

Safety Assessment of Mixed Traffic Flow on Port Access Roads Considering the Randomness of Human-Driven Vehicle Following

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Abstract: In controlled environments like ports, CAV platoons (CAVPs), leveraging cooperative control and communication technologies, have emerged as leading innovators in enhancing traffic safety. The probabilistic characteristics of human drivers are central to traffic flow dynamics.. Unfortunately, this randomness is often overlooked in existing studies examining mixed traffic scenarios in mixed traffic flow. To bridge the gap in modeling interactions between automated vehicle platoons (CAVPs), human-driven cars (HDCs), and trucks (HDTs), this paper introduces a complex mixed traffic model that captures their hierarchical dynamics. To address the limitations of deterministic driver models, this paper employs the Stochastic Intelligent Driver Model (SIDM) to characterize human-driven vehicle (HDV) following behavior with uncertainty. The results reveal that greater platoon length. Under high traffic flow conditions, the presence of CAVPs may adversely affect safety. Furthermore, longer CAVPs, while enhancing coordination, are more susceptible to stochastic disturbances.

Keywords: Port collecting and distributing road, Mixed-Traffic Flow, Automated and connected vehicle formation, Stochasticity, safety analysis

1. Introduction

In the context of smart city ecosystems, connected autonomous vehicles (CAVs) serve as cyber-physical enablers for sustainable transportation. By integrating V2X connectivity (5G-NR) and autonomous control (model predictive control), CAVs resolve the trilemma of congestion (via dynamic routing), safety (via cooperative perception), and sustainability (via electrified powertrains). In relatively closed environments such as ports, connected and automated vehicle platoons (CAVPs) can significantly improve traffic system safety, becoming a popular research topic [1]. The stochastic behavior of human drivers is a primary cause of traffic oscillations and instability [2]. However, this randomness has not been sufficiently addressed in most existing safety analyses of mixed traffic flow. A Cyber-Physical Modeling Framework for Heterogeneous Port Traffic: Integrating Automated Platoons (CAVPs), Human-Driven Vehicles (HDCs), and Freight Trucks (HDTs). The Stochastic intelligent Driver Model (SIDM) is employed to capture the randomness in human driving behavior. By bridging a gap in the current literature, this research provides targeted theoretical support for traffic management on port access roads, ultimately contributing to enhanced safety and efficiency . The manuscript is structured to fulfill the research objectives through five sections: Chapter 2 is the

theoretical foundation. Chapter 3 is the simulation experiment. Chapter 4 is the conclusion and outlook.

2. Methodology

2.1. Composition of mixed traffic flows

Assuming there are n vehicles in the new complex mixed traffic flow, the penetration rates of HDCs, HDTs and CAVPs are denoted as P_{HDC} , P_{HDT} and P_{CAVP} respectively, satisfying Eq. (2-1).

$$P_{HDC} + P_{HDT} + P_{CAVP} = 1 \quad (2-1)$$

2.2. Model hypothesis

Considering the probabilistic nature of human driver behavior—manifested in both light-duty (HDCs) and heavy-duty (HDTs) vehicles—this study employs the Stochastic Intelligent Driver Model (SIDM) to characterize their longitudinal and lateral dynamics. For connected automated vehicles (CAVs), two longitudinal control models are adopted: Cooperative Adaptive Cruise Control (CACC—V2X-enabled platoon coordination) and Adaptive Cruise Control (ACC—single-vehicle speed regulation). These models characterize CAV operational behaviors in mixed traffic scenarios. Therefore, the overall framework can be summarized as HDC (SIDM) + HDT (SIDM) + CAV (CACC + ACC).

2.3. Stochastic Vehicle Following Behavior of Human Drivers

In the current study, the acceleration rate of the ego vehicle n at time t within the context of the SIDM model [3] is determined by Eq.(2-2) and (2-3).

$$a_n^{SIDM}(t) = a \left[1 - \left(\frac{v_n(t)}{v_f} \right)^4 - \left(\frac{s^*(v_n(t), \Delta v(t))}{s_n(t)} \right)^2 \right] + \sigma \sqrt{v_n(t)} dW_n \quad (2-2)$$

$$s^*(v_n, \Delta v) = s_0 + v_n(t)T + \frac{v_n(t)\Delta v(t)}{2\sqrt{ab}} \quad (2-3)$$

Where the maximum acceleration is denoted by a , while its comfort deceleration is represented by b . The parameter σ is a positive dissipation parameter that describes the strength of stochasticity.

