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Comparing Vehicle Trajectories Generated by Microscopic Traffic Simulation and Vehicle Dynamic Simulation

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Abstract

This paper presents a comparative study between microscopic traffic simulation and vehicle dynamics simulation to evaluate their consistency and applicability for driver behavior analysis. The study focuses on four representative driving scenarios: roundabouts, four-way intersection, highway overtake, and U-turn. Traffic simulations were conducted using SUMO, while vehicle dynamics simulations utilized the double-track vehicle model in MATLAB SIMULINK, driven by the Pure Pursuit control algorithm. Trajectories were visually compared using x-y plots, and the maximum positional deviations were calculated. Speed profiles and heading angles were analyzed as functions of distance, complemented by a quantitative metric based on phase, amplitude, and topology errors. This metric, developed in earlier work, provides a method for comparing vehicle behaviors. The research results highlight the need to incorporate detailed vehicle dynamics into traffic simulations for improved realism, especially in scenarios with high lateral acceleration and abrupt steering inputs. Refining traffic simulations with improved vehicle behavior will also make road traffic flow predictions more realistic and reliable.

Keywords

microscopic traffic simulation, vehicle dynamics simulation, SUMO

1 Introduction

As traffic networks become more interconnected, vehicle testing requires more extensive and complex scenarios. Historically, car manufacturers focused solely on the performance of their vehicles, often disregarding their impact on other traffic participants. However, with the rapid advancements in advanced driver assistance systems, autonomous vehicle perception, and Vehicle-to-Everything (V2X) communication, the focus has shifted toward modeling and simulating the surrounding environment as well. (Lovas et al., 2022; Gomes, 2022; Szalay, 2021; Ghadi, 2024; Sakhno et al., 2024; Henchey et al., 2014; Kaths et al., 2019; Mullakkal-Babu et al., 2021; Choi et al., 2006)

Addressing large-scale traffic scenarios without compromising the model accuracy of the EGO vehicle (the vehicle under test) requires either a multi-scale co-simulation approach or the careful optimization of a lower-fidelity but more scalable simulator. This paper focuses on the latter approach.

Microscopic traffic simulation tools, such as the Simulation of Urban Mobility (SUMO) (Lopez et al., 2018), are widely used for modeling traffic flow and behavior at a microscopic level. On the other hand, vehicle dynamics simulations (Gangel et al., 2021), such as MATLAB SIMULINK's Vehicle Dynamics Blockset, provide detailed models for analyzing the physical motion and control of individual vehicles.

This paper aims to bridge the gap between these two paradigms by comparing their outputs under identical driving scenarios, assuming the traffic simulation is the meta-model of the vehicle dynamics simulation. The primary objective is to assess the extent to which microscopic traffic simulations can approximate the detailed behaviors observed in vehicle dynamics simulations. The comparison focuses on four representative scenarios: navigating roundabouts, turning right in a four-way intersection, executing highway overtake, and performing a U-turn. The relevance of this research lies in the fact that co-simulating vehicle dynamics and traffic (Kaths and Krause, 2016) is getting more and more common, however if there is a discrepancy between the two simulators, the co-simulation outputs may be biased.

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The study employs both qualitative and quantitative comparison methodologies. Qualitative analysis includes visual inspection of trajectories on x-y plots, while quantitative analysis involves calculating maximum positional deviations and comparing speed profiles and heading angles as functions of distance. Additionally, a quantitative metric based on phase, amplitude, and topology errors is employed to evaluate differences in the behaviors.

While microscopic traffic simulators like SUMO and vehicle dynamics models like MATLAB SIMULINK's Vehicle Dynamics Blockset are commonly used in transportation research, direct comparisons between these tools are limited.

There are a handful of papers dealing with vehicle dynamics model validation and assessing traffic models. Kutluay and Wimmer (2014) did an extensive review in the field of vehicle dynamics model validation, where he reviewed several articles dealing with different aspects of model validation for vehicle dynamics models.

Kaths and Krause (2016) introduced a method for integrating microscopic traffic simulation (SUMO) with vehicle dynamics simulation (IPG CarMaker) to enhance accuracy. By combining the strengths of both tools, the integrated simulation improves traffic flow realism, as shown in two use-cases. In the first, vehicle dynamics simulations refine speed distributions on a curvy road, while the second tests an automatic cruise control system in stochastic traffic, highlighting the limitations of traffic simulations and the added precision from vehicle dynamics models.

