Signal Offset Design Based on Upstream Vehicle Speeds: Considering Vehicle Behavior in Dilemma Zones

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Abstract The Type II Dilemma Zone (DZ) is critical for traffic safety at intersections. The high accident rate at signalized intersections can be related to the indecisive situations drivers face when the yellow light is on. Moreover, platoon progression may lead to more aggressive driver behavior at signalized intersections. However, the common signal offset design only considers the efficiency of platoon progression, but not the safety of intersections. This study proposes a signal control framework to reduce the impact of sharp acceleration, deceleration, and DZ hazards on traffic safety by adjusting the signal offset design. The framework is developed based on the field survey data to estimate the traffic flow speed trajectory, which reflects the change of vehicle behavior upon signal switch, and thereupon to minimize DZ hazards. The research results are expected to be a reference for the signal timing offset design and DZ protection of arterial roads.

Key-words: Signalized Intersections, Dilemma Zone, Offset, Signal Control, Upstream Vehicle Speed, Dilemma Zone Protection Algorithms

1. INTRODUCTION

Signal timing is designed to provide a safe and efficient traffic environment for road users. However, the risk of intersection crashes remains due to differences in driving behavior. Approximately 30%-40% of crashes occur at intersections, and the uncertainty in driver decision-making behavior accounts for half of these crashes (Lu et al., 2008; Choi, 2010; Li and Abbas, 2010). When the yellow light is on at an intersection, different factors, including reaction time and personality tendencies, may affect a driver’s decision-making process. Primarily, deciding whether to stop before/at the stop line or pass through the intersection is a critical issue for drivers, and such indecisive driving behavior implicates that the vehicles trapped into the so-called Dilemma Zone (DZ) (Gates et al., 2007), also known as the option zone. When the number of vehicles trapped into the DZ increases, it will increase the chance of intersection accidents, especially red-light running, which is more likely to result in right-angle collisions (Parsonson et al., 1974; Zegeer & Dean, 1978; Wu et al., 1982). Therefore, reducing the Number of Vehicles trapped into the Dilemma Zone (NVDZ) can improve the overall safety of the associated intersection.

Furthermore, the design of upstream and downstream roadway progression can also be an important cause of intersection accidents. Most of the previous studies on offset design focus on traffic flow efficiency in terms of maximizing progression/throughput, while the safety-related issues at downstream intersections are not fully considered. For example, drivers are generally and naturally averse to wait for a long red light; hence, when the yellow light is on, or the green light is counting down, some drivers may show aggressive driving behavior. Frequent speed acceleration and deceleration of vehicles can lead to a higher probability of intersection conflicts and collisions, especially when running a red light, which is one of the major causes of traffic accidents. If the offset design also incorporates the consideration of safety at intersections, the probability of accidents may be better contained.

Driver behavior through intersections is affected by a variety of factors which are inherently dynamic, and the effects also vary across vehicles with different speeds. Hence, to entirely eliminate the existence of the DZ may not be practically possible (Urbanik & Koonce, 2007). Various protection methods with respect to DZ have been proposed in the literature, such as in-vehicle warning, green light countdown timer, and extended green light duration for signal control (Zegeer & Dean, 1978; Wu et al., 1982; Chang et al., 2013; Islam et al., 2017). However, the current system of signal control is limited by the efficiency of road traffic flow and the lack of advanced facilities (e.g., no vehicle detectors at each intersection to track the trajectory of each vehicle), which has compromised the effectiveness of prevention measures on intersection safety. Inevitably, vehicles are trapped into DZs, and it can lead to the situation of sharp acceleration and deceleration of vehicles occurring across signal cycles. Moreover, it is difficult to predict driving behavior and provide early warning or prevention for potentially dangerous vehicles. In view of the aforementioned limitations, it is an important goal to reduce the potential hazards caused by the downstream DZ and improve the overall intersection safety by a more complete analysis of the speed variation of vehicles and relevant behavior changes throughout road sections and upon the changes of upstream signals. Accordingly, this research seeks to develop an approach that can:

- Analyze the behavior of vehicles upon the change of the upstream signal;
- Provide a control strategy to prioritize the safety of the DZ and adjust the upstream and downstream signal timing offset design;
- Demonstrate the speed variation along the trajectories of vehicles crossing the upstream intersection and road section; and
- Address the potential intersection safety problems caused by the driving behavior in DZ.

Based on the better understanding of driving behavior in terms of these aspects, it may enable more comprehensive signal control strategies to minimize the impact of NVDZ and sharp acceleration/deceleration on traffic safety by adjusting the signal timing offset design. Accordingly, the consideration of driving behavior can be better incorporated into signal and progression design, thereby balancing the concerns for both safety and traffic flow efficiency.

The rest of the paper is organized as follows. Section 2 provides a review of relevant studies and clarifies the associated problem characteristics. In Section 3, the research framework of this study and data collection are described. Additionally, a preliminary investigation is presented, including the description of the study site and basic statistics of the collected data. Finally, we summarize the research findings and discuss the expected results from future research.

