ESTIMATION OF ILLEGAL CROSSING ACCIDENT RISK USING STOCHASTIC PETRI NETS

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Abstract
Pedestrian illegal crossing is strongly related to the risk of accident, due to disobedience of signal control and dedicated crossing space. The study on the pedestrian illegal crossing and accident risk normally focuses on either spatial or temporal crossing violation behavior. Thus, this paper attempts to fill the gap by analyzing accident risk of the combination illegal crossing of pedestrians, which is seldom explored. The risk of illegal crossing behavior of pedestrians at signalized intersections is modeled based on the crossing scenario observed in the study locations. Pedestrian crossing scenario captured from video provides information related to behavioral pattern, and accident event sequence valuable for the model development using Petri Nets. The combined effects of spatial and temporal illegal crossing on their crossing risk were analyzed using the steady state analysis built in this model. The results show that the risk of the temporal illegal behavior has greater effect on pedestrian safety compared to the spatial illegal behavior. Escalating pedestrian volume tends to increase the risk of the illegal crossing behavior at the signalized intersection.

Keywords: Pedestrian, Illegal crossing, Accident risk, Signalized intersection, Petri Nets.

1. Introduction
Crossing at road section has become part of the activities for pedestrians to reach their target destination. However, the probability of pedestrians involved in an accident is high when they cross at road section [1]. Their risk is getting even
higher when pedestrians adopt illegal crossing behaviour such as crossing against
the traffic signal or not in a crosswalk [2]. Issues related to illegal behaviours of
the pedestrians can be differentiated by two basic elements: temporal and spatial.
The non-compliance behaviours to these two elements can be referred to as
temporal and spatial violation. The temporal violation denotes the disobedience of
pedestrian with respect to time and spatial violation denotes the disobedience of
pedestrian with respect to space.

At a signalized intersection, the accident risk level would increase eight times
when pedestrians adopted an illegal crossing compared to the legal crossing
behaviours [3]. Being in a hurry is the key motive for a pedestrian to violate the
signal at signalized intersections [4] and this type of temporal violation is actually
associated with the subjective norm behaviour [5]. This explains why pedestrian
violations associated with pedestrian accident is higher at signalized intersections
compared to other crossing facilities [6].

Pedestrians are considered committing the spatial crossing violation when
they enter a road section to start or to end their crossing outside the designated
crossing facility. This kind of behaviour is known as jaywalk. Jaywalking
behaviour is expected to be a factor associated with pedestrian accidents at
signalized intersections when the number of pedestrian crosses increased [7].
Jaywalking behaviour of pedestrians is among the most common violation [6],
and pedestrians are more likely to jaywalk at the first stage of crossing and wait at
the median to find the gap in second stage crossing [8]. Jaywalking is already a
habit to adult pedestrians and demographics does not significantly affect this
behaviour [9]. The distance of a crosswalk to the desired pedestrians’ endpoint
might become a factor for jaywalking [10].

Though illegal behaviour of pedestrians is believed to associate with higher
accident risk, there are limited numbers of studies that have been devoted to
investigate the impact of pedestrian illegal behaviour on their safety. Related
work of King et al. [3] quantified the relative risk of illegal crossing to the legal
crossing in Brisbane CBD, Australia based on the pedestrian behavioural
observation and the historical accident records at six selected signalized
intersections. The calculation of risk per crossing event was determined as the
number of accidents per unit time in that behavioural category divided by number
of crossing per unit time for the category, while relative risk by mathematical
calculation was counted as the accidents per crossing event for an illegal
behaviour divided by accidents per crossing event for legal crossing. With about
20% of observed illegal crossing, the risk of this behaviour was significantly
higher compared to legal crossing. However, the effect of the mixed pedestrian
illegal behaviour is not examined in their work.