2.4. ACC and CACC vehicles in CAVP

2.4.1. The ACC model.

The acceleration rate of the ego vehicle n at time t in the ACC model [1] is given in Eqs.(2-4) and (2-5).

$$a_n^{ACC}(t) = k_1 e_n(t) + k_2 \Delta v_n(t) \quad (2-4)$$

$$e_n(t) = \Delta x_n(t) - l - s_0 - t_a v_n(t) \quad (2-5)$$

Where, k_1 and k_2 are the control parameters. $\Delta v_n(t)$ is the speed difference between the two cars at time $t-1$; e is the error between the actual and expected gap distance, and t_a is the desired headway time distance of the ACC car.

2.4.2. The CACC follow-up model

The CACC model [2] can be formulated as follows in Eq.(2-6) and (2-7).

$$v_n(t + \Delta t) = v_n(t) + k_p e_n(t) + k_d \dot{e}_n(t) \quad (2-6)$$

$$e_n(t) = \Delta x_n(t) - l - s_0 - t_c v_n(t) \quad (2-7)$$

Where, k_p and k_d are model control parameters, t_c is the desired headway of the CACC trucks at time, and $\dot{e}_n(t)$ is the derivative form of e , as shown in Eq.(2-8).

$$\dot{e}_n(t) = \Delta v_n(t) - t_c a_{n,0}^{CACC}(t) \quad (2-8)$$

Where, $\Delta v_n(t)$ is the speed deviation between the two vehicles at time t , and $a_{n,0}^{CACC}(t)$ is the acceleration of the vehicle at the moment t .

2.5. Traffic flow safety analysis methods

Time-to-Collision (TTC)—a key safety performance measure (SPM)—is widely used for traffic safety assessment. Two derivative metrics, Time-to-Encroachment (TET) [4] and Time-to-Influence (TIT) [5], extend TTC for advanced safety evaluations. Among them, the formula for TTC is shown in Eq.(2-9).

$$TTC_n(t) = \frac{x_{n-1}(t) - x_n - l}{v_n(t) - v_{n-1}(t)}, \quad v_n(t) > v_{n-1}(t) \quad (2-9)$$

The evaluation indexes TET and TIT derived based on TTC are calculated in Eq (2-10) and (2-11).

$$TET(t) = \sum_{i=1}^I \sum_{t=1}^T \Delta t, \quad 0 < TTC(t) < TTC^* \quad (2-10)$$

$$TIT(t) = \sum_{i=1}^I \sum_{t=1}^T [TTC^* - TTC(t)] \Delta t, \quad 0 < TTC(t) < TTC^* \quad (2-11)$$

Where $TTC(t)$ is the longitudinal collision time. i is the vehicle number, I is the total number of vehicles, t is the simulation moment, and TTC^* generally takes values of 1.0 ~3.0 s [3].

3. A Simulation Framework for Quantifying Safety in Mixed Traffic Environments

3.1. Experimental Framework

Figure 1 illustrates a synthetic 8-kilometer single-lane freeway featuring a mid-section velocity bottleneck, constructed for traffic flow simulation purposes. It is assumed that there exists a bottleneck section in the middle of the road with a length of 2 km. The simulation time step was set at 0.1 s, and the total simulation duration was 30 min.

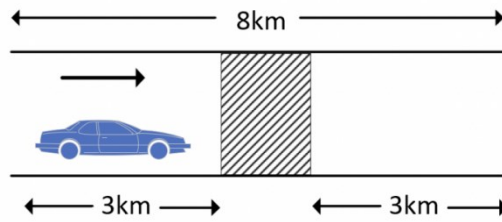


Figure 1: Simulation experiment scene

3.2. Safety analysis

3.2.1. Different penetration rates, different formation lengths

When $P_{HDC} = 0.1$, the safety indexes with different permeability and different L_{max} are obtained, which are shown in Fig.2. where the horizontal coordinate is the change of P_{CAVP} , and the vertical coordinate is the normalised TET and TIT.

