

## Possibility of Crosswalk Design Independent from Signals at Basic Road Sections

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**Abstract:** In Japan lots of traffic signals have been installed even in small intersections or crosswalks at narrow basic road sections. However, it is said that signal controlling is not always the most efficient and the safest considering various situations, especially for areas with not-so-high traffic volume. In this paper, “two-step crossing” was proposed as one of the alternatives of safety measure for non-signalized crosswalk and a risk index was derived to evaluate risks of three design types of crosswalk: “do-nothing” case, “two-step crossing” case and “signalization” case. A number of incidents was considered as the risk index and pedestrians’ and drivers’ incident occurrence was formulated in stochastic way that reflects people’s perception and psychology. As a result, by defining parameters and variables arbitrarily we found that the “two-step crossing” can be a solution to improve a crosswalk in particular conditions while “signalization” has a significant effect on risk reduction.

*Keywords:* Two-step crossing, Pedestrian, Safety, Stochastic model, Crosswalk design

### 1. INTRODUCTION

In Japan, every time a traffic accident occurs and somebody is killed, the traffic administrator, in Japan the police agency, tends to equip signals even at a small non-signalized intersection or a crosswalk in a narrow basic road section as a safety measure. This tendency has continued for a long time and as a matter of fact the number of signals in Japan has been increasing gradually year by year (Figure 1).

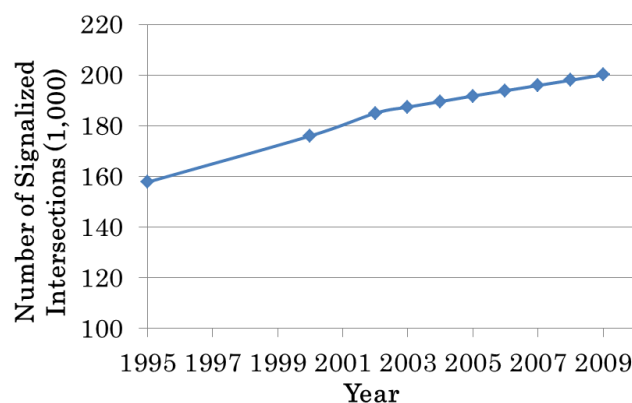


Figure 1. Increasing trend of number of signalized intersections

It is considered that this tendency will continue in step with the aging of the population. However, it is not always an optimal solution. If there are few traffic at an intersection, signals may increase total delay of both cars and pedestrians. And it is obvious that it needs a certain amount of expense to install and maintain signals. In this situation prioritization of crossing roads is said to be enough in terms of traffic efficiency (The Institution of Highways & Transportation, 1997). Moreover, from our experience of the great earthquake and tsunami disaster on March 11<sup>th</sup>, 2011, we found that high dependency on signals may be dangerous under electric outage. Most of the drivers did not know how to maneuver their vehicles at intersections where signals did not work and lots of pedestrians felt uneasy to cross roads because drivers seldom gave the right of way to them (Hatoyama and Hamaoka, 2011).

Therefore, it is necessary to find any designs that substitute for installing signals to improve non-signalized intersections and crosswalks from the viewpoint of both drivers and pedestrians. In this paper, we consider that to install “two-step crossing” by equipping pedestrian refuges at the middle of crosswalks is one of the solutions. Two-step crossing is not so unique in itself and can be found in European countries (Figure 2). The main merit of this design is thought that it is not necessary to equip signals at the crosswalks because pedestrians and drivers can look at each other easily and carefully. Pedestrians should be careful to look in only one direction before reaching pedestrian refuges, and after that they only have to look in the other direction, which may keep the traffic safety at the crosswalks.



Figure 2. Examples of two-step crossing in Paris (left) and London (right)

This paper develops one methodology to evaluate safety of two-step crossing by considering risks stochastically under not-so-high traffic volume from the viewpoints of both drivers and pedestrians and considers conditions where two-step crossing can be the best solution. As a first stage, this paper deals with crosswalks at narrow basic road sections and compares safety of various design patterns.

## 2. LITERATURE REVIEW

There have been a lot of researches that dealt with safety of intersections. Most researchers have tried to establish empirical models to find out the relationship between accident frequencies and geometric characteristics of intersections and traffic related variables such as traffic volume. Jovanis and Chang (1986) explained accident occurrence as a function of vehicle miles of travel and whether conditions using Poisson regression model. Miaou and Lum (1993) also applied the same methodology by including geometric characteristics into

the model, such as horizontal curvature, and vertical gradient. Other than Poisson regression model, Miaou (1994) suggested Negative Binomial (NB) regression to overcome the limitation of Poisson regression model. Shankar *et al.* (1995), Poch and Mannering (1996), Maher and Summersgill (1996) and Abdel-Aty and Radwam (2000) basically continued using the model. Fridstrom *et al.* (1995) explained road accident counts by taking randomness, exposure, weather, and daylight as the explanatory variables using the generalized Poisson regression models. Recently, Anastasopoulos and Mannering (2009) attempted to expand the NB model by using random-parameters, and Ibrahim and Sayed (2011) improved it by introducing the probability of non-compliance in safety performance functions. Most of them used the real accident data and aimed to find out critical measures that may increase accident frequency. Therefore, through this approach it is not easy to evaluate hidden risks that a certain design pattern of an intersection or a crosswalk implicitly has.

