Dilemma Zone: A Comprehensive Study of Influential Factors and Behavior Analysis

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Abstract— **In this paper, we examine the problem of the Dilemma Zone (DZ) in depth, weaving together the various influences that span the environment, the ego-vehicle, and ultimately the characteristics of the driver. Driver behavior in dilemma zone situations is crucial, and more research is urgently needed in this area. The journey through various modeling approaches and data acquisition techniques sheds new light on driver behavior within the dilemma zone context. Our thorough examination of the current research landscape has revealed that several significant areas remain overlooked. As well as the dynamic impact of vehicles, vehicle interactions, and a strong tendency to over-rely on infrastructure information, there are also concerns about the lack of comprehensive evaluation tools. However, we do not see these gaps as stumbling blocks, but rather as steppingstones for future research opportunities. A more focused study of cooperative solutions is required considering the potential of personalized modeling, the untapped power of machine learning techniques, and the importance of personalized modeling. It is our hope that by embracing innovative approaches that can capture and simulate personalized behavioral data using "everything-in-the-loop" simulations, future research endeavors will be guided. To effectively mitigate the DZ problem, we also point out the research gaps and opportunities for further research in the DZ.**

I. INTRODUCTION

Traffic management at signalized intersections, a critical aspect of urban planning and safety, is teeming with challenges [1]. One significant issue that has proven to be perennially perplexing, both from theoretical and practical standpoints, is mitigation of the dilemma zone at intersections [2]. The dilemma zone describes a space before a signalized intersection where drivers face a predicament [3]. As the traffic light switches from green to yellow, they must quickly decide whether to cross the intersection or decelerate and stop, which may both carry risks. Accelerating to cross the intersection can potentially lead to running a red light, posing a significant safety risk [4]. On the other hand, braking abruptly can cause rear-end collisions and disrupt traffic flow [5]. The understanding and appropriate management of this issue can have a substantial impact on traffic safety and efficiency, optimizing traffic signal timing and mitigating risk associated with driver behavior [6]. Although modern traffic management technology is scientifically avoiding the occurrence of dilemma zone problems to the greatest extent possible, dilemma zone issues can still cause some traffic accidents, depending on the personalized characteristics of different drivers [3]. Consequently, not only in transportation engineering, but also with the popularity of Connected and automated vehicle (CAV) technology in recent years, many approaches have emerged combining intelligent vehicle and traffic infrastructure to mitigate the dilemma zone problem [7], [8]. By relying on programmed responses, these automated vehicles must learn how to navigate this ambiguous zone in a safe and efficient manner, presenting new challenges to traffic management and vehicle automation.

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Innovations:

This paper concerns the complexities associated with the management of dilemma zone. Specifically, we explore how advanced technology can be utilized to mitigate or even eliminate driver dilemmas.

1) Recent Developments in CAV and V2X Technologies: With strides in hardware development and advances in communications technologies, the field of Connected and Autonomous Vehicles (CAV) has been witnessing unprecedented progress over the past few years. A multitude of Vehicle to Everything (V2X) algorithms have been developed in the last few years, highlighting a paradigm shift in the capabilities and scope of Intelligent Transportation Systems (ITS). By integrating these advanced V2X algorithms, our research provides a comprehensive overview of the latest techniques for mitigating Dilemma Zones (DZ). As a result of the use of these cutting-edge technologies, traffic safety and efficiency can be enhanced by managing DZ situations optimally.

2) The Role of Personalized Factors in DZ Issues: Personalized factors play a major role in DZ issues, which is the focus of our study. There is currently a dearth of research focused on how individual attributes influence drivers' decision-making processes within the dilemma zone. This is why we explore this under-researched area, aiming to provide insight into how driving behavior, experience, and risk perception affect DZ-related outcomes and decision-making. In the dilemma zone, we can gain insights into the factors contributing to dilemmas by considering drivers' personality traits and driving styles [6]. As a result, personalized interventions and algorithms that promote safer and more efficient decision-making can be developed, particularly in the context of connected and automated vehicles.

II. Formulation of Dilemma Zone Problem

Given the significant heterogeneity inherent among environments, ego-vehicle and drivers, most of existing methods that describe the dilemma situations adopt a collective approach. Specifically, they statistically analyze the behavior of the traffic flow or a specific group when a yellow light is present. To provide a comprehensive analysis of personalized driving behavior in dilemma zone. In this section we first review existing approaches for defining the dilemma zone. Subsequently, we analyze the various factors that influence driving behavior, emphasizing the need for further consideration of these dynamics.

Given the inherent difficulty for drivers to accurately determine whether to halt or proceed during the yellow (amber) phase of a traffic light cycle, a so-called "dilemma zone" is consequently formed in the approach lanes [9]. There are two general ways to defining a dilemma zone: Type I dilemma zone and Type II dilemma zone. Gazis et al. first introduced the Type I dilemma zone in 1960, which defined the "Amber Light Dilemma" as a situation that a driver may not stop safely after the yellow light comes on or be able to clear an intersection before the end of the yellow duration, even if comply with the traffic ordinances [10], [11]. This may result from poor intersection design associated with errors in signal timing and detector placement [12]. The Type I dilemma zone is measured in the distance to the stop-line in meter [13]. As illustrated in Figure 1, the boundaries of Type I dilemma zone can be defined using the critical distance X_c for stopping before the stop-line using a comfortable deceleration and the critical distance X_s for crossing the stop-line using a comfortable acceleration [10].

$$X_c = v_0\delta_1 + \frac{v_0^2}{2a_1} \tag{1}$$

$$X_S = v_0\tau + 0.5a_2(\tau - \delta_2)^2 - W - L \tag{2}$$

where v_0 is the approaching speed of the vehicle, δ_1 and δ_2 are the average perception-reaction time (PRT) for stopping and crossing, respectively; a_1 and a_2 are the comfortable deceleration and acceleration rates, respectively; τ is the duration of the yellow phase, W is the effective width of the intersection and L is the vehicle length. When $X_S < X_c$, the zone between X_S and X_c is defined as the Type I dilemma zone (as show in Figure 1). In contrast, when $X_S > X_c$, the zone between X_S and X_c is an option zone (as show in Figure 2), where is the upstream of the intersection in which the driver can either stop or clear the intersection in complete safety. If $X_S = X_c$, there is neither the Type I dilemma zone nor option zone [2].

