A Reproducible Rule-Based Baseline for Multi-Lane Highway Interaction: Integrating IDM, MOBIL, and Hysteretic Following

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1 Introduction

This paper provides a reproducible and interpretable rule-based baseline for highway driving, designed to compare the decision-making philosophy of conventional rule-based methods against the proposed prediction-aware framework (Simulation Case 2 [Siyuan2025]). It integrates the Intelligent Driver Model (IDM)[1] for longitudinal control, the minimizing overall braking induced by lane change (MOBIL) [2] criterion for lane-change decisions, and a quintic time-scaling profile for lateral motion generation. To mitigate oscillatory braking behavior often induced by Time-to-Collision (TTC) triggers, a hysteretic car-following mechanism is incorporated for the primary interacting vehicle (SV1). Specifically, SV1 performs an event-triggered acceleration when the ego vehicle (EV) initiates a lane change, and subsequently switches to a latching proportional-derivative (PD) following law that regulates inter-vehicle spacing and relative velocity. The framework attributes vehicles undergoing lane changes to their target lanes for consistent safety evaluation and employs asynchronous longitudinal and lateral update cycles to emulate realistic driver behavior. Overall, this baseline serves as a fundamental benchmark for assessing the differences between conventional rule-based approaches and the proposed HMDP-MPC decision-making framework[Siyuan2025].

2 Methodology

2.1 Longitudinal Control - IDM

The longitudinal acceleration a_x follows the classical IDM formulation:

$$a_x = a_0\left[1-\left(\tfrac{v}{v_0}\right)^{\delta}-\left(\tfrac{s^*(v,\Delta v)}{s}\right)^{2}\right], \quad s^* = s_0 + vT + \frac{v\,\Delta v}{2\sqrt{a_0 b}},$$

where v and Δv denote the ego and relative velocities, and s represents the inter-vehicle gap. The parameters a_0, b, v_0, T, and s_0 correspond to the maximum acceleration, comfortable deceleration, desired speed, desired time headway, and minimum spacing, respectively.

2.2 Lateral Decision - MOBIL

The lateral maneuver decision follows the MOBIL rule, where a lane change is triggered when the overall incentive gain

$$G = \Delta a_{\text{ego}} + p\big(\Delta a_{\text{new}} + \Delta a_{\text{old}}\big) - \beta_{\text{keep}} > a_{\text{thr}},$$

and both the new and old followers satisfy the safety condition $a_{\text{f,new}}, a_{\text{f,old}} \geq -b_{\text{safe}}$. Here, p denotes the politeness factor, β_{keep} penalizes unnecessary lane changes, and a_{thr} defines the minimum required incentive for execution.

2.3 Lateral Motion Generation - Quintic Polynomial

Once a lane-change decision is approved by the MOBIL rule, the lateral trajectory of the EV is generated using a quintic polynomial that ensures smooth position, velocity, and acceleration transitions.

A normalized temporal variable $\tau = t/T_{\mathrm{lc}}$ defines the progression between the initial lane center y_0 and the target lane center y_1:

$$y(\tau) = (1-s)y_0 + s\,y_1, \qquad s = 10\tau^3 - 15\tau^4 + 6\tau^5.$$

This polynomial guarantees zero initial and terminal lateral velocities and accelerations, producing dynamically feasible, jerk-free lane-change motions.

2.4 PD Following with Hysteresis

Once a leader exists in SV1's current or target lane, the vehicle regulates longitudinal spacing using a PD law around a time-headway setpoint:

$$s_{\mathrm{des}}(v) = s_0 + T_{\mathrm{h}}v, \qquad e_s = g - s_{\mathrm{des}}(v), \qquad a_{\mathrm{pd}} = K_p e_s + K_d(v_{\mathrm{lead}} - v),$$

where g is the bumper-to-bumper gap, and v, v_{lead} are the current and leader velocities. A latch mechanism with two thresholds suppresses high-frequency switching:

$$\text{enter following if } e_s < \eta_{\mathrm{in}}, \qquad \text{exit following if } e_s > \eta_{\mathrm{out}} \text{ and } (v - v_{\mathrm{lead}}) \le 0,$$

with $\eta_{\mathrm{in}} < \eta_{\mathrm{out}}$. This hysteresis eliminates TTC-driven oscillations while preserving responsiveness in following control.