Even for pedestrian safety at crosswalks, the basic stance of researches seems to be similar as the above introduced ones. Leden (2002) estimated accident counts between pedestrians and left- and right-turning vehicles on crosswalks based on the NB model and found that pedestrian risk may decrease with pedestrian flow. Miranda-Moreno *et al.* (2011), Pulugurtha and Sambhara (2011) and Ukkusuri *et al.* (2012) also chose NB models to compare pedestrian-vehicle collision frequency and surrounding environment such as land use, geometric characteristics of intersections and so on, while Wier (2009) analyzed them by using a simple regression model. As other types of researches, Yannis *et al.* (2007) developed a pedestrians' crossing behavior model by a nested logit model and a regression model and considered how to think about the risks while they are crossing. Tiwari *et al.* (2007) conducted a video survey and found that longer signal waiting time make pedestrians get impatient and violate the traffic signal, which increases risk of being struck by a motor vehicle. And as a research that deals with two-step crossing, Li and Fernie (2010) checked pedestrian behavior at a long crosswalk with a thick pedestrian refuge in terms of pedestrian compliance rate and made a statistical analysis under different weather conditions.

It was found that in the most cases researchers tended to find important factors that may cause accidents and there were fewer researches that consider psychological principles of both drivers and pedestrians. This paper tries to develop a risk evaluation model that includes psychological principles.

### **3. RESEARCH METHODOLOGY**

#### **3.1 Research Framework**

This paper aims to evaluate two-step crossing as an alternative of safety measures at non-signalized crosswalks on narrow roads, whose width are less than 10 m, with not-so-heavy traffic volume from the viewpoint of both vehicles and pedestrians. Here the basic framework of this paper is introduced.

##### **3.1.1 Three patterns of crosswalk design**

In this paper, three patterns of crosswalk design cases: “do-nothing” case, “two-step crossing” case and “signalization” case. In “two-step crossing” case we suppose to equip a pedestrian refuge at the middle of a crosswalk. When crossing this crosswalk, pedestrians have to look in just one direction before and after the pedestrian refuge. In “signalization” case, we suppose to equip signals for drivers and pedestrians. The signals change their phases in a fixed cycle

time. In “do-nothing” case, we suppose not to equip anything. Pedestrians should look in two directions at once before decide to start crossing.

### 3.1.2 Definition of risk

It is obvious that it is difficult to deal with accident frequency directly as a risk evaluation index because accidents are infrequent events. To consider risks as more frequent events, we defined a risk index as an expected number of occurrences of “incidents” for both drivers and pedestrians in a unit of time. Incidents are considered as events that are not as severe as accidents. If a driver or a pedestrian gets a fright when they encounter each other, it is counted as an incident. That is to say, an incident occurs basically if at least one of the two (a driver and a pedestrian) misperceives the other’s behavior. We formulate an expected number of occurrences of incidents by taking following phenomena into account. Collisions among vehicles is not considered here because this paper, as a first step, deals with crosswalks at narrow basic road sections where main incidents must be caused by drivers and pedestrians.

1) For the “do-nothing case” and the “two-step crossing case”

An incident occurs if a driver and a pedestrian encounter each other at a crosswalk and at least one of them misperceives the other’s behavior. Here a probability of an encounter (encounter probability) and a probability of a misperception (misperception probability) should be formulated.

2) For the “signalization case”

An incident occurs when a pedestrian decides to violate the signal and encounters a driver at a crosswalk and when at least one of them misperceives the other’s behavior. Here a probability of pedestrian violation of the signal (pedestrian violation probability) should be formulated in addition to the two probabilities above. Moreover, an incident may occur when a pedestrian crosses the crosswalk aggressively while the phase of the pedestrian signal is changing from red to green and encounters a driver. Therefore a probability of a pedestrian’s aggressive crossing (pedestrian aggressive crossing probability) is also formulated in this paper.

## 4. DEFINITION OF RELATED PROBABILITIES

### 4.1 Encounter probability

First of all, the encounter probability is discussed. In this paper two kinds of encounter probability can be defined: a pedestrian’s encounter probability with a vehicle and a driver’s encounter probability with a pedestrian. A pedestrian’s encounter probability with a vehicle ( $P_{enc\_ped}$ ) is defined as a probability that more than one vehicle arrive at the crosswalk while a pedestrian is crossing the crosswalk. A driver’s encounter probability with a pedestrian ( $P_{enc\_veh}$ ) is defined as a probability that more than one pedestrian arrive at the crosswalk between the time when a driver arrives at the “perception limit point” before the crosswalk and the time when the driver arrives at the crosswalk. The perception limit point is defined as a braking distance in which the driver can stop in front of the crosswalk after he/she perceives a pedestrian. Here arrival distributions of pedestrians and vehicles are based on Poisson arrival. Figure 3 shows basic variables to be considered here. For the analysis, a crosswalk space is divided into two sections: the near side (section 1) and the far side (section 2).

