Beyond the red and green: Effects of rational and irrational factors on pedestrian choice at two-stage signalized crossings with independent phases

ABSTRACT

Pedestrian safety warrants significant attention, specifically red-light violation behavior at these two-stage signalized crossings. Distinct from pedestrian behaviors at one-stage crossings, the decision-making processes at two-stage signalized intersections can be influenced by the signal conditions of the subsequent crossing stage. Moreover, the rational assessment of trade-offs between time and safety may shift under different situational conditions at two-stage intersections. To investigate these dynamics, the current study employs a stated preference (SP) survey to elucidate the factors influencing pedestrian crossing decisions at two-stage signalized crossings. A random parameter random regret multinomial logit model is utilized to quantify the probabilities of different crossing behaviors. The results demonstrate the presence of a green signal at the subsequent stage is positively with the likelihood of red light violation at the current stage, suggesting a predominant preference for time-saving over rule adherence, despite associated risks. Intriguingly, individuals characterized by low risk-taking and time-saving proclivities exhibit a significantly greater likelihood of red light running. These findings contribute to a nuanced understanding of pedestrian behavior, offering strategic insights for behavioral interventions and transportation planning, such as optimizing signal time plan, implementing advanced transportation facilities, improving junction design and enhancing deterrence measures, thereby enhancing safety and promoting walkability in urban environments.

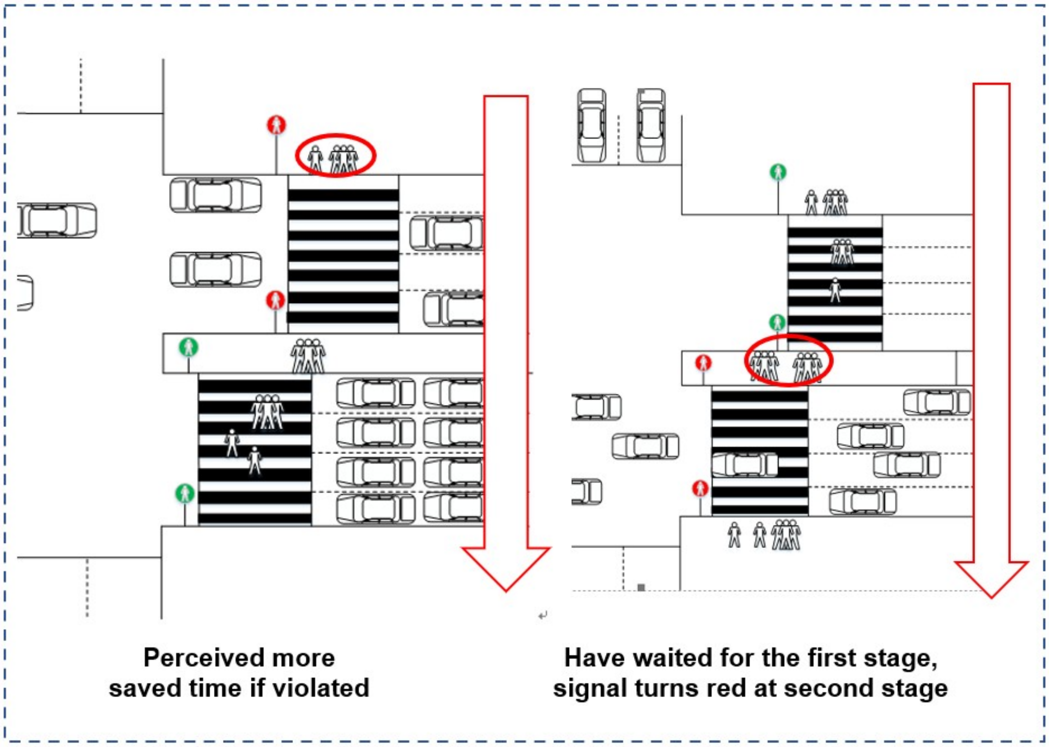
Keywords: Two-stage crossings; Trade-off analysis; Pedestrian safety; Independent signal phase; Stated preference survey; Walkability

1. INTRODUCTION

Pedestrian safety has emerged as a critical concern, especially given the heightened vulnerability of pedestrians to fatalities and severe injuries in traffic accidents compared to vehicle occupants. This issue has gained prominence with the accelerated pace of urban construction and the expansion of transportation infrastructure, leading to an increase in pedestrian crossings in urban settings. As such, ensuring the safety of these crossings has become a focal point of attention.

The two-stage crossings involve the installation of pedestrian center-islands at crosswalks, dividing the crosswalk into two sections so that pedestrians can cross the road in two phases. Two-stage signalized crossings for pedestrians are typically set up at signalized intersections on wide streets with high volumes of vehicle and pedestrian traffic, aiming to enhance safety, convenience, pedestrian crossing efficiency, and intersection utilization. This kind of design was first proposed and has been widely adopted in European countries. In recent years, it has become particularly prevalent at intersections with independent signal phase in Mainland China (Ma and Lu, 2011). However, a significant problem exists in the timing of traffic signals at these crossings. The primary aim of the signal timing is often to minimize vehicle delay, while overlooking the impact on pedestrian wait times and overall crossing experience. This lack of consideration for pedestrian needs not only undermines their convenience and safety but may also inadvertently encourage risky behaviors, particularly running red lights (Zhu et al., 2021a).

Compared to pedestrian behavior at single-stage signalized crossings, the waiting time prior to pedestrians' crossing the first stage at two-stage signalized crossings may influence their decision to cross in the latter stages (Rosenbloom and Pereg, 2012; Zhu and Sze, 2021). Furthermore, the pedestrian signal in the latter stage can also affect the pedestrians' crossing in the former stage, people may perceive save more time if violate the red light for the former stage (as indicated in Figure 1). Risky behavior like red light violation behavior might be generated from two aspects: From rational perspective, people will weigh costs (e.g., perceived risk) and benefits (e.g., time saving) to decide whether to engage in this behavior (Evans and Norman, 1998; Zhu et al., 2021a); on the other hand, people might make irrational decisions solely due to personal preferences or personality traits (Raoniar and Maurya, 2022). However, limited attention has been paid to investigate the trade-offs between time and safety of red light violation behavior under different situations, especially at two-stage crossings with independent phases. The role of irrational and inherent factors like personal traits, risk perception and walking habits were not yet explained.



Perceived more saved time if violated

Have waited for the first stage, signal turns red at second stage

Figure 1. Factors considered at different stages

Therefore, investigating pedestrian crossing decisions at two-stage crossings enriches the understanding of pedestrian behavior in urban settings, laying a solid scientific foundation for the formulation of more effective traffic management strategies. This type of research is pivotal in uncovering the underlying psychological and behavioral dynamics that pedestrians exhibit when navigating complex traffic scenarios. The insights garnered can drive the optimization of traffic systems, significantly boosting pedestrian safety and satisfaction. Such nuanced understanding allows for a more informed balancing act between traffic fluidity and pedestrian security, providing targeted and human-centric guidance for the refinement of urban traffic planning and management practices.

1.1 Objectives

The objective of this paper is to explore how situational feature (e.g., waiting time, perceived risk, signal condition), environmental conditions (e.g., weather condition, pedestrian position), and personal characteristics influence the pedestrians' decisions at two-stage crossings. Through a stated choice experiment, this study would analyze pedestrian responses to various hypothetical scenarios that differ in perceived relative risk, anticipated waiting time, crossing locations and weather variables. It aims to understand the complex interplay of these factors in shaping pedestrian choices, considering individual differences such as socio-demographic factors, walking habits, and personality traits.