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2. LITERATURE REVIEW

There are two types of Dilemma Zones defined at signalized intersections. Gazis et al. (1960) defined the Type Ⅰ DZ where drivers are unable to safely cross an intersection or stop by the stop line when they see the light turning yellow. Later researchers identified Type Ⅱ DZ (Parsonson et al., 1974), in which drivers are facing the difficulty in deciding whether to stop or pass through an intersection upon the change from green light to yellow light (Urbanik, 2007) due to the complexity of the driving decision process (Parsonson, 1992; Gates et al., 2007). Type II DZ is also known as indecision zone or optional zone (Saito et al., 1994; Gates et al., 2007). This study focuses on Type II DZ to investigate the complexity of the driver decision-making process at existing signalized intersections, seeking to reduce the risk of DZ by signal control strategies.

2.1 Boundary of a Dilemma Zone

Figure 1 illustrates the definition of Type II DZ. In Figure 1, X_c is the minimum distance from the stop line where a vehicle can stop safely before the stop line. X_s is the maximum distance from the stop line where the vehicle can cross and clear the intersection before the yellow light ends. According to the Gazis-Herman-Maradudin (GHM) model, X_c and X_s are demonstrated as follows (Gazis et al., 1960):

$$X_c = v_0\delta_1 + v_0^2/2a_1$$
$$X_s = v_0\tau + 0.5a_2(\tau - \delta_2)^2 - W - L$$

where,

v_0 : speed of the approaching vehicle (ft/s),

δ_1, δ_2: driver's perception reaction time for stopping and crossing respectively,

a_1, a_2 : vehicle's maximum deceleration and acceleration rates (ft/s^2),

τ: yellow light duration (s),

W: intersection width (ft), and

L: vehicle length (ft).

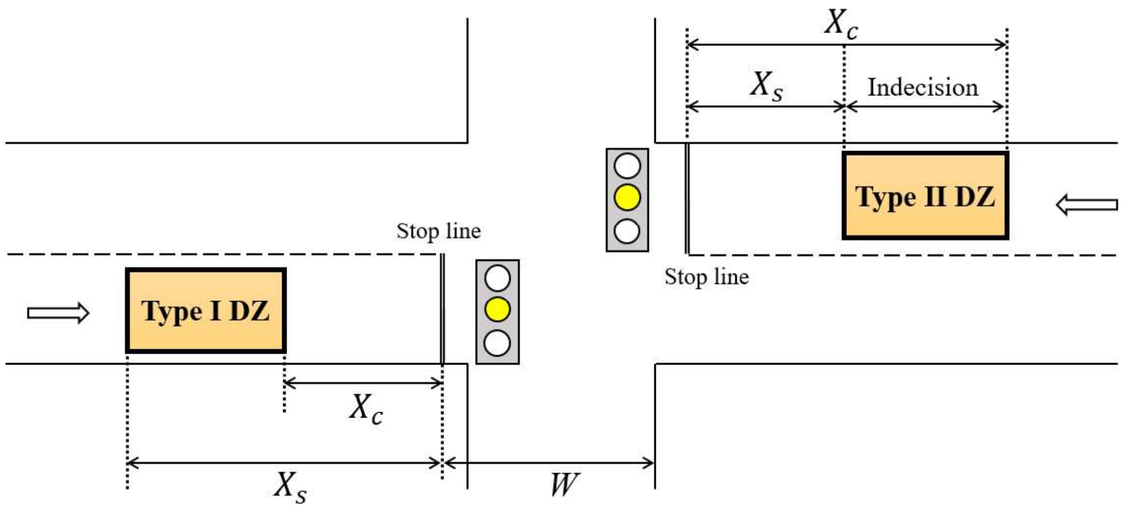

Figure 1. The Definition of DZ

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As shown in Figure 1, $X_s < X_i < X_c$ (X_i represents the current location of the vehicle), implying that the vehicle is trapped into Type II DZ. If $X_s = X_c$, DZ does not exist, which can be the best design. However, reaction time and vehicle length are different across drivers and vehicles, and the speed of the vehicle approaching the intersection also changes over time. Hence, the optimal design does not exist, and the DZ cannot be completely eliminated.

Zegeer and Dean (1978) defined the DZ as the zone between 10% and 90% of drivers choosing to stop at a yellow light, based on the Time To Stop line (TTS). Most studies nowadays use the definition proposed by Bonneson et al. (2002), where the range between 2.5 s and 5.5 s from the stop line is the Type II DZ. Logistic regression modeling is the most commonly used approach to explain the behavior (Gates et al., 2007; Papaioannou, 2007; Long et al., 2013; Pathivada & Perumal, 2019). Some studies use the probit model (Li & Abbas, 2010; Sharma et al., 2011) or the ordered probit model (Liu et al., 2012). Due to the imprecision of the driver's perception of speed and distance, fuzzy logic may contribute to identifying the boundary of Type II DZ. (Moore & Hurwitz, 2013; Yang et al., 2014).