The Type II dilemma zone (also called indecision zone) in Figure 3 is characterized as a region preceding the stop-line at an intersection where drivers often encounter difficulty in

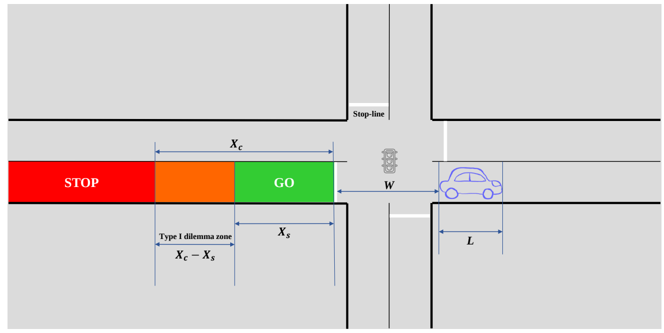

Fig. 1: Type I dilemma zone

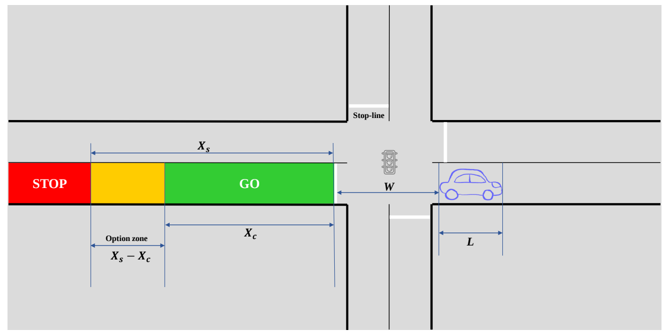

Fig. 2: Option zone

decision-making, i.e., whether to stop or clear the intersection when the yellow light is presented [2], [14]. There are two common methods to quantify the Type II dilemma zone: one is proposed by [15], the length of the Type II dilemma zone can be calculated as the distance interval within which there is a probability of drivers stopping ranging from 10% to 90%, another method estimates the start and the end point of the Type II dilemma zone by considering the travel time to the stop-line and the approach speed [16]. Bonneson et al. pointed out the travel time to the beginning and end of the dilemma zone is about 5.5s and 2.5s [17]; Rakha et al. further add that the travel time interval could be expanded to a range from 5.5s to 1.5s for all age and gender groups [18]. It is worth noting that researchers have developed a diverse array of criteria to identify dilemma zones, considering a multitude of varying factors. This diversity makes delineating the boundaries of a dilemma zone a complex task. Next, we examine the influence these factors may exert on driving behavior and delve into the nature of personalized dilemma zones.

III. Influential Factors

There are relatively large proportion of drivers who are not willing to stop at onset of amber signal, but 70% of yellow light running vehicles decelerate while crossing the stop-line [19], [20]. It is difficult to model or predict the dynamic and stochastic nature of driver behavior precisely [21]. The delineation of the dilemma zone's perimeters and the scrutiny of driver behavior within this zone are governed by many influential factors, yet these factors have not been systematically organized and classified in existing literature

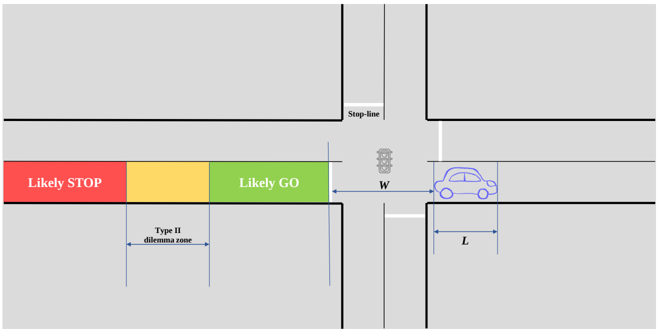

Fig. 3: Type II dilemma zone

[22]–[24]. This diverse combination of factors culminates in a personalized driver performance within the dilemma zone. The intricacy and unique interplay of these elements highlight the complexity of understanding and predicting driver behavior in dilemma zones. Building on this observation, we expand the discussion to encompass the roles of environment, ego-vehicle and driver, conducting a meticulous evaluation of their respective impacts on personalized driving behavior.

A. Environment

Environment, as an external factor, has been demonstrated to exert a subtle influence on driving behavior [24], [25]. In this context, we further develop the discussion by differentiating between static environment and dynamic environment, examining their unique impacts on driving behavior.

(1) Static environment

(i) *Intersection geometry:* The geometric characteristics of an intersection typically encompass various aspects such as the number of intersecting roads, the quantity of lanes, the width of the roadway, approach grades, and other structural features. These elements collectively define the layout and can significantly influence the driving behavior at the intersection. Drivers are more likely to stop in the dilemma zone of a 3-arm intersection than a 4-arm one, as the latter typically involves longer waiting times at red lights [26].The approach grade can extend both the length and the distance from the stop-line of the dilemma zone as it may obstruct drivers' fields of vision [27].

(ii) *Speed limits:* The speed limit as the maximum speed a driver can reach in law is always used as a measure of the range of the dilemma zone. However, this is not always the case. Pawar et al. noted that the 85th percentile speed at the onset of the yellow light frequently surpasses the posted speed limit [28]. Nonetheless, the speed limit does play a role in influencing driver behavior. Also, lower speed limits are more likely to bring about stopping [29].