The works of Olstam and Tapani (2004) provide a thorough analysis of various car-following models used in traffic flow simulation. The authors compare different mathematical approaches to model the behavior of vehicles following one another, examining their strengths, limitations, and applications in traffic simulation. The study aims to assess how well these models predict real-world driving behavior and their suitability for various traffic management scenarios. By reviewing a range of models, including both simple and more complex ones, the paper contributes to understanding the trade-offs involved in selecting appropriate car-following models for specific simulation needs, especially in the context of traffic flow analysis and road safety.

These studies underline the need for a systematic comparison of traffic and vehicle dynamics simulation to assess their relative inaccuracies and identify potential improvements for traffic simulations. SUMO models traffic flow and vehicle interactions, whereas MATLAB SIMULINK's models simulate detailed vehicle dynamics. However, the accuracy of traffic simulations in representing vehicle behavior, when compared to a validated vehicle dynamics model, has not been thoroughly investigated.

Understanding where and how traffic simulations deviate from validated vehicle dynamics simulations is essential for improving the reliability of traffic modeling. This paper compares SUMO and MATLAB simulations to identify discrepancies and highlights the limitations of traffic simulations in capturing detailed vehicle behavior.

The main contribution of this research is twofold. On the one hand, the results highlight the need to integrate detailed vehicle dynamics into traffic simulations to improve realism, especially in scenarios involving higher lateral acceleration and significant or abrupt steering inputs. On the other hand, our study underlines the importance of improving traffic simulations to more accurately capture vehicle behavior and thereby improve traffic flow predictions. This is particularly important for future automotive developments, where not only the vehicle itself but also the surrounding traffic flow must be taken into account. The paper adapts the Validation Metric (Widner et al., 2022) to compare two simulators of different levels of detail. This previously developed metric is used to quantitatively assess the discrepancies between traffic simulation and vehicle dynamics simulation.

This study reveals several key discrepancies between the simplified vehicle dynamics in SUMO and a more realistic model implemented in SIMULINK. Notably, SUMO exhibits oversimplification in lane-changing maneuvers, representing them as lateral "drifts" without heading adjustments. This unrealistic trajectory proves unattainable with the higher-fidelity SIMULINK model. A similar discrepancy is observed in the U-turn scenario, where SUMO generates a square-like path. Furthermore, cornering velocity, which significantly influences vehicle behavior in real life and in the SIMULINK model, has a negligible effect on trajectories generated by SUMO.

The paper is structured as follows: Section 2 summarizes a previously developed validation framework for vehicle dynamics simulation, and describes a validation metric which is used in this study as well. Section 3.1 offers a brief overview of the simulation tools used for the study: SUMO and MATLAB SIMULINK's Vehicle Dynamics Blockset. Section 3.2 introduces the scenarios and the results. Finally, Section 4 summarizes the key findings.

2 Methodology

In this study, we utilize a previously developed metric to quantitatively assess the discrepancies between traffic simulation and vehicle dynamics simulation. This metric, referred to as the Validation Metric (*VM*), is comprehensively detailed in (Widner et al., 2022). Originally designed within a framework for validating vehicle dynamics models against real measurements. The *VM* provides a quantitative approach for comparing system response quantities (*SRQ*) to facilitate model validation. Although initially intended for validating vehicle dynamics models against real-world vehicle data, the *VM* is versatile and can be applied to compare two simulators (models) of differing granularity. Additionally, it serves as a tool to fine-tune vehicle model parameters using a genetic algorithm, enabling the generation of more realistic simulation results.

The *VM* compares the *SRQ*s from a simulation and a real-life experiment or between two simulations. The study by Sarin et al. (2008) introduces a structured combination of measures, employing vector norms, cross-correlation analysis, and the dynamic time warping (*DTW*) technique to categorize error components into three physically meaningful properties: phase, magnitude, and topology. These measures quantify the discrepancies effectively.

The Phase Error is calculated using a cross-correlation function. After minimizing global and local phase differences between the datasets, an $\boldsymbol{L}_1$ vector norm measures the relative magnitude differences. The *DTW* method is applied to reduce local phase differences. The Topology Error, which accounts for discrepancies in the slope, is computed on the derivative channels using the $\boldsymbol{L}_1$ norm. The *VM* utilized in this study is based on the work of Sarin et al. and is detailed as follows.

First, the Phase Error (e_P) is calculated as the absolute value of the time difference between the simulation channel (SRQ^1) and (SRQ^2), determined using the cross correlation function.