2.2 Hazard measurement and DZ protection system

The main parameters entered in the past studies of hazard and safety measurement methods in the DZ include Time To Intersection (TTI), Time To Collision (TTC), and Number of Vehicles in DZ (NVDZ). Li and Abbas (2010) developed a model to quantify the hazard level of vehicles in DZ as a function of their remaining TTI at the yellow onset. TTC is the primary measure of conflict severity and is defined as the expected time for two vehicles to collide while maintaining their speeds and directions (Gettman & Head, 2003). Machiani et al. (2016) created a Safety Surrogate Histogram (SSH) based on TTC that captures the degree and frequency of DZ-related conflicts for each intersection approach. Najmi et al. (2019) studied the DZ of roundabouts and the driving factors using TTC and Kinematic Motion (KM) methods. The results obtained show that the DZs of roundabouts are shorter and closer to the stop line compared to those at regular signalized intersections, and drivers are more conservatively at roundabouts and more willing to stop. Li et al. (2015) proposed a new Markov process-based DZ protection algorithm, which treats the number of vehicles in the DZ as a Markov process over time. Moreover, providing additional DZ protection against trucks allows trucks to take extra time and distance to stop, thereby reducing the number of trucks in the DZ and red-light running behavior (Zimmerman, 2007).

Previous studies have installed green light extension protection systems at intersections, and the frequency of traffic accidents and traffic conflicts was significantly reduced after installing such systems (Zegeer & Dean, 1978; Wu et al., 1982). Li et al. (2015) also used the Markov process-based DZ protection algorithm to predict the number of vehicles in the DZ and optimize the green light end time to reduce the number of vehicles caught in the DZ per hour. Studies have been further conducted to install onboard DZ warning systems to alert drivers with audible cues to respond appropriately (Moon et al., 2003; Chang et al., 2013). Islam et al. (2017) adopted a green light countdown timer that increased the DZ driving stopping probability by 13.10% while decelerating by 1.5 ($\mathrm{ft/s^2}$).

2.3 Signal control method

Most of the design methods regarding arterial interconnections are controlled by the maximum green light bandwidth and minimum negative utility. (Yang et al., 2015; Zhang et al., 2015). However, these studies on signal design only consider the traffic flow efficiency and rarely factor downstream intersection safety.

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Some previous studies on signal control methods for intersection safety have shown that setting up a countdown timer can reduce the chance of red-light running by 50%, but others have also shown that reducing the green light stopping rate and extending the DZ by even 28 meters still cannot reduce the DZ problem (Kidwai et al., 2005; Chiou & Chang, 2010). Kosonen (2003) proposed a traffic signal control system based on real-time simulation, multi-agent control scheme, and fuzzy inference, which allows a combination of various aspects like fluency, economy, environment, and safety. Wu et al. (2018) used cellular automata simulations to show that flashing green measures are not effective in reducing either rear-end collision risk or Red-Light Running (RLR) violations.

Furthermore, He et al. (2014) uses Vehicle-to-Infrastructure (V2I) communication in a connected vehicle system, where priority-eligible vehicles, such as emergency vehicles, buses, commercial trucks, and pedestrians, are able to send priority request messages to a traffic signal controller when approaching a signalized intersection. Recent studies have used reinforcement learning to adjust the signal timing. Kwon et al. (2020) used a deep convolutional neural network to adjust the duration of all-red signals based on the detected RLR with a hierarchical linear regression model. Nonetheless, few studies have considered platoon progression with intersection safety in mind.

2.4 Summary of literature review

This study reviews the definition and boundary of DZ, hazard measurement and DZ protection system, driving behavior modeling in signal intersections, and safety-based signal control strategies to help this study better investigate how to improve the safety of signalized intersections. This helps this study to use the most practical parameters as the basis for our study. The main parameter that we obtained for the past DZ protection system is NVDZ. Afterward, the literature on driving behavior modeling in signal intersections to help this study understand the behavior of drivers in DZ is reviewed. It can be inferred that even if the intersections are designed according to the standard method of signal control, the vehicles may still trap into the DZ due to different driving behaviors, vehicle lengths, and external environments. Based on the previous literature review, it can be found that no study has been conducted to reduce the DZ hazard and improve the safety of downstream intersections by adjusting the signal offset design based on the upstream vehicle behavior.

3. METHODS AND DATA COLLECTION

The number of vehicles trapped in a DZ is influenced by the speed trajectory across the associated road section, which in turn is affected by the design of the upstream and downstream signals. However, most of the previous studies on the DZ problems primarily focus on the driving behavior of vehicles in the DZ before passing through the intersection but do not consider the speed variation across the associated road section and the behavior upon passing through the (upstream) intersection. Hence, this study seeks to investigate the behavior of vehicles after passing through the upstream intersection and adjust the offset between upstream and downstream signal timing to mitigate the situation of vehicles trapped in the downstream DZ and the associated sharp acceleration/deceleration.

