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Propensities of red light running of pedestrians at the two-stage crossings with split pedestrian signal phases

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ABSTRACT

Two-stage crossing with a median refuge island is commonly installed at the busy urban signalized intersections. To accommodate for the high traffic flow in different directions, split phasing is often applied for pedestrians' right of way of the two crossing stages. Previous studies mainly focus on the time delay, capacity and operation efficiency of two-stage crossings. It is rare that safety of two-stage crossings is investigated. Crossing behaviors and propensities of red light running at the two crossing stages (i.e. from the curbside to a central island, and then to another side of the road) are different from that of single stage crossing. Also, there could be interferences in the crossing behaviors and situational features between the two stages. This study aims to identify the personal characteristics, traffic attributes and environmental factors that affect the red light running propensities of pedestrians at the two-stage crossings, based on the video observation surveys at six urban signal intersections in Hong Kong. Random parameter logit regression approach is applied to measure the association between possible factors and propensities of red light running of pedestrians, with which the effect of unobserved heterogeneity is accounted. Results indicate that, other than the pedestrians' characteristics, pedestrian signal of the second stage, maximum waiting time and traffic flow significantly affect the propensity of red light running in the first stage. Also, there are significant interaction effects between pedestrians' characteristics and situational features on the propensity. On the other hand, pedestrians' waiting time before crossing the first stage significantly affects the propensity of red light running in the second stage. Findings are indicative to the design of pedestrian crossing, signal time plan and effective enforcement and education strategies that can deter against the red light running behaviors of pedestrians. Therefore, safety of two-stage signalized crossings can be enhanced.

Keywords: Red light running violation; Pedestrian safety; Two-stage crossings; Observation survey; Random parameter logit model

1. INTRODUCTION

Two-stage pedestrian crossings are commonly found at the signalized intersections, where the pedestrian and vehicular traffic volumes are high, in Hong Kong (Transport Department, 2018), Mainland China (Wang et al., 2009; Ma and Lu, 2011), Germany (RiLSA, 1992), Canada (Li and Fernie, 2010) and Middle East (Hamed, 2001; Rosenbloom and Pereg, 2012). To reduce the vehicle delays, the pedestrians' right of ways (i.e. green pedestrian signal phases) of different stages are often split (Tian et al., 2001). Also, a wide central island is usually provided at the two-stage crossings. Pedestrians would cross to the central island and have to wait for the right of way to complete the crossing. Majority of prior research has been focusing on the intersection capacity, time delays (of pedestrians and vehicular traffic) and operation efficiency (Ma and Lu, 2011). However, it is rare that safety of two-stage crossings is studied. Red light running violation of pedestrian is of one the major causes of pedestrian-vehicle crashes at the signalized intersections (Transport Department, 2018). Studies indicate that pedestrians' demographics, social influences, environmental and traffic conditions can affect the propensities of red light running of pedestrians at the one-stage crossings (de Lavalette et al., 2009; Guo et al., 2011). However, relationship between influencing factors and red light running behaviors of pedestrians at the multi-stage crossings could be different. For example, waiting time before crossing the first stage may affect the cross decision of pedestrian in the subsequent stages (Rosenbloom and Pereg, 2012). Also, the pedestrian signal in the subsequent stage can affect the decisions of pedestrians in the first stage. It is necessary to assess the differences in the effects of possible factors on the red light running propensities of pedestrians between different stages of crossing.

This study aims to investigate the red light running behaviors of pedestrians at the two-stage crossings, with which the green pedestrian signal phases in the two stages are split. Two research questions are addressed: First, what are the differences in the explanatory factors to the propensities of red light running of pedestrians in the first and second stages? We hypothesize that when the pedestrian signal of the second stage is green, pedestrian's propensity of red light running in the first stage is higher. In addition, if the waiting time before crossing the first stage is longer, propensity of red light running in the second stage is higher. Second, what are the effects of the presence and behaviors of other pedestrians on the propensity of red light running in the first and second stages? We hypothesize that propensity of red light running violation is lower when there are other pedestrians waiting, but such propensity would increase when other pedestrians are seen to violate the red light.

In this study, the crossing behaviors of 3,320 pedestrians at six two-stage pedestrian crossings in Hong Kong are investigated. A random parameter logit regression approach is applied to measure the association between possible factors and pedestrian's propensity of red light running. Results should be indicative to the understanding of the pedestrians' crossing behaviors at the two-stage signalized crossings, and more importantly, development of effective measures that can deter against the red light running violations of pedestrians.

Remainder of this paper is organized as follows. Section 2 provides the literature review. Study design, data collection and analysis method are described in Section 3. Section 4 and Section 5 presents the results and discusses the policy implications respectively. Finally, concluding remarks and future research directions are given in Section 6.