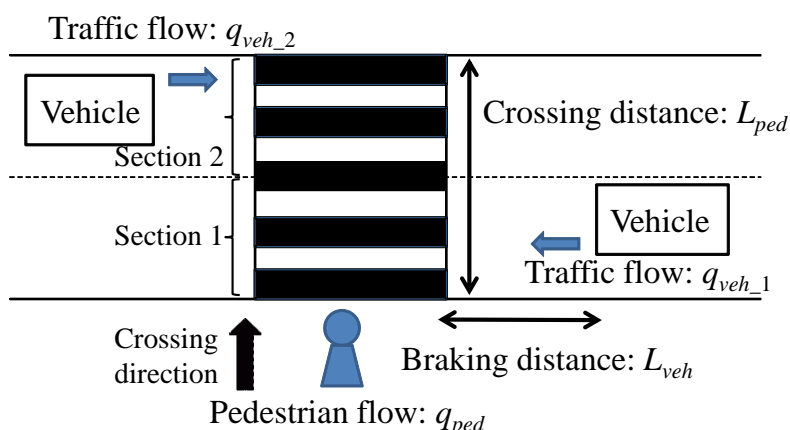


Figure 3. Basic variables for encounter probabilities

#### 4.1.1 A pedestrian's encounter probability with a vehicle

Here,  $N(q,t)$  and  $P(N(q,t) = k)$  is defined as a number of arrival of vehicles or pedestrians during  $t$  [s] with flow  $q$  [1/s] and a probability that  $k$  vehicles or  $k$  pedestrians arrive at the crosswalk during  $t$ . The necessary time for a pedestrian to finish crossing the crosswalk ( $t_{ped}$  [s]) is expressed as  $t_{ped} = L_{ped} / V_{ped}$ , where  $L_{ped}$  [m] and  $V_{ped}$  [m/s] denote the crossing distance and the pedestrian walking speed. By using  $t_{ped}$ , a probability that a pedestrian encounters more than one vehicle in the section 1 or in the section 2 can be written:

$$P_{enc\_ped\_1} = 1 - P(N_1(\alpha \cdot t_{ped} / 2) = 0) = 1 - \exp(-\alpha \cdot q_{veh\_1} \cdot t_{ped} / 2)$$

$$P_{enc\_ped\_2} = 1 - P(N_2(\alpha \cdot t_{ped} / 2) = 0) = 1 - \exp(-\alpha \cdot q_{veh\_2} \cdot t_{ped} / 2)$$
(1)

where,

$\alpha$  : a factor of safety ( $>1$ ), and  
 $q_{veh\_1}, q_{veh\_2}$  : traffic flow of vehicles in section 1 and section 2 [veh./s].

#### 4.1.2 A driver's encounter probability with a pedestrian

Here, a driver's encounter is considered as an encounter while the driver is in the braking distance before the crosswalk. In the same way as above, by using the braking distance  $L_{veh}$  [m], the vehicle speed  $V_{veh}$  [m/s], the passing time for a driver to pass through the braking distance ( $t_{veh}$  [s] =  $L_{veh} / V_{veh}$ ) and pedestrian flow in one direction  $q_{ped}$  [person/s], a probability that a driver encounters more than one pedestrian can be written:

$$P_{enc\_veh} = 1 - P(N(\alpha \cdot t_{veh}) = 0) = 1 - \exp(-\alpha \cdot q_{ped} \cdot t_{veh})$$
(2)

#### 4.2 Misperception probability

Second, the misperception probability is defined as a probability that a driver or a pedestrian does not recognize the other's existence, or misjudges the other's behavior. The influence factors to be included into this probability must be the other's traffic flow. If there is little pedestrian traffic a driver may approach the crosswalk without enough care, whereas if there

is heavy pedestrian traffic a driver should be very careful while passing the crosswalk. Therefore vehicle flow or pedestrian flow may have a negative impact on the other's misperception probability. Moreover, the marginal impact of the flow may be big when the flow itself is small and may decrease as the flow gets heavier. Therefore exponential distributions are applied for the misperception probability in this paper. This probability can be considered different depending on the existence of a pedestrian refuge as follows.

#### 4.2.1 Misperception probability with the existence of a pedestrian refuge

Figure 4 shows the basic setting of this case from the viewpoint of a pedestrian.

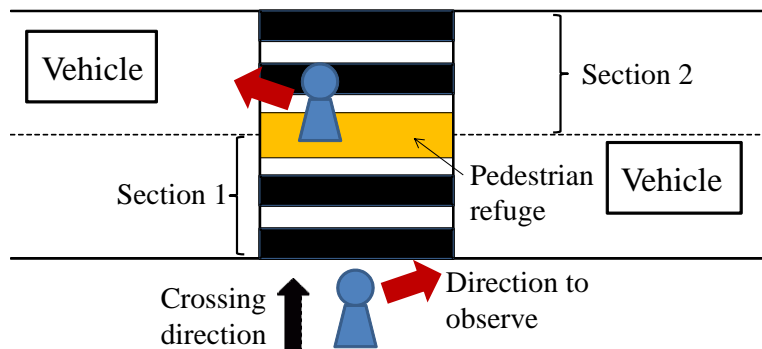


Figure 4. The direction to observe with a pedestrian refuge

In this case a pedestrian crosses the crosswalk in a two-step manner: the section 1 first and the section 2. While crossing each section, he/she has to observe just one direction to check whether a vehicle is approaching or not. Probabilities here that the pedestrian misperceives ( $P_{mis\_ped\_with}$ ) for each section can be considered as:

$$\begin{aligned}
 P_{mis\_ped\_with\_1} &= p_1 \cdot \exp(-\lambda_1 / f(n_{d1}) \cdot q_{veh\_1}) + p_0 \\
 P_{mis\_ped\_with\_2} &= p_1 \cdot \exp(-\lambda_1 / f(n_{d2}) \cdot q_{veh\_2}) + p_0 \\
 f(n_{di}) &= n_{di}, n_{d1} = n_{d2} = 1
 \end{aligned}
 \tag{3}$$

where,

- $p_1$  : a ratio of people that misperceives due to the other's flow ( $p_1 < 1 - p_0$ ),
- $p_0$  : a ratio of people that tend to misperceive inherently,
- $f(\cdot)$  : a misperception increase function due to a number of directions to observe,
- $n_{di}$  : a number of directions to observe at the section  $i$ , and
- $\lambda_1$  : a parameter to reflect the misperception decrease due to the other's flow.

