

Research Article

The Dilemma of Self-Driving Cars: Evaluating Decision-Making Uncertainty at Unsignalized Intersections

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ABSTRACT

Interactions between autonomous vehicles (AVs) and human-driven vehicles (HVs) remain challenging in mixed-traffic environments, particularly at unsignalized intersections where right-of-way decisions rely on implicit negotiation. This study analyzes AV-HV encounters using a microscopic traffic simulation framework and temporal interaction metrics derived from vehicle trajectories. The results show that many encounters occur within a near-neutral timing region where small temporal differences may alter yielding outcomes. This phenomenon reveals the inherent ambiguity of mixed-traffic interactions and suggests that such uncertainty may be associated with the staleness of dynamic information. The findings provide insights into how information uncertainty can influence decision-making in autonomous driving systems.

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1. Introduction

With the rapid advancement of smart cities and Intelligent Transportation Systems (ITS) [1], autonomous vehicles (AVs) are poised to significantly enhance traffic efficiency and road safety. Recent studies on autonomous driving in smart cities have also emphasized that AV deployment requires the integration of sensing, communication, artificial intelligence, and emerging networking technologies to support safe and efficient mobility [2]. However, in real-world urban environments, AVs rarely operate in isolation; they must coexist and interact with human-driven vehicles (HVs) within heterogeneous mixed-traffic conditions. These interactions introduce substantial behavioral uncertainty, as human drivers exhibit diverse responses governed by varying perception levels, reaction times, and idiosyncratic driving styles.

Such uncertainty is particularly pronounced at unsignalized intersections. Unlike signalized environments where the right-of-way is explicitly regulated by traffic lights, vehicles at unsignalized intersections must resolve crossing orders through implicit negotiation. In these scenarios, marginal deviations in arrival timing or motion patterns can lead to divergent interaction outcomes. Consequently, seemingly identical

traffic conditions may result in variability in decision outcomes, highlighting the acute sensitivity of the negotiation process in mixed-traffic environments.

To investigate this challenge, this study leverages a microscopic traffic simulation framework to analyze vehicle interactions at unsignalized intersections. By examining temporal interaction metrics derived from vehicle trajectories, we explore how relative timing differences influence yielding behaviors between AVs and HVs. The analysis identifies a "near-neutral" timing region where interaction outcomes become less predictable due to inherent decision ambiguity. Our findings suggest that interaction outcomes are not merely a function of deterministic timing but are also influenced by information uncertainty. These observations provide a conceptual foundation for understanding interaction ambiguity and underscore the critical role of information freshness in shaping interaction ambiguity and decision boundaries within complex urban settings.

2. Related Work

The safety and efficiency of autonomous vehicles in mixed-traffic environments depend on robust decision-making and reliable coordination. To contextualize the challenges of vehicle interactions at unsignalized intersections, this section reviews relevant literature across

three key dimensions. First, we examine current decision-making frameworks and game-theoretic models for intersection management. Second, the role of microscopic simulation in analyzing traffic conflicts and safety indicators is discussed. Finally, we explore the potential of communication-based coordination and the impact of information-related uncertainty on mixed-traffic behavioral modeling.

2.1. Autonomous Vehicle Interaction at Unsignalized Intersections

Decision-making for autonomous vehicles has been widely studied in recent years, particularly in complex urban traffic scenarios. Prior research has explored how autonomous vehicles interpret surrounding environments and determine appropriate driving actions using perception, environment reasoning, and behavioral prediction mechanisms [3]. Recent studies have further addressed AV decision-making at unsignalized intersections by considering interaction-aware prediction, collision-point traversal, and safe speed planning [4]. In addition, interaction-aware frameworks have been proposed to explicitly model the strategic behavior of surrounding drivers. For example, multi-level game-theoretic approaches describe vehicle interactions as decision processes in which each agent considers the potential responses of other road users [5]. While these models provide structured representations of vehicle interaction, they often rely on predefined payoff assumptions or cooperative behavior, which may not fully capture the variability of real-world mixed-traffic encounters. Interaction-aware motion prediction has also been studied for unsignalized intersections, where vehicle intentions, road layout, and traffic rules are jointly considered to handle the probabilistic nature of vehicle interactions [6]. However, these approaches often emphasize decision structure or prediction performance, rather than the analysis of interaction patterns derived from observable temporal features.