(iii) *Speed and red-light cameras:* The deployment of enforcement cameras has been proven to reduce the PRT of drivers and would increase the likelihood of stopping [29], [30]. However, the presence of visible speed/red-light cameras can paradoxically influence driver decision-making within the dilemma zone. While intended to enforce compliance, these cameras might inadvertently contribute to an increase in the likelihood of collisions [31].

(2) Dynamic environment

(i) *Weather:* Rain significantly affects the boundaries of dilemma zone, even more so in snowy conditions [32]. Yi et al. pointed out that weather-induced reductions in roadway friction may move the dilemma zone further away from the stop-line [33].

(ii) *Time of day:* Time of day is typically classified into categories such as peak and off-peak hours, as well as morning, midday, afternoon, and night [6]. Rahman et al. presented that the dilemma zone length and location would change by time of day even if vehicles arrive at the intersection with the same approaching speed [21]. Gates and Noyce also found that drivers not inclined to stop in dilemma zone during peak hours [6].

(iii) *Traffic lights:* Many traffic signal setting parameters have been shown to influence driving behavior in dilemma zone, such as length of yellow interval, green ratio, cycle length, control type (e.g, fixed and actuated), and the presence of countdown timers [34]. Paul et al. declared that cutdown timers can improve the safety at signalized intersections [35].

B. Ego-vehicle

(i) *Vehicle type:* The diversity in vehicle operating performance that results from vehicle type has been widely concerned in studies of dilemma zones. Gates and Noyce categorized vehicle type into five groups: car; light truck; single-unit truck; and tractor trailer, and found that the vehicle type affected the deceleration rate and probability of red light running, but not the braking reaction time [6]; Pathivada and Perumal also observed a significant effect of vehicle type on the stopping probability of the drivers [26].

(ii) *Approach speed:* As the approach speed increases, both the start and end points of the dilemma zone move further from the stop-line [11], [26], [33].

(iii) *Vehicle position:* Studies have established a direct correlation between the vehicle's position relative to the stop-line at an intersection and the likelihood of the driver making a stop decision. Specifically, the greater the distance from the stop-line, the higher the probability that the driver will decide to stop [26].

(iv) *Time to intersection:* Time to intersection has been identified as the most influential variable affecting the stop-go decision among all other considered factors. Drivers was found to be more likely to stop rather than to go as the time to intersection increases [18].

C. Driver

(i) *Age:* The dilemma zone is observed to be wider and closer to the stop line for older age groups [18]. A comparative study across different age groups has shown that both older and younger drivers often exhibit lower rates of acceleration and deceleration compared to middle-aged drivers [36].

(ii) *Gender:* Female drivers tend to be more cautious, often stopping more frequently, and their dilemma zone is generally closer to the intersection. This could be interpreted as a more conservative driving style. In contrast, male drivers are typically observed to be more aggressive and willing to accept higher levels of risk [3], [18]. Furthermore, female drivers are noted to have a greater level of variability in their driving style, which may reflect a broader range of factors influencing their driving decisions [36].

(iii) *Perception-Reaction Time (PRT):* Drivers' PRT is subject to variability and is influenced by a multitude of factors. These factors encompass age, gender, visibility, concentration, and the prevailing environmental conditions at the time of response. For instance, an increase in PRT can be observed with the consumption of alcohol or the onset of fatigue. Conversely, factors such as accrued driving experience and heightened attention can contribute to a reduction in PRT [37], [38].

In the driver-related studies, part of the investigation initially entirely disregards personal driver data. Conversely, another segment of the research emphasizes the collection of specific driver group information, such as age and gender. However, to facilitate a more comprehensive understanding of personalized dilemma zone driving behavior, an analysis extending beyond these general characteristics is necessary. This entails a meticulous examination of a series of individual driver actions, delving into the driver's depth of behavior. Such an approach aims to develop a robust foundation to support personalized protection strategies within dilemma zones.

IV. Modeling and Analyzing Driver Behavior in Dilemma Zone

In this section, we present the various methodologies, approaches, and tools utilized for modeling and analyzing driving behavior within the dilemma zone.

A. Approaches to Modeling Behaviors in Dilemma Zone

1) Generalized driving behavior modeling: Most existing approaches to modeling driving behavior within the dilemma zone rely on statistical methods such as binary logistic, binary probit, and fuzzy logic models [2], [34]. These models assess the likelihood of a driver stopping at a yellow light, using statistical analysis of various factors to probabilistically depict driver responses in the dilemma zone. While this technique enhances understanding of driving behavior, it may not capture every personalized characteristic and specific situational influence. Existing models often analyze specific factors impacting driving behavior, focusing on selected variables rather than a comprehensive framework. This leaves a gap in research for personalized models in the dilemma zone that consider a wider range of driver-related factors. This gap in research underscores the complexity of personalized driving behaviors and presents an opportunity for further exploration and development of models that can more accurately represent the multifaceted nature of driving behavior within the dilemma zone.

2) Personalized driving behavior modeling: Personalized driving behavior modeling plays a pivotal role in enhancing the safety and efficiency of vehicular traffic, particularly in complex scenarios such as the dilemma zone. Each driver has unique attributes such as reaction time, risk tolerance, and decision-making patterns. Personalized models must incorporate these individual characteristics to predict how different drivers will behave when approaching a traffic signal. Traditionally, generalized models assume uniform responses from drivers to traffic signals, vehicle dynamics, and road conditions [39]. These models, however, do not adequately capture the subtleties and diversity of individual driver behavior, thus resulting in inadequate predictions and strategies for managing dilemma zones.