Emergency Braking (Optional Fallback). If activated, a TTC guard applies only under rare closing scenarios:

$$\mathrm{TTC} = \frac{g}{\max\{v - v_{\mathrm{lead}}, \varepsilon\}}, \qquad \begin{cases} \mathrm{TTC} < \tau_{\mathrm{hard}} \Rightarrow a \leftarrow \min(a, -a_{\mathrm{hard}}), \\ \mathrm{TTC} < \tau_{\mathrm{soft}} \Rightarrow a \leftarrow \min(a, -b_{\mathrm{soft}}). \end{cases}$$

In the nominal Case 2 configuration, this safeguard remains inactive but bounds risk under unexpected closures.

3 Simulation

The case considers a straight three-lane highway with lane centers located at $y = \{4, 0, -4\}$. Five vehicles are involved: the EV, initially driving in the middle lane and permitted to perform lane changes; an interactive SV1 positioned in the left-rear region; a leading vehicle (SV2) ahead of the EV in the same lane; and two long trucks occupying the rightmost lane, which discourage merging maneuvers. The EV is therefore restricted from entering the truck lane, focusing its decisions on interactions with SV1 and SV2 in the adjacent and current lanes.

Figures 1-3 present the comparative results under this baseline. Figure 1 illustrates six snapshots of the traffic scene at key decision moments under the rule-based baseline. Initially, the EV maintains cruising in Lane 2 while SV1 in the adjacent lane is cruising. At $t = 5.85$ s, the EV initiates a lane-change maneuver toward Lane 1. As shown in Fig. 1(c), SV1 has begun to accelerate and is continuously closing in from behind while the EV is lane changing. Despite the decreasing gap, the EV continues the lane-change maneuver without adjustment, leading SV1 to perform an abrupt deceleration to avoid a potential collision. The EV then completes the lane change and overtakes the slower leading vehicle (SV2). However, after overtaking, it continues cruising in the overtaking lane without autonomously returning to its original lane. The corresponding velocity profiles of the EV and SVs are shown in Fig. 2. The complete trajectory of the EV throughout the episode is depicted in Fig. 3.

4 Summary

The rule-based baseline is constructed on a set of well-established models and control principles that collectively emulate structured human driving behaviour. Longitudinal motion is governed by the IDM, which captures both steady-state car-following behaviour and transient gap-closing dynamics. Lateral maneuver decisions follow the MOBIL criterion, expressing lane-change incentives through a