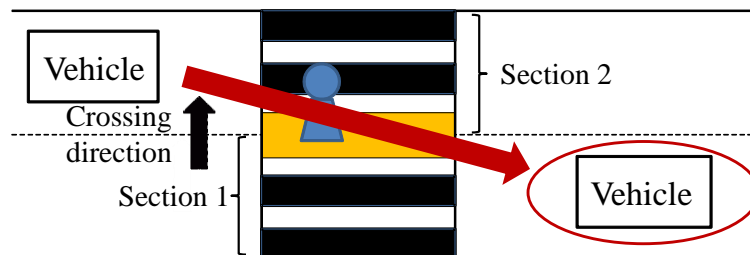


Figure 5. A vehicle referring a vehicle coming from the opposite direction

From the viewpoint of drivers, it is considered that a vehicle approaching the crosswalk in the far side of the road (section 2) can perceive a pedestrian crossing from the right side more than a vehicle approaching in the near side (section 1). The reasons of this consideration are; the driver in the section 2 has more time to perceive a pedestrian while he/she is crossing in the section 1; the driver in the section 2 can also perceive a vehicle in the section 1 that gives the right of way to a pedestrian, which can be a cue to perceive the pedestrian (Figure 5). Then, probabilities here that the driver misperceives ( $P_{mis\_veh\_with}$ ) in each section can be written:

$$\begin{aligned} P_{mis\_veh\_with\_1} &= p_2 \cdot \exp(-\lambda_2 \cdot q_{ped}) + p_0 \\ P_{mis\_veh\_with\_2} &= p_2 \cdot \exp(-\lambda_2 \cdot q_{ped} - \rho_{with} \cdot \lambda_3 \cdot q_{veh\_1}) + p_0 \end{aligned} \quad (4)$$

where,

- $p_2$  : a ratio of people that misperceives due to the other's flow ( $p_2 < 1 - p_0$ ),
- $\lambda_2$  : a parameter reflecting misperception decrease due to the other's flow,
- $\rho_{with}$  : a ratio of cue vehicles in the opposite direction in this case, and
- $\lambda_3$  : a parameter reflecting misperception decrease due to vehicles in the opposite direction.

#### 4.2.2 Misperception probability without the existence of a pedestrian refuge

Figure 6 shows the basic setting of this case from the viewpoint of a pedestrian.

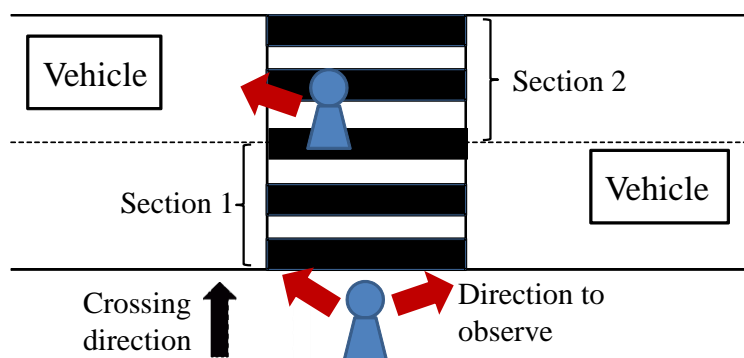


Figure 6. The directions to observe without a pedestrian refuge

In this case, when a pedestrian crosses the crosswalk, he/she has to observe two directions before crossing the section 1. When crossing the section 2, he/she does not have to check two directions. However, different from the previous case he/she has no time to relax at the middle of the road, which may affect the probability of misperception. Consequently, a probability here that the pedestrian misperceives ( $P_{mis\_ped\_without}$ ) for each section can be considered as:

$$\begin{aligned} P_{mis\_ped\_without\_1} &= p_1 \cdot \exp(-\lambda'_1 / f(n_{d1}) \cdot q_{veh\_1}) + p_0 \\ P_{mis\_ped\_without\_2} &= p_1 \cdot \exp(-\lambda'_1 / f(n_{d2}) \cdot q_{veh\_2}) + p_0 \end{aligned} \quad (5)$$

$$f(n_{di}) = n_{di}, n_{d1} = 2, n_{d2} = 1, \lambda'_1 < \lambda_1$$

where,

$\lambda_1'$  : a parameter to reflect the misperception decrease due to the other's flow.