Unlike generalized models, personalized modeling approaches acknowledge and incorporate individual differences in driving behavior, such as reaction times, risk tolerance, decision-making patterns, and even emotional states [40]. This method recognizes that drivers' responses in dilemma zones are influenced by a multitude of personal factors, including but not limited to their driving experience, age, gender, and vehicle type. A young, inexperienced driver might respond differently to a yellow light than a seasoned driver, or a driver in a heavy vehicle might make different considerations than one in a small vehicle.

B. Strategies to Mitigate Dilemma Zone

The dilemma zone presents significant challenges to traffic safety, resulting in numerous studies and initiatives aimed at mitigating its risks [41]. A fundamental resolution to this issue remains elusive due to the inherent variability in individual driving behavior and characteristics. In response, researchers have shifted their focus towards vehicle-borne approaches to avoiding dilemma zones. Accordingly, this section will categorize the discussion of DZ Protection Strategies from two perspective: the design/planning perspective and the operational (ITS).

1) From the design/planning perspective: In configuring traffic controls at intersections, it's essential to devise long-term, preemptive strategies to avert Dilemma Zone issues. This involves optimizing traffic signal timing, which adjusts dynamically to real-time traffic conditions, particularly the yellow light phase based on approaching vehicles' speed and position. Additionally, clear and strategically placed roadway signs can provide early warnings about upcoming intersections and suggest speed adjustments, thereby reducing instances of vehicles getting trapped in the Dilemma Zone. These comprehensive measures can substantially improve intersection safety and efficiency.

(i) *Traffic signal extension systems:* In order to minimize dilemma zone risks, many cities use dynamic traffic signal controls, such as Green Extension Systems (GES) [15]. GES ends the green light phase when no vehicles are detected in the dilemma zone or if the green light duration reaches its maximum preset time.

Despite these measures, the effectiveness of simply extending yellow light duration to address dilemma zones has been limited due to varied driver behaviors and changing traffic conditions. It has been reported that prolonged yellow lights can cause confusion among drivers, resulting in a wider Type II dilemma zone [42]. Furthermore, these extensions can distort the yellow signal's purpose, increase delay, and potentially induce more red-light running. Also, drivers might engage in more red-light running behavior when they perceive that yellow lights are going to last longer [43].

In order to maintain traffic safety during conflict phases, an all-red period is often implemented after the yellow phase in order to clear the intersection. However, both overly short and long durations bring their own inefficiencies. Amer et al. [44] and Wang et al. [45] have proposed innovative yellow light timing algorithms, considering the randomness of variables such as gender, age, reaction time, deceleration rate, and vehicle speed, to prevent vehicles from getting trapped in the dilemma zone.

(ii) *Traffic signal warning systems:* Advanced Warning Systems for DZ are utilized to alert drivers prior to entering the Dilemma Zone by displaying distinctive warning signs. One popular method in use is the Advanced Warning Flasher (AWF) [46], which facilitates incoming vehicles' readiness to stop, thus reducing the risk of them entering the DZ [47]. Researchers have found that while the AWF reduces accident rates, it also unintentionally increases the likelihood of rear-end collisions and red-light running [48].

A wide variety of intersections across different countries and regions have also been equipped with traffic light signal warning systems. Through the implementation of countdown mechanisms attached to their traffic signals, these systems reduce the dilemma zone's extent, thereby minimizing the likelihood of vehicles becoming trapped within the zone [49]. As indicated by the survey [48], setting up a green light countdown increases the number of vehicles running red lights in the dilemma area to a certain extent, whereas setting up a red light countdown reduces the number of accidents to a certain degree.

2) From the Operational (ITS) Perspective: This classification corresponds to real-time, reactive measures leveraged through Intelligent Transportation Systems (ITS). In addressing the dilemma zone from an operational perspective, we categorize the mitigation strategies into three distinct types: infrastructure-based, vehicle-infrastructure cooperative, and vehicle-based strategies. Each category plays a unique role in addressing the complexity of dilemma zones.

(i) *Infrastructure-based Strategies:* Many studies have been carried out to achieve dilemma zone protection, utilizing the deployment of traffic infrastructures, such as loop detectors, traffic cameras and radars. Middleton et al. recommended to place the loop detectors at 85th percentile of all approach speeds to the intersection, a strategy aimed at reducing the likelihood of vehicle running red lights [50]; Zimmerman employed the detection control system, a product of the Texas Transportation Institute, to propose a high-speed dilemma zone protection scheme for trucks, relying on data from loop detectors [51]; Tarko et al. suggested the use of a likelihood function, which leverages video data to estimate the probability of a driver encountering a dilemma zone [52]. This probability then informs decisions on whether to extend the green light interval; similarly, Rahman et al. utilized radar-collected data on vehicle speed and location to determine if extending the green light duration was necessary to protect vehicles in the dilemma zone [4]; Yi et al. designed the video cameras as relocatable detectors to improve the reliability of high-speed dilemma zone protection [33]. Park et al. took a different route, utilizing variable message signs to pre-inform drivers about upcoming signal states, which can facilitate drivers to prepare in advance for the upcoming yellow light [7]. Furthermore, a considerable number of studies have explored the application of vehicle-to-everything (V2X) communication technology [53]. In the context of dilemma zone protection, V2X communication systems function as a vital component of smart traffic infrastructure, enabling real-time interaction between traffic management systems and vehicles [54]. When it comes to the application of V2X technology, the focus is more on how infrastructure can facilitate better communication and decision-making. For instance, Zha et al. focused on balancing the benefit of providing green extension for major through vehicles and the cost of delay incurred by vehicles from conflicting movements using V2X information [55]; Das et al. proposed a traffic signal control strategy for connected emergency vehicles considering protection of freight vehicles in dilemma zone [56].