2. LITERATURE REVIEW

2.1 Factors affecting the red light running propensity of pedestrian

For the pedestrian demographics, studies indicated that the propensity of red light running of male was higher than that of female (Rosenbloom, 2009; Guo et al.,2011; Xie et al., 2017), and the propensity of red light running of young people was higher than that of others (Kim et al., 2008;

Wang et al., 2011). Also, older pedestrians were more willing to wait at the crosswalks and obedience to the traffic rules (Guo et al., 2011; Zhang et al., 2016; Diependaele, 2019). However, a recent Chinese study indicated that older pedestrians had a higher likelihood to violate the red light, compared with the younger adults (Cao et al., 2017).

For the geometric design and traffic control, number of traffic lanes (i.e. length of crosswalk), presence of central island, and presence of signal countdown device all affect the red light running rate of pedestrian (de Lavalette et al., 2009; Yan et al.,2016). For example, increase in the number of traffic lanes is associated with the reduction of the red light running rate (Van Houten et al., 2007; de Lavalette et al., 2009; Diependaele, 2019). In addition, presence of pedestrian signal countdown (to green) device is associated with the reduction of the red light running rate of pedestrians (Markowitz et al., 2006). On the other hand, increase in maximum waiting time (i.e. red time) of pedestrians is associated with the increase in red light running rate of pedestrian at the midblock crossing (Van Houten et al., 2007; Brosseau et al., 2013). Moreover, increases in the volume of conflicting traffic stream (Wang et al., 2011; Koh et al., 2014; Koh and Wong, 2014) and speed of approaching traffic (Lobjois et al., 2013; Sun et al., 2015) are associated with the reduction of red light running rate of pedestrians.

Environmental factors including land use, weather and lighting condition can also affect the behavior and red light running propensity of pedestrians. Li and Fernie (2010) indicated that walking speed and red light running rate of pedestrians under the snowy and cold weather conditions were higher than that under the warm weather condition. Liu and Tung (2014) revealed that pedestrians tended to be more cautious and had a lower likelihood to violate the red light under the dark and poor visibility conditions.

Social influence can also affect the pedestrian behaviors. For example, propensity of red light running of pedestrians is lower when there are other pedestrians because of social norms. Increase in the number of other pedestrians is associated with the reduction of red light running rate (Russo et al., 2018; Zhuang et al., 2018; Zhu et al., 2021). However, Rosenbloom (2009) suggested that the relationship between social influence and propensity of red light running could be modified by pedestrian's demographics. For example, risk-taking behavior of adolescents is more profound when there are more pedestrians waiting. On the other hand, social norms can play a more important role in the behavior of female pedestrians (Sorenson and Taylor, 2005).

To conclude, studies have attempted the roles of possible factors including personal characteristics and environmental factors in the propensity of red light running of pedestrians. However, majority of the studies focused on the pedestrian behaviors at the (simple) one-stage crossings only. Findings could not be generalized to the multi-stage crossings, with split pedestrian signal phases in different stages. It is necessary to investigate the effects of the presence of split phasing on pedestrian's decision, and therefore, the red light running behaviors.

2.2 Multi-stage pedestrian crossings

A few studies have examined the perception and behavior of pedestrians at the multi-stage unsignalized crossings (Hamed, 2001; Rosenbloom and Pereg, 2012; Ma and Lu, 2011). Hamed (2001) indicated that the pedestrian's waiting time before crossing the first stage was negatively correlated to that before crossing the second stage at the divided street. It implied that the behaviors were different when a pedestrian was crossing from one side of the road to the central island and from the central island to another side. Rosenbloom and Pereg (2012) extended the research by examining the pedestrian behaviors at the three-stage unsignalized crossings. Results indicated that waiting time before crossing the first stage was positively correlated to that of second stage when there was a wide central island, but there was no correlation when the central island was narrow. Also, there was a positive correlation between the waiting times in the second and third stages, regardless of the island width. Finding was indicative to the innovative design (e.g. road signs) that can affect the pedestrian's level of patience and decision to stop and wait between two crossings.

Majority of studies focused on the pedestrian flow capacity and time delay of two-stage signalized crossings. A microscopic traffic simulation study indicates that the pedestrian signal time plan of a two-stage crossing (i.e. whether split or not split) would affect the number of pedestrians waiting (both at the curbside and central island), and therefore determine the minimum area required for the central island (Ma and Lu, 2011). Pedestrian delays at the two-stage crossing are sensitive to the signal time plan and compliance of pedestrians (i.e. crossing during the green pedestrian signal phase). Some innovative measures like overlap phases can significantly reduce the pedestrian delays (Wang et al., 2009; Wang and Tian, 2010).

A few studies have attempted the safety of two-stage signalized crossing. An empirical study investigated the behavior and compliance of pedestrians when crossing an eight-lane two-stage crossing in Toronto under the cold weather condition. Results indicated that the non-compliance rate of pedestrians under adverse weather condition was higher than that under favorable weather condition (Li and Fernie, 2010). On the other hand, a perception survey indicated that the propensity of red light running of older pedestrians was higher (Cao et al., 2017). However, these studies did not consider the correlation in the pedestrian behaviors between the first and second stages. Also, effects of social influences (i.e. presence and behaviors of other pedestrians) and traffic flow conditions were not considered.

