Fault Tolerance Analysis of Lane-Changing Models for Autonomous Vehicles

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***Abstract*—Sensor measurements of Autonomous Vehicles (AVs), crucial for the execution of precise lane changes, are often error-prone. Microscopic lane-changing models govern the dynamic lateral maneuvers of AVs. To our knowledge, there is no assessment of lane-changing models under sensor uncertainty for AVs. In this study, we evaluate two prominent lane-changing models, Minimize Overall Braking Induced by Lane-change (MOBIL) and Cooperative Lane-changing Algorithm (CLA) under sensor error conditions through detailed simulations, analyzing their performance in terms of safety, trip times, traffic flow, and merging time. Our findings reveal that sensor inaccuracies substantially affect both safety and traffic flow across both models. Although none of these models is entirely fault-tolerant, as evidenced by instances of collisions and the increased time taken to change lane, CLA emerges as more robust option, demonstrating less collision and realistic lane-change behavior along with acceptable trip times and merging times.**

***Index Terms*—Lane-changing model, autonomous vehicle (AV), global positioning system (GPS) receiver error, radar sensor error.**

I. Introduction

AVs, equipped with advanced sensors and cameras such as Light Detection And Ranging (LiDAR) and infrared, enable them to navigate independently following traffic regulations. These technologies make it possible to precisely monitor the positions and velocities of the preceding cars, enabling intelligent speed regulation and efficient lane change. GPS receiver errors may occur due to signal blockage and multipath effects, while radar sensor measurement errors can result from hardware malfunctions, road curves, grades, and large inter-vehicle gaps on highways [1]. The GPS sensor's RMS error is 7.2 m [2], while LiDAR's longitudinal RMSE is 0.033m [3]. These errors can cause fatal accidents and casualties on the road. Surprisingly, there is not much research on the effect of sensor errors on microspopic travel models. There is only one paper addressing fault tolerance in car-following models [4], and no study has yet focused on lane-changing models.

A review of various lane-changing decision-making models [5]—including those based on the Gipps framework, utility theory, cellular automata, Markov processes, and artificial intelligence— reveals that MOBIL, proposed by Kesting *et al.*, [6] is a notable variant of the Gipps-type approaches. This is because MOBIL takes into account both safety and incentive criteria. Furthermore, MOBIL offers two main advantages [7]: (1) it features a simplified decision-making process that is easy to implement, and (2) it can be readily integrated with a car-following model to simulate both longitudinal and lateral interactions on highways. Again, CLA, proposed by Tanveer

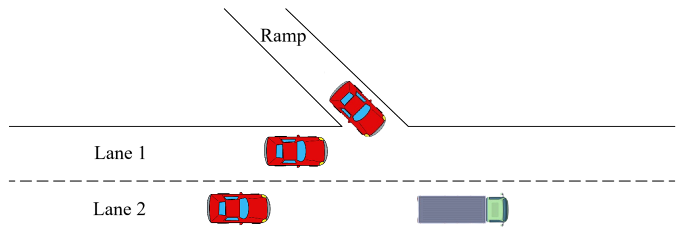

Fig. 1: Simulation Road

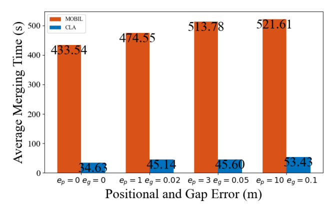

Fig. 2: Average Merging Time for Different e_p and e_g

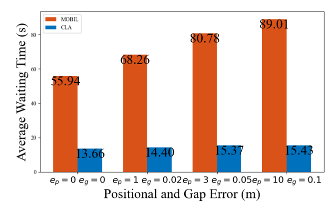

Fig. 3: Average Waiting Time for Different e_p and e_g

et al., [8] shows significant performance improvement over MOBIL. Therefore, we have selected the MOBIL and CLA model for simulating lane-changing maneuvers in our fault tolerance analysis.

The contribution of this study is as follows:

- This study is the first to evaluate the performance of prominent lane-changing models under imperfect sensor information, with a focus on transportation efficiency and safety. Our analysis demonstrates that sensor errors have varied impacts on the performance of these models.
- We simulate various sensor errors both individually and in combination to assess their individual and combined impacts on the performance of lane-changing models.

II. Methodology

To evaluate the fault tolerance of lane-changing models under sensor errors, we follow a simulation-based approach. We select two widely used lane-changing models for comparison, MOBIL and CLA.

The simulation is conducted in MATLAB with an open-system traffic environment. The underlying Intelligent Driver Model (IDM) is used for car-following behavior.