In conclusion, a multitude of studies have been conducted to enhance the protection measures within the dilemma zone by leveraging different traffic infrastructure components. These include loop detectors, traffic cameras, and connected vehicle technologies, along with vehicle-to-everything (V2X) communication systems. These infrastructures serve to improve road safety by mitigating the potential risks associated. Various methodologies have been proposed, ranging from strategic placement of detectors and usage of variable message signs to more technologically advanced solutions, such as the deployment of advanced analytics and probabilistic models. These efforts highlight the significant role of traffic infrastructure in ensuring safer, more efficient dilemma zone protection system.

(ii) *Vehicle-Infrastructure Cooperative Strategies:* In recent years, Vehicle-to-Infrastructure (V2I) technology has developed quite significantly [1]. Using V2I, vehicles communicate directly with the infrastructure they encounter, such as traffic signals and road signs, promising to significantly reduce road traffic accidents and congestion, and improve overall road safety [8]. With the maturation of V2I technology, it is increasingly being applied to address a wide variety of complex traffic problems, including the dilemma zone problem. In addition to providing drivers with accurate, real-time information regarding the status of traffic signals and the optimal speed for clearing the intersection, V2I technology can also assist them in navigating the dilemma zone effectively by facilitating real-time communication between vehicles and traffic signals. Moon et al. introduced an onboard collision warning system that connects vehicles to roadside antennas and traffic signal controllers among the relatively early proposals [57]. Their method alerts drivers when they are potentially entering a dilemma zone, signaling a significant step in V2X applications for traffic safety. Following this, several researchers explored the strategy of establishing communication between vehicles and Roadside Units (RSUs) [58]. They converted data obtained from vehicle-road systems into valuable information for traffic signal optimization, providing drivers with timely warnings to prepare for potential dilemma zones.

Although technological advancements have contributed to addressing the dilemma zone problem, there remains one undeniable fact that every driver has unique driving characteristics. The Avoiding DZ and Warning System (ADZW) proposed by Chang et al. has taken into consideration this factor. Not only does their system incorporate roadway configuration and vehicle motion information, but it also incorporates a driver's reactions speed into its calculations [59]. However, studies have highlighted the varying impacts of car warning information on psychological load and anti-collision functions due to driver individuality [60]. This can potentially lead to negative effects on the driver's performance, emphasizing the complexity of the dilemma zone issue and its potential solutions.

(iii) *Vehicle-based strategies:* While several approaches rely heavily on infrastructure communication, it is worth noting that there are also strategies that depend less on such interconnectivity. For instance, Noh et al. proposed a decision-making framework for road intersections, which uses onboard GPS and digital maps to predict future paths of other vehicles, identify potential threats, and collision zones [61]. Under this framework, vehicles conduct a dilemma zone check before entering an intersection. Similarly, Cheng et al. developed a framework for dilemma zone avoidance, which comprises a perception module, a decision-making module, and an operation module [41]. This approach is designed so as to take into account the safety of the following vehicles while also addressing dilemma zone concerns. In a slightly different approach, Park et al. proposed a composite dilemma zone protection system [7]. By controlling the vehicle's speed, this system assists in preventing collisions caused by dilemma zones at intersections.

Automated vehicles (AVs) have also been examined in the context of dilemma zones. In a study by Brown et al., it was concluded that incorporating AVs with human drivers on the road does not eliminate collisions [62]. Human-centric factors were identified as obstacles to implementation, underlining the complex dynamics of integrating human and machine behavior in real-world driving scenarios.

V. Discussion

A. Research Gaps

1) *Dynamic impact of vehicles:* A common theme in much of the existing literature is a focus on traffic light dynamics, which often ignores vehicles themselves. The above presentation presents a simplistic view of DZ situations that fails to acknowledge that vehicles play a fundamental role in shaping these scenarios. In light of the fact that the speed, size, and behavior of every vehicle can have a dramatic impact on the DZ landscape, it is imperative that future research incorporates these variables in order to gain a deeper and more nuanced understanding of these situations. Taking a holistic approach to mitigation would provide a more effective framework for designing and implementing effective mitigation strategies for DZs.

2) *Vehicle interactions:* Another noticeable research shortfall is that it is rarely considered how vehicles interact, specifically the influence a leading vehicle can exert on a following vehicle. The dynamics within the DZ can be significantly altered by vehicle interactions, affecting the drivers' decision-making processes and subsequent actions. Future research can generate a more accurate representation of real-world DZ scenarios by incorporating such interaction effects into their models, allowing for the formulation of mitigation strategies that are more realistic and effective.

3) *Overreliance on Infrastructure Information:* Much of the current research seems to lean heavily on infrastructure information, thus risking a skewed interpretation of DZ issues. This overreliance limits the breadth and depth of insights that can be derived about DZ problems. A broader range of factors – including driver behavior, vehicle dynamics, and environmental conditions – needs to be considered for a more comprehensive understanding of DZ situations. Addressing this gap can lead to the development of more holistic, multifaceted solutions to DZ issues.

4) *Absence of evaluation tools:* The current lack of reliable and comprehensive evaluation tools to assess DZ mitigation strategies' effectiveness poses a significant challenge. Future research should prioritize such tools. Evaluation mechanisms that are comprehensive will allow policymakers and practitioners to evaluate different mitigation strategies objectively and compare them, ultimately guiding them in selecting the most effective strategy.

B. Opportunities

Amid these research gaps, we identify several promising opportunities that, if capitalized on, can substantially advance the field of DZ research:

1) *Personalized models:* The field of DZ has traditionally relied on broad demographic categorizations of drivers based on factors such as their age or gender. However, these classifications do not capture the full spectrum of driving behaviors and may oversimplify the intricacies of DZ situations. Technology has made it possible for us to gain a deeper understanding of individual driving habits and behaviors. With this, we have the opportunity to develop more nuanced and personalized models that go beyond demographic classifications. By considering individualized driving habits, these models can offer a richer and more detailed representation of driver behavior, thus enhancing the precision and effectiveness of DZ mitigation strategies. Through a more individualized approach, DZ issues can be mitigated in a more targeted and efficient manner, resulting in better traffic flow and safety.

