

Research Article

The Impact of V2X Penetration Rates on Mixed-Traffic Coordination

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ABSTRACT

Navigating unsignalized mixed-traffic intersections presents a complex decentralized decision-making challenge. To address this, we propose a Dynamic Bayesian Game (DBG) framework that continuously recalculates optimal strategies under real-world V2X communication uncertainties. Our approach integrates a physical-layer model, utilizing AWGN and path loss-dependent SNR to evaluate realistic packet delivery. Crucially, the system relies on an autonomous belief-updating mechanism where vehicles construct probability distributions over opponents' hidden driving types. These beliefs are instantly refined upon receiving V2X packets, while safely reverting to a shared prior distribution during transmission dropouts. Comprehensive MATLAB-SUMO co-simulations confirm the architecture's ability to ensure robust vehicle safety and high macroscopic efficiency despite severe communication instabilities.

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1. Introduction

The management of traffic at unsignalized intersections represents a critical bottleneck in modern intelligent transportation systems, particularly when prioritizing the rapid and safe transit of Emergency Vehicles (EVs) [1]. As transportation networks transition toward mixed traffic environments comprising both Connected and Automated Vehicles (CAVs) and traditional human-driven vehicles the need for reliable, decentralized coordination becomes increasingly urgent.

While game theory has been widely recognized as a powerful tool for decentralized right-of-way allocation, conventional game-theoretic models often exhibit significant limitations. Primarily, these approaches frequently rely on computationally intensive, iterative simulations to formulate payoff matrices, which severely hinders their real-time applicability [2]. Additionally, traditional models tend to assume perfect information and agent homogeneity, thereby ignoring the diverse driving styles and unpredictable behaviors inherent in human

drivers. In reality, vehicular coordination must also contend with physical-layer uncertainties, such as Vehicle-to-Everything (V2X) communication packet loss and signal degradation, making perfect information assumptions impractical [3].

To overcome these challenges, this study proposes a computationally efficient, decentralized decision-making framework based on a non-cooperative Dynamic Bayesian Game (DBG) [4]. Our approach is specifically designed to manage heterogeneous, mixed-ability traffic under conditions of incomplete information. The core innovation of our methodology is the development of a novel analytical payoff function that operates independently of slow simulation processes, thereby resolving traditional computational bottlenecks.

Within this DBG framework, autonomous agents autonomously form probabilistic beliefs regarding the unobservable driving types of their opponents. These beliefs are dynamically refined using precise data from successful V2X transmissions; in the event of communication failures, the agents safely revert to a shared

prior probability distribution to maintain operational stability. By utilizing the Iterated Best Response (IBR) algorithm, the system rapidly computes a Pure Strategy Nash Equilibrium (PSNE) in real-time, effectively ensuring robust conflict resolution and absolute EV preemption despite severe environmental and communication uncertainties.

2. Related Work

Decentralized intersection coordination traditionally utilizes rule-based heuristics [5], reinforcement learning (RL) [6], and Model Predictive Control (MPC) [7]. However, heuristics lack adaptability in mixed traffic, RL suffers from an uninterpretable black-box nature, and MPC incurs exponentially growing computational costs as vehicle density increases.

Game theory mitigates these issues by modeling multi-vehicle conflicts as strategic interactions [8]. While dynamic games resolve the rigidity of early single-interaction static models, they typically assume complete information. Although Bayesian games address unobservable private driving intentions, most existing studies still assume flawless observation channels, critically ignoring the severe impacts of V2X communication loss in real-world environments [3].

Furthermore, emergency vehicle (EV) preemption has shifted from centralized infrastructure, which is highly vulnerable to single-point failures, toward decentralized V2V coordination [1]. Yet, current heuristic and advanced game-theoretic EV strategies predominantly rely on perfect communication assumptions, often risking secondary congestion. These gaps highlight the urgent need for a robust decision-making framework that guarantees safety and absolute EV priority under severe communication uncertainty.

3. Dynamic Bayesian Game Framework

To handle the highly dynamic and uncertain nature of mixed-traffic unsignalized intersections, we propose a decentralized coordination mechanism governed by a Receding Horizon Control (RHC) architecture. Instead of relying on static, one-time decisions, the system continuously re-evaluates environmental states and re-optimizes strategies at every discrete time step Δt . Within this framework, the interaction among vehicles is mathematically abstracted into a Dynamic Bayesian Game (DBG)

3.1. System Architecture and Game Formulation

At any given time step t , the multi-vehicle interaction problem is formally abstracted into a Bayesian game tuple denoted as

$$\Gamma = \langle \mathcal{N}_t, \mathcal{A}, \Theta, \mathcal{U}, \mathcal{B}_t \rangle \quad (1)$$

Within this mathematical framework, $\mathcal{N}_t$ defines the dynamic set of active players, representing all vehicles currently situated within the intersection's predefined

geometric coordination zone. To guarantee the computational feasibility required for real-time execution on vehicular onboard units, the complex continuous longitudinal trajectories are deliberately simplified. Specifically, the action space $\mathcal{A}$ is discretized, restricting each player i to a strict binary decision set $\mathcal{A}_i = \{Go, Yield\}$.