To sum up, studies that investigate the propensity of red light running of pedestrians at the two-stage crossings (with split pedestrian signal phases) are rare. Particularly, the main effects and interaction effects of factors including pedestrian demographics, social influences, built environment, traffic condition and traffic control on the red light running propensities in different stages should be considered. Results should be indicative to the design of (pedestrian) signal time plan that can deter against red light running violation of pedestrians and enhance the overall safety and operation of signalized intersections in urban area (where split of signal phase is common).

3. METHOD

3.1. Video observation survey

The video observation surveys were conducted at six two-stage signalized crossings in Hong Kong during the period from November 2019 to July 2020. **Figure 1** illustrates the locations of the six survey sites. All of them are in Kowloon, the most densely populated urban area (i.e. 2.2 million in 2016) in Hong Kong (Census and Statistics Department, 2018). For each site, the survey time was four hours (two in the morning and two in the afternoon). At the times of surveys, the weather and lighting conditions were fine.

[Insert Figure 1 here]

Table 1 provides the details of the six survey sites under investigation. Number of traffic lanes of the crossings ranges from 2 to 4. Overall, crossing behaviors and compliances of 3,332 pedestrians during the solid red pedestrian signal phases were observed. As shown in Table 1, the pedestrian signal phases of different stages were split at all the sites. It should be noticed that the signal time phases at most of the signal intersections in Hong Kong are not fixed. They are adaptive to the real-time vehicular traffic flow. Cycle times, green times and red times presented in Table 1 are for illustrative purpose only.

[Insert Table 1 here]

3.2. Study design

As discussed earlier, the pedestrian signal phases in different stages are split at the survey sites. It is possible that when the pedestrians are waiting to cross from one side of the road (i.e. pedestrian signal of the first stage is red), the signal of another stage (i.e. crossing from the central island to other side) is green. On the other hand, after crossing from the side to the central island (i.e. pedestrian signal of the first stage is green), pedestrians have to wait at the island to complete the crossing (i.e. pedestrian signal of the second stage is red). In this study, we aim to examine the factors that affect the non-compliances of pedestrians in the first (i.e. crossing from one side of the road to the central island, Model 1) and second (i.e. crossing from the island to other side, Model 2) stages.

3.3 Factor attributes

In this study, effects of the factors including pedestrian demographics, behavioral characteristics, geometric design, signal time and traffic conditions on the propensity of red light running of pedestrians are investigated. For the pedestrian demographics, effects of gender and age (i.e. adolescent, younger adult and elderly) are considered. For the behavioral characteristics, social influences by the factors including the presence of a companion, number of other pedestrians waiting, and presence of a violator (non-compliance to red pedestrian signal) are considered. It is suspected that a pedestrian who is accompanied by a friend or family member may have a lower tendency to run the red light. Also, propensity of red light running may be lower when there are more pedestrians (especially none violates the red light) waiting.

For the signal time, factors considered are red time and maximum waiting time (time between the arrival of a pedestrian and the end of red). Maximum waiting time indicates the time that a violator would have to wait if he or she had complied with the pedestrian signal. It is suspected that the propensity of red light running may increase when the red time and maximum waiting time increase. To address the question of whether the situational features in the two stages (especially the green pedestrian phases are split) are interrelated, factors including signal of the second stage (Model 1) and waiting time before crossing the first stage (Model 2) are also considered. It is suspected that when the pedestrian signal of the second stage is green, the pedestrians may have a higher tendency to violate the red light and cross to the central island. On the other hand, when the waiting time before crossing to the island is long, pedestrians may become less patience in the subsequent stage. Also, pedestrians who comply to the red signal in the first stage tend to be obedient in the second stage, regardless of the waiting time.

Nevertheless, factors including traffic volume, percentage of heavy vehicle and number of traffic lanes are also considered. **Table 2** summarizes the characteristics of sample. For the non-compliance of the first stage, 2,747 pedestrians were surveyed (843 (30.4%) violated the red light). For the second stage, 2474 pedestrians were surveyed (423 (17.1%) violated the red light).

[Insert Table 2 here]

3.4 Analysis Method

In this study, as the dependent variable is dichotomous (i.e., running the red light or not), the binary logit regression method is applied. To address the problem of unobserved heterogeneity, the random parameter approach is deployed (Hensher and Greene, 2003). For instances, it can account for the effects of the variations in personality, perception and safety attitude, which are often not observed and measured, on the propensity of red light running violation among the pedestrians of the same personal characteristics and under the same situation. As the effects of demographics on the propensities of red light running in the two stages of crossing are expected to be the same, the parameters of demographics are constrained between the two stages. Formulation of the proposed random parameter logit regression model is given as follows.