From the viewpoint of drivers, it is considered in almost the same way. The different point is that a driver can be more carefully about a vehicle coming from the opposite direction because of lack of the pedestrian refuge (i.e.  $\rho_{without} > \rho_{with}$ ). Therefore, probabilities here that the driver misperceives ( $P_{mis\_veh\_without}$ ) in each section can be written:

$$\begin{aligned} P_{mis\_veh\_without\_1} &= P_{mis\_veh\_with\_1} = p_2 \cdot \exp(-\lambda_2 \cdot q_{ped}) + p_0 \\ P_{mis\_veh\_without\_2} &= p_2 \cdot \exp(-\lambda_2 \cdot q_{ped} - \rho_{without} \cdot \lambda_3 \cdot q_{veh\_1}) + p_0 \end{aligned} \quad (6)$$

$$\rho_{without} > \rho_{with}$$

### 4.3 Pedestrian signal violation probability

In the case of “signalization,” it is necessary to consider a probability that a pedestrian violates the signal during a red light ( $P_{ped\_violate}$ ). Here, a probability that a pedestrian decides to cross as a first person among waiting pedestrians and a probability that a pedestrian decides to do after the first person are different probabilities. Both are discussed below.

#### 4.3.1 Signal violation probability for a first pedestrian

The signal violation probability for a first pedestrian ( $P_{ped\_violate\_1}$ ) can be influenced by the signal cycle length, the pedestrian flow and the vehicle traffic flow; the cycle length must have a positive effect and the pedestrian flow and the vehicle traffic flow must have a negative effect on this probability. If the cycle length is longer, more pedestrians want to violate the signal as is checked by Tiwari *et al.* (2007). And if there are many waiting pedestrians, the first violator tends to hesitate to implement his/her behavior in full view of everyone (Figure 7). If there is much traffic, of course it is hard to find an enough gap to cross. Putting all of these factors together, a signal violation probability for a first pedestrian can be written:

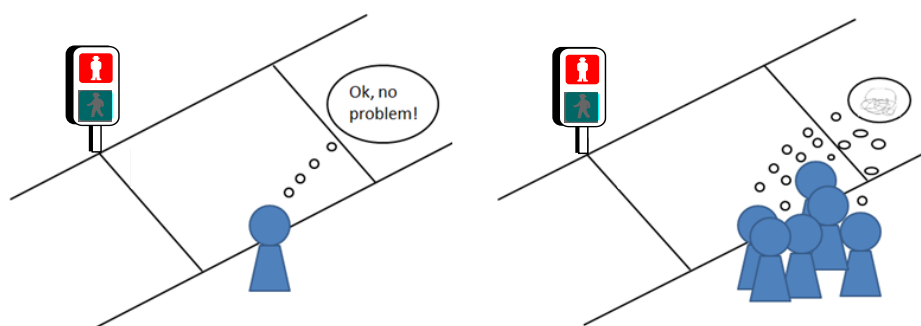


Figure 7. Relationship between a first violator and waiting pedestrians

$$P_{ped\_violate\_1} = \exp(-\lambda_4 \cdot q_{ped}) \times \{1 - \exp(-\lambda_5 \cdot g \cdot C)\} \times \exp\{-\lambda_6 \cdot (q_{veh\_1} + q_{veh\_2})\} \quad (7)$$

where,



$\lambda_4, \lambda_5, \lambda_6$  : parameters reflecting effects of each factor,  
 $g$  : a ratio of the green time for vehicles to the cycle length, and  
 $C$  : the signal cycle length [s].

### 4.3.2 Signal violation probability for followers

The signal violation probability for followers can be influenced by the signal cycle length and the vehicle traffic flow. The psychological barrier, such as pedestrian flow, does not work here because the first violator has already broken the barrier.

$$P_{ped\_violate\_2} = \{1 - \exp(-\lambda_7 \cdot g \cdot C)\} \times \exp\{-\lambda_8 \cdot (q_{veh\_1} + q_{veh\_2})\} \quad (8)$$

where,

$\lambda_7, \lambda_8$  : parameters reflecting effects of each factor.

Within each signal cycle,  $q_{ped} \cdot g \cdot C$  pedestrians should wait in from of the crosswalk. Therefore, the probability that nobody decides to cross during one red light is derived as  $(1 - P_{ped\_violate\_1})^{q_{ped} \cdot g \cdot C}$ . And  $1 - (1 - P_{ped\_violate\_1})^{q_{ped} \cdot g \cdot C}$  denotes a probability that at least one pedestrian decides to cross and the other pedestrians decide based on  $P_{ped\_violate\_2}$ . Finally, a pedestrian signal violation probability  $P_{ped\_violate}$  can be written:

$$P_{ped\_violate} = \left\{1 - (1 - P_{ped\_violate\_1})^{q_{ped} \cdot g \cdot C}\right\} \left\{1 + P_{ped\_violate\_2} \cdot (q_{ped} \cdot g \cdot C - 1)\right\} / q_{ped} \cdot g \cdot C \quad (9)$$

### 4.4 Pedestrian aggressive crossing probability

Here a probability that a pedestrian aggressively decides to cross the crosswalk when the pedestrian signal is changing from red to green. The way of thinking is similar to the previous probability while the number of pedestrians that remain until signal changing point ( $n_{ped}$ ) in one signal cycle is:

$$n_{ped} = q_{ped} \cdot g \cdot C - \left\{1 - (1 - P_{ped\_violate\_1})^{q_{ped} \cdot g \cdot C}\right\} \left\{1 + P_{ped\_violate\_2} \cdot (q_{ped} \cdot g \cdot C - 1)\right\} \quad (10)$$