This paper proposes three research questions: First, how do pedestrians balance perceived risk, waiting time, and crossing decisions? It is assumed that a positive correlation between waiting time and the propensity for red light violation, and a negative correlation between perceived risk and the propensity of red light violation are obtained. Moreover, the pedestrians' sensitivity on time and safety might not be equal. Second, what are the differences in the factors that influence the propensity of pedestrians to run red lights at different stages? We hypothesize that pedestrians have a higher tendency to run red lights in the former stage when the pedestrian signal of the latter stage is green. Additionally, the propensity to run red light at the latter stage is higher if the wait time before arriving at central island is longer. Third, if weather conditions affect pedestrians' propensity of red light violation at both stages? We made an assumption that rainy weather is positively correlated with the propensity for red light violation at both stages.

By employing a Random Regret Minimization approach within a random parameter random regret MNL, the study estimates the trade-offs pedestrians make regarding time and convenience against other crossing attributes. The results are expected to provide insightful recommendations for the planning and design of pedestrian crossing facilities, aiming to enhance the overall safety of intersections.

2 Literature review

2.1 Influence of traffic and environment factors

Previous researches have enriched to the literature by examining the relationship between pedestrians' behavior to cross against a red light and traffic environment variables, including roadway environment, traffic conditions and signal timing phases based on observational and perceptional survey (Hamed, 2001; Guo et al., 2011; Zhu et al., 2021a). A key influencing factor is signal timing phase. For instance, Shah and Pradhananga (2024) found that when the remaining duration of the red phase is less than 50 seconds, pedestrians are more likely to wait for the green light; however, when faced with more than 100 seconds of remaining red phase duration, they tend to violate the signal almost immediately. Furthermore, traffic condition factors, such as nearby pedestrians not adhering to the signals, also affect the likelihood of running red light. For example, Raoniar and Maurya (2022) found that if pedestrians observe a large number of neighbors crossing during the red phase, the likelihood of their own signal violations increases. Moreover, weather conditions can influence pedestrians’ crossing decisions, with rainy conditions being negatively correlated with the tendency to run red light (Zhu et al., 2021a). However, the existing survey research has primarily focused on single-stage signalized crossings, how different traffic environment features affect pedestrians’ crossing decision at the two-stage or multi-stage crossings remains unclear.

2.2 Influence of rational factors on red light running propensity

Literature surveys indicate that rational factors, such as perceived safety, risk perception, and perceived benefits, typically influence pedestrians' crossing decisions (Salducco et al., 2022; Raoniar and Maurya, 2022; Saxena, 2023; Feng et al, 2024a; Ye et al., 2024). On one hand, risk perception affects pedestrians' crossing decisions. Pedestrians with a higher level of risk perception tend to be more conservative when crossing (Feng et al, 2024a). On the other hand, the anticipated waiting time at signalized intersections also impacts pedestrians' rule-breaking behaviors. For instance, in a single-stage crossing scenario, Zhu et al. (2021a) conducted a self-reported survey on pedestrians' red light violation behavior, examining the trade-off between expected waiting time and perceived safety. They found that pedestrians' choices are more sensitive to reductions in time loss compared to increases in equivalent safety risk. However, how these factors influence pedestrians' crossing decisions in a two-stage crossing scenario requires further research, particularly considering how these influences might vary based on pedestrians' positions at different stages.

2.3 Influence of irrational factors on red light running propensity

However, decision-making is not solely rational, irrational factors such as personal preferences, attitudes, and socio-demographic characteristics also play crucial roles in pedestrians' likelihoods of committing red light violations. For example, some individuals may choose to disobey crossing rules if they perceive the penalties as negligible or challenging to enforce.

(a) Demographic characteristics. The influence of demographic characteristics (gender and age) on pedestrians' tendency to run red light varies. Raoniar and Maurya (2022) found that female pedestrians engage in little red light running compared to male pedestrians. Most studies also reported similar findings (Diaz, 2002; Tiwari et al., 2007; Brosseau et al., 2013; Paschalidis et al., 2016; Bendak et al., 2021). Regarding age, Kumar and Ghosh (2022) found that younger pedestrians are more likely to violate traffic signals compared to middle-aged and older individuals, with elderly pedestrians exhibiting the lowest violation rates. However, in contrast, Zhu et al. (2021b) found that older pedestrians have a higher likelihood to red-light violation.

(b) Subjective attitudes. Researchers have investigated the relationship between pedestrians' tendency to take risks and their subjective attitudes (Soathong et al., 2021). Rosenbloom (2006) found that among those who run the red light, there are more high sensation seekers than low sensation seekers. Furthermore, pedestrians' attitudes toward this behavior influence their rule-breaking, with time-pressed pedestrians being more likely to cross against the signal (Zhang et al., 2016; Moshki et al., 2019).

(c) Walking habits. The literature has examined the relationship between pedestrians' walking habits (such as the walking trip frequency per day and the number of trip making day per week) and their crossing decisions (Cœugnet et al., 2019; Feng et al., 2024). However, research on how walking habits influence pedestrians' tendency to run the red light is limited.

Ultimately, the comprehensive effects of traffic environment factors, rational factors, and irrational factors on pedestrians' propensity to violate red lights in two-stage crossings warrant further exploration.

3. METHOD

3.1 Stated preference experiment

To explore the balance between anticipated waiting time and perceived relative risk for whether running the red light at two-stage crossings, a stated preference (SP) experiment is employed. Stated preference (SP) method is a robust survey technique for assessing individual choice decisions in varied scenarios where multiple factors' attributes change. This method is widely applied in the analyzing transportation mode selection (Majumdar and Mitra, 2018; Ho et al., 2020; Manca et al., 2023; Pollock et al., 2024), traffic safety (Li et al., 2014; Niroomand and Jenkins, 2017; Steinbakk et al., 2019), and crossing decisions (Feng et al., 2024a). In the context of pedestrian crossing decisions, Willingness-to-pay (WTP) analysis emerges as a potent tool to further explore the trade-offs between time and safety (Puttawong and Chaturabong, 2020). By leveraging the SP survey and choice modeling analysis, researchers can quantify the extent of risk pedestrians are prepared to accept in exchange for reduced waiting times, revealing the maximum risk they are willing to endure to save time.

Therefore, this study proposes a SP choice set based on two-stage crossing scenario. The pedestrian is presumed to encounter three crossing choices (i.e., Choice 1: adhere to pedestrian signals, Choice 2: not to adhere but wait for a suitable gap and Choice 3: not to adhere and cross immediately) and makes decisions based on the available information. Table 1 lists the important attributes and associated levels considered in this experiment that affect pedestrian crossing preferences. Eventually, the formal survey encompassed six attributes: anticipated waiting time, perceived relative risk, far roadside to center-island signal phase, near roadside to center-island signal phase, pedestrian waiting time at the near roadside under different positions. In the formal SP experiment, each choice scenario will present three alternatives. Additionally, two levels of anticipated waiting time (i.e., 60, 35, and 5s versus 45, 25, and 0s) and two combinations of perceived relative risk (i.e., 0%, 25 %, and 40 % versus 0%, 15 %, and 25 %) are considered. The selected attribute values for waiting time are commonly experienced in Mainland China, the common cycle length for signalized crossing is around 120 seconds, of which red time often accounts for half. In addition, the red light violation propensity of pedestrians who arrived at (near) roadside might be affected by the signal phase of far roadside to central island. Also, when pedestrian arrived at central island, whether he or she has waited for a certain period time would probably affect the subsequent decision. Therefore, signal phase of near roadside to center-island when pedestrian arrived at central island is considered. However, pedestrian position is correlated with the waiting time at central island, particularly when different signal conditions involved, we have to ensure the presented attribute level is available. Hence, an integrated factor

"Pedestrian position × Time has been waited at central island" is included with three levels of assumed waiting time before arriving at central island under different positions.