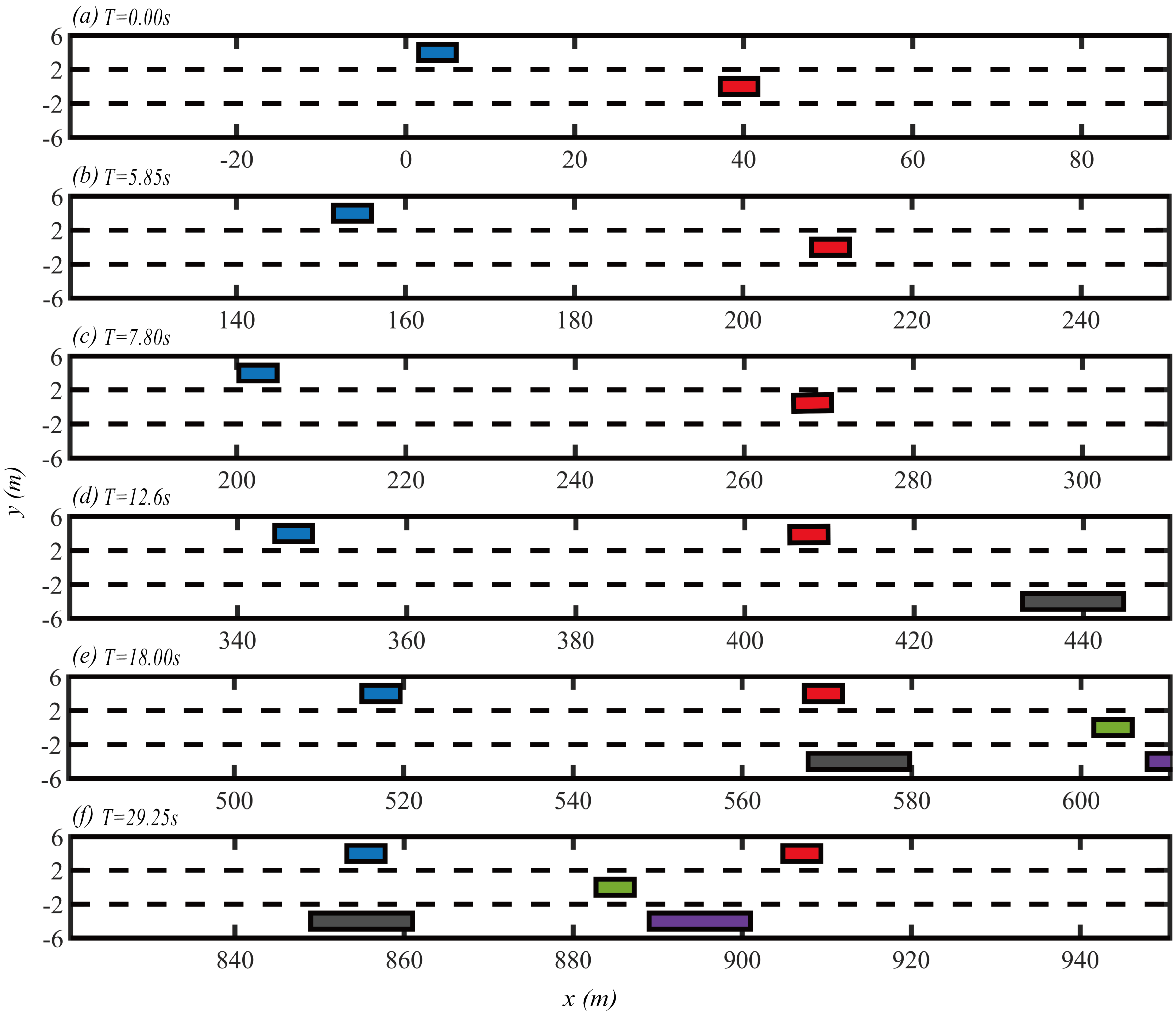

Figure 1: Snapshots of EV maneuver under the rule-based method at five six decision moments. Subfigures (a)-(f) correspond to the time points 0.00 s, 5.85 s, 7.80 s, 12.6 s, 18.00 s, and 29.25 s, respectively, as marked in the velocity profile (Fig. 2).

balance between ego acceleration benefits, politeness toward surrounding vehicles, and explicit safety constraints. The executed lane-change trajectory is generated via a quintic polynomial profile, providing dynamically smooth lateral motion with continuous derivatives.

To stabilise interactive behaviour, the framework incorporates a hybrid control structure: a latching PD-based following law with hysteresis suppresses rapid mode switching and mitigates oscillatory dynamics induced by short-term spacing fluctuations. Interaction assessment is further structured through lane-based leader/follower attribution, ensuring coherent safety evaluation even during transient lane-change phases. Finally, asynchronous decision and integration time-scales reflect the separation between high-level intent updates and low-level continuous control, improving behavioural realism.