2) *Advanced modeling approaches:* The advent of Machine Learning (ML) and other advanced modeling techniques has opened new frontiers in traffic research. Although

these innovative approaches have yet to be fully utilized in DZ research, they have the potential to enhance our understanding and handling of DZ issues. In order to develop more accurate, dynamic, and adaptable DZ models, more research effort should be devoted to exploiting these cutting-edge techniques.

3) *Cooperative solutions:* Another untapped opportunity lies in exploring cooperative solutions, such as vehicle-to-vehicle and vehicle-to-infrastructure communication. The combination of these strategies can facilitate a synergistic approach to addressing DZ issues, optimizing the use of available resources to create a safer and more efficient traffic system. The development of innovative solutions in this field could significantly reduce the prevalence and impact of DZ issues with additional research.

4) *Everything-in-the-loop simulations:* The "everything-in-the-loop" simulation approach presents a valuable opportunity to obtain personalized behavioral data and simulate individual behaviors under different DZ scenarios. It can help provide a richer, more realistic view of DZ situations, improving predictive accuracy and facilitating the development of more effective mitigation strategies.

VI. Conclusion

The aim of this paper was to explore the complexities of the DZ problem in detail, taking into account the different influences from the environment, the ego-vehicle, and the characteristics of the driver. In particular, we emphasize the importance of driver behavior in DZ situations and the need for further research. Our analysis of various modeling approaches and data acquisition techniques further illuminated the intricacies of driver behavior in DZ. In addition, we proposed an array of mitigation strategies, ranging from design and planning perspectives to operational strategies that consider infrastructure, vehicle dynamics, and cooperative efforts between vehicles and infrastructure. Our discussion revealed several significant gaps in current research, including the frequently ignored dynamic impact of car and vehicle interactions, as well as the prevailing overreliance on infrastructure information. Among the major drawbacks of existing studies is the absence of comprehensive evaluation tools.

Nevertheless, these gaps offer potential opportunities for future research. Personalized models might provide a more in-depth understanding of the DZ problem. Machine learning techniques are largely underutilized in this context and could significantly advance the field. Moreover, cooperative solutions that harmonize infrastructure and vehicle dynamics warrant further investigation. There is a need for innovative approaches that can effectively capture and simulate individual behavior data as a result of the call for 'everything-in-the-loop' simulations.

In the future, these gaps and opportunities should guide our research endeavors. By addressing these gaps and leveraging potential opportunities, we will be able to significantly improve our understanding and handling of the DZ problem.

References

[1] Z. Qin, A. Ji, Z. Sun, G. Wu, P. Hao, and X. Liao, "Game theoretic application to intersection management: A literature review," *arXiv preprint arXiv:2311.12341*, 2023.

[2] Y. Zhang, C. Fu, and L. Hu, "Yellow light dilemma zone researches: a review," *Journal of traffic and transportation engineering (English edition)*, vol. 1, no. 5, pp. 338–352, 2014.

[3] P. Papaioannou, "Driver behaviour, dilemma zone and safety effects at urban signalised intersections in greece," *Accident Analysis & Prevention*, vol. 39, no. 1, pp. 147–158, 2007.

[4] M. Rahman, M.-W. Kang, and P. Biswas, "Dynamic dilemma zone protection system for high-speed signalized intersections: A comprehensive safety-operational assessment," *Transportation Engineering*, vol. 12, p. 100174, 2023.

[5] T. Urbanik and P. Koonce, "The dilemma with dilemma zones," *Proceedings of ITE District*, vol. 6, 2007.

[6] T. J. Gates and D. A. Noyce, "Dilemma zone driver behavior as a function of vehicle type, time of day, and platooning," *Transportation Research Record*, vol. 2149, no. 1, pp. 84–93, 2010.

[7] S. Y. Park, C.-L. Lan, G.-L. Chang, D. Tolani, and P. Huang, "Design and predeployment assessment of an integrated intersection dilemma zone protection system," *Journal of transportation engineering*, vol. 142, no. 12, p. 04016063, 2016.

[8] X. Yang, G.-L. Chang, Z. Zhang, and P. Li, "Smart signal control system for accident prevention and arterial speed harmonization under connected vehicle environment," *Transportation research record*, vol. 2673, no. 5, pp. 61–71, 2019.

[9] R. Chauhan, A. Dhamaniya, and S. Arkatkar, "Analysing driver's decision in dilemma zone at signalized intersections under disordered traffic conditions," *Transportation research part F: traffic psychology and behaviour*, vol. 89, pp. 222–235, 2022.

[10] D. Gazis, R. Herman, and A. Maradudin, "The problem of the amber signal light in traffic flow," *Operations research*, vol. 8, no. 1, pp. 112–132, 1960.

[11] C. Liu, R. Herman, and D. C. Gazis, "A review of the yellow interval dilemma," *Transportation Research Part A: Policy and Practice*, vol. 30, no. 5, pp. 333–348, 1996.

[12] D. S. Hurwitz, H. Wang, M. A. Knodler Jr, D. Ni, and D. Moore, "Fuzzy sets to describe driver behavior in the dilemma zone of high-speed signalized intersections," *Transportation research part F: traffic psychology and behaviour*, vol. 15, no. 2, pp. 132–143, 2012.

[13] A. V. Shah, P. N. Patel, L. Zala, and A. Amin, "Analysis of driver behaviour in dilemma zone at signalized intersection under heterogeneous traffic," in *Intelligent Infrastructure in Transportation and Management: Proceedings of i-TRAM 2021*. Springer, 2022, pp. 53–63.