$Y_{it} = 1$ denotes that pedestrian i violates the red light in stage t, and $Y_{it} = 0$ the otherwise. Suppose the probability of $Y_{it} = 1$ is p, then we have (Fricker and Zhang, 2019),

$$y_{it} \sim Binomial\ (p)$$

$$logit(p) = log(\frac{p}{1-p}) = \boldsymbol{X}_{it}\boldsymbol{\beta}' + \boldsymbol{Z}_i\boldsymbol{\alpha}' + \varepsilon_{it} \quad (1)$$

where $\boldsymbol{X}_{it}$ is the vector of unconstrained explanatory variables, $\boldsymbol{Z}_i$ is the vector of constrained explanatory variables, $\boldsymbol{\beta}$ is the vector of corresponding coefficients for unconstrained explanatory variables, $\boldsymbol{\alpha}$ is the vector of corresponding coefficients for constrained explanatory variables, and ε_{it} is the identically and independently distributed random error term respectively.

Equation (1) assumes that the effect of individual explanatory variable is fixed across observations. To account for the effect of unobserved heterogeneity, coefficients are assumed to be randomly distributed with the specification given as follows,

$$\beta_{it} = \beta_t^* + \varphi_{it}$$

$$\alpha_i = \alpha^* + \psi_i \quad (2)$$

where β_t^* and α^* denote the mean effects of the variables, and φ_{it} and ψ_i are normally distributed with the means of zero and variances of θ^2 and σ^2 respectively (Christoforou et al., 2010; Milton et al., 2008).

Then, the random parameter model is established based on the conditional probability specified as follows,

$$P(y_{it} = 1|x_{it}, \beta_{it}, z_i, \alpha_i) = F(\beta_{it}x_{it} + \alpha_i z_i) \quad (3)$$

Parameter estimation of the proposed random parameter logit regression model is carried out using the maximum likelihood approach using the mlogit package of *R* software (R Core Team, 2013) and NLOGIT (Version 5.0) software (Greene, 2012). If the standard error of a parameter is statistically significant at the 10% level, then the parameter will be specified as “random”. The model is estimated using the simulated maximum likelihood with 200 Halton draws (Train, 2009). In addition, a stepwise iterative approach is applied to assess the random parameter (Islam and Jones, 2014; Zhai et al., 2019). The variables are tested one by one. The iterative process would continue until the improvement in overall model fit is incremental.

To assess the prediction performance of candidate models, the Akaike Information Criterion (AIC) is used. AIC takes into account both the model fit and model complexity. AIC is specified as follows,

$$AIC = -2\ln(L) + 2K \tag{4}$$

where L refers to the maximum likelihood function and K refers to the number of parameters respectively.

4. RESULTS

In this study, random parameter logit regression models are developed to measure the association between possible factors and propensities of red light running of pedestrians in Stage 1 (Model 1) and Stage 2 (Model 2). Prior to the association measure, a multi-collinearity test is conducted to ensure that the independent variables included in the final model are not correlated. For instances, there is remarkable correlation between 'maximum waiting time' and 'cycle time', therefore, only the former is included in the final model. For all other independent variables, there is no correlation. **Table 3** presents the parameter estimation results of the proposed random parameter logit regression models. To account for the possible confounding effects, some factors like male, elderly, number of lanes, red time and percentage of heavy vehicles are included in the model even they are not statistically significant (Elvik, 2002). Also, the interaction effects between personal characteristics (i.e. gender and age group) and situational features (i.e. presence of violator, with a companion, and signal time, etc.) are considered.

As shown in Table 3, for the pedestrian demographics, gender significantly affects the propensity of red light running at the 1% level. For instances, propensity of red light running of male pedestrians is higher (β = 0.872) than that of female. Also, age group is significantly associated with the propensity at the 1% level. For example, adolescents have a lower propensity (β = -0.302) to run the red light, compared with younger adults.

4.1 Model 1: Non-compliance of red pedestrian signal in the first stage

In the first stage, for the behavioral characteristics, presence of a companion, presence of violator, and number of pedestrians waiting significantly affect the propensity of red light running, all at the 1% level. For instances, presence of a companion (β = -1.331) and increase in the number of pedestrians waiting (β = -0.108) are associated with the reduction in red light running violation propensity. However, presence of a violator is associated with the increase in red light running violation (β = 0.962). For the effect of geographical location, propensity of red light running at Site 3, 4, 5 and 6 is higher than that at Site 1 and 2 (β = 0.076).

For the signal time, maximum waiting time and pedestrian signal of the second stage significantly affect the propensity of red light running in the first stage, both at the 1% level. For instances, increase in maximum waiting time is associated with the increase in red light running propensity (β = 0.012). Also, if pedestrian signal of the second stage is green, propensity of red light running (Stage 1) increases (β = 0.579).

For the traffic condition, increases in the traffic volume (β = -0.271) and percentage of heavy vehicle (β = -0.016) are associated with the reduction in red light running propensity, both at the 1% level. For the geometric design, propensity of red light running of shorter crosswalk (i.e. when there are two traffic lanes) is significantly higher (β = 0.390), at the 1% level.

For the interactions between personal characteristics and situational features, 'gender X pedestrian signal of the second stage' (β = 0.714) and 'adolescent X with a companion' (β = 0.601) significantly affect the propensity of red light running at the 1% level and 5% level respectively. Also, 'presence of a violator X with a companion' (β = -0.031) marginally affect the propensity at the 10% level.