The models are evaluated using the following key performance indicators: merging time, merging rate, waiting time, trip time, number of collision, and frequency of lane change.

Finally, the metrics are compared to find out which model is more fault tolerant.

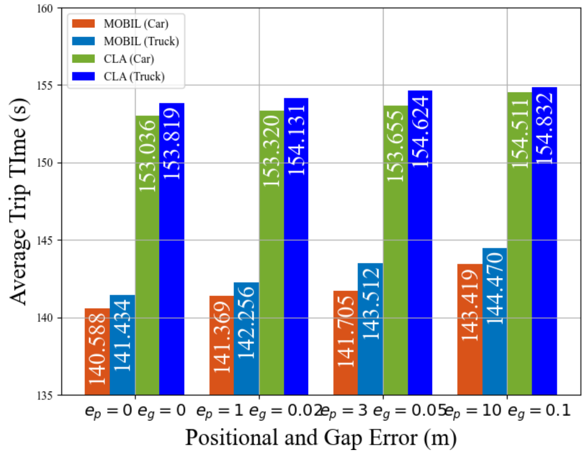

Fig. 4: Average Trip Time for Different e_p and e_g

III. Evaluation through Simulation

In this section, we compare performance of the lane-changing models in presence of sensor errors.

A. Simulation Settings

The inflow *i.e.,* vehicle arrival rate is Poisson distributed, 30 vehicles/min (vpm). A single-lane on-ramp of 500m intersects a 3km long two-lane main road at the middle on lane 1 as depicted in Figure 1. Driver decides at decision making point, D_r, whether to merge or wait 200m before the merging point. The simulation length is 1200s. The desired velocity for cars is 27.78*m/s* (100*km/h*) and 22.22*m/s* (80*km/h*) for trucks.

B. Simulation Results

Let e_p and e_g denote positional error and gap error respectively. We vary value of both errors in our simulation and the following results are obtained:

1) *Average Merging Time and Merging Rate:* As shown in Fig 2, CLA achieves a merging time of 34.63s under no sensor error and takes upto 53.43s for maximum error. On the other hand, average merging time under no sensor error for MOBIL is 433.54s and goes upto 521.61s for maximum error. Again, CLA achieves a merging rate of 27.65 vpm and remains almost constant for different sensor errors. On contrary, MOBIL achieves merging rate of 14.7 vpm and falls down to only 2.6 vpm for maximum sensor error.
2) *Waiting Time:* We consider the time spent between D_r and merging point as waiting time. In Fig 3, less waiting time and deviation for different combination of e_p and e_g is observed in CLA than MOBIL.
3) *Average Trip Time:* Under no sensor error, at a Poisson distributed arrival rate of 30 vpm, MOBIL has the lower average travel time, 140.588s for cars and 141.434s for trucks arriving from main road (see Fig. 4). On the other hand, CLA shows a higher trip time for both cars and trucks, 153.036s and 153.819s respectively. However, CLA boasts a standard deviation of only 0.859 under different combination of e_p and e_g.

TABLE I: Number of collision for MOBIL and CLA across different error parameters

Model	$(e_p, e_g) = (0, 0)$	$(e_p, e_g) = (1, 0.02)$	$(e_p, e_g) = (3, 0.05)$	$(e_p, e_g) = (10, 0.1)$
MOBIL	3.28	13.2	102.84	138.36
CLA	1.16	4.2	24.72	65.2

TABLE II: Average Number of lane changes per vehicle for MOBIL and CLA across different error parameters

Model	$(e_p, e_g) = (0, 0)$	$(e_p, e_g) = (1, 0.02)$	$(e_p, e_g) = (3, 0.05)$	$(e_p, e_g) = (10, 0.1)$
MOBIL	6.434	6.611	7.033	7.682
CLA	5.847	6.464	6.232	7.635

4) *Number of Collision:* After simulating the scenario for different combinations of sensor error 25 times, the results after averaging is shown in Table I.
5) *Number of Lane Changes:* In Table II, we can see the average number of lane changes per vehicle to be slightly higher for MOBIL ($p = 0.8$) than CLA. However, in both models, number of lane change increases with errors primarily due to positional error.

IV. Conclusion

Sensor errors drastically impair lane-changing performance, compromising both safety and traffic flow in autonomous vehicles. The MOBIL model, though efficient under ideal conditions, is notably vulnerable to such inaccuracies. In contrast, CLA exhibits enhanced fault tolerance and delivers a more robust performance under varied error conditions. For future work, the fault tolerance of the LMRS lane-changing model can also be analyzed and compared with MOBIL and CLA. Additionally, a new fault-tolerant model can be proposed based on the analysis of sensor error effects on lane-changing models.

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