To provide Intuitive selection scenarios, we provided scene diagram of pedestrian crossing situations based on domestic urban areas. Since there are six factors in the SP design, if a full factorial design is used, there will be (2 × 2 × 2 × 2 × 2 × 3) = 96 factorial attribute combinations. However, some unavailable combinations should be excluded, e.g., green signal for both stages, pedestrian at central island × green signal at far roadside, pedestrian at near roadside × green signal at near roadside. Then, an orthogonal factorial design was used and the number of scenarios was reduced to 16, because measuring respondents' decisions is not efficient and practical when all alternatives are considered. Moreover, a randomized block design approach was used to stratify the four choice scenarios into four subsets.

Table 1. Factors and attributes considered in the SP design

Factor		**Attribute**		
		Choice 1: Adhere to pedestrian signals	**Choice 2: Not to adhere but wait for a suitable gap**	**Choice 3: Not to adhere and cross immediately**
Anticipated waiting time	Level 1	60 seconds	35 seconds	5 seconds
	Level 2	45 seconds	25 seconds	0 seconds
Perceived relative risk	Level 1	0%	25%	40%
	Level 2	0%	15%	25%
Weather condition	Level 1	Fine weather		
	Level 2	Raining condition		
Far roadside to center-island signal phase	Level 1	Red		
	Level 2	Green		
Near roadside to center-island signal phase	Level 1	Red		
	Level 2	Green		
Pedestrian position × Time has been waited at central island	Level 1	Near roadside × 0 seconds		
	Level 2	Central island × 15 seconds		
	Level 3	Central island × 30 seconds		

3.2 Other questions

In addition to the SP choices, the questionnaire also included the following components: (a) Attitudinal questions; (b) walking habits (i.e., walking frequency per day); and (c) socio-demographics information (i.e., gender, age). Attitudinal questions including attitude toward red light violation, behavioral control influenced by other pedestrians, risk pursuit in self-evaluation and time saving tendency will be obtained by adopting the seven-point Likert scale (Jiang et al., 2017). To illustrate, four questions, e.g. "Do you think you will run the red light if there is no penalty?", "Do you think other pedestrians is more likely to influence your crossing choice rather than yourself?", "Do you think you tend to pursue benefit rather than avoid risk?", and "Do you think saving time is more important than obey the rule?" are adopted (Zhu et al., 2021a; Rakotoarivelo et al., 2023; Nguyen-Phuoc et al., 2024).

A questionnaire survey was conducted via the online Credamo platform (www.credamo.com) between 7 June 2023 and 15 July 2023. The inclusion criteria require participants to be residents of Mainland China who are 18 years or older. In the Credamo platform, participants who register using their mobile phone number are required to provide information on their personal characteristics, including their age and sex. To reduce the respondents' concern on reporting red light running violation intention, we made a claim with real name at the beginning of the questionnaire that the data would only be used for scientific study and no personal identity information will be traced or leaked. To improve participation, a compensation of 5 RMB would be awarded for each valid questionnaire.

3.3 Analytic method

The choice outcome is discrete, encompassing more than two unordered outcomes, therefore, a multinomial logit (MNL) model is applied (Koo et al., 2015; Wirth et al., 2020; Ye et al., 2021). Additionally, a panel mixed approach was employed, which can capture both potential unobserved heterogeneity and correlations between choices responded from same individual, thereby reducing estimation bias (Train, 2001; Chen et al., 2020). This approach also accounts for individual fixed effects and random effects to more accurately reflect individual behavior in different scenarios.

Moreover, the Random Utility Maximization (RUM) framework is commonly employed in discrete choice model outcomes (Anciaes et al., 2018; Beitel et al., 2018; Anciaes and Jones, 2020), predicated on the assumption that individuals opt for the alternative yielding the greatest satisfaction (Train, 2009). Hence, the RUM model is used to estimate pedestrian choice behavior. However, the RUM model may introduce bias in parameter estimation due to its capacity to compensate for the underperforming attributes with the overperforming ones (Chorus et al., 2008). As a compelling alternative, the Random Regret Minimization (RRM) model is also employed in this study for estimation. It has three primary benefits: it considers the attributes of both chosen and unchosen alternatives, leading to choices that minimize regret; it potentially enhances model fit; and it allows for more flexible assumptions regarding WTP estimates, thereby providing a more nuanced understanding of attribute trade-offs (Iraganaboina et al., 2021; Zhu et al., 2021a). In this study, a 200 Halton draw in the simulation maximum likelihood estimation (Train, 2009) were used to estimate the RUM and RRM models. Furthermore, the random parameter was assessed through a stepwise iterative method (Zhai et al., 2019).

3.3.1 RUM model

As shown in Equation 1, the relationship between the utility of individual i (i = 1, 2, …, I) selecting choice k (k = 1, 2, and 3) in a given scenario j (j = 1, 2, 3 and 4) is given by (Hensher and Greene, 2003)

$$U_{ijk} = (\alpha' + \gamma_i')z_{ijk} + \xi_{ijk} \qquad \text{(Eq. 1)}$$

where z_{ijk} is a vector of all the observed variables, α' is a vector representing the coefficients of mean effects, γ_i' denotes the random effect, normally distributed ($\gamma_i' \sim N(0, \tau^2)$), and ξ_{ijk} is an error term with Gumbel distribution.

Then, the probability can be given as:

$$P_{ijk} \left| \gamma_i' \right. = \frac{e^{[(\alpha' + \gamma_i')z_{ijk}]}}{\sum_{k=1}^{K} e^{[(\alpha' + \gamma_i')z_{ijk}]}} \qquad \text{(Eq. 2)}$$

The unconditional probability is thus:

$$P_{RUM} = \int_{\gamma_i} (P_{ijk} \left| \gamma_i' \right.) dF(\gamma_i' \left| \tau \right.) \qquad \text{(Eq. 3)}$$

where ***F*** is the multivariate cumulative normal distribution.

3.3.2 RRM model

Unlike utility-based model, in the random regret model, the random regret RR_{ijk} for individual i to select alternative k in choice scenario j is given by (Chorus et al., 2008; Iraganaboina, 2021)

$$RR_{ijk} = \sum_{s \neq k} \sum_{m} \ln\{1 + \exp[(b' + r_i')(z_{ismj} - z_{ikmj})]\} e_{ijk} \qquad \text{(Eq. 4)}$$

where z_{ikmj} and z_{ismj} represent the variable vectors of chosen alternative k and unchosen alternative s respectively, b' is a vector of coefficients that represent the mean effects, r_i' denotes the normally distributed random effect ($r_i' \sim N(0, \sigma^2)$), and e_{ijk} is an error term with Gumbel distribution.

Consequently, the probability of an alternative k being chosen can be formulated as described by McFadden (1978).

$$P_{ijk} = \frac{e^{-RR_{ijk}}}{\sum_{k=1}^{K} e^{-RR_{ijk}}} \qquad \text{(Eq. 5)}$$

The unconditional probability is then

$$P_{ik} = \int_{\rho_i} (P_{ijk} \mid \rho_i') dF(\rho_i' \mid \sigma) \qquad \text{(Eq. 6)}$$

where ***F*** is the multivariate cumulative normal distribution.

For the observed choice sequence of individual *i*, the likelihood function conditional on ρ_i is written as

$$L_i(\alpha \mid \rho_i) = \prod_{j=1}^{J} \left[\prod_{k=1}^{K} \{P_{ijk} \mid \rho_i\}^{\delta_{ijk}} \right] \quad \text{(Eq. 7)}$$

where δ_{ijk} is an indicator variable that takes a value of 1 when alternative *k* is chosen and 0 otherwise.

Finally, the unconditional likelihood function is given by

$$L_i(\alpha, \sigma) = \int_{\rho_i} L_i(\alpha \mid \rho_i) dF(\rho_i \mid \sigma) \quad \text{(Eq. 8)}$$

A simulation approach is applied to estimate the parameters that maximize the likelihood function (see Hajivassiliou and Ruud, 1994; McFadden and Train, 2000).