By using this number, a pedestrian aggressive crossing probability  $P_{ped\_aggressive}$  can be written:

$$P_{ped\_aggressive} = \left\{1 - (1 - P_{ped\_aggressive\_1})^{n_{ped}}\right\} \left\{1 + P_{ped\_aggressive\_2} \cdot (n_{ped} - 1)\right\} / n_{ped}$$

$$P_{ped\_aggressive\_1} = \exp(-\lambda'_4 \cdot q_{ped}) \times \left\{1 - \exp(-\lambda'_5 \cdot g \cdot C)\right\} \times \exp\{-\lambda'_6 \cdot (q_{veh\_1} + q_{veh\_2})\} \quad (11)$$

$$P_{ped\_aggressive\_2} = \left\{1 - \exp(-\lambda'_7 \cdot g \cdot C)\right\} \times \exp\{-\lambda'_8 \cdot (q_{veh\_1} + q_{veh\_2})\}$$

where,

$\lambda'_4, \lambda'_5, \lambda'_6, \lambda'_7, \lambda'_8$  : parameters reflecting effects of each factor,

We consider using those probabilities to define a risk index.

## 5. FORMULATION OF A RISK INDEX

Using above-defined probabilities, it is possible to formulate a risk index as is the expected number of incidents. In the case of “do-nothing” and the “two-step crossing,” incidents may occur if a driver and a pedestrian encounter each other and at least one of them misperceives the other’s behavior. That is to say, it is necessary to consider following three situations under the condition that both a driver and a pedestrian encounter each other:

- (1) Both the driver and the pedestrian misperceive the other’s behavior,
- (2) The pedestrian misperceives the driver’s behavior while the driver perceives properly, and
- (3) The driver misperceives the pedestrian’s behavior while the pedestrian perceives properly.

### 5.1 A risk index for “two-step crossing” case

The risk index for “two-step crossing” case ( $R_{tsc}$ ) should be composed of expected numbers of incident occurrence under the three situations ((1) to (3)) mentioned above from the viewpoint of both pedestrians and drivers.

$$R_{tsc} = R_{tsc1} + R_{tsc2} + R_{tsc3} \quad (12)$$

$$R_{tsc1} = \sum_{i=1}^2 (q_{ped} \cdot P_{enc\_ped\_i} \cdot P_{mis\_ped\_with\_i} \cdot P_{mis\_veh\_with\_i}) + \sum_{i=1}^2 (q_{veh\_i} \cdot P_{enc\_veh\_i} \cdot P_{mis\_ped\_with\_i} \cdot P_{mis\_veh\_with\_i}) \quad (13)$$

$$= \sum_{i=1}^2 (q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P_{enc\_veh\_i}) \cdot P_{mis\_ped\_with\_i} \cdot P_{mis\_veh\_with\_i}$$

$$R_{tsc2} = \sum_{i=1}^2 (q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P_{enc\_veh\_i}) \cdot P_{mis\_ped\_with\_i} \cdot (1 - P_{mis\_veh\_with\_i}) \quad (14)$$

$$R_{tsc3} = \sum_{i=1}^2 (q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P_{enc\_veh\_i}) \cdot (1 - P_{mis\_ped\_with\_i}) \cdot P_{mis\_veh\_with\_i} \quad (15)$$

where,

- $R_{tsc1}$  : an expected incident number when both misperceive,
- $R_{tsc2}$  : an expected incident number when only a pedestrian misperceives, and
- $R_{tsc3}$  : an expected incident number when only a driver misperceives.

### 5.2 A risk index for “do-nothing” case

In the same way as the previous one, the risk index for “do-nothing” case ( $R_{dn}$ ) can be written:

$$R_{dn} = R_{dn1} + R_{dn2} + R_{dn3} \quad (16)$$

$$R_{dn1} = \sum_{i=1}^2 (q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P_{enc\_veh\_i}) \cdot P_{mis\_ped\_without\_i} \cdot P_{mis\_veh\_without\_i} \quad (17)$$

$$R_{tsc2} = \sum_{i=1}^2 (q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P_{enc\_veh\_i}) \cdot P_{mis\_ped\_without\_i} \cdot (1 - P_{mis\_veh\_without\_i}) \quad (18)$$

$$R_{tsc3} = \sum_{i=1}^2 (q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P_{enc\_veh\_i}) \cdot (1 - P_{mis\_ped\_without\_i}) \cdot P_{mis\_veh\_without\_i} \quad (19)$$

### 5.3 A risk index for “signalization” case

In the case of “signalization,” incidents should be counted if a pedestrian violates the signal, encounters a driver and at least one of them misperceives, and if a pedestrian crosses the crosswalk aggressively while the phase of the pedestrian signal is changing from red to green and encounters a driver. The former situations can be formulated by the similar method. Here a risk index for “signalization” case ( $R_{sig}$ ) is written:

$$R_{sig} = R_{sig1} + R_{sig2} + R_{sig3} + R_{sig4} \quad (20)$$

$$R_{sig1} = \sum_{i=1}^2 (P_{ped\_violate} \cdot g \cdot q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P'_{enc\_veh\_i}) \cdot P_{mis\_ped\_without\_i} \cdot P'_{mis\_veh\_without\_i} \quad (21)$$