Overall, these components form a theoretically grounded and interpretable rule-based benchmark that reproduces key characteristics of multi-lane highway driving. As a representative rule-based strategy, this baseline serves as a consistent reference for examining the behavioural differences between conventional reactive approaches and the proposed HMDP-MPC decision-making framework.

References

[1] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Physical review E*, vol. 62, no. 2, p. 1805, 2000.

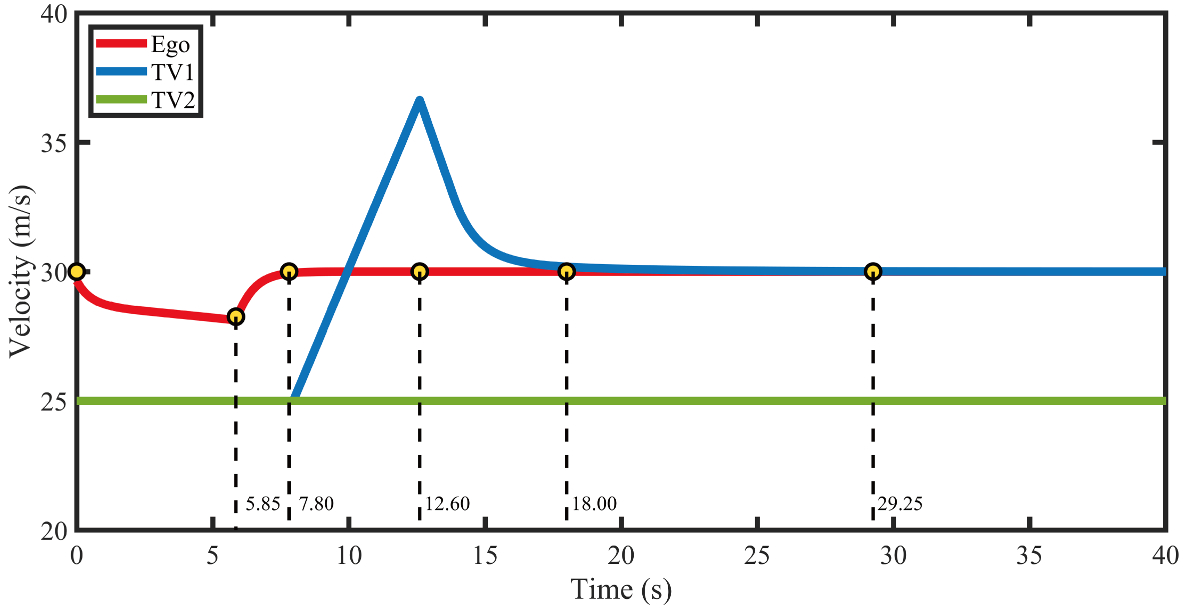

Figure 2: Velocity profile of the EV and SVs under the rule-based method.

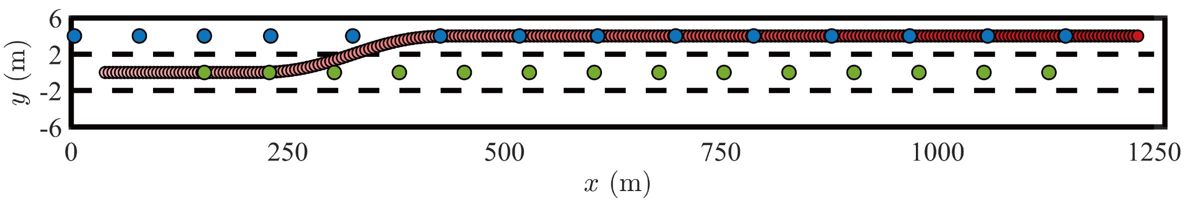

Figure 3: Complete EV trajectory under the rule-based method.

[2] A. Kesting, M. Treiber, and D. Helbing, "General lane-changing model mobil for car-following models," *Transportation Research Record*, vol. 1999, no. 1, pp. 86–94, 2007.