3.1 Research Framework

The speed trajectory of traffic through the roadway affects the number of vehicles trapped in the DZ, which is one of the significant objectives of this study. The speed trajectory needs to

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obtain the speed change of vehicles over a period of time; therefore, the actual survey can effectively obtain the real traffic speed and further analyze how the upstream and downstream signals affect the speed trajectory.

Figure 2 shows the research flowchart of this study. We first investigate the traffic flow at the upstream intersections and downstream road sections, record the locations of vehicles and their passage timestamps to calculate the speed of each vehicle. Then, we further estimate the successive travel speeds of the vehicles based on an equal-speed estimation model and plot their time-space trajectories to facilitate the observation and analysis of vehicle behavior through the intersection.

Based on the flow speed trajectory data obtained from the field survey, the speed of traffic arriving at the downstream intersection can be estimated. Thereby, the number of vehicles trapped in the downstream DZ can be calculated based on the Type II DZ definition proposed by Bonneson et al. (2002). by incorporating the signal timing design. Finally, the platoon progression and car-following model are associated with attaining more accurate and effective modeling of vehicle behavior across signalized intersections. The final objective is to minimize the NVDZ in downstream, and the optimal timing offset design of the model is calculated.

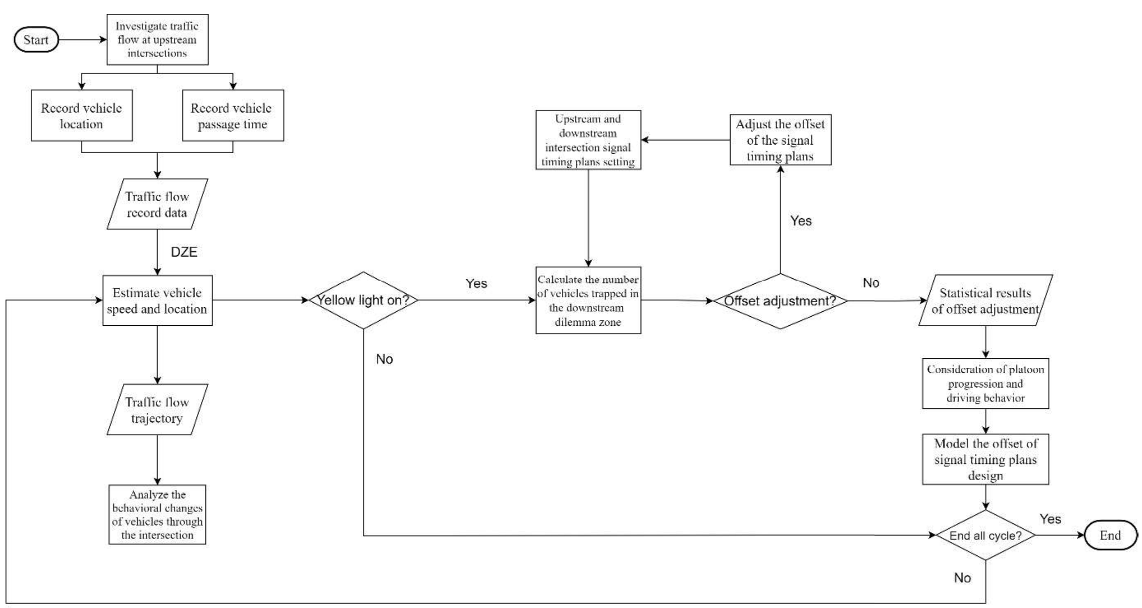

Figure 2. Research Flowchart

3.2 Surveying Vehicular Flows across Signalized Intersections

The intersection of Xinyi Road and Keelung Road, Keelung Road southbound, Taipei, Taiwan, was selected as the study site. Field observations at the surveyed intersections were conducted from 10:00 AM to 11:00 AM on October 14 (Wednesday), 2020. A high-definition video camera was placed at the vantage point of a footbridge above the intersection, about 5 meters above ground level, and a tripod was used as an anti-vibration device during the recording. The collected content included vehicles, intersections, downstream road sections, and current signal timing. The standard recording rate used was 60 frames per second (fps). Moreover, the

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intersection and the downstream section were used as reference points with 5-meter and 20-meter marks, respectively, for camera calibration and video benchmarking in order to obtain the exact positions of vehicles and avoid distortion of speed in subsequent calculations. A snapshot of the field video recording is shown in Figure 3; the green area in the figure is the road section of the survey, and the red lines are the reference points.

The actual recording area of the intersection is 20m-25m from the upstream stop line, and the recording location of the downstream road is 70m-90m from the upstream stop line. The recorded images were examined reconnaissance, and the time of each vehicle's rear end at the intersection and downstream road, and its current number were recorded. Finally, according to the kinematic formula, the average spatial speed is used to calculate the vehicle speed.