Next, prior to calculating the subsequent error components, the (SRQ^2) values are delayed by this phase error to minimize the global phase difference, ensuring it does not affect the remaining error components. The adjusted channel is denoted as (SRQ^2_{TS}), where "*TS*" indicates a time-shifted channel.

The Magnitude Error (e_M) eliminates local phase differences using the *DTW* algorithm, creating SRQ^1_{DTW} and $SRQ^2_{TS\_DTW}$. The magnitude error is then calculated as the Euclidean distance between the two vectors:

$$e_M = \frac{\left\| SRQ^1_{DTW} - SRQ^2_{TS\_DTW} \right\|}{\left\| SRQ^1_{DTW} \right\|} \tag{1}$$

The Topology Error (e_T) is computed by applying the same procedure used for the magnitude error to the derivative channels, $SRQ^1_{D\text{-}DTW}$ and $SRQ^2_{TS\_D\_DTW}$, capturing differences in the slope:

$$e_M = \frac{\left\| SRQ^1_{DTW} - SRQ^2_{TS\_D\_DTW} \right\|}{\left\| SRQ^1_{D\_DTW} \right\|} \tag{2}$$

The weighted sum of the three error components yields the *VM* for a given channel:

$$VM_{SRQ} = \frac{c_p \cdot e_p + c_M \cdot e_M + c_T \cdot e_T}{c_p + c_M + c_T} \tag{3}$$

where c_P , c_M, and c_T are the weight factors for each error component. In this study, these weight factors are set to 1. However, using different weight factors for critical error components - for example emphasizing the topology error in cornering cases - seems to have potential, this is outside of the scope of this paper and part of the future work.

Finally, the weighted sum of the *VM*s for all channels provides the *VM* for the test scenario:

$$VM = \sum_{n=1}^{m} c_n \cdot VM_{SRQ\_n} \tag{4}$$

where c is the weight factor for each *SRQ*, and VM_{SRQ_n} is the *VM* of the respective *SRQ*.

The weight factor for each channel's *VM* is determined based on two considerations. The first is the importance of the channel for the specific application, which is somewhat subjective. In this study 1 is used for each *SRQ*. The second is the uncertainty of the measurement system. However, as this study deals exclusively with simulations, measurement uncertainty does not apply due to the absence of measurement inaccuracies.

3 Simulation based analysis

3.1 Traffic and vehicle dynamics simulation

3.1.1 SUMO - Simulation of urban mobility

SUMO (Lopez et al., 2008) is an open-source, microscopic traffic simulation tool used for modeling the movement and interaction of individual vehicles and pedestrians within traffic networks. It supports large-scale simulations and can be customized with various traffic flow models, routing algorithms, and traffic control strategies.

3.1.2 MATLAB SIMULINK - Vehicle dynamics blockset

The Vehicle Dynamics Blockset (MathWorks, online(b)) in MATLAB SIMULINK (MathWorks, online(a)) provides a detailed double-track vehicle model used to simulate vehicle motion under various conditions. For this study, the Pure Pursuit controller (MathWorks, 2020), a well-established path-following algorithm, is employed to simulate vehicle trajectory tracking. This controller calculates the necessary steering angle to minimize the lateral deviation from a reference trajectory, ensuring the vehicle accurately follows its intended path. It is widely used in vehicle dynamics research to model and control precise vehicle behavior.

3.1.3 Scenario descriptions

In this section, the detailed descriptions of the scenarios employed in the simulations are provided. For all SUMO scenarios, the following general settings were used: the Intelligent Driver Model was utilized, and the step-length value was set to 0.001 (same as in SIMULINK environment).

Four-Way Roundabout: This scenario consists of four distinct sub-scenarios, each involving an exit at one of the four available exits of the roundabout (first, second, third, or fourth). The maximum velocity in this scenario is approximately 9 m/s, and the diameter of the roundabout's central circular section is 40 meters. The SUMO roundabout scenario can be seen in Fig. 1

Right Turn at an Intersection with Varying Speeds: In this scenario, vehicles perform a right turn at an intersection under different velocity conditions (Fig. 2). The maximum and minimum velocities for each condition are detailed in Table 1.