4. Data and sample

The questionnaire survey collected valid data from 337 respondents. **Table 2** presents the distribution of pedestrians' choices in different scenarios. Since four hypothetic scenarios were presented for every individual, the dataset contains total 337 × 4 = 1348 choice decisions. Of the 1348 choice decisions, 945 (70.1%) adhere to pedestrian signal, 291 (21.6%) not to adhere but wait, and 187 (8.3%) not to adhere and cross immediately respectively. This reflects the overall pedestrian crossing trend in Mainland China, as demonstrated in the survey results, where adhering to pedestrian signal has the highest share of choice. This differs slightly from the research by Zhu et al. (2021a) on pedestrians in Hong Kong. One reason for this discrepancy may be that pedestrians in mainland China are less willing to run red lights, as adhering to signals provides greater safety benefits compared to not adhering them. Additionally, the phenomenon may be influenced by social approval effects. The survey also found that the proportion of “adhere to the signal” tends to increase when anticipated waiting time is shorter, relative risk level is higher, red signal exist in the far side and there is a warning sign.

Table 2. Distributions of choice decision in different scenarios

Scenario							**Choice decision**		
	Waiting time	**Perceived relative risk**	**Weather condition**	**Far roadside to center-island signal phase**	**Near roadside to center-island signal phase**	**Position vs. Time has been waited at the near roadside**	**Choice 1: Adhere to pedestrian signals**	**Choice 2: Not to adhere but wait for a suitable gap**	**Choice 3: Not to adhere and cross immediately**
1	(60s,35s,5s)	(0%,25%,40%)	Fine	Red	Red	Near side vs. 0s	69(83.13%)	9(10.84%)	5(6.02%)
2	(60s,35s,5s)	(0%,25%,40%)	Fine	Green	Red	Near side vs. 0s	66(78.57%)	18(21.43%)	0(0%)
3	(60s,35s,5s)	(0%,25%,40%)	Raining condition	Red	Red	Near side vs. 0s	72(88.89%)	9(11.11%)	0(0%)
4	(60s,35s,5s)	(0%,25%,40%)	Raining condition	Green	Red	Near side vs. 0s	74(83.15%)	14(15.73%)	1(1.12%)
5	(45s,25s,0s)	(0%,15%,25%)	Fine	Red	Red	Near side vs. 0s	78(92.86%)	4(4.76%)	2(2.38%)
6	(45s,25s,0s)	(0%,15%,25%)	Fine	Green	Red	Near side vs. 0s	61(73.49%)	14(16.87%)	8(9.64%)
7	(45s,25s,0s)	(0%,15%,25%)	Raining condition	Red	Red	Near side vs. 0s	79(88.76%)	10(11.24%)	0(0%)

8	(45s,25s,0s)	(0%,15%,25%)	Raining condition	Green	Red	Near side vs. 0s	67(82.72%)	11(13.58%)	3(3.7%)
9	(60s,35s,5s)	(0%,25%,40%)	Fine	Red	Red	Central island vs. 15s	58(71.6%)	19(23.46%)	4(4.94%)
10	(60s,35s,5s)	(0%,25%,40%)	Fine	Red	Green	Central island vs. 30s	73(82.02%)	11(12.36%)	5(5.62%)
11	(60s,35s,5s)	(0%,25%,40%)	Raining condition	Red	Red	Central island vs. 15s	60(72.29%)	16(19.28%)	7(8.43%)
12	(60s,35s,5s)	(0%,25%,40%)	Raining condition	Red	Green	Central island vs. 30s	60(71.43%)	16(19.05%)	8(9.52%)
13	(45s,25s,0s)	(0%,15%,25%)	Fine	Red	Red	Central island vs. 15s	77(86.52%)	9(10.11%)	3(3.37%)
14	(45s,25s,0s)	(0%,15%,25%)	Fine	Red	Green	Central island vs. 30s	62(76.54%)	15(18.52%)	4(4.94%)
15	(45s,25s,0s)	(0%,15%,25%)	Raining condition	Red	Red	Central island vs. 15s	68(80.95%)	11(13.1%)	5(5.95%)
16	(45s,25s,0s)	(0%,15%,25%)	Raining condition	Red	Green	Central island vs. 30s	58(69.88%)	13(15.66%)	12(14.46%)

4.1 Socio-demographic and walking habit

Table 3 presents the socio-demographic, walking habit, and attitude and personality traits of the respondents. Overall, ratio of male to female is 695 to 1,000. It is slightly skewed from that of Mainland China population (i.e., 1048 to 1,000) (National Bureau of Statistics, 2022). For age distribution, there was a relatively high proportion of the respondents with ages from 25 to 45 years, although we attempted to avoid the questionnaire reaching only a limited range of respondents. This is a limitation of the selected sample. However, this could be attributed to the fact that aging people is less willing to participate in the SP survey and may have difficulty in understanding the survey process. In terms of the level of educational, 82.5% of respondents have obtained a college degree or above, which is much higher than that of the Chinese population (18.86%) (National Bureau of Statistics, 2022). Moreover, monthly incomes of 54.3 % of respondents are less than 6000 RMB, and that of 10.1 % of respondents are more than 15000 RMB respectively. For the walking habit, 87.8 % of respondents hold a driving license. In addition, over half of the respondents (59.6%) travel less than 2 times per day, and 41.5% of respondents walk 3-5 days per week.

4.2. Attitude and personality traits

For the attitude toward red light violation, 63.4% of respondents reported that even without considering penalty, they still disagree with the violation behaviors, while 32.3% of respondents would maintain neutrality. For self-control of behavior, 53.7% of respondents keep neutral, while 37.1% of respondents disagree with that crossing choice is more likely to be affected by others. For time saving tendency, only 6.2 % of respondents strongly tend to save time, while 43.6% of them are reported as no tendency. For risk proneness, majority of respondents (83.4%) consider themselves as having high awareness with low risk-taking tendency, 15.7% of the respondents consider themselves neutral about the risk-taking, only three respondents reported themselves as high level of risk proneness.

Table 3. Distribution of the sample

Category	Factor	Attribute	Count	%
Demographics	Gender	Male	138	41.0
		Female	199	59.0
	Age	25years old and below	71	21.1
		26-45 years old	251	74.5
		46 years old or above	15	4.5
Socio-economics	Educational level	Senior high school and below	31	9.2
		Bachelor degree	279	82.8
		Graduate degree	27	8.0
	Occupation	Government functionary	20	5.9
		Social productive personnel	253	75.1
		Student and others	64	19.0
	Monthly income	Less than 6000 RMB	183	54.3
		6000-15000 RMB	120	35.6
		Over 15000 RMB	34	10.1
Walking habit	Possession of driving license	Yes	296	87.8
		No	41	12.2
	Walking trip frequency per day	0-2 times	201	59.6
		3-5 times	124	36.8
		6 times or more	12	3.6
	Number of trip making day per week	2 days and below	114	33.8
		3-5 days	140	41.5
		6-7 days	83	24.6
Attitude and personality traits	Tend to run the red light if no penalty	Strongly disagree	214	63.5
		Neutral	110	32.6
		Strongly endorse	13	3.9
	The choice to run a red light is more likely to be influenced by others	Strongly disagree	125	37.1
		Neutral	185	54.9
		Strongly endorse	27	8.0
	Tend to save time	Strongly disagree	147	43.6
		Neutral	169	50.2
		Strongly endorse	21	6.2

	Tend to be low risk	Strongly disagree	3	0.9
		Neutral	53	15.7
		Strongly agree	281	83.4

5. RESULTS

Table 4 presents the results of random parameter logit model with different estimation ways (i.e., RUM and RRM respectively). Overall, the RRM model's estimation results are better than those of the RUM model, as reflected in the smaller AIC value, higher log-likelihood value and higher R square value. It should be noted that the estimation results are different, potentially due to the different optimization algorithms in parameter estimation process (Chorus and Arentze, 2008). Therefore, we mainly present and discuss the results of parameter estimation of the RRM model. When considering the random components of coefficients, several typical distributions are taken into account, including the normal, Gumbel, and log-normal distributions. Among these, normal distribution offers the most optimal fit in the random parameter estimation.