4.2. Model 2: Non-compliance of red pedestrian signal in the second stage

In the second stage, as also shown in Table 3, for the behavioral characteristics, again, presence of a companion (β = -1.020) and increase in the number of pedestrians (β = -0.150) significantly reduce the propensity of red light running, both at the 1% level. In contrast, presence of a violator (β = 1.380) significantly increases the propensity at the 1% level. For the effect of geographical location, propensity of red light running at Site 3, 4, 5 and 6 is higher than that at Site 1 and 2 (β =1.231).

For the signal time, propensities of red light running of pedestrians are lower when the waiting time of the first stage increases (β=-0.017) at the 1% level. Also, increase in maximum waiting time (β = 0.022) is associated with the increase in red light running propensity at the 1% level of significance.

For the traffic condition, there is no significant association between percentage of heavy vehicle and propensity of red light running. However, increase in traffic volume (β = -0.294) is significantly associated with the reduction in red light running propensity at the 1% level. For the geometric design, propensity of red light running is lower when the crosswalk is long (i.e. four traffic lanes, β = -0.475) at the 5% level of significance.

Nevertheless, for the interactions between personal characteristics and situation features, 'presence of a violator X maximum waiting time' (β = 0.681) significantly increases the propensity of red light running at the 1% level.

[Insert Table 3 here]

5. DISCUSSION

In this study, propensities of red light running of pedestrians in different stages of the two-stage crossing are investigated, with which the effects of pedestrian demographics, behavioral characteristics and social influences, geometric design, signal time, and traffic conditions are considered. In addition, possible interactions between personal characteristics and situational features are considered. Moreover, marginal effects of individual factors on the red light running propensities are estimated.

5.1 Interferences between crossing stages

5.1.1 Effect of pedestrian signal of the second stage on the red light running propensity in the first stage

As speculated, when the pedestrian signal of the second stage (i.e. crossing from the central island to the other side of the road) is green, propensity of red light running of pedestrians in the first stage (i.e. crossing to the central island) increases. As shown in Table 3 (Model 1), the parameter is normally distributed (with a standard deviation of 1.064), therefore, probability that a pedestrian would violate the red light in the first stage if the signal of the second stage is green is 70.4%. This could be attributed to the considerable 'time saving' anticipated for one to violate the red light and cross to the island (first stage), where the right of way of completing the crossing (second stage) is given. This echoes with the findings of previous studies that time saving is one of the major contributory factors that affect the crossing decision of pedestrians (Demiroz et al., 2015; Sinclair and Zuidgeest, 2016). In particular, there is no pedestrian signal countdown device in Hong Kong. Some pedestrians may consider that the time saving (for violating the red light and cross to the island, and complete the crossing immediately) are substantial. Such phenomenon is more profound when the pedestrian signal phases in different stages are split. For example, if one wait for the green pedestrian signal to cross to the island, the signal in the second stage would then turn 'red', hence, the total waiting time would increase remarkably. However, information on the acceptable waiting time is not available in current study. In the future study, it is worth exploring the trade-off between time saving and safety risk of pedestrians when making crossing decision in the perception survey. Therefore, it is possible to evaluate the effectiveness of possible countermeasures, i.e. modified signal time plan, pedestrian signal countdown device and pedestrian warning sign, in combating the red light running behaviors of pedestrians at the two-stage crossings.

5.1.2 Effect of waiting time in the first stage on the red light running propensity in the second stage

It is speculated that if the waiting time before crossing the first stage increases, propensity of red light running of pedestrians in the subsequent stage might increase (Hamed, 2001). However, as shown in Table 3 (Model 2), for the pedestrians who have longer waiting time in the first stage, propensities of red light running in the second stage are lower. It is speculated that the pedestrians who have waited for long (not violating the red light) tend to be more obedient. They are relatively less sensitive to the waiting time and anticipated time saving for non-compliance (Rosenbloom, 2009). Such phenomenon can be explained by the social control theory that peoples would limit the illegal acts because of internal morality and beliefs, and motivations are usually not considered (Hirschi and Stark, 1969). Also, it could be attributed to the safety orientation of road users (Lajunen et al., 1998). For example, the red light running rate in Stage 2 of pedestrians who do not need to wait in Stage 1 is 26.2%, that of pedestrians who have waited for less than 10 seconds is 22.5%, and the overall red light running rate is 17.1% (see Table 2) respectively. This is consistent to the finding of an empirical study at a multi-stage unsignalized crossing that there is positive correlation in the waiting time between different stages (Rosenbloom and Pereg, 2012). Nevertheless, it is worth investigating the effects of personal traits and risk perception on the propensity of red light running when comprehensive data is available in the attitudinal survey (Dai and Fishbach, 2013). Therefore, it is indicative to the development of effective road safety education and promotion strategies that can enhance the safety awareness and compliance of pedestrians. Also, the pedestrian signal time plan could be optimized, taking into account the acceptable waiting time of pedestrians.