Furthermore, to accurately capture the diverse driving styles and varying vehicle priorities present in real-world traffic, the model incorporates a private type space Θ . For any given player i , their specific profile is drawn from [9]:

$$\Theta_i = \{Aggressive, Normal, Conservative, EV\} \quad (2)$$

In this formulation, the Emergency Vehicle classification acts as a critical edge condition that inherently demands absolute right-of-way priority during the entire coordination process.

3.2. Belief Formation under Communication Uncertainty

In mixed-traffic environments, unequipped human-driven vehicles (HDVs) and V2X packet dropouts caused by physical-layer degradations like AWGN and path loss create significant information uncertainty. Our Dynamic Bayesian Game (DBG) framework adapts to real-time channel reliability by maintaining a belief distribution $\mathcal{B}_t$ over opponents' hidden types. When ego vehicle i successfully receives a message from opponent j , the driving type θ_j becomes deterministic, reducing the interaction to a complete information game. Conversely, during communication failures or encounters with unconnected HDVs, the framework transitions into a Bayesian game. Under these imperfect conditions, vehicle i estimates θ_j by reverting to a shared prior probability mass function $P(\theta_j)$, which allocates fixed probabilities to diverse driving styles (30% aggressive, 40% normal, and 30% conservative) to guarantee safe navigation despite information degradation [10].

3.3. Expected Utility and Equilibrium Solving

Autonomous agents maximize their Expected Utility (EU) by integrating the deterministic payoff $\mathcal{U}_i$ across all possible opponent types, weighted by their belief distribution $\mathcal{B}_i$:

$$EU_i(a_i, a_{-i}^*, \theta_i) = \sum_{\theta_{-i} \in \Theta_{-i}} \mathcal{B}_i(\theta_{-i}) \cdot \mathcal{U}_i(a_i, a_{-i}^*, \theta_i, \theta_{-i}) \quad (3)$$

The base payoff $\mathcal{U}_i$ balances throughput against collision risk. *Yield* incurs a constant delay penalty, while *Go* provides a transit reward offset by an exponential Time-to-Collision (TTC) risk penalty. These payoffs are further scaled by risk sensitivity multipliers reflecting the inferred driving styles.

Crucially, to guarantee absolute priority for emergency responders, a Dynamic Safety Bubble applies an overwhelming proximity penalty to conflicting agents' *Go* payoffs, proportional to the EV's velocity v_{EV} :

$$U_i(Go) = U_{i,base}(Go) - W_{EV} \times \frac{v_{EV}}{v_{ref}} \quad (4)$$

where $U_{i,base}(Go)$ is the standard payoff, W_{EV} is a massive priority weight, and v_{ref} is a reference speed. This profound mathematical pressure coerces surrounding traffic into yielding.

Finally, to rapidly converge on a Pure-Strategy Bayesian Nash Equilibrium (PBNE) within stringent computational limits, we employ the Iterated Best Response (IBR) algorithm. IBR utilizes simultaneous updates via a memory buffer to eliminate strategy oscillations [11]. If convergence fails within a strict iteration limit due to symmetrical deadlocks, a deterministic safety fallback mechanism forces unresolved conflicting vehicles into a conservative *Yield* state.

4. Experiments and Analysis

To rigorously validate the robustness and computational efficiency of the proposed Dynamic Bayesian Game (DBG) framework, an extensive series of high-fidelity co-simulations was conducted using the integrated MATLAB-SUMO platform. The experimental environment was constructed around a standard four-way, two-lane unsignalized intersection to represent a typical urban bottleneck. A total of 500 highly randomized traffic scenarios were generated to ensure the statistical significance of the evaluation. Within these simulated environments, each vehicle was autonomously and randomly assigned a specific behavioral profile categorized as Aggressive, Normal, Conservative, or Emergency. The corresponding kinematic parameters for each driving style were meticulously mapped to the underlying SUMO microscopic traffic model to recreate authentic mixed-traffic dynamics.

4.1. Simulation Setup and Scenario Configuration

The primary independent variable investigated in this study was the market penetration rate of V2X communication technologies. By evaluating the system at distinct penetration levels (0%, 50%, and 100%), the experiments aimed to expose the framework's adaptability to varying degrees of information uncertainty. To comprehensively assess system performance, two primary evaluation dimensions were established. The first dimension is macroscopic intersection efficiency, quantified by the average total travel time of all vehicles and the specific transit delay experienced by emergency responders. The second dimension is game-theoretic stability and computational load, measured by the average number of Iterated Best Response (IBR) calculation cycles required for the onboard units to reach a Nash equilibrium.

4.2. Performance Evaluation and Discussion

An in-depth examination of the 500 randomized simulation trials uncovers a profound, non-linear correlation between the market penetration of V2X technology and the overall operational efficiency of the intersection. While connected vehicle technologies exhibit substantial potential for optimizing traffic flow, the empirical data strongly indicates that a fully equipped vehicle fleet is essential to unlock these macroscopic benefits.