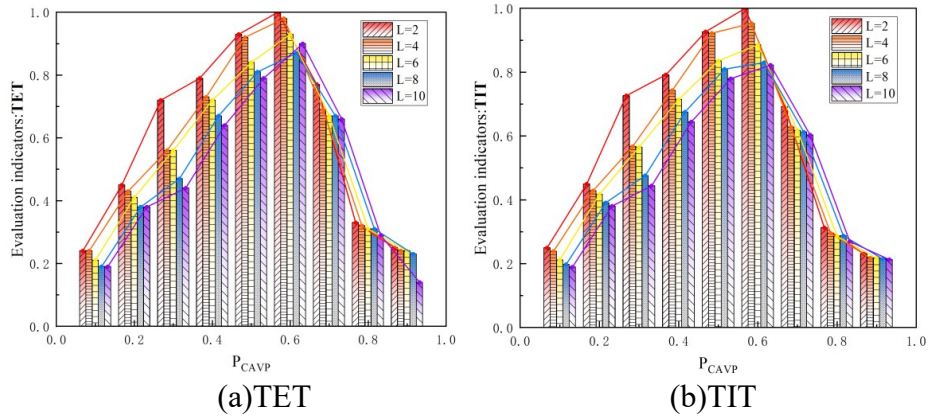


Figure 2: Effect of different infiltration rates and different Lmax on the safety of mixed traffic flow

As can be seen in Figure 2, TET and TIT decrease with increasing Lmax, i.e., the safety of mixed traffic flow increases. This indicates that there exists a critical value, when $P_{HDC} < 0.6$, the traffic flow is less cooperative and it is difficult to achieve large-scale following behaviour, resulting in the efficiency and safety of the traffic flow decreasing instead. Beyond this value, the synergy between vehicles will be fully utilised, significantly improving the dynamic characteristics of the traffic flow.

3.2.2. Stochastic intensity

The Lmax was chosen to be 4 and 8, $P_{CAVP} = 0.1$, and the values of TET and TIT were varied when the random intensities of HDC and HDT were varied. Based on the percentage change, see Eq.(3-1).

$$\begin{cases} PC_{TET} = \frac{TET_{n2} - TET_{n1}}{TET_{n1}} \\ PC_{TIT} = \frac{TIT_{n2} - TIT_{n1}}{TIT_{n1}} \end{cases} \quad (3-1)$$

Where TET_{n1} (TIT_{n1}) denotes the result of the operation obtained before TET_{n2} (TIT_{n2}), and the effect of different stochastic intensities on the safety level of the mixed traffic flow is shown in Fig.3.

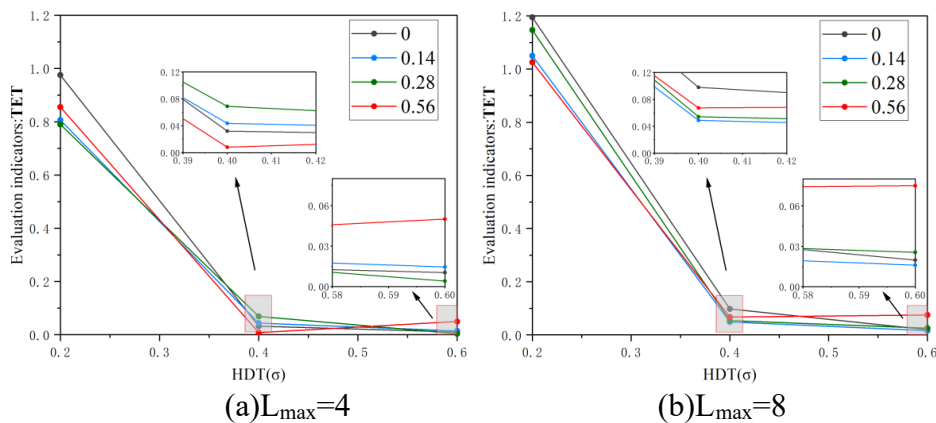


Figure 3: Percentage change in the effect of different stochastic intensities

As can be seen in Fig.3, randomness makes the longer Lmax more susceptible compared to the shorter Lmax. Thus, while the longer Lmax show greater traffic flow coordination, they are also more susceptible to randomness due to human drivers.

4. Conclusion

This paper evaluates the safety of a novel mixed traffic flow comprising CAVPs, HDCs, and HDTs under different stochastic conditions. To model the behavior of HDVs we utilized SIDM to demonstrate the stochasticity involved. On the one hand, this paper only considers longitudinal collisions in CAVP, and does not take into account the collision risk when moving laterally; on the other hand, this paper considers the mixed traffic flow consisting of HDC, HDT, and CAVP, and does not deal with other types of vehicles or more complex traffic scenarios. These factors limit the comprehensiveness and depth of stochasticity studies and are important tasks for future research.

References

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