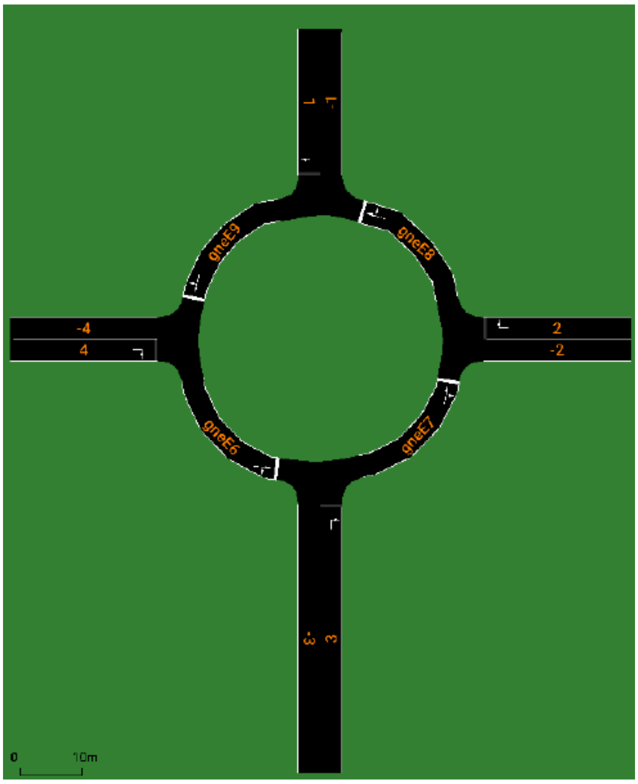

Fig. 1 SUMO roundabout scenario. The vehicle starts from lane 3, then exits in lane −2, −1, −4, −3

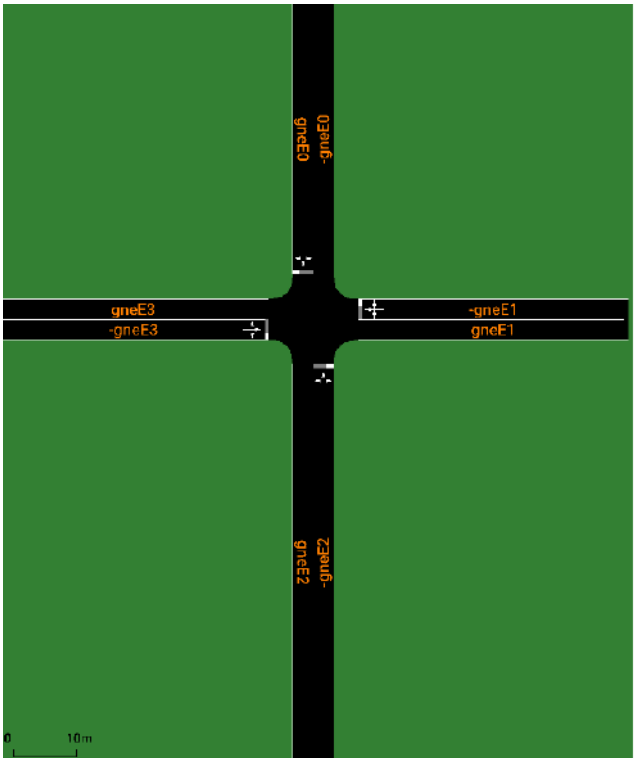

Fig. 2 SUMO turning right scenario. The vehicle starts in lane -gneE2, then exits in -gneE1

Table 1 Maximum and minimum velocities for the right-turn cornering scenario. All values are in meter per second (m/s)

Speed condition	Max. Velocity	Min. Velocity (m/s)
Low	6.0	5.6
Medium	9.0	6.3
High	12.0	6.5

Highway Overtaking Maneuver: In this scenario, the ego vehicle initially travels at a velocity of 35 m/s in the outer lane of a highway. The vehicle then executes a lane change to overtake a slower-moving vehicle, proceeds to pass it, and subsequently returns to the outer lane. U-Turn Scenario: This scenario involves a 180-degree turn performed by the ego vehicle in a narrow route segment. The vehicle operates at low speeds to navigate the tight turn.

3.2 Comparing the simulation

The same scenarios were executed in both SUMO and MATLAB, with the results compared using both quantitative and qualitative methods.

The driving scenarios in Table 2 were employed to evaluate the simulation models.

To quantify the differences between the simulations, the metrics shown in Table 3 were employed.