In another study, Tiwari et al. [11] analysed the unsafe behaviour of
pedestrians at signalized intersections in Delhi, India, which was associated with
the waiting time and gender. The unsafe behaviour in their study focused on the temporal illegal crossing which was expected to be at risk. The risk as an event is identified when a pedestrian starts crossing when the yellow and green signal for the vehicle are displayed. The occurrences of risk event were observed and the probability of safe crossing is plotted as the survival function of pedestrian with respect to waiting time. The result showed that the survival function has varied with time among male and female pedestrian. However, the estimation of accident risk for the pedestrians who are committed with unsafe behaviour is not considered in their study.

Study related to the estimation of accident risk for pedestrian behaviour would propose a different approach. Yannis et al. [12] proposed an estimation of pedestrian risk related to the crossing behaviour based on the total accident risk for the entire pedestrian trip. The total accident risk was determined by summing up the crossing probability and accident risk at each crossing location. Nested logit and linear regression models were merged to develop a pedestrian crossing behaviour model for the estimation of crossing probability. However, this study did not consider illegal behaviour of the pedestrian.

Previous effort in estimating the risk of pedestrian accident focusing on their crossing behaviour may be limited. The effect of illegal behaviours to the risks are seldom being explored, especially the combination effect of their temporal and spatial violation. This may be due to the complexity of these behaviours and the absence of the behavioural data in the accident database. Thus, this paper aims to introduce an approach in quantifying the risk of crossing pedestrian, taking into consideration the combination of spatial and temporal violation, together with the effect of increasing pedestrian volume using stochastic Petri Nets. The estimation of pedestrian crossing risk focuses on the signalized pedestrian crossing.

2. Methodology

The risk for pedestrians is recognised when they have a great potential colliding with coming vehicles on the road section while crossing. The collision of a pedestrian and a vehicle occurs when both are present at the same point of the road section at the same time. The movement of a pedestrian and a vehicle prior to their collision can be plotted as an accident event sequence which will end as an accident. Thus, an understanding of this accident event sequence acquires a series of observation at the study locations.

In this study, Petri Nets (PN) was employed to model pedestrian accident event sequence as the crossing scenario was observed at signalized intersections. The structure of the PN model consists of places, transitions and arcs. The places in PN model are used to represent the condition of the agents or variables of the event. In this context, the agents refer to pedestrians and vehicles. Meanwhile, the transitions in PN model are used to represent the occurrence of the event or activities in the system with time elapse.

In particular, the pedestrian accident risk related to the combination of the temporal and spatial illegal crossing behaviours is needed to be explored first. For this purpose, the pedestrian crossing scenario was observed at eight selected signalized intersections in Kuala Lumpur, Malaysia. An example of a pedestrian
crossing scenario at one of the study locations near a shopping complex is shown in Fig. 1. Recording the pedestrian crossing scenario at the study location using video camera provided information related to pedestrian behaviour and pedestrian accident event sequence. The evaluation of pedestrian risky behaviour at sites is important to reveal the abnormal environment that is missing in the police report [13].

Fig. 1. Pedestrian crossing scenario at the signalised intersection in Kuala Lumpur.

2.1. Pedestrian crossing behavior

Video data provide useful information related to the pedestrian crossing behaviour. In this study, the data were coded based on several behavioural elements according to the crossing activity; the place when start crossing, the signal when start crossing, the place at the end of crossing and the signal when pedestrians end crossing. These behavioural data of crossing pedestrians were transcribed into a specific worksheet to identify different patterns of pedestrian behavioural elements. The four types of behaviours identified are related to spatial and temporal aspects: comply spatial, violate spatial, comply temporal and violate temporal. However, there are also the mixed behaviours of the identified four patterns.