2.2. Temporal Safety Indicators for Traffic Conflict Analysis

Temporal safety indicators such as time-to-collision (TTC) and post-encroachment time (PET) have been widely used to evaluate potential conflicts in traffic scenarios. These indicators are commonly adopted to identify potential interactions and conflicts by quantifying temporal proximity between road users [7]. These metrics quantify the temporal proximity between vehicles and provide insights into interaction timing and collision risk, particularly in dynamic environments such as unsignalized intersections. In mixed-traffic safety analysis, such indicators are often categorized as time-based surrogate safety measures and are widely used to evaluate potential conflict risk [8].

Microscopic traffic simulation has become an important tool for studying such temporal interactions under controlled yet diverse traffic conditions. Simulation

platforms enable researchers to generate reproducible scenarios and analyze vehicle interactions without the safety risks associated with real-world testing. Previous studies have shown that microscopic traffic simulators can effectively model automated driving behaviors and traffic performance under various operational conditions [9]. These environments allow systematic variation of maneuver types, vehicle speeds, and interaction timing, making them suitable for analyzing complex encounters at unsignalized intersections.

These indicators are primarily used for post hoc safety assessment or collision avoidance, whereas this study focuses on the decision boundary prior to conflict resolution.

2.3. Behavioral Uncertainty in Mixed Traffic

Beyond perception-based decision-making, communication technologies are increasingly considered as a potential solution for improving coordination among vehicles in intelligent transportation systems, as V2V communication can compensate for perception limitations and reduce uncertainty in predicting surrounding vehicles' behaviors [10]. Vehicle-to-vehicle communication frameworks have been proposed to support distributed consensus mechanisms that enable cooperative driving behaviors [11]. Secure message dissemination schemes have also been developed to ensure reliable communication in networks of autonomous vehicles [12]. In addition, research on distributed coordination in multi-agent systems highlights the importance of communication and information sharing for collaborative decision-making [13]. These developments suggest that communication-enabled interaction mechanisms may help mitigate the uncertainty observed in mixed-traffic scenarios. In particular, the freshness of information plays a critical role in such interactions, as delayed or outdated information may lead to deviations in timing estimation. However, the relationship between information quality and interaction uncertainty remains insufficiently explored, particularly from a temporal perspective.

3. Simulation Scenario and Temporal Metrics

To investigate vehicle interactions at unsignalized intersections, a microscopic traffic simulation environment was constructed using SUMO. The simulation models encounter between an autonomous vehicle (AV) and a human-driven vehicle (HV) approaching an unsignalized intersection from different directions. The AV follows a time-efficient driving strategy that attempts to pass the intersection when sufficient temporal advantage exists, while the HV follows typical human driving behavior governed by gap-acceptance principles. These settings allow natural negotiation situations to emerge between the two vehicles.

To characterize the interaction dynamics, two temporal quantities are defined. The arrival time to the conflict zone is denoted as T_c , and the time required for a vehicle to

completely clear the intersection is denoted as T_s , as illustrated in Figure 1.

To analyze the competitive timing relationship between vehicles, relative temporal differences are defined as

$$\Delta T_c = T_c^{HV} - T_c^{AV} \quad (1)$$

$$\Delta T_s = T_s^{HV} - T_s^{AV} \quad (2)$$

These features describe the relative temporal advantage between the interacting vehicles. When the temporal difference approaches zero, the interaction outcome becomes less predictable, forming an ambiguous interaction region that is further analyzed in the following section.

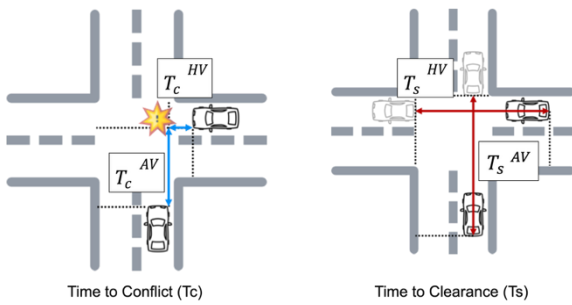


Figure 1 Illustration of T_c and T_s in an AV-HV Interaction at an Unsignalized Intersection

4. Behavioral Analysis of Vehicle Interaction

To understand the underlying decision-making logic and the resulting safety implications in mixed-traffic scenarios, it is essential to examine how Autonomous Vehicles (AVs) and Human-driven Vehicles (HVs) resolve conflicts at intersections. This section analyzes the interaction behaviors through the lens of temporal relationships. By mapping the simulated encounters into a specialized feature space, we can identify patterns of precedence and the conditions under which the interaction outcomes become unpredictable. The following analysis first explores the deterministic trends in vehicle behavior and subsequently investigates the impact of information staleness on decision boundaries.