This section presents the results of the analyses, including both visual comparisons and quantitative metrics, highlighting

Table 2 Scenarios used for comparing the simulation

Scenario	Description
Four-way roundabout	Exiting on the first, second, third then fourth exit.
Turning right in an intersection	Turning right in an intersection with different velocity.
Highway overtake	Vehicle lane changes and overtaking at high velocity
U-turn	A sharp 180° turn.

Table 3 Scenarios used for comparing the simulation

Evaulation Method	Description
Positional Deviations	Calculating the maximum distance between trajectories.
Vehicle Velocity	Visually comparing velocity as a function of distance.
Heading Angles	Visually comparing heading angles over the driving path.
Validation Metric	A metric based on phase, amplitude, and topology errors to capture temporal and spatial discrepancies in vehicle behavior.

key differences and similarities between the SUMO traffic simulation and MATLAB's vehicle dynamics model.

The scenarios in SIMULINK were developed using data from the SUMO simulation. The target trajectory is designed to follow the same path, and the target velocity is consistent with that of the SUMO simulation. In cases where the SUMO trajectory is simplified and the SIMULINK model cannot precisely follow it due to vehicle dynamics limitations, the trajectories were adjusted to closely align with the SUMO path while still allowing the vehicle to smoothly follow the line. This adjustment was necessary to avoid large discrepancies between the two simulations.For instance, during a high-velocity lane-change maneuver, the heading of the SUMO vehicle remains unchanged, and the vehicle "drifts" into the adjacent lane while maintaining the same orientation throughout the maneuver, as shown in Fig. 3.

Although the target trajectory is identical for both the SIMULINK model and SUMO, it is evident that the trajectory generated by SUMO during the lane-change maneuver is unrealistic. The more sophisticated vehicle dynamics model fails to replicate this behavior and instead begins to oscillate due to the abrupt steering input, which is similar to the characteristics of a step-steer maneuver. As in the SIMULINK model the lookahead parameter has a significant effect on the oscillation; several iterations were made to find the best parameter for this test case to mitigate the oscillation.

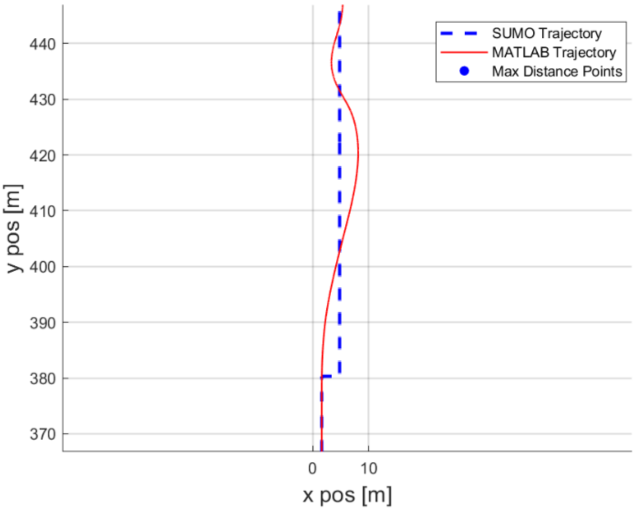

Fig. 3 Trajectory differences during a high velocity lane change maneuver

Significant differences were also observed in the U-turn maneuver, as shown in Fig. 4.

The SUMO trajectory follows a square-like path, which the SIMULINK model is unable to replicate. The maximum deviation between the two trajectories is 2.36 m.

The effect of velocity is examined in the following. In the SUMO simulation, the vehicle's velocity appears to have minimal impact on the trajectory. However, in SIMULINK, it becomes evident that as velocity increases, the differences between the trajectories become more pronounced. This is attributed to lateral friction: higher velocities during a turn lead to greater lateral acceleration, and if the vehicle have a slight understeering characteristics — common in most passenger cars — it will gradually slip off the intended path. This phenomenon can be seen in Fig. 5.