[14] K. Zimmerman and J. A. Bonneson, "Intersection safety at high-speed signalized intersections: Number of vehicles in dilemma zone as potential measure," *Transportation Research Record*, vol. 1897, no. 1, pp. 126–133, 2004.

[15] C. V. Zegeer and R. C. Deen, *Green-extension systems at high-speed intersections*. Citeseer, 1978, vol. 496.

[16] M.-S. Chang, C. J. Messer, and A. J. Santiago, "Timing traffic signal change intervals based on driver behavior," *Transportation Research Record*, vol. 1027, pp. 20–30, 1985.

[17] J. Bonneson, D. Middleton, K. Zimmerman, H. Charara, and M. Abbas, "Intelligent detection-control system for rural signalized intersections," *Texas Department of Transportation*, 2002.

[18] H. Rakha, A. Amer, and I. El-Shawarby, "Modeling driver behavior within a signalized intersection approach decision–dilemma zone," *Transportation Research Record*, vol. 2069, no. 1, pp. 16–25, 2008.

[19] A. Najmi, A.-A. Choupani, and I. Aghayan, "Characterizing driver behavior in dilemma zones at signalized roundabouts," *Transportation research part F: traffic psychology and behaviour*, vol. 63, pp. 204–215, 2019.

[20] O. C. Puan and C. R. Ismail, "Dilemma zone conflicts at isolated intersections controlled with fixed-time and vehicle actuated traffic signal systems," *International Journal of Civil & Environmental Engineering*, vol. 10, no. 3, pp. 19–25, 2010.

[21] M. Rahman, M.-W. Kang, and P. Biswas, "Predicting time-varying, speed-varying dilemma zones using machine learning and continuous vehicle tracking," *Transportation research part C: emerging technologies*, vol. 130, p. 103310, 2021.

[22] R. C. Majhi and V. Senathipathi, "Analyzing driver's response to yellow indication subjected to dilemma incursion: An econometric approach," *Transportation research procedia*, vol. 48, pp. 1111–1124, 2020.

[23] C. Wei, C. Liu, and S. Chi, "A driver distraction detection method based on convolutional neural network," in *2022 7th International Conference on Computer and Communication Systems (ICCCS)*. IEEE, 2022, pp. 272–277.

[24] A. Calvi and C. Petrella, "An evaluation of the effectiveness of countermeasures for improving the safety of dilemma zones: A driving simulator study," *Transportation research part F: traffic psychology and behaviour*, vol. 87, pp. 295–312, 2022.

[25] S. Kim, Y.-J. Son, Y.-C. Chiu, M. A. B. Jeffers, and C. D. Yang, "Impact of road environment on drivers' behaviors in dilemma zone: Application of agent-based simulation," *Accident Analysis & Prevention*, vol. 96, pp. 329–340, 2016.

[26] B. K. Pathivada and V. Perumal, "Analyzing dilemma driver behavior at signalized intersection under mixed traffic conditions," *Transportation research part F: traffic psychology and behaviour*, vol. 60, pp. 111–120, 2019.

[27] M. Rahman and M.-W. Kang, "Analysis of intersection site-specific characteristics for type ii dilemma zone determination," *Journal of transportation engineering, Part A: Systems*, vol. 147, no. 10, p. 04021072, 2021.

[28] D. S. Pawar, D. Pathak, and G. R. Patil, "Modeling dynamic distribution of dilemma zone at signalized intersections for developing world traffic," *Journal of Transportation Safety & Security*, vol. 14, no. 5, pp. 886–904, 2022.

[29] P. T. Savolainen, A. Sharma, and T. J. Gates, "Driver decision-making in the dilemma zone–examining the influences of clearance intervals, enforcement cameras and the provision of advance warning through a panel data random parameters probit model," *Accident Analysis & Prevention*, vol. 96, pp. 351–360, 2016.

[30] T. Gates, P. T. Savolainen, and H.-U. Maria, "Impacts of automated red light running enforcement cameras on driver behavior," in *Transportation Research Board 93rd Annual Meeting*, Washington, DC, 2014.

[31] O. Almutairi and H. Wei, "Effect of speed/red-light cameras and traffic signal countdown timers on dilemma zone determination at pre-timed signalized intersections," *Accident Analysis & Prevention*, vol. 154, p. 106076, 2021.

[32] A. Sharma, N. Burnett, and D. M. Bullock, "Impact of inclement weather on dilemma zone boundaries," in *Transportation Research Board 89th Annual Meeting*, Washington, DC, 2010.

[33] P. Yi, T. Flickinger, J. Lu, L. A. Klein, and S. Dissanayake, "Relocatable detector concept for dilemma zone protection at high-speed intersections," *Journal of Intelligent Transportation System*, vol. 6, no. 4, pp. 327–350, 2001.

[34] M. Abbas, S. G. Machiani, P. M. Garvey, A. Farkas, R. Lord-Attivor *et al.*, "Modeling the dynamics of driver's dilemma zone perception using machine learning methods for safer intersection control," Mid-Atlantic Universities Transportation Center, Tech. Rep., 2014.

[35] M. Paul, I. Ghosh, and M. M. Haque, "The effects of green signal countdown timer and retiming of signal intervals on dilemma zone related crash risk at signalized intersections under heterogeneous traffic conditions," *Safety science*, vol. 154, p. 105862, 2022.

[36] S. M. Lavrenz, V. D. Pyrialakou, and K. Gkritza, "Modeling driver behavior in dilemma zones: A discrete/continuous formulation with selectivity bias corrections," *Analytic Methods in Accident Research*, vol. 3, pp. 44–55, 2014.