In order to simplify the pattern of pedestrian behaviour, the representation of pedestrian behaviour in this study focused on two types of behaviour, comply spatial and violate spatial, which refer to the compilers and the jaywalkers respectively. The complier pedestrians refer to those who cross at the designated crossing area while crossing at signalized intersection, known as crosswalk. This area is marked by yellow stripes (zebra lines) which are normally placed immediately after the vehicle stop line. Meanwhile, the jaywalker pedestrians refer to those who cross outside the designated crossing area or crosswalk at signalized intersections. A pedestrian who crosses in this area is technically committed with spatial violation.
These two types of pedestrians have a tendency to either comply or violate the green man signal while they are crossing at signalized intersections. Generally, the complying pedestrians need to wait for the entire red man phase until the green man appeared. Unlike the violating pedestrians, who seem to value time more than their safety will cross the road on the red man phase. This type of pedestrians can be categorised as the risk-taking pedestrians, who tend to take risk to cross the road section whenever possible [14]. Higher risk can be expected if the pedestrians tend to cross when the signal displays green to the vehicles’ right of way. The variety of pedestrian behaviour according to the spatial and temporal aspect of this study is illustrated in Fig. 2.

The observation on pedestrian behaviors was extended to identify the pedestrian accident event sequence in the crossing scenario. The scenario was captured and filmed using video cameras as a qualitative data for the model development. This data is very important to understand the causal relationship and risky situation of a complex interaction between pedestrians and vehicles at signalized intersections.

2.2. Modeling pedestrian accident event sequence in Petri Nets

The proposed model in this study is adopted from the scenario observed in the study location, called a pedestrian crossing scenario. An accident event sequence in pedestrian crossing scenario is expected to identify the hazard event for a crossing pedestrian. The hazard event or the risky situation in a pedestrian crossing scenario is extracted from the observation of the conflict and near miss situation occurred during field studies. Conflict and near misses are the event that is close to the accident. An interaction of people in a system that possesses hazardous characteristics can be used to describe risk scenario [15]. Therefore, observing the interaction between pedestrians and vehicles in the conflict or near miss event provides the same scenario in the accident event. Pedestrians and vehicles are identified as agents in describing the pedestrian-vehicle interaction.

The observation of the interactions of pedestrian-vehicle in the conflict event started when both agents were in the safe place. The situation before a pedestrian
started crossing and before the vehicle approached the intersection, identified as the initiating events in this context. The observation was continued until the conflict or near misses of these two agents were identified. The starting point which was the safe event, to the ending which was the hazard event (conflict or near misses) can be seen as a process. Thus, the sequence of event was structured as the process of pedestrian accident at signalized intersection.

In this event sequence, the movement of the two agents were considered: pedestrians and vehicles. The movement of pedestrians as they were crossing a signalized intersection and the movement of vehicles as they were passing the same interaction zone (IZ) were segregated into several positions. The description of the pedestrian accident process was separated according to the movement of the agents in the system as follows; pedestrian and vehicle.

**Pedestrian movement:**

It is defined as pedestrian who intend to cross at a signalized intersection, and starts by approaching the waiting zone (WZ). As he arrives at WZ, the pedestrian is expected to push the button and wait for his right of way to cross the road. Pedestrian right of way or ROW is allocated when the pedestrian traffic signal shows the green man phase. Due to long wait, the pedestrian tends to take the opportunity to cross whenever the signal indicates red for the vehicle to stop. The situation becomes dangerous when the pedestrian decides to start crossing during the green signal for the vehicle or vehicle ROW. Once the pedestrian starts crossing, he will enter the interaction zone (IZ). While the pedestrian is in the IZ, there is a time where he will pass the conflict zone (CZ), zone established in defining the point where a pedestrian may have a conflict with the vehicle.

**Vehicular movement:**

The movement of vehicle considered in this process started as it approached to the interaction zone (IZ). Alerted by the green signal indication displayed on the traffic light, the vehicle’s driver needs to respond either by decelerating speed, ready to stop, or maintaining his speed to continue movement. As the driver responds to the signal, the driver is entering the interaction zone with a certain speed, called the approaching speed. While the driver is in the IZ, there is a time where the driver will pass the conflict zone (CZ). The vehicle may have collided with the pedestrian if he shares the conflict zone at the same time.