$$R_{sig2} = \sum_{i=1}^2 (P_{ped\_violate} \cdot g \cdot q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P'_{enc\_veh\_i}) \cdot P_{mis\_ped\_without\_i} \cdot (1 - P'_{mis\_veh\_without\_i}) \quad (22)$$

$$R_{sig3} = \sum_{i=1}^2 (P_{ped\_violate} \cdot g \cdot q_{ped} \cdot P_{enc\_ped\_i} + q_{veh\_i} \cdot P'_{enc\_veh\_i}) \cdot (1 - P_{mis\_ped\_without\_i}) \cdot P'_{mis\_veh\_without\_i} \quad (23)$$

where,

$$P'_{enc\_veh} = 1 - \exp(-\alpha \cdot P_{ped\_violate} \cdot q_{ped} \cdot t_{veh}) \quad (24)$$

$$P_{mis\_veh\_without\_1} = p_2 \cdot \exp(-\lambda'_2 \cdot q_{ped}) + p_0, \lambda'_2 < \lambda_2 \quad (25)$$

$$P_{mis\_veh\_without\_2} = p_2 \cdot \exp(-\lambda'_2 \cdot q_{ped} - \rho_{with} \cdot \lambda'_3 \cdot q_{veh\_1}) + p_0$$

To write  $R_{sig4}$ ,  $P_{veh\_aggressive}$  is defined as a following probability assuming that a driver tends to rush into the crosswalk if the waiting time for him/her is long:

$$P_{veh\_aggressive} = 1 - \exp\{-\lambda_g \cdot (1 - g) \cdot C\} \quad (26)$$

where,

$\lambda_g$  : a parameter reflecting effect of the waiting time.

Using this probability, we define encounter probabilities for both pedestrians and drivers in this situation as:

$$P'_{enc\_ped} = 1 - \exp\{-\alpha \cdot P_{veh\_aggressive} \cdot (q_{veh\_1} + q_{veh\_2}) \cdot t_{ped}\} \quad (27)$$

$$P''_{enc\_veh} = 1 - \exp\{-\alpha \cdot P_{ped\_aggressive} \cdot n_{ped} / (g_{ig} \cdot C) \cdot t_{veh}\} \quad (28)$$

where,

$g_{ig}$  : a ratio of the inter green time for vehicles to the cycle length.

Then  $R_{sig4}$  can be written:

$$R_{sig4} = P'_{enc\_ped} \cdot P_{ped\_aggressive} \cdot n_{ped} / C + P''_{enc\_veh} \cdot P_{veh\_aggressive} \cdot g_{ig} \cdot (q_{veh\_1} + q_{veh\_2}) \quad (29)$$

## 6. ANALYSIS AND DISCUSSION

### 6.1 Simulation setting

In this paper, lots of variables and parameters were introduced into the risk index. Here, to check whether the introduced model can work or not, the variables and parameters are set as follows arbitrarily but not unreasonably, since no other research was found that mentions about the values of the parameters introduced.

1) Controlled variables:

$$t_{ped} = 8[s], t_{veh} = 3[s], \alpha = 1.1, C = 75[s], g = 0.65, \text{ and } g_{ig} = 0.06.$$

2) Perceptual parameters:

$$p_0 = 0.1, p_1 = 0.7, \lambda_1 = 20, \lambda'_1 = 12, p_2 = 0.5, \lambda_2 = 40, \lambda'_2 = 4, \lambda_3 = 10, \lambda'_3 = 2, \\ \rho_{with} = 0.3, \text{ and } \rho_{without} = 0.6.$$

3) Psychological parameters:

$$\lambda_4 = 3, \lambda'_4 = 1.8, \lambda_5 = 0.02, \lambda'_5 = 0.01, \lambda_6 = 3.6, \lambda'_6 = 1.2, \lambda_7 = 0.04, \lambda'_7 = 0.03, \\ \lambda_8 = 1.8, \lambda'_8 = 0.9, \text{ and } \lambda_9 = 0.01.$$

### 6.2 Relationship between traffic flow and the risk index

Figure 8 shows the results of the calculation of risk index for each crosswalk design.

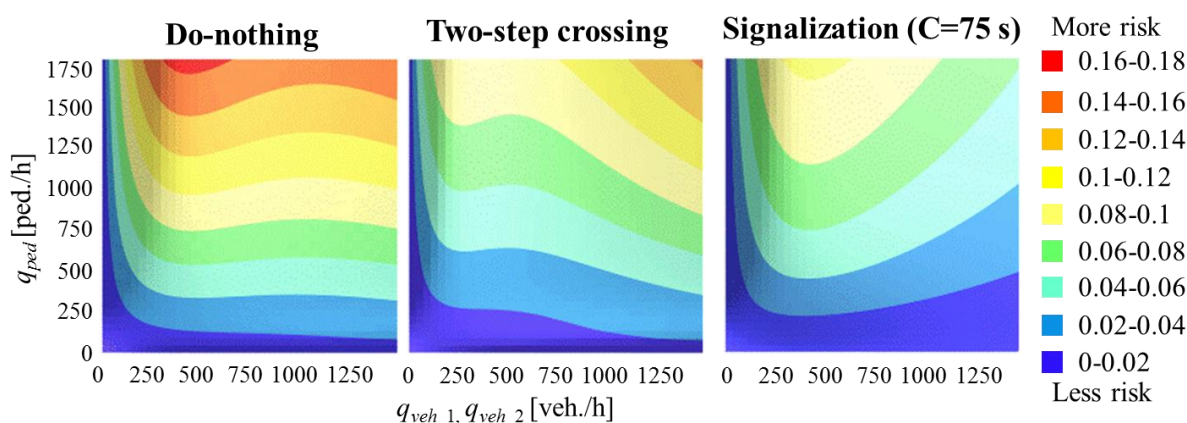


Figure 8. Relationship between traffic flow and the risk index

In the “do-nothing” case, if vehicle traffic flow is constant, the larger pedestrian flow becomes, the higher the risk index goes, while the risk index does not change much due to the increase of vehicle traffic flow if it is over 400 [veh./h]. The reason can be considered that if vehicle traffic flow increases the probability of pedestrian’s misperception of vehicles decreases.