[37] R. Kaul and M. Jipp, "Influence of cognitive processes on driver decision-making in dilemma zone," *Transportation research interdisciplinary perspectives*, vol. 19, p. 100805, 2023.

[38] H. Wei, Z. Li, P. Yi, and K. R. Duemmel, "Quantifying dynamic factors contributing to dilemma zone at high-speed signalized intersections," *Transportation research record*, vol. 2259, no. 1, pp. 202–212, 2011.

[39] W. Li, L. Tan, and C. Lin, "Modeling driver behavior in the dilemma zone based on stochastic model predictive control," *PLoS ONE*, vol. 16, 2021.

[40] J. V. Lint and S. Calvert, "A generic multi-level framework for microscopic traffic simulation—theory and an example case in modelling driver distraction," *Transportation Research Part B: Methodological*, 2018.

[41] Z. Cheng, Y. Zhang, C. Du, J. Chen, T. You, and L. Bai, "A rule-based decision-making framework for dilemma zone protection at signalized intersections," in *2022 IEEE 7th International Conference on Intelligent Transportation Engineering (ICITE)*. IEEE, 2022, pp. 493–499.

[42] Y. Liu, G.-L. Chang, R. Tao, T. Hicks, and E. Tabacek, "Empirical observations of dynamic dilemma zones at signalized intersections," *Transportation Research Record*, vol. 2035, no. 1, pp. 122–133, 2007.

[43] P. T. Martin, V. C. Kalyani, and A. Stavanovic, "Evaluation of advance warning signals on high speed signalized intersections," Mountain-Plains Consortium, Tech. Rep., 2003.

[44] A. Amer, H. Rakha, and I. El-Shawarby, "Novel stochastic procedure for designing yellow intervals at signalized intersections," *Journal of transportation engineering*, vol. 138, no. 6, pp. 751–759, 2012.

[45] F. Wang, K. Tang, and K. Li, "A stochastic computational model for yellow time determination and its application," *Journal of advanced transportation*, vol. 49, no. 3, pp. 457–474, 2015.

[46] T. Sayed, H. Vahidi, and F. Rodriguez, "Advance warning flashers: Do they improve safety?" *Transportation Research Record*, vol. 1692, no. 1, pp. 30–38, 1999.

[47] J. Appiah, B. Naik, R. Wojtal, and L. R. Rilett, "Safety effectiveness of actuated advance warning systems," *Transportation research record*, vol. 2250, no. 1, pp. 19–24, 2011.

[48] J.-j. Shen and W. Wang, "Effects of flashing green on driver's stop/go decision at signalized intersection," *Journal of Central South University*, vol. 22, no. 2, pp. 771–778, 2015.

[49] Y. Ni and K. Li, "Estimating rear-end accident probabilities at signalized intersections: a comparison study of intersections with and without green signal countdown devices," *Traffic injury prevention*, vol. 15, no. 6, pp. 583–590, 2014.

[50] D. Middleton, R. L. Nowlin, M. Shafer, A. H. Parham, and D. Jasek, "Evaluation of detector placement for high-speed approaches to signalized intersections," Tech. Rep., 1997.

[51] K. Zimmerman, "Additional dilemma zone protection for trucks at high-speed signalized intersections," *Transportation research record*, vol. 2009, no. 1, pp. 82–88, 2007.

[52] A. Tarko, W. Li, and L. Laracuente, "Probabilistic approach to controlling dilemma occurrence at signalized intersections," *Transportation research record*, vol. 1973, no. 1, pp. 55–63, 2006.

[53] H. Zhou, W. Xu, J. Chen, and W. Wang, "Evolutionary v2x technologies toward the internet of vehicles: Challenges and opportunities," *Proceedings of the IEEE*, vol. 108, no. 2, pp. 308–323, 2020.

[54] J. Wang, Y. Shao, Y. Ge, and R. Yu, "A survey of vehicle to everything (v2x) testing," *Sensors*, vol. 19, no. 2, p. 334, 2019.

[55] L. Zha, Y. Zhang, P. Songchitruksa, and D. R. Middleton, "An integrated dilemma zone protection system using connected vehicle technology," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 6, pp. 1714–1723, 2015.

[56] D. Das, N. V. Altekar, K. L. Head, and F. Saleem, "Traffic signal priority control strategy for connected emergency vehicles with dilemma zone protection for freight vehicles," *Transportation research record*, vol. 2676, no. 1, pp. 499–517, 2022.

[57] Y.-J. Moon, J. Lee, and Y. Park, "System integration and field tests for developing in-vehicle dilemma zone warning system," *Transportation research record*, vol. 1826, no. 1, pp. 53–59, 2003.

[58] H. S. Basheer, C. Bassil, and B. Chebaro, "Bayesian trust scheme: A decentralized safety message trust method in multi-hop v2v networks." *J. Commun.*, vol. 12, no. 4, pp. 214–220, 2017.

[59] T.-H. Chang, S.-M. Yu, and Y.-J. Wu, "Dilemma zone avoidance development: an on-board approach," *IET Intelligent Transport Systems*, vol. 7, no. 1, pp. 87–94, 2013.

[60] R. M. James and B. E. Hammit, "Identifying contributory factors to heterogeneity in driving behavior: clustering and classification approach," *Transportation research record*, vol. 2673, no. 10, pp. 343–353, 2019.

[61] S. Noh, "Decision-making framework for autonomous driving at road intersections: Safeguarding against collision, overly conservative behavior, and violation vehicles," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 4, pp. 3275–3286, 2018.

[62] B. Brown, D. Park, B. Sheehan, S. Shikoff, J. Solomon, J. Yang, and I. Kim, "Assessment of human driver safety at dilemma zones with automated vehicles through a virtual reality environment," in *2018 systems and information engineering design symposium (SIEDS)*. IEEE, 2018, pp. 185–190.