5.2 Effects of pedestrian demographics

Results indicate that propensities of red light running of male pedestrians are higher than that of female in both stages. This is consistent to the findings of previous studies (Guo et al., 2011; Rosenbloom, 2009; Xie et al.,2017). Indeed, fatal crash involvement rate of female pedestrians is also lower than that of male (Harre et al., 1996). As also shown in Table 3 (Model 1), there is significant interaction effect for 'male X pedestrian signal of the second stage'. This suggests that male pedestrians tend to be more risk-taking and sensitive to the anticipated time saving for non-compliance. However, there is no significant difference in the red light running propensities in the second stage between male and female. Yet, it is worth exploring the gender effect on the safety attitude and hence the crossing behaviors using the perceptional survey in the future study (Ren et al., 2011).

For the effect of age, adolescent pedestrians have a lower tendency to run the red light in both stages, compared with younger adults. It could be because adolescents (especially for those who have attained higher education) tend to have stronger sense of conformity and law compliance

(Lee and Tsang, 2004). However, there is significant interaction effect for 'adolescent X with a companion'. This suggests that the sense of conformity of adolescents could be mediated by peer influence. For instances, presence of peer can impair the self-regulation and safety awareness, and the propensities of non-compliance increase (Barrett et al., 2006).

5.3 Effects of social influences

Results indicate that the red light running propensities of pedestrians are lower when there is a companion. The parameters are normally distributed (with standard deviations of 1.51 in Stage 1 and 0.51 in Stage 2), therefore, probabilities of the pedestrians who have a companion would run the red light are 19.2% in the first stage and 2.4% in the second stage. In addition, propensities of red light running decrease when there are more pedestrians waiting. For instances, when the number of pedestrians waiting is increased by 1%, probabilities of red light running would reduce by 0.16% in the first stage and 0.17% in the second stage. This could be attributed to the influences of social norms (Rosenbloom, 2009; Zhang et al., 2016; Russo et al., 2018). Moreover, when there is at least one other pedestrian violated the red light, propensities of red light running would increase. This suggests some peoples could have been motivated (to violate the traffic rules) after the first violator has appeared. However, this can be mediated by the presence of a companion (as shown in Table 3 (Model 1), there is significant interaction effect for 'presence of a violator X with a companion'). Above finding is indicative to the effective enforcement and penalty strategies that can improve the pedestrian safety. For instances, increases in the (manual or automated) enforcement and penalty levels can enhance the deterrent effects against red light running and other traffic violations (Chen et al., 2020).

5.4 Effects of geometric design, signal time and traffic condition

For the effect of pedestrian signal time, propensities of red light running are positively associated with the maximum waiting time, in both the first and second stages. It can be because peoples are annoyed when they anticipate that the waiting times are long (Brosseau et al., 2013). When the maximum waiting time is increased by 1%, probabilities of red light running will be increased by 0.45% in the first stage and 0.32% in the second stage. Indeed, percentage of red light running in the first stage increases remarkably from 18.7% when the maximum waiting time is less than 20 seconds to 35.8% when the maximum waiting time is more than 40 seconds. Similar phenomenon can also be observed in the second stage. In addition, effect of maximum waiting time on the propensity of red light running in the second stage can be magnified by the presence of a violator. This is indicative to the planning of signal time phases and implementation of initiatives including pedestrian signal countdown (to green) devices that can mediate the influences of anticipated waiting time of pedestrians.

For the effect of traffic condition, when the traffic volume is increased by 1%, probabilities of red light running will be reduced by 0.48% in the first stage and 0.47% in the second stage respectively. In addition, propensities of red light running decrease when the percentage of heavy vehicles in the traffic increases. When the percentage of heavy vehicle is increased by 1%, propensities of red light running are reduced by 0.49% in Stage 1 and 0.44% in Stage 2 respectively. This could be attributed to the increase in the perceived risk when overall traffic flow and percentage of heavy vehicle increase (Koh et al., 2014; Wang et al., 2011; Koh and Wong, 2014). However, vehicular speed, which is closely related to the crash risk, is not measured in this study. In the future study, it is worth exploring the effects of pedestrian-vehicle interactions on the propensity of red light running of pedestrians, when comprehensive information on traffic characteristics (i.e. density, speed and flow) and vehicle trajectories are available.

For the effect of geometric design, increase in the number of traffic lanes (i.e. crosswalk length) is associated with the reductions in the propensities of red light running. For example, probability of red light running at the shorter crosswalk (i.e. crossing two traffic lanes) is 1.5 times higher than that of crossing three traffic lanes. Again, such finding is consistent to that of previous studies (Van Houten et al., 2007; de Lavalette et al., 2009; Diependaele, 2019).

6. CONCLUSION

Multi-stage pedestrian crossings, with split pedestrian signal phases, are commonly used at the urban signalized intersections that have high pedestrian and/or vehicular traffic flow. Studies have been focusing on the time delay, capacity and operation efficiency of multi-stage crossings. It is rare that the crossing behaviors of pedestrians at the multi-stage signalized crossings are attempted. Particularly, relationship between possible explanatory factors and propensities of red light running should be different in different stages when the pedestrian signal phases are split.