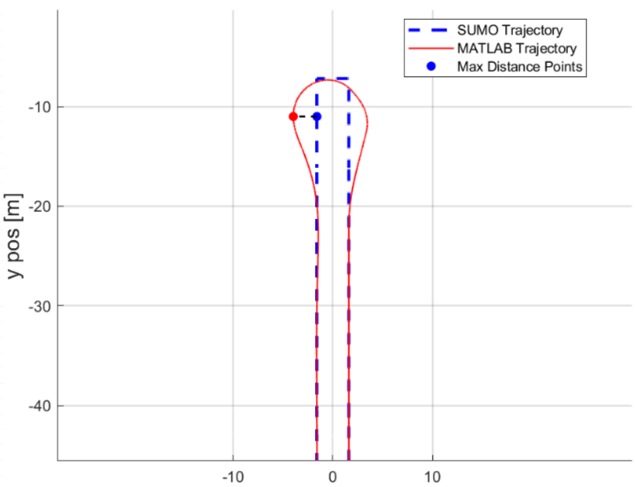

Fig. 4 Trajectory differences during a U-turn maneuver. The SUMO trajectory is simplified as a square, the maximum distance between the two trajectories is 2.36m

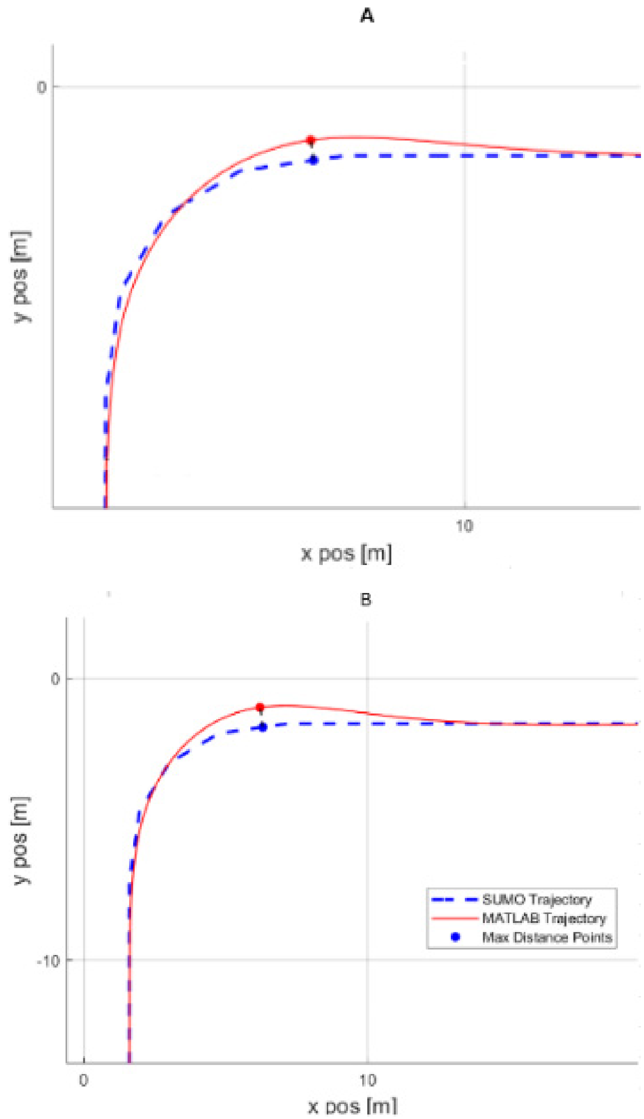

Fig. 5 The effect of velocity on SUMO and SIMULINK model trajectories. Minimum cornering velocities A: 5.6 m/s, the deviation is 0.47 m, B: 6.3 m/s, the deviation is 0.71m.

The lateral gap between the SUMO and SIMULINK trajectories is 0.47 m at low cornering velocities and increases to 0.71 m at higher velocities.

This effect is also evident in the heading angles shown in Fig. 6, where the overshoot at the corner exit is more pronounced in the SIMULINK model than in SUMO.

At higher velocities, the overshoot becomes more significant. The Validation Metric calculated on the heading channels also reflects this difference. At low velocity, the heading *VM* is 9.79, while at higher velocity, it decreases slightly to 9.7. (A *VM* value of 10 would indicate that the two heading channels are identical, while lower values represent greater discrepancies between the channels.)

The following four roundabout scenarios are investigated, with the trajectories shown in Fig. 7. Of all the analyzed scenarios, these were the closest to the SIMULINK trajectories.