The event sequence of pedestrian accident based on the pedestrian and vehicle movement is modelled into PN called pedestrian crossing scenario model as shown in Fig. 3. This event sequence, then needs to be translated into PN elements: places (represented by circles), transition (represented by bars) and arcs (represented by arrows). The procedure involved and the illustration of the pedestrian crossing scenario model can be referred to Hamidun et al. [16]. The association of pedestrian volume parameter with the risk of crossing is embedded into this model. Consideration of pedestrian volume in this model is represented in unit pedestrian per hour. This model will be linked with other sub models in the hierarchical structure of a model called the PedCRA model.
2.3. Pedestrian crossing risk assessment (PedCRA) model

The pedestrian crossing risk assessment (PedCRA) model is designed in the hierarchical structure to link the pedestrian crossing scenario model with other sub models that considers the effect on pedestrian illegal behaviour. The arrangement of the sub models in this PedCRA model is illustrated in Fig. 4.

The main model of the PedCRA model is designed to quantify the crossing risk occurrence in the pedestrian crossing scenario. The risk of pedestrian is counted when both vehicle and pedestrian arrive at the conflict zone simultaneously. Under laid this main model is the pedestrian crossing scenario model, considered as the first hierarchy of the PedCRA model. The movement of the vehicles and pedestrians in the accident process is modeled, and the volume of pedestrians crossing the intersection is also considered in this model. The linkage of pedestrian behavior to their crossing risk is modeled in another sub model. Consideration of the spatial crossing behavior is modeled as the sub model 1 in the second hierarchy, and consideration of temporal crossing behavior is modeled as the sub model 2 in the third hierarchy.

In the sub model 1, the two types of pedestrian according to their crossing pattern (compliers and jaywalkers) are separately represented by different places, transition and arrows. The tendencies of these two types of pedestrians to violate the signal are modeled in two separate sub models in the third hierarchy. In this sub model 2, the violation of either the complier or jaywalker pedestrians is considered when they cross the road during the vehicle’s ROW or the green for the vehicle.
3. Model Analysis

The proposed model can be used to estimate the potential risk of pedestrian, according to their compliance to spatial and temporal elements. Different conditions of behavior compliance were analysed using steady state analysis that is built in the PN model. The risk the complier and jaywalker pedestrians, and the mixed of them were estimated when they commit with the temporal violation behavior. The estimated risks of these pedestrians are shown in Fig. 5.

If both, complier and jaywalker pedestrians comply with the signal, the potential risk of these pedestrians and the mixed of them can be considered low. However, if only the compliers violate signal, the potential risk of the jaywalker pedestrians and the mixed of them are lower as compared to the complier pedestrians only. On the other hand, if only jaywalkers violate the signal, the potential risk of the jaywalker pedestrians and the mixed of them are higher. The potential risks of all pedestrian groups might be higher if both, complier and jaywalker pedestrians violate signal.

Different risk values can be observed for the different types of pedestrian behaviors. The effect of spatial violation is not obvious when the pedestrians comply with the temporal aspects. However, the high risk value can be expected for both, complier and jaywalker pedestrians if they violate the signal.

The effect of pedestrian volume on crossing risk, according to their spatial and temporal violation behavior can be observed in Fig. 6. The result shows that the pedestrian risk increased as the pedestrian volume increased. The risk of violating pedestrians was much higher compared to complying pedestrians at the same volume. High risk of violating pedestrians was expected as they were sharing the...
allocated time for vehicular traffic while crossing the same road section. The difference of the risk value for the complying and violating pedestrians was smaller when the volume was low, and the difference of risk was greater as the volume of pedestrians increased.

**Fig. 5.** Potential risk of crossing pedestrian according to the spatial and temporal behaviour.

**Fig. 6.** The effect of pedestrian volume and behaviour to their crossing risk.
The potential risks of crossing pedestrians at an increasing volume were compared for the different types of pedestrian groups; compliers complying signal, compliers violating signal, mixed of compliers and jaywalkers complying signal, mixed of compliers and jaywalkers violating signal. High accident risk was expected if the compliers violated signal. However, the presence of jaywalking behavior in the pedestrian group would increase their risk compared to the group with the compliers alone.