5.1 Effect of alternative-specific variable

As shown in **Table 4**, the coefficient for anticipated waiting time is negatively associated with compliance to the pedestrian signal (β = -0.058) and not to adhere but wait for a suitable gap (β = -0.026). This indicates that pedestrians have a higher regret to adhere to pedestrian signal when anticipating a higher waiting time. In contrast, the coefficient for perceived relative risk is positively associated with the compliance to the signal (β = 0.934) and not to adhere but wait (β = 2.441). This implies that pedestrians have a lower regret to adhere to the signal when they perceived a higher risk of crash and injury.

5.2 Situational features

Contrary to expectation, there is no significant relationship between weather condition and red-light violation propensity. Compared with not to adhere and cross immediately, likelihood of adhere to the nearside signal when signal of far side is green is significantly lower than that of when red signal exists in far side, at 1% level (Choice 1: -0.793; Choice 2: -0.384). In addition, propensities of immediate red light violation (the second stage) are significantly higher when the signal of first stage is green.

5.3 Socio-demographics and walking habit

For the effects of personal attributes including socio-demographics and travel characteristics, as also shown in **Table 4**. Contrary to our expectation, gender did not show significant effect on the propensities. For age group, likelihood of immediate red light violation of respondents who are 25 years old and below are significantly higher (Choice 1: -0.345) than that who are 26 to 45 years old. Respondents who are of 46 years old or above have higher tendency to choose "Choice 2" compared with "Choice 3" (β=1.042). For educational level, propensities of not to adhere but wait of respondents who have attained graduate degree are significantly lower (Choice 2: -0.12) compared to immediate violation crossing, at the 1% level. Furthermore, propensities of red light immediate running violation of respondents who have lower salaries (i.e., less than 6000 RMB per month, Choice 2: -0.458) are significantly higher. For occupation, students have lower tendency to adhere to pedestrian signal compared to social productive personnel (Choice 1: -0.869), at the 5% level. Nevertheless, propensities of not to adhere but wait of respondents who have a full driving license are significantly higher (Choice 2: 0.745), at the 5% level. For walking habit, propensities of "adhere to pedestrian signal" (Choice 1: -0.453) of respondents who walk six times a day are marginally lower, as compared to those who walk three to five times a day, at the 10% level.

5.4 Attitude and personality traits

For the effect of pedestrians' perception, respondents who strongly disagree with the violation behaviors have lower compliance tendency to pedestrian signal for both choice 1 (-1.611) and choice 2 (-1.125), at the 5% and 1% level of significance respectively. This may indicate that there is a huge gap between what people reported about behavior tendencies and what they presented in specific scenarios. In addition, respondents who strongly disagree with “choice to run a red light is more likely to be influenced by others” have significantly lower tendency to adhere to pedestrian signal at the 1% level. Also, propensities of (immediate) red light violation of respondents who reported themselves as no tendency to save time (Choice 1: -1.543; Choice 2: -0.954) and low risk (Choice 1: -1.547; Choice 2: -1.004) are significantly higher, at the 1% level.

Table 4. Results of parameter estimation of panel mixed multinomial logit models

Category	Factor	Attribute	RRM model (Omitted choice: Choice 3)				RUM model (Omitted choice: Choice 3)			
			Choice 1: Adhere to pedestrian signals		Choice 2: Not to adhere but wait		Choice 1: Adhere to pedestrian signals		Choice 2: Not to adhere but wait	
			Coefficient	S.E.	Coefficient	S.E.	Coefficient	S.E.	Coefficient	S.E.
	Constant		IS		IS		IS		IS	
SP attribute	**Anticipated waiting time**		-0.058*	0.014	-0.026*	0.013	IS		0.034*	0.015
	Perceived relative risk		0.934*	0.382	2.441*	1.381	IS		3.414*	1.537
	Weather condition (Control: Raining Condition)		IS		IS		IS		IS	
	Far roadside to center-island signal phase (0-Red, 1-Green)		-0.793**	0.279	-0.384**	0.188	-0.587*	0.252	IS	
	Near roadside to center-island signal phase (0-Red, 1-Green)		IS		-0.300*	0.177	-0.969*	0.556	-0.898***	0.264
Demographics	**Gender (Control: Female)**		IS		IS		IS		IS	

	Age (Control: 26-45 years old)	**25 years old and below**	-0.345*	0.143	IS		IS		IS	
		46 years old or above	IS		1.042**	0.524	IS		IS	
	Educational level (Control: Bachelor degree)	**Senior high school and below**	IS		IS	IS	IS		IS	
		Graduate degree	IS		-0.922**	0.46715	IS		-1.101***	0.426
	Monthly income (Control: 6000-15000 RMB)	**Less than 6000 RMB**	IS		-0.458**	0.21691	IS		-0.613***	0.220
		Over 15000 RMB	IS		IS		IS		-0.793**	0.362
	Occupation (Control: Social productive personnel)	**Government functionary**	IS		IS		IS		0.807**	0.339
		Student and others	-0.869*	0.475	IS		-0.978*	0.518	IS	
Walking habit	**Holding a driving license (Control: No)**		IS		0.745*	0.342	IS		IS	
	Walking trip frequency per day (Control: 3-5 times)	**0-2 times**	IS		IS		IS		0.438**	0.207
		6 times or more	0.453*	0.187	IS		-1.470^	0.584	IS	
	Number of trips making day per week (Control: 3-5 days)	**2 days and below**	IS		IS		IS		IS	
		6-7 days	IS		IS		IS		-0.641**	0.246

Attitude and personality trait	**The attitude towards running a red light without considering the penalty (Control: Neutral)**	**Disagree**	**Mean**	-1.611*	0.742	-1.125**	0.320	IS		-0.569**	0.210
			SD	2.130**	0.973	1.617**	0.323				
		Strongly agree		IS		IS		IS		IS	
	The choice to run a red light is more likely to be influenced by others (Control: Neutral)	**Disagree**		IS		-0.673**	0.267	IS		-0.917**	0.268
		Strongly agree		IS		IS		0.782*	0.420	IS	
	Tend to save time (Control: Neutral)	**Disagree**		-1.543**	0.579	-0.954**	0.296	-2.371**	0.690	-1.393***	0.276
		Strongly agree		IS		IS		1.798**	0.448	0.847**	0.340
	Tend to be low risk (Control: Neutral)	**Disagree**		IS		IS		3.441**	1.321	IS	
		Strongly endorse	**Mean**	-1.547**	0.606	-1.004***	0.233	-1.275***	0.365	-1.029**	0.225
			SD	1.508**	0.621	1.055**	0.239				
Number of parameters				27				27			
Restricted log likelihood				-1480.93				-1480.93			
Unrestricted log likelihood				-580.54				-605.21			
McFadden Pseudo R-square				0.608				0.603			
AIC				1277.1				1322.4			

*Notes: ** Statistically significant at the 1% level; * Statistically significant at the 5% level; ^ Marginal at the 10% level; IS denotes Insignificant*

6. DISCUSSION

6.1 Decision-making between time and safety

Consistent with findings from previous research (Zhu et al., 2021a), this study confirms the positive correlation between time to be waited and the propensity for red light violation, as well as a negative correlation between perceived risk and such propensities. Furthermore, adherence to pedestrian signals shows less sensitivity to increases in perceived risk. This observation aligns with the principles of loss aversion as postulated by prospect theory (Andersson et al., 2019), which suggests that individuals disproportionately dislike losses compared to equivalent gains. Consequently, travelers often exhibit a greater willingness to accept risks to avoid losses, such as time delays (Wang and Zhao, 2019; Flügel et al., 2019; Hu et al., 2019).