This study investigates the variation of traffic flow speed trajectories at intersections and downstream roads under different signals. However, it is hardly obtaining the speed of vehicles at each location without advanced equipment. Therefore, this study uses an equal-speed estimation model to fit the traffic trajectory by using the weighted average of the speeds at the intersection and the downstream road. By adding the estimated speeds at 0 m and 110 m from the upstream stop line, the variation of the traffic flow speed trajectory can be effectively fitted. After predicting the vehicle trajectory, the number of vehicles located in the downstream DZ can be estimated. The vehicles in the DZ can be counted at any point in time.

The lane-changing behavior of vehicles is not considered in this study, so as to avoid the complexity related to the distortion of speed trajectory estimation. Although vehicles may change lanes to maintain their desired speeds, some previous studies have reported that this assumption holds for moderate or high traffic volumes (Bonneson et al., 2002; Chaudhary et al., 2003). Furthermore, only cars are considered in this study; that is, the complex interactions between multiple traffic modes and traffic flows, particularly the interactions with motorcycles or bicycles, are not within the scope of this study. Accordingly, we focus the traffic on the inner lane and the median lane in the field survey because the vehicles on the outer lane involve more of such interactions and may turn right when traveling through the downstream intersection.

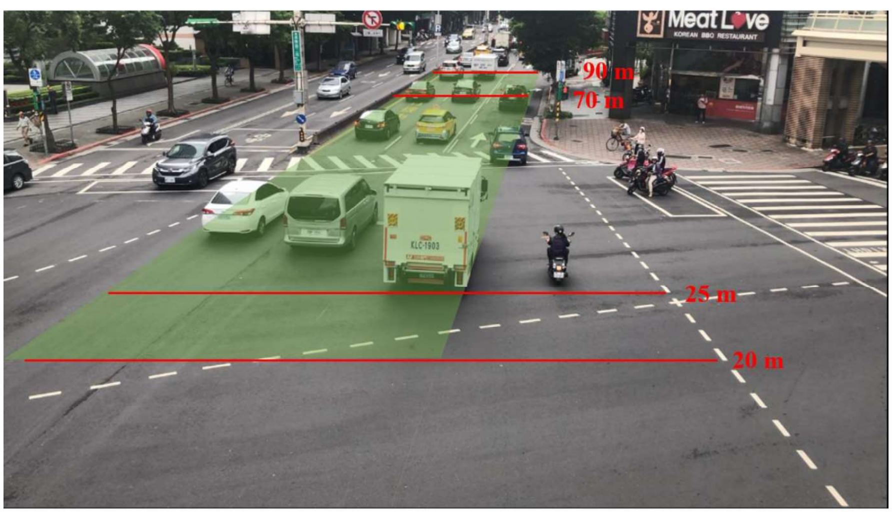

Figure 3. Field Video Recording and Reference-Point Marking

4. RESULT ANALYSIS

The survey data are analyzed statistically as shown in the following table, Table 1 for the inner lane and Table 2 for the median lane. Each table represents the velocity (V) and number (N) of vehicles along the signal time, G represents the green light, Y_{10} represents the green light

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countdown for 10 seconds, Y represents the yellow light, R represents the red light, and average (AVG) speed is shown in the last column. The categories on the left are the intersections (INT) and downstream roads (RD) over four signal cycles.

As shown in Table 1, for the inner lane during the first cycle, the speed of the vehicles on the yellow and red light is 65% and 87% higher than that on the green light, respectively. This result clearly shows that vehicle speeds through the intersection become faster as the signal time approaches the red light. In addition, for those passing through the intersection during the green light, their speeds are higher in the downstream road section, compared with their speeds at the intersection. That is, there is a slowdown of the vehicles when they pass through the intersection. It is probably because of the behavior that even if the signal is green, drivers still tend to slow down when passing through the intersection to observe the surrounding area to ensure safety. However, when comparing with the vehicles passing through the intersection around the signal switch, they show rather contrary behavior. In the 10 seconds before the yellow light, the speed of the vehicles through the intersection increases significantly, and it is 100% higher during yellow light, and 120% higher during a red light.

Similar behavior was observed from the vehicular flow on the median lane (Table 2), where the speeds of vehicles passing through the intersection during the yellow light and red light are 65% and 87% higher, respectively, compared with those passing through the intersection during the green light of the first cycle. By investigating the speeds at the intersection and in the downstream road section, the vehicle speed through the intersection increases significantly at the 10-second countdown to the end of the green light, during the yellow light and red light, with the speeds upon the yellow light and red light being 100% and 120% higher, respectively.

From the survey results, it can be found that when the signal time is close to the yellow light, the speeds at the intersection are much greater than those in the downstream road section, implying that vehicles have significant acceleration behavior. Such sharp acceleration and deceleration of driving behavior can be a major cause of the possibility of traffic accidents.