This study investigated the crossing behaviors of pedestrians at the two-stage signalized crossings based on the video observation surveys at six urban intersections in Hong Kong. Not only the influences of pedestrian demographics, behavioral characteristics, geometric design, pedestrian signal time and traffic condition, but also the interaction effects between personal characteristics and situational features on the propensities are considered.

Random parameter logit regression models are developed to model the relationship between possible explanatory factors and propensities of red light running in the first and second stages. There are remarkable interferences in the crossing behaviors between the two stages, with split pedestrian signal phases. Results indicate that propensity of red light running in the first stage is higher when the pedestrian signal of the second stage is green. In addition, for pedestrians who have a long waiting time before crossing the first stage, their propensities of red light running in the second stage are lower. In addition, social influences can affect the crossing behaviors. When there is a companion and there are more pedestrians waiting, propensities of red light running of pedestrians are lower. Moreover, effects of the social influences on red light running propensities can be mediated by pedestrian demographics and situational features. Above findings are indicative to effective enforcement, education and publicity strategies that can enhance the safety awareness and combat the red light running behaviors of problematic pedestrian groups. Also, the signal time plan can be optimized to reduce the pedestrian delay (waiting time). Nevertheless, it is worth exploring the effectiveness of advanced traffic control techniques (i.e. adaptive signal time plan in response to real-time pedestrian volume) that can enhance the operation efficiency and safety of signalized crossings.

Nevertheless, this study has some limitations. First, some environmental factors like weather and lighting condition were not considered. Second, effects of vehicular speed and drivers' yielding behavior on the red light running behavior of pedestrians were not assessed. In the future study, it is worth investigating the interactions between pedestrians and vehicles and their effects on red light running behavior of pedestrians based on comprehensive trajectory data.

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TABLES AND FIGURE

Table 1. Summary of survey sites

Site location			Number of traffic lanes	Pedestrian signal phases	Pedestrian observed
1	Cheung Sha Wan Road/ Tonkin Street	Stage 1	3	104s – 36s	621
		Stage 2	3	104s – 36s	
2	Cheung Sha Wan Road/ Hing Wah Street	Stage 1	3	112s – 57	718
		Stage 2	4	78s – 91s	
3	Hung Hom South Road/ Po Loi street	Stage 1	2	67s – 64s	583
		Stage 2	3	62s – 40s – 29s	
4	Gillies Ave South/ Baker Street	Stage 1	2	83s – 47s	527
		Stage 2	3	77s – 33s – 20s	
5	Hung Hom South Road/ Tai Wan Road East	Stage 1	2	24s – 122s	330
		Stage 2	2	20s – 124s	
6	Hung Hom South Road/ Dyer Ave	Stage 1	2	105s – 26s	553
		Stage 2	2	45s – 62s – 24s	

Table 2. Descriptive statistics of the samples

Scope of work	Factor	Attribute	Stage 1				Stage 2			
			Count	Mean	%	Std. dev.	Count	Mean	%	Std. dev.
Outcome	Red light running violation	No	1931		69.6%		2051		82.9%	
		Yes	843		30.4%		423		17.1%	
Demographic	Gender	Male	1382		49.8%		1119		45.2%	
		Female	1392		50.2%		1355		54.8%	
	Age	Adolescent	626		22.6%		431		17.4%	
		Younger adult	1686		60.8%		1609		65.0%	
		Elderly	462		16.6%		434		17.6%	
Behavioral characteristics	With a companion	No	2291		82.6%		2004		81.0	
		Yes	483		17.4%		470		19.0%	
	Presence of a violator	No	1472		53.1%		1883		76.1%	
		Yes	1302		46.9%		591		23.9%	
	Number of pedestrians waiting	Min = 0 Max = 16		3.21		3.61		2.25		2.67
Geometric design	Number of traffic lanes	2	1603		57.8%		566		22.9%	
		3	1171		42.2%		1312		53.0%	
		4	N/A				596		24.1%	
Geographical location	Area	Site 1 and 2	1171		42.6%		1066		43.1%	
		Site 3, 4, 5 and 6	1630		57.4%		1408		56.9%	
Pedestrian signal time	Maximum waiting time (second)	Min = 0 Max = 130		49.24		30.26		16.92		19.25
	Red time (second)	Min = 24 Max = 132		94.39		20.26		55.14		24.63
	Pedestrian signal of the second stage	Green	2281		82.2%		N/A			
		Red	493		17.8%					

	Waiting time before crossing the first stage (second)	Min = 0 Max = 121	N/A					28.22		32.67
Traffic condition	Traffic flow rate (vehicle/minute)	Min = 3.51 Max = 129.62		21.89		8.21		41.52		18.80
	% of heavy vehicle	Min = 0% Max = 100%		21.41		11.58		19.59		12.72