This section delves into the decision analysis when considering the risk and return for time and safety. Analogous to the trade-off analysis between travel time and travel cost found in route choice modeling (Iraganaboina, 2021), the interplay between time and risk can be conceptualized as a risk-return rate (RR-Rate). This metric quantifies the extent of risk a pedestrian is willing to accept to save a unit of time, for instance, 30 seconds. Within the framework of random regret, these trade-offs are influenced by the levels of attributes, which can be computed to provide a more granular understanding of pedestrian decision-making under varying traffic conditions and signalization contexts, as:

$$RR - Rate_{RRM} = \frac{\sum_{j \neq i} - \beta_{wt} (1 + \frac{1}{\exp[\beta_{wt}(t_j - t_i)]})}{\sum_{j \neq i} - \beta_{pr} (1 + \frac{1}{\exp[\beta_{pr}(r_j - r_i)]})} \qquad \text{(Eq. 9)}$$

Where β_{wt} and β_{pr} are estimates of alternative-specific variables from panel mixed regret-based MNL model respectively, t_i and t_j represent the waiting time attributes for the chosen alternative i and considered alternative j, respectively. r_j and r_i represent the perceived risk attributes for the chosen alternative *i* and considered alternative *j*, respectively. As shown in Figure 2, risk-return rate varies from 1 to 4 %/second, which indicates pedestrian would be willing to suffer increased 30% to 120 % perceived risk to save time of 30 seconds. Compared with previous study (Zhu et al., 2021b), results of this study indicate a higher level of risk proneness when making crossing decision in general.

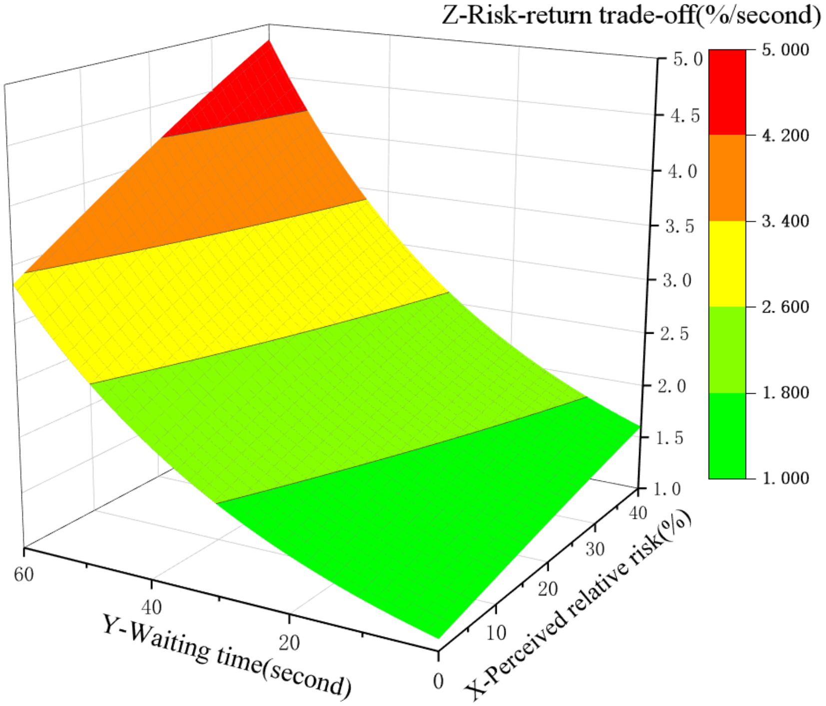
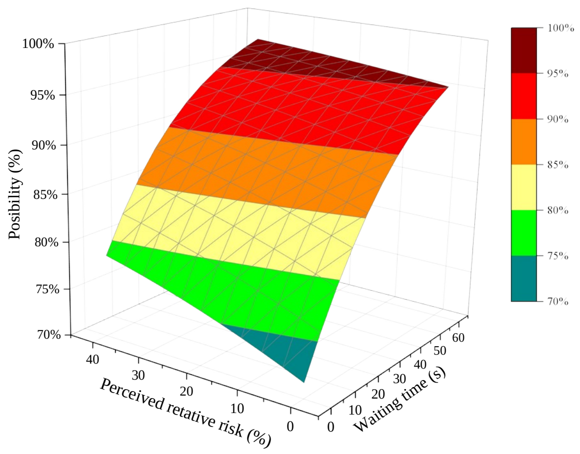
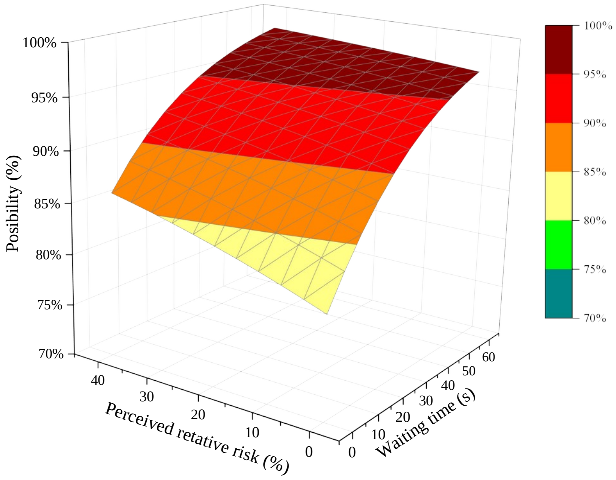
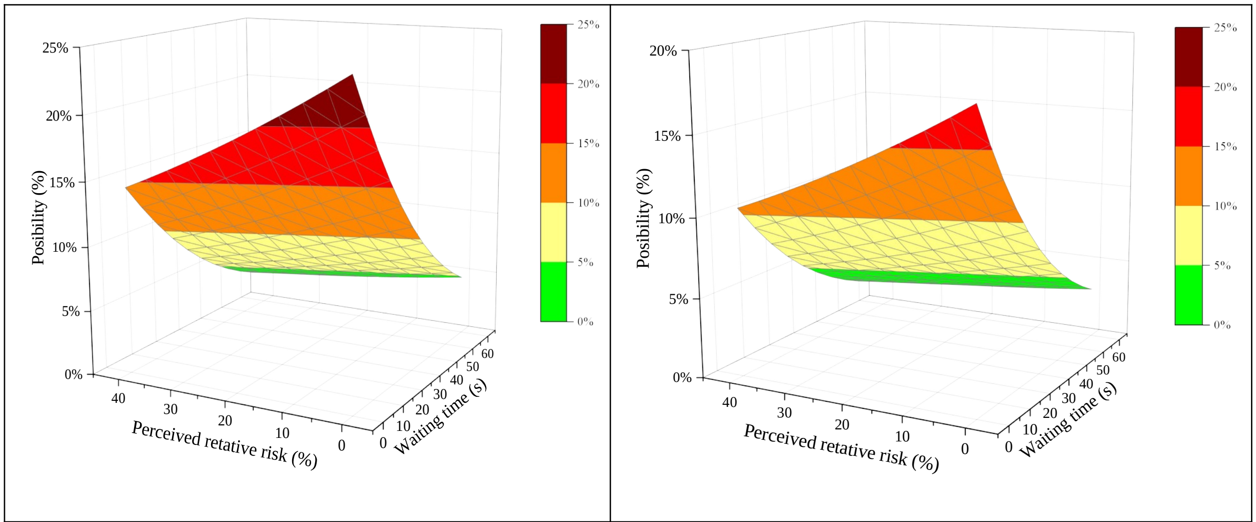


Figure 2. Risk-return rate

6.2 Situational features

Likelihoods of adhering to the pedestrian signal are lower when the signal phase of second stage (e.g., central island to far roadside) is green. As we assumed in “introduction” section, pedestrian could perceive more time to be saved if run the red light of the first stage, when green signal exists in the subsequent stage. The finding is consistent with a previous observation study (Zhu and Sze., 2021). However, it is inferred that the green signal of the subsequent stage will significantly affect the rational decision process for a pedestrian to consider the trade-off between time and safety. Specifically, as show in Figure 3, the overall choice probability for "adhere to pedestrian signal" when green signal exists in subsequent stage is obviously lower than that when red signal exists. Moreover, we could find that even when the perceived relative risk is higher than 40%, the compliance rate (for first stage) when green signal exists in second stage is still significantly lower than that when red signal exists. In addition, respondents will tend to immediately run the red light of the subsequent stage when the signal phase of first stage is green. Effects of weather condition was not found in this study, which is beyond our expectation and not consistent with previous studies (Liu and Tung, 2014). This could be attributed to the scenarios were not presented by real-world picture or video, which may lead to respondents not being able to feel the impact of weather changes firsthand.