Table 1. Descriptive Statistics (inner lane)

		G		Y_{10}		Y		R		AVG	
		V(m/s)	N(veh)	V(m/s)	N(veh)	V(m/s)	N(veh)	V(m/s)	N(veh)	V(m/s)	N(veh)
1	INT	10.077	17	12.523	5	16.577	2	18.868	1	11.438	25
	RD	10.504	16	10.408	5	8.624	2	8.617	1	10.248	24
2	INT	10.821	21	15.272	2	-	0	-	0	11.208	23
	RD	11.458	21	13.633	2	-	0	-	0	11.647	23
3	INT	8.446	20	17.388	2	-	0	-	0	9.259	22
	RD	10.389	19	14.097	2	-	0	-	0	10.742	21
4	INT	11.344	20	19.815	2	23.742	2	-	0	13.083	24
	RD	12.933	19	17.940	2	17.113	2	-	0	13.732	23

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Table 2. Descriptive Statistics (median lane)

		G		Y_{10}		Y		R		AVG	
		V(m/s)	N(veh)	V(m/s)	N(veh)	V(m/s)	N(veh)	V(m/s)	N(veh)	V(m/s)	N(veh)
1	INT	7.766	20	8.326	4	11.521	1	14.970	1	8.273	26
	RD	10.465	20	9.529	4	9.333	1	10.277	1	10.270	26
2	INT	8.463	21	20.000	1	-	0	-	0	8.987	22
	RD	11.500	20	17.406	1	-	0	-	0	11.781	21
3	INT	7.565	19	15.528	1	-	0	-	0	7.963	20
	RD	9.409	19	14.993	1	-	0	-	0	9.688	20
4	INT	7.746	18	14.749	3	14.368	1	-	0	9.002	22
	RD	10.842	18	11.734	3	11.862	1	-	0	11.010	22

4.1 Vehicle Trajectory

The time trajectory diagram is shown in Figure 4 and Figure 5; X-axis is the time, which is the same as the actual sign time, $X = 0$ means the green light is on. Y-axis is the distance, which is the same as the actual intersection position, and $Y = 0$ is the position of the stop line. The position at the bottom of the diagram represents the current signal. The irregular blue curve is the traffic flow speed trajectory after curve fitting, and the points on the trajectory are the actual points participating in curve fitting.

Figure 4 shows the time range for the green light after the countdown of ten seconds. Take the lane in the first cycle as an example; it can be seen that when the green light is counted down, and the yellow light is on, the slope of the trajectory will gradually increase when the vehicle passes the intersection, which means that there is an acceleration behavior of the vehicle. When the vehicle reaches the downstream road, the slope of the trajectory will gradually slow down, representing the speed reduction behavior. Furthermore, the greater the change of the trajectory amplitude, the greater the change of the vehicle speed from the intersection to the upstream road, and these results are consistent with the descriptive statistics of Table1. Similar results can be seen for Middle land (Figure 5).

In Figure 5, it is worth noting that the last vehicle to cross the intersection when the green light is counting down also has a significant acceleration in the trajectory. This is probably due to the driver's pre-observation of the red countdown timer on the east-west bound Xinyi Road. The driver then senses that the green light in his direction may be ending soon, causing the driver to accelerate.

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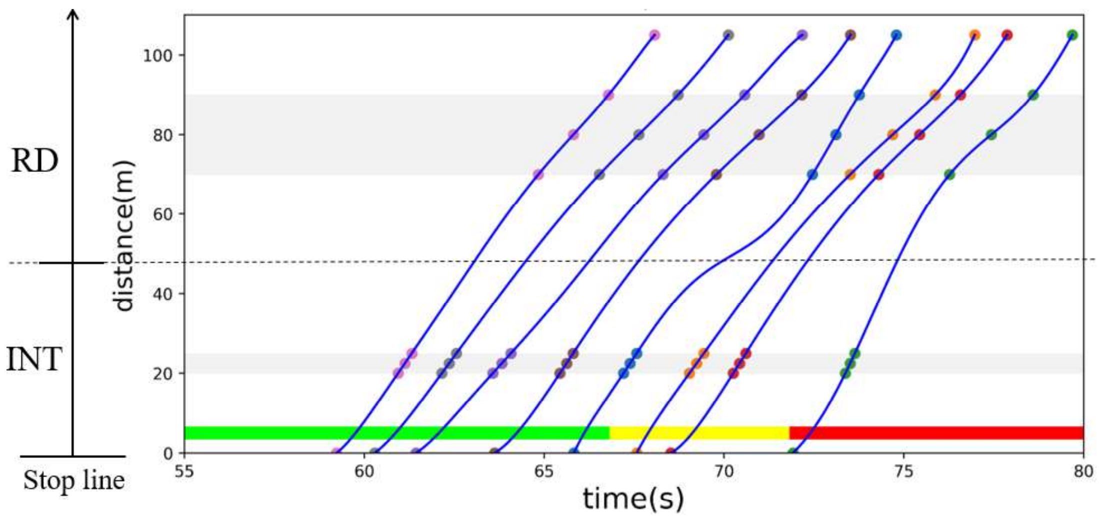