Table 3. Estimation results of random parameter binary logit model

Scope of work	Factor		Stage 1			Stage 2		
			Coefficient	Standard error	Z-value	Coefficient	Standard error	Z-value
Constant			-1.453**	0.201	-3.31	-1.525**	0.322	-4.19
Demographics	Male		0.872**	0.078	10.28	0.872**	0.078	10.28
	Adolescent		-0.302**	0.102	-2.95	-0.302**	0.102	-2.95
	Elderly		Insignificant			Insignificant		
	Younger adult		Control			Control		
Behavioral characteristics	With a companion	Mean	-1.331**	0.171	-8.39	-1.020**	0.213	-4.71
		SD	1.515**	0.214	6.45	0.517*	0.231	2.08
	Presence of a violator		0.962**	0.094	10.15	1.380**	0.168	12.19
	Number of pedestrians waiting	Mean	-0.108**	0.017	-5.62	-0.150**	0.015	-2.67
		SD	N/A			0.168**	0.054	2.40
Number of traffic lanes	Two lanes		0.390**	0.148	3.30	Insignificant		
	Three lanes		Control			Control		
	Four lanes		N/A			-0.475*	0.201	-1.96
Geographical location	Area 1 (Site 1 and 2)		Control			Control		
	Area 2 (Site 3, 4, 5 and 6)		0.076**	0.031	2.41	1.231**	0.285	4.33
Pedestrian signal time	Maximum waiting time		0.012**	0.001	5.99	0.022**	0.003	6.70
	Red time		Insignificant			Insignificant		
	Pedestrian signal of the second stage is green	Mean	0.579**	0.124	3.84	N/A		
		SD	1.064**	0.358	7.18	N/A		
	Waiting time before crossing the first stage		N/A			-0.017**	0.003	-3.79
Traffic condition	Traffic flow rate		-0.271**	-0.082	-2.66	-0.294**	0.021	-6.70
	% of heavy vehicle		-0.016**	0.004	-4.89	Insignificant		

Interaction term	Presence of a violator x With a companion		-0.031^	0.015	-1.98	N/A		
	Male x Pedestrian signal of the second stage is green		0.714**	0.212	4.37			
	Adolescent x With a companion		0.601*	0.304	2.16			
	Presence of a violator x Maximum waiting time					0.681**	0.080	9.34
Goodness-of-fit	AIC		4312.3					
	Number of observations		5221					
	Unrestricted log likelihood		-1617.1					
	Restricted log likelihood		-1641.4					
	Chi-square statistics		48.6					

Notes:
*** statistically significant at the 1% level*
** statistically significant at the 5% level*
^ *marginally significant at the 10% level*

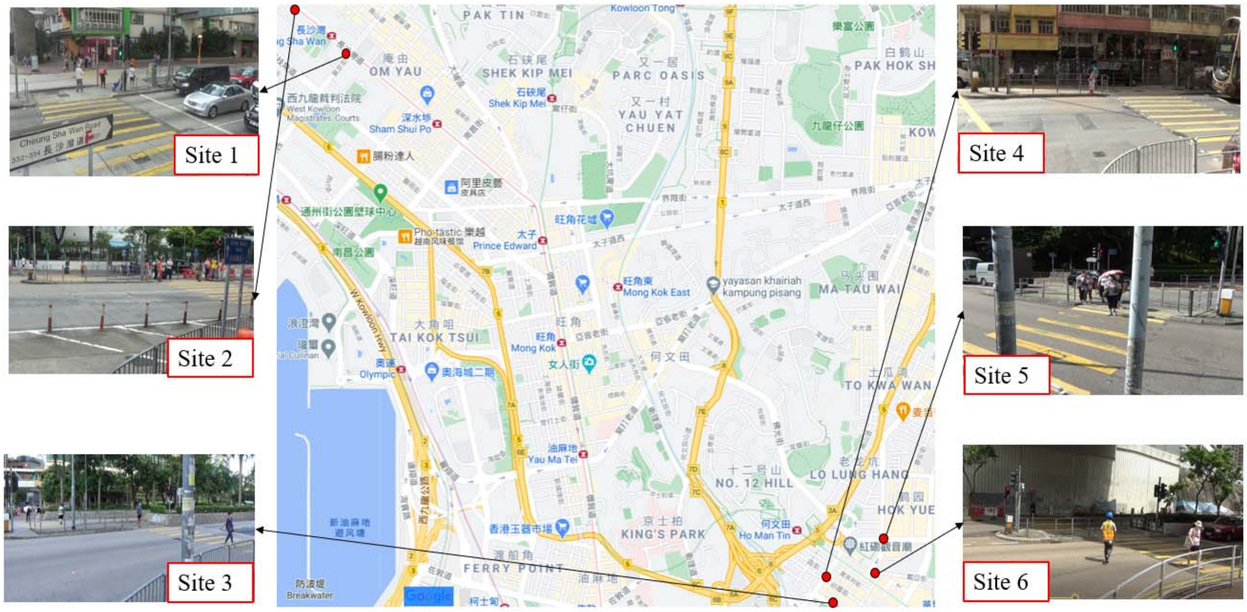

Figure 1. Locations of the survey sites