4.1. Feature-space Distribution

The interaction outcomes between AVs and HVs are analyzed in the feature space defined by the temporal differences ΔT_c and ΔT_s . Figure 2 illustrates the distribution of simulated encounters and the corresponding yielding behaviors. The results exhibit a clear diagonal trend in the feature space, indicating that vehicles arriving earlier at the conflict zone tend to clear the intersection earlier as well.

However, a noticeable overlap between yielding and non-yielding behaviors appears when the temporal differences approach zero. In this near-neutral region, both vehicles reach the conflict zone at nearly the same time, making the interaction outcome less deterministic. As a result, small variations in the estimated arrival time may influence which vehicle proceeds first. This observation suggests the existence of an ambiguous interaction region in mixed-traffic environments, where vehicle decisions become highly sensitive to small temporal differences. Such sensitivity motivates further investigation into potential sources of temporal estimation uncertainty, which are discussed in the following subsection.

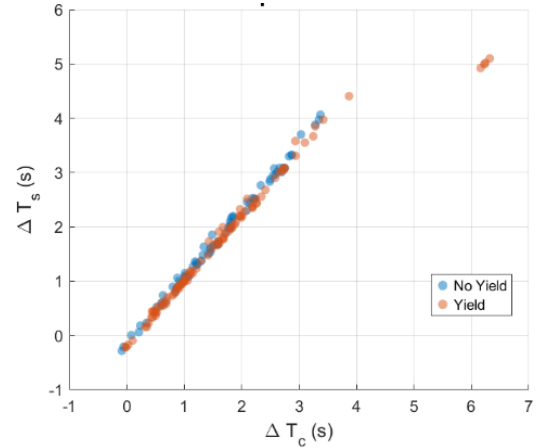


Figure 2 Feature-Space Distribution of AV-HV Interactions

4.2. Temporal Uncertainty Interpretation

The presence of an ambiguous interaction region suggests that the decision outcome becomes highly sensitive to small temporal deviations. Such deviations can be represented as a temporal estimation error, denoted as ΔT . In connected autonomous driving systems, these deviations may arise from stale or delayed information caused by periodic sensing or communication updates. Prior VANET studies have shown that intermittent connectivity can increase delivery delay, which is critical for time-sensitive road safety information [14]. Such information staleness has been shown to degrade perception accuracy and decision quality, thereby potentially compromising driving safety [15].

The staleness of dynamic information can be characterized using the concept of Age of Information (AoI), which represents the elapsed time since the most recent update of a vehicle's state. In general, AoI evolves as a sawtooth function, increasing linearly over time and dropping upon receiving new updates [16].

For simplicity, this study adopts a discrete approximation of AoI under periodic updates, expressed as

$$AoI \approx \left\lceil \frac{\Delta t}{T_{update}} \right\rceil \cdot T_{update} \quad (3)$$

where T_{update} denotes the update interval and Δt represents the elapsed time since the last update. This formulation can be interpreted as an effective discrete representation of information staleness.

Inspired by this concept, the temporal estimation error can be conceptually expressed as

$$\Delta T = \alpha \cdot \Gamma_{MAP} \cdot AoI \quad (4)$$

Where Γ_{MAP} denotes a conceptual modulation factor that reflects how the availability of static prior information (e.g., map knowledge of road topology and potential conflict zones) influences the effect of information staleness on timing estimation, and α is a scaling parameter capturing the overall sensitivity of the decision process to information freshness.

5. Conclusion

This study investigates AV-HV interactions at unsignalized intersections using temporal interaction metrics derived from simulated trajectories. The results reveal that a significant number of interactions occur within a near-neutral timing region, where small temporal differences may lead to different yielding outcomes. This finding highlights the presence of an ambiguous interaction region in mixed traffic environments. Furthermore, the observed sensitivity to small temporal variations suggests that information uncertainty, such as that characterized by AoI, may influence interaction decisions. These insights provide a conceptual basis for understanding decision variability in autonomous driving and highlight the potential role of connectivity in reducing uncertainty.

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