in a joint study group for neighborhood traffic environment, under the cooperation of the Division of Safety Facilities Construction of Osaka City Government. The authors would like to thank members of the study group, especially Dr. Hino of Osaka Municipal University, Dr. Tsukaguchi of Ritsumeikan University and Dr. Odani of Kobe University of Mercantile Marine.

References