	
(a) Choice 1-Green signal exits in subsequent stage	**(b) Choice 1-Red signal exits in subsequent stage**



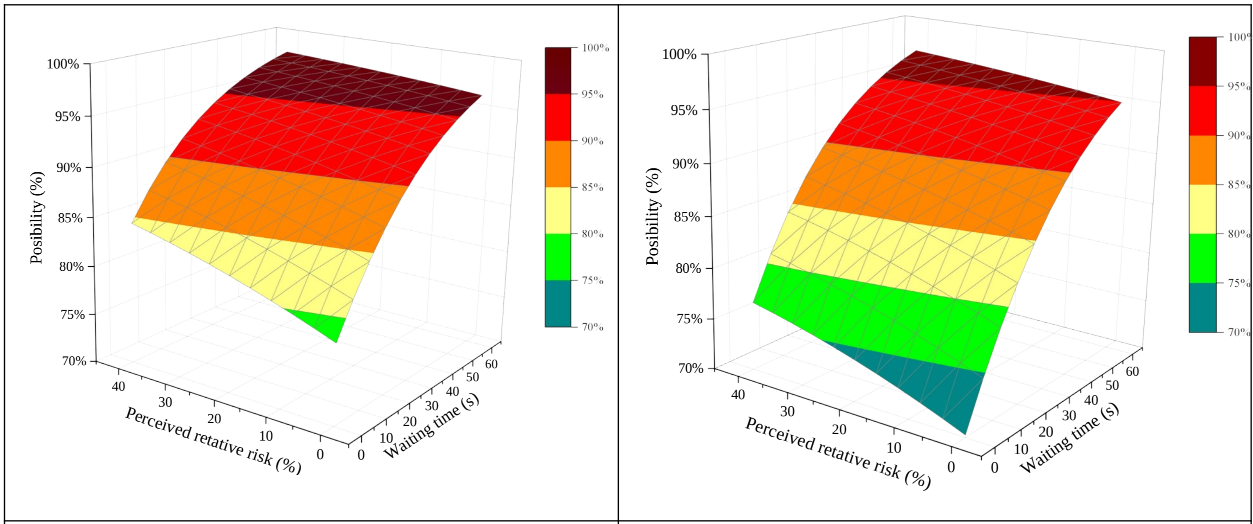
(c) Choice 2- Green signal exits in subsequent stage

(d) Choice 2-Red signal exits in subsequent stage

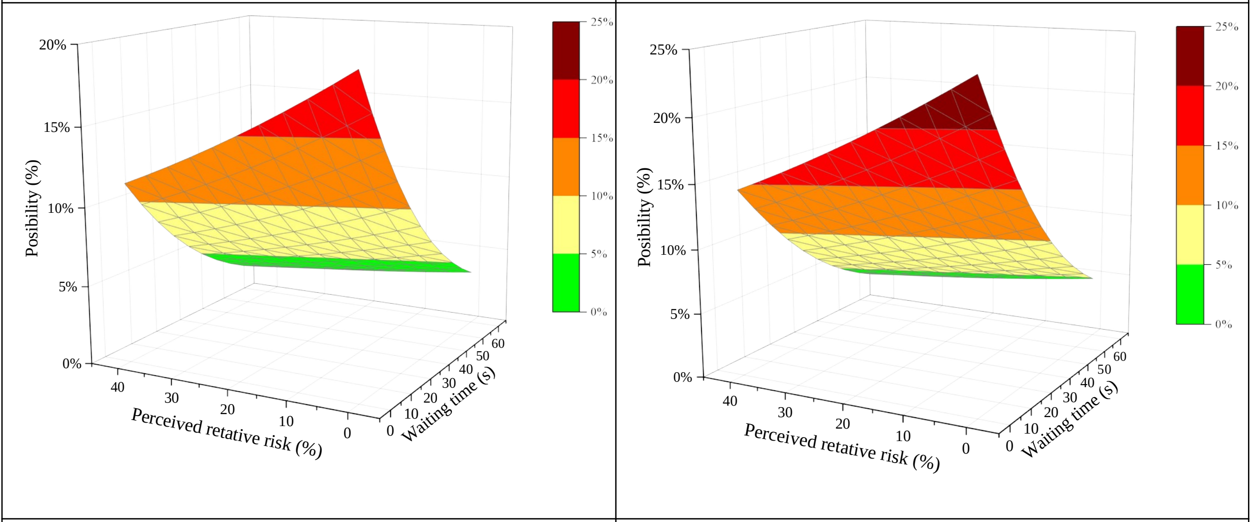
Figure 3. Choice probability for Choice 1 and 2 under different signal phase

6.3. Attitude and personality traits

As revealed in this study, attitude towards red light violation without considering the penalty show negative effects on the choice. For instance, pedestrians who do not agree that they can run a red light without considering penalty exhibit significantly lower tendency to comply with the red light. Such unfavorable effect could also be found in the respondents with self-reported as low time-saving tendency and low risk-taking tendency. As shown in Figure 4, pedestrians who consider themselves as low time-saving tendency have lower probability with 5%-8% to adhere to pedestrian signal than that of all the respondents, under all levels of risk-return rate. The findings are beyond our expectation. However, the difference between self-expression and reporting/actual behavior has also been mentioned in the literature (Jones and Blankenship, 2021). The self-expression and cognition of the subjects may be self-glorified, resulting in differences from truth (Krueger et al., 2017); or probably due to the social approval effect, they are not willing to expose real traits that contradict the expected image of society (Bundy and Pfarrer, 2015). It is interesting to find the contradictory issue for pedestrian red light violation behavior, which is rarely mentioned or found in previous crossing behavior studies.



(a) Choice 1-Over all **(b) Choice 1-Tend to save time (Disagree)**



(c) Choice 2- Over all **(d) Choice 2-Tend to save time (Disagree)**

Figure 4. Comparison between all respondents and respondents with different time-saving tendencies

6.4 Demographics and socioeconomics

There was no significant association between gender and the propensity of red light violation, which is contrary to the expected results. For effect of age group, respondents of 25 years old and below have lower tendencies to comply with pedestrian signal, compared to respondents of 26 to 45 years old. This is probably because that pedestrians with 25 years old and below might be more sensitive to the anticipated waiting time with less consideration about the risk, for example, they could be more likely to perceive time-saving when the signal of subsequent stage is green. The finding is consistent with one previous study in the same city (Zhang et al., 2016), but inconsistent with others (Kim et al., 2008; Wang et al., 2011; Zhu et al.,2021a). In particular, two previous studies conducted in Hong Kong found that pedestrians with over 65 years old have higher tendency to run the red light (Zhu and Sze, 2021; Zhu et al., 2021b). The contrary findings could be attributed to the difference on cultural background and city environment. Hong Kong is an aging city where walkability system plays a vital role in daily trip. Higher proportion of elderly pedestrian with more walking trips would probably trigger a higher non-compliance rate on the signal rules (Zhu et al., 2021b).