In the “two-step crossing” case, it is found that the risk of this case is generally safer

than the “do-nothing” case. It is also remarkable that if vehicle traffic flow becomes more than 500 [veh./h], increase of vehicle traffic flow causes increase of the risk index. The main reason must be the difference of the drivers’ perception in the section 2 (far side). In this case, drivers in the section 2 is considered not to look the vehicles in the other direction as cues to perceive walking pedestrians. And pedestrians encounter in the section 2 may meet with an incident more frequently.

In the “signalization” case, the biggest difference from the other two cases is that if pedestrian flow is constant, the risk index first rises due to the increase of vehicle traffic but after passing a local maximum value it descends again. The main reasons of the phenomenon are the decrease of pedestrians’ misperception and the decrease of pedestrians’ signal violation due to the vehicle traffic increase.

### 6.3 Desirable crosswalk design from the viewpoint of risk

Using above shown results, finally, it can be possible to create a figure that illustrates the desirable crosswalk design associated with traffic flows from the viewpoint of risk under the conditions defined in this paper. By checking which design has a minimum risk index in each combination of pedestrian and vehicle traffic flow, Figure 9 can be derived.

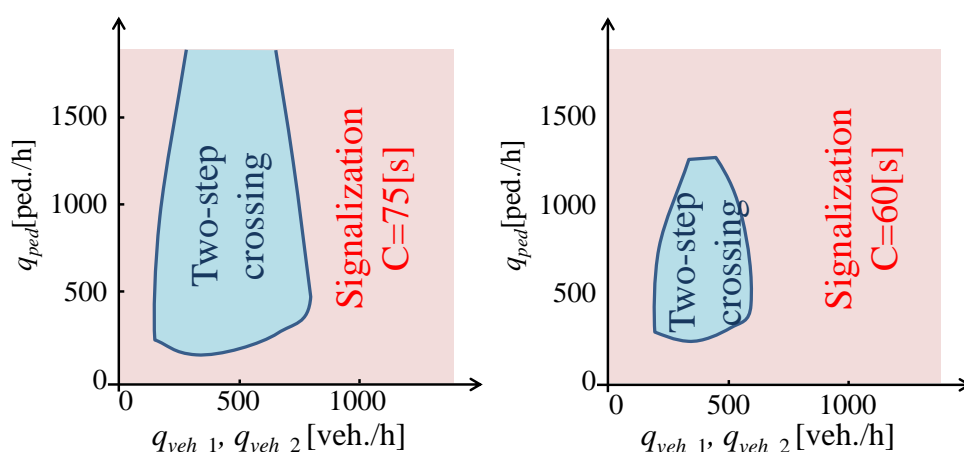


Figure 9. Desirable crosswalk design map

From this figure, it is safe to say that there is a substantial area where “two-step crossing” is desirable, although “signalization” has an advantage when the traffic flow is heavy or very small. Moreover, in the case of short cycle length, the area for “two-step crossing” is shrunken. This is simply because in the shorter signal cycle, pedestrians tend not to decide to violate the signal while they are waiting in front of the crosswalk.

Under the condition of very small traffic flow, again, “signalization” is considered as a desirable way to improve crosswalk safety. However, in the very small traffic flow, there is not a significant difference between the “signalization” case and the “two-step crossing” case in risk index. Therefore equipping signals in this area cannot always an appropriate solution. It is necessary to evaluate also from the viewpoint of efficiency and cost-effectiveness in this area, which is not achieved in this paper.

## 7. CONCLUSION

In this paper, “two-step crossing” was proposed as one of the alternatives of safety measure

for non-signalized crosswalk and a risk index was derived to evaluate risks of three design types of crosswalk: “do-nothing” case, “two-step crossing” case and “signalization” case. A number of incidents was considered as the risk index and pedestrians’ and drivers’ incident occurrence was formulated in stochastic way that reflects people’s perception and psychology.

As a result, by defining parameters and variables arbitrarily we found that the “two-step crossing” can be a solution to improve a crosswalk in particular conditions while “signalization” has a significant effect on risk reduction.

In the future following five major tasks should be carried out:

- 1) Validation of the parameters used in the models by conducting a sensitivity analysis to show that the conclusion remains essentially the same even if the parameters vary within reasonable ranges,
- 2) Validation of stochastic models by experiment and accident data analysis,
- 3) Model improvement to include the other possible factors such as geometric factors and signal-related factors (for example, the influence of crosswalk length and green-time duration on the signal violation probability),
- 4) Consideration of efficiency and cost, and
- 5) Application of this methodology to three-legged or four-legged intersections.

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