Figure 4. Vehicle Time-Space Trajectory (1st cycle, inner lane)

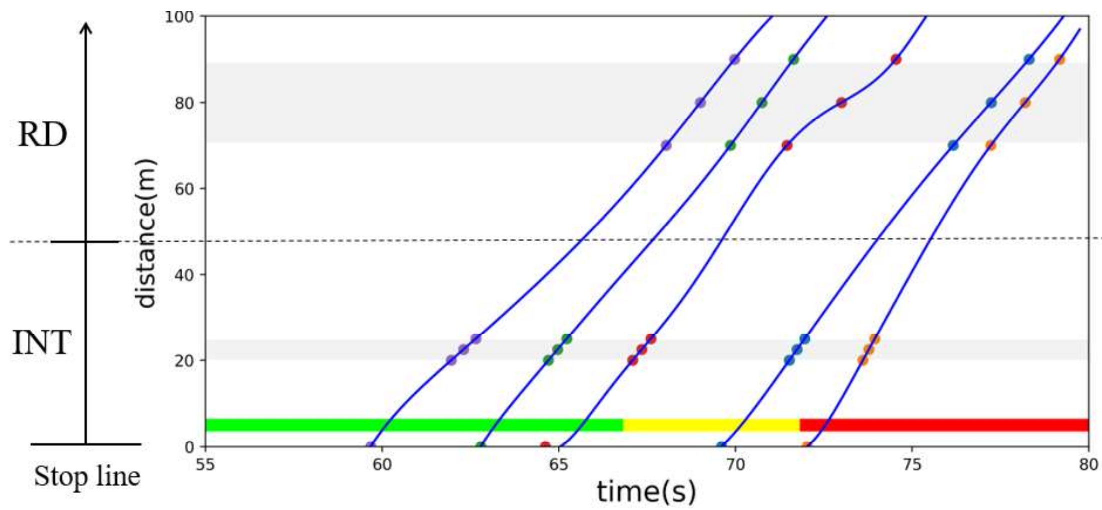

Figure 5. Vehicle Time-Space Trajectory (1st cycle, middle lane)

4.2 Estimating Vehicles in Dilemma Zone

After estimating the velocity trajectory from the field data, the NVDZ calculation can be performed. Figure 6 displays the flow chart of the DZ estimation, and the detailed flow is described as follows.

- Step 1: The vehicle speed data obtained from the field data in Section 3.4 are used first. Based on the DZE, the upstream and downstream vehicle speeds are estimated, and the vehicle positions D_i are obtained by $v(t)$. Then execute Step 2.
- Step 2: In order to avoid overtaking, the model must check the time at the stop line. If $D_{i-1} < D_i$ is not valid, change the speed of the V_i to the speed of the V_{i-1}. Conversely, if $D_{i-1} < D_i$ Is valid, then continue to Step 3.
- Step 3: Determine whether the yellow light is on at the downstream intersection, and if the yellow light is on, calculate the vehicle's distance to the intersection $t_{SL} = (\mathrm{I} - D_i)/v(t)$. Then execute the next step; otherwise, no data are output.
- Step 4: According to the definition of Bonneson et al. (2002), if $2.5 < t_{SL} < 5.5$, it means the vehicle traps into DZ; conversely, no data are output

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- Step 5: Calculate the NVDZ of each cycle and output the result.
- Step 6: If the model needs to continue, return to Step 1; otherwise, stop the execution.

where,

$v(t)$: speed of the approaching vehicle at time t (m/s),

D_i, V_i: position of vehicle i, and speed of vehicle i,

D_{i-1}, V_{i-1} : position of vehicle $i-1$ (m), and speed of vehicle $i-1$ (m/s),

t_{SL}: time to stop line (s), and

I: distance between two intersections (m).