Moreover, the study reveals that respondents with lower monthly incomes exhibit higher propensities for red light violation violations. This trend suggests that individuals are relatively insensitive to monetary fines as deterrents for such violations when compared to more stringent penalties, such as illegal driving (Wong et al., 2008; Li et al., 2014). According to deterrence theory, the effectiveness of sanctions is influenced by their perceived severity, certainty, and swiftness (Kergoat et al., 2017).

6.5. IMPLICATIONS FOR POLICY AND PRACTICE

6.5.1. Signal time plan and junction design at two-stage crossings

Our results indicate a notable trend: pedestrians are more inclined to disregard the red light at the initial stage of the crossing if the subsequent signal displays green. This behavior underscores the significance of temporal perceptions and perceived time savings in pedestrian decision-making at signalized intersections. To address the challenge of red-light violations at two-stage crossings, several strategies merit consideration. Optimizing signal time plan emerges as a crucial strategy to mitigate red-light violations and enhance intersection safety. It is recommended that coordinated signal phasing and leading pedestrian intervals should be considered (Gavric et al., 2023; Goughnour et al., 2021). For instance, maintaining consistent phases for the two-stage signals and minimizing the duration of the red phase may help curb violations. Dynamic signal control based on real time traffic volume could improve the road usage efficiency during pedestrian red signal and thus reduce the red light running behavior of pedestrian. More specifically, we do find that the green signal of the second stage indicate a reduced waiting time for pedestrian when choose to run the first stage, but if the traffic volume remains high and steady during the red pedestrian signal, pedestrians will perceive high risk and have to obey the signal. For junction design, in intersections where longer red phases are unavoidable, implementing grade-separated facilities could be beneficial. These measures not only address temporal perceptions but also promote compliance with traffic regulations, thereby enhancing overall intersection efficiency and safety.

6.5.2. Targeted enforcement, education campaigns and deterrence measures

Apart from optimizing the signal time plan and junction design, how to develop targeted enforcement and education campaigns as well as effective deterrence measures would matter. Transport authorities can leverage the study's findings to implement targeted interventions aimed at reducing red-light running incidents among at-risk demographic groups. More specifically, two directions could be applied for targeted countermeasures. For targeted pedestrian group (i.e., younger pedestrians and individuals from lower-income communities), one way is to enhance science popularization and education on road traffic safety in high school. It is meaningful to enhance this kind of education in high school. Compared to college students, high school students are more likely to develop an awareness of obey rules and protecting their own safety (Darling et al., 2007), and most of them have not yet formed an independent social consciousness during high school, which is an important stage of safety education and publicity. The reason for this kind of measure is that pedestrians may have a lucky mentality, thinking that they won't be caught when running a red light. According to deterrence theory (Ellis, 2003), deterrence is most likely to be successful when a prospective attacker believes that the probability of success is low and the costs of attack are high. Therefore, simply imposing fines might not be sufficient to deter pedestrians from breaking red-light rules effectively, how to make them believe it is possible or even certain to be traced and get punished is a more important issue. It is recommended to set up advanced computer vision system (i.e., Proactive warning system with intelligent recognition technology) at intersections with high pedestrian and vehicle volume to recognize and record the red light running violation of pedestrian (Zhang et al., 2014; Zhu et al., 2020). For penalty system, introducing demerit point systems, where offenders collect points leading to license suspension (similar to vehicles), or other penalties such as a one-hour detention (Shah and Pradhananga, 2024), can also make the consequences more certain. The fear of losing driving privileges can be a strong deterrent, especially when paired with educational campaigns stressing the importance of road safety. Therefore, a comprehensive approach that combines monetary fines, non-monetary sanctions, and demerit point systems is likely to have the biggest impact on reducing red-light violations and promoting pedestrian safety.

6.5.3. Improving pedestrian (crossing) facilities

The study highlights the trade-off between how long pedestrians feel they wait and how safe they perceive their crossing to be. It stresses the need for urban areas to prioritize safety and ease for pedestrians. Transportation policies should aim to make walking more appealing by planning pedestrian routes thoroughly, implementing measures to slow traffic, and considering pedestrian needs when designing and building in cities. Using designated pedestrian paths can significantly lower the risk of accidents by reducing the chances of vehicles and pedestrians conflicting. However, while using infrastructure like footbridges and underground tunnels can enhance safety, it often means pedestrians have to take longer routes, which can be less convenient (Chan et al., 2022; Soliz and Pérez-López, 2022). Our study suggests that improving walkability and accessibility could be another solution. For example, in Singapore and Hong Kong, a comprehensive footbridge system goes beyond simple crossings (Xu et al., 2022; Zhu et al., 2023a; (Xu et al., 2022; Zhu et al., 2023b; Zhu et al., 2024). It includes features like lifts for people with disabilities, ensuring connections between destinations and transit are walkable, and having multiple entry points (Chan et al., 2023; Li et al., 2023). In the short term, making pedestrian crossings more direct and convenient, and installing signals that prioritize pedestrians, could discourage people from running red lights by making waiting times feel shorter.

7. CONCLUSION AND LIMITATION

In this study, a stated preference survey was conducted to examine the effects of time and safety, weather condition, pedestrian signal phase, and other individual characteristics on the red light violation behaviors of pedestrians. Then, a regret-based multinomial logit model is established to analyze the choices between (i) adhere to pedestrian signal, (ii) not to adhere but wait for a suitable gap, and (iii) not to adhere and cross immediately. Results indicate that pedestrians' propensities to violate red lights is positively associated with anticipated waiting time, but negatively correlated with perceived relative risk. Also, compared with random utility model, regret-based model provided a flexible trade-off analysis between cost and benefit (i.e., risk-return rate). In addition, signal condition of other stages (both for nearside stage and further side stage) could affect the propensities of red light violation of pedestrians. For example, propensities of red light violation on the current stage will increase when there is a green signal on the other stage. Moreover, personality traits including attitude, self-control of behavior, time-saving tendency and risk-taking tendency also affect the crossing choice. These insights significantly enhance the knowledge of the interconnections among pedestrian decision-making, the incidence of red light violation, and individual characteristics. These results strongly suggest the adoption of innovative traffic control interventions, such as the implementation of variable message signs and flashing warning signs, which could enhance compliance. Moreover, these findings support the refinement of enforcement strategies and the calibration of penalties to better align with pedestrian behaviors and propensities. Furthermore, they underscore the importance of designing targeted road safety education and promotional campaigns, particularly at locations identified as high-risk for pedestrian incidents.

Nevertheless, there are still some limitations. First, this study is limited to a skewed sample distribution, with a relatively high proportion of respondents aged 26 to 45, female respondents, and those with higher education, although we have attempted to avoid the issue. The skewed distribution might lead to a higher or lower compliance rate on pedestrian signal. Hence, future studies should take measures to ensure a more balanced sample distribution to mitigate potential negative impacts from sample bias. Second, this study considered the inherent factors as observable variables (e.g. risk perception) rather than latent variables. Future research could consider latent variables and employ latent class methods (such as the integrated choice and latent variable model) for a more comprehensive estimation of pedestrians' crossing decisions. Third, other situational variables, such as trip purpose and safety-in-numbers, should also be further explored in future studies. Finally, since the data is collected via online survey, the respondents may acknowledge that the IP address and nickname might be used to trace their identity (although we have clearly clarified the issue before the survey), and it is possible that some respondents may perceive the "relative risk" as real probability of being involved in crash, which would possibly affect the data quality and generalization of results. In future study, it would be valuable to consider the effect of prevalence of e-bikes near crossings on pedestrian crossings, considering the traffic environment in Mainland China (Tang et al., 2024).

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