4. Discussion

The proposed model in this study is able to estimate the potential accident risk of crossing pedestrians related to the spatial and temporal violation behaviour. The model was developed based on the pedestrian crossing scenario observed at the study locations. Identified accident event sequence in the pedestrian crossing scenario was translated into PN elements: places, transitions and arcs. The model was structured in the hierarchical form to consider the accident event sequence, the risk quantification and relation of behavioural factors. The consideration of pedestrian volume is embedded in the first hierarchy of the PedCRA model. The second hierarchy model considers the spatial behaviour of the pedestrians and the third hierarchy model considers the temporal behaviour related to the complier and jaywalker pedestrians. The model in hierarchical structure seems to provide an advantage to consider the combination of factors for the accident prediction model. An improvement on the hierarchical model structure may allow the consideration of other factors in the risk estimation of pedestrian crossing.

The data on pedestrian behaviour were qualitatively presented in the pedestrian accident sequence of events. The places and transitions as the basic element of PN model were arranged according to this sequence of event. In addition, the identification of hazardous event considered as the potential risk in this model also relies on this event sequence. All these processes show how important the pedestrian behaviour data are and can be considered as scenario analysis. The pedestrian behaviour data obtained from the video observation can be generalised according to the eight study locations.

From the model analysis, the spatial violation of pedestrians seems to give mild effect to the expected risk value. The presence of jaywalkers in the pedestrian crossing population gave higher risk value compared to the population of the compliers alone. This is supported with the finding similar to Elvik et al. [17] where higher risk was observed for the sharing pedestrians with higher percentage of them crossing outside marked crosswalk (jaywalkers). However, the percentage of jaywalkers in crossing pedestrians is not covered in this study as to obtain this information requires extensive observation and behavioural analysis at all tested intersections.

The model is sensitive to the temporal violation of pedestrians. Signal violation of pedestrians gives a fairly significant increase of risk value to the pedestrians in the same environment. It is reflected when researchers studying pedestrian behaviours labelled this type of pedestrian as risk takers [18]. The result is consistent with the finding concluded by King et al. [19] that the risk of crossing against light was approximately eight times higher compared to the
legal crossing at signalized intersections. The frequent occurrence of such behaviour on the signalized intersection increases the likelihood of being involved in a road accident since pedestrians tend to start crossing when the vehicle traffic begins moving.

Providing a crosswalk at signalized intersections as crossing facility is able to guide pedestrians to cross at the proper location. Reluctance of using this facility may slightly increase the likelihood of accidents. Unfortunately, the risk is much higher if pedestrians refuse to obey the signal indication. The countdown timer or adjustment of signal phasing may help in reducing the temporal violation behaviour of pedestrians, hoping to reduce their risk of being involved in an accident. Applying such engineering measures alone without support from the enforcement and education agencies, may not guarantee the safety of pedestrians since the modification of behaviour to temporal element is difficult to predict.

5. Conclusions

This paper proposes the method in assessing the risks of pedestrian illegal crossing to be involved with an accident at signalized intersections. Estimation of risk covers the temporal, spatial and the combination of illegal crossing behaviours of pedestrians that can be extracted from the real scenario at the study locations. Translation of the event sequence in the crossing scenario to the PN model is able to provide the risk estimation in the numerical value. Modelling with Petri Nets also allows the development of model in hierarchical structure. In this study, the consideration of pedestrian volume, the spatial and temporal behaviours of pedestrians were modelled in the separate sub models under different hierarchy. Thus, the effect of an increasing pedestrian volume with different types of behaviour could also be estimated.

Summarising the effect of temporal and spatial violation of pedestrians, the higher risk can be predicted for those who are violating the temporal violation towards signal indication compared to the spatial violation. Their risk is greater when the volume of pedestrians at a signalized intersection increases. Proposed countermeasure should take pedestrian behaviours into consideration since the risk of pedestrians at this particular place might depend on their behavioural effect.

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