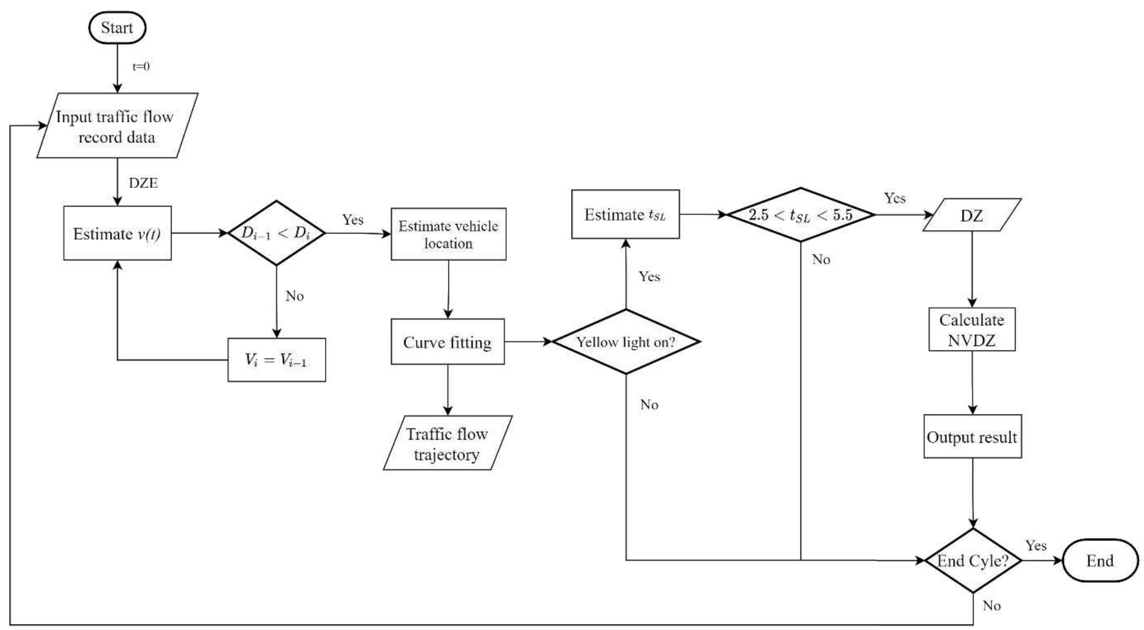

Figure 6. Flowchart of the Dilemma Zone Estimation

4.3 Discussion

This study proposes a signal control method to minimize the DZ hazard, which contributes to the DZ protection and signal control design. The future work will incorporate the modeling of the following traffic and the consideration of the platoon progression to establish a model for the signal offset design considering the DZ safety, in order to combine the intersection safety and the overall traffic flow efficiency. Furthermore, to make the study results more representative, the study will continue to investigate other intersections to verify that the framework has adequate validity, and future work is expected to validate the model results with SUMO simulation. The model will be validated with SUMO simulations to verify the model's optimal timing offset design by incorporating the desired traffic flow speed trajectory into the simulation and adding the platoon progression and car-following model.

Moreover, the present work can be extended to the following cases:

1) Dynamic adjustment of the signal offset design

The framework of this study assumes that the data are obtained from past traffic flow data. However, the traffic flow in different sections of the road on different days can greatly affect

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the shift time of the same road and affect the traffic speed. In this case, the dynamic signal offset control method is more responsive to the current traffic flow, and the implementation of this condition can improve the results.

2) The setting of the early warning system

The proposed framework is applied to each numbered interlocking intersection to minimize the NVDZ. However, despite the minimization of the hazard level, a small number of vehicles are still trapped into the DZ. In order to increase the safety of intersections, this problem can potentially be solved by targeting a small number of vehicles with early warning.

3) Modeling of the self-driving scenario

In this study, the upstream traffic speed trajectory at the downstream intersection is considered as the basis for signal timing offset control. However, each driver's behavior is different, and the traffic trajectory is not easy to predict. Therefore, if the popularity of self-driving vehicles increases in the future, the speed data can be obtained immediately by connecting to the network. The structure of this model can prevent self-driving vehicles from trapping into DZ, and the effect will be more significant.

5. CONCLUDING REMARKS

In this study, a DZ signal control framework is proposed to reduce sharp acceleration and deceleration at intersections, as well as the hazards at DZ. This research also analyzes the driving behavior during signal transitions and investigates the traffic flow speed variation at signal intersections in the field. Based on the field survey, the trajectories of traffic flow speeds are plotted for the subsequent DZ model construction. The results show that there is a significant change in the traffic flow speed during the signal change, and it can cause sharp acceleration and deceleration, which leads to an increase in the intersection hazard level.

However, the suitability of the signal control framework in this study as a practical signal timing offset design may be questioned. The signal control strategy based on intersection safety may lead to delayed traffic flows. Furthermore, the assumptions of the equal-speed estimation model may have some bias compared with the actual traffic flow situation due to the lack of advanced equipment to obtain the data of traffic flow speed trajectory. Subsequent simulations are needed to validate the model. Fortunately, in the proposed framework, the NVDZ can be reduced, which should be able to improve the safety of intersections, and it is expected that both safety and efficiency can be incorporated into the model simultaneously upon the consideration of platoon progression.

There are still several research aspects that are worth discussing with respect to the framework proposed in this study. For example, even though the minimized NVDZ has reduced the hazard level, there are still a few vehicles trapped into DZ. Such a problem can be the potential direction for future research to provide early warning for those vehicles in DZ. Additionally, in the scenario of self-driving vehicle development, such early warning may even alert drivers at upstream intersections to reduce the likelihood of hazards.

In-depth inspection is necessary to address the issues raised above, and the following methods can be further elaborated and implemented in future research: (1) converting the problem into a *multi-objective optimization* by assigning appropriate penalty value to the delay of traffic flow, (2) constructing the trajectories of speed variation from OBU (On-Board-Unit) data instead of employing equal-speed estimation, or using advanced equipment for image

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recognition, which may predict vehicle trajectories more accurately.

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