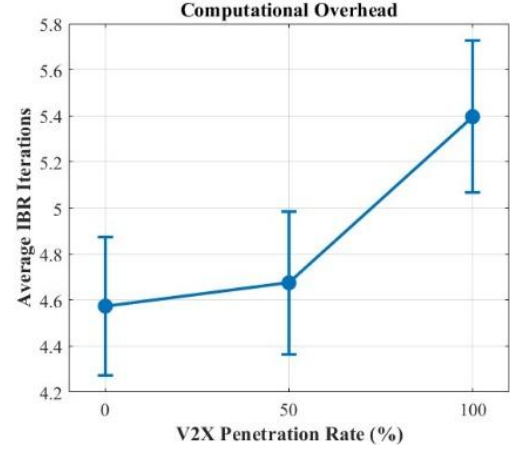


Fig. 1 Computational Overhead (IBR Iterations)

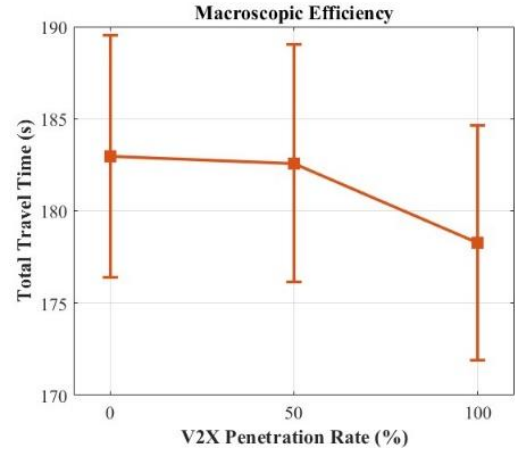


Fig. 2 Macroscopic Efficiency (Total Travel Time)

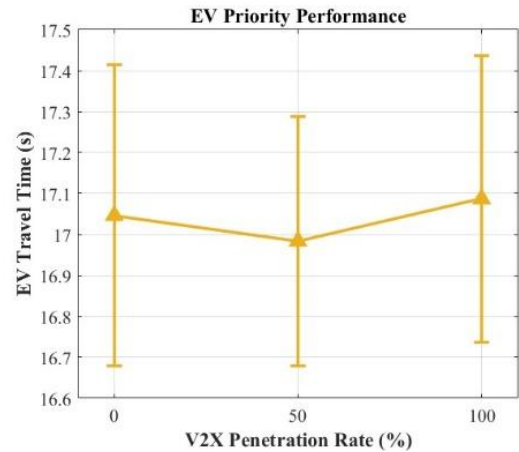


Fig. 3 Emergency Vehicle Priority Performance

As illustrated in Fig. 2, an intermediate penetration rate of 50% yields only a marginal improvement in the average total travel time, reducing it merely from 182.97 seconds at the 0% baseline to 182.57 seconds. Paradoxically, as shown in Fig. 1, this partial deployment phase actually imposes a heavier computational burden on the decision-making framework, elevating the average Iterated Best Response (IBR) iterations from 4.57 to 4.67. Consequently, a mixed-traffic ecosystem characterized by partial connectivity proves to be fundamentally inefficient regarding system-wide throughput. In stark contrast, a significant breakthrough in macroscopic efficiency is uniquely realized under a 100% penetration rate, where the total travel time dramatically plummets to 178.25 seconds. This observed non-linear impact of communication penetration on traffic flow aligns perfectly with findings documented in existing literature [12]. Furthermore, Fig. 3 validates the robust design of the dynamic payoff mechanism concerning emergency vehicle preemption.

Irrespective of the V2X penetration level and the associated fluctuations in general traffic efficiency, the transit time for emergency vehicles remained exceptionally stable at approximately 17 seconds. This demonstrates that the proposed Bayesian game model successfully guarantees the absolute right-of-way for critical responders, seamlessly maintaining safety and priority even under severe communication uncertainty.

5. Conclusion

In this study, a computationally efficient Dynamic Bayesian Game (DBG) framework was introduced to address the decentralized coordination of mixed traffic at unsignalized intersections. By integrating an autonomous belief-updating mechanism and a dynamic payoff function, the risks associated with unobservable driving behaviors and V2X communication uncertainties are effectively mitigated by the proposed model. Through comprehensive MATLAB-SUMO co-simulations, it was demonstrated that absolute right-of-way for emergency vehicles is successfully guaranteed by this framework under all conditions. Furthermore, a critical non-linear relationship between V2X penetration and macroscopic intersection efficiency was identified through an analysis of 500 randomized scenarios. It is indicated by the empirical results that while negligible travel time improvements are offered by partial V2X deployment (e.g., 50%) due to the necessity of conservative safety inferences, achieving a 100% penetration rate is absolutely essential for the system-wide throughput benefits of connected autonomous traffic to be fully unlocked.

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