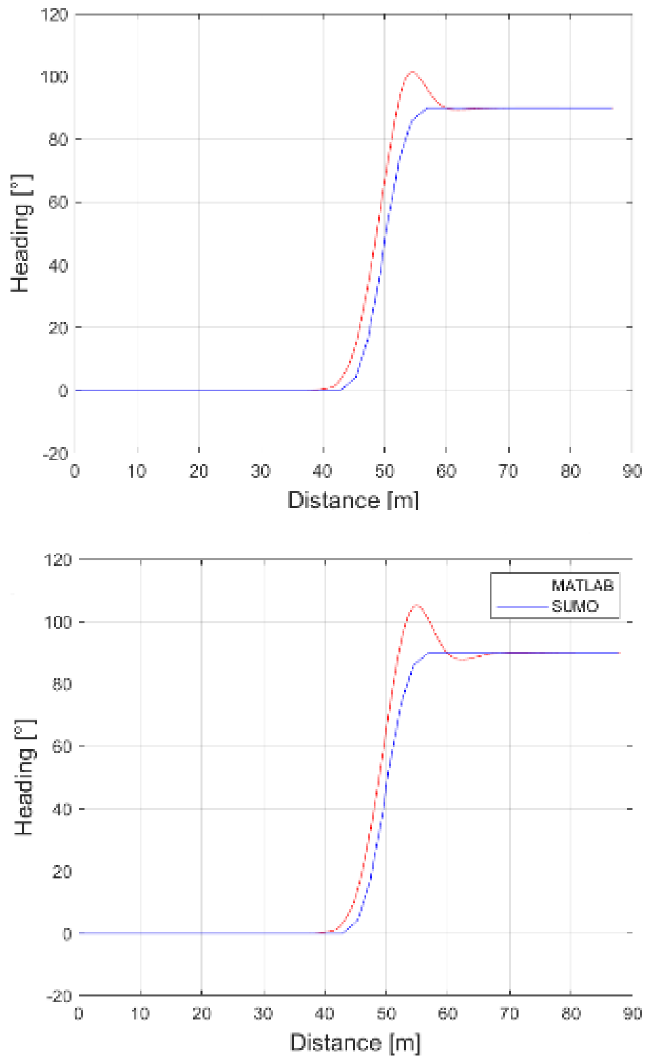

Fig. 6 The effect of velocity on SUMO and SIMULINK model heading values. Minimum cornering velocities above: 5.6 m/s below: 6.3 m/s.

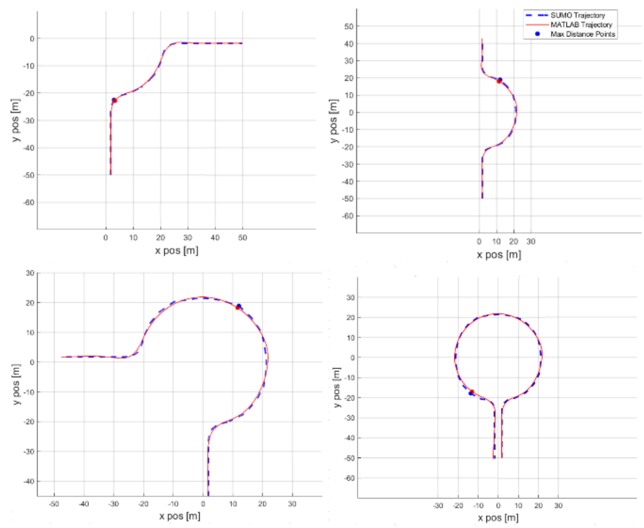

Fig. 7 Roundabout scenarios

The line closely follows the SUMO trajectory, although there are some noticeable deviations ranging from 0.45 to 1.13 m. This difference arises from the fact that, in SUMO, roundabouts are constructed from small straight segments, as can be observable in Fig. 8.

The summarized results are in Table 4.

Generally, in other model validation cases every *VM* value above 9.75 is considered "good", however in this case we have to take into account the effect these discrepancies have on the traffic flow metrics. This is part of the future work and requires analyzing a lot of cases, then formulating a connection between the *VM* and the discrepancies in the traffic flow metrics.

4 Conclusion

This study compared the SUMO traffic simulation with the SIMULINK vehicle dynamics model, focusing on trajectory differences and the impact of vehicle dynamics. The results revealed that SUMO in some cases oversimplifies vehicle motion, particularly during lane changes and U-turns, where it maintains a constant heading. Additionally, the effect of velocity was more pronounced in SIMULINK, where higher speeds increased trajectory discrepancies due to lateral friction and understeering characteristics.

In all the investigated scenarios, the SUMO model does not exhibit any overshoot in the heading channel, indicating that it does not slide off the path. This holds true even in high-velocity scenarios, where the SIMULINK model shows greater deviation from the target trajectory. The roundabout scenarios, in particular, showed the closest alignment between the SUMO and SIMULINK trajectories, although some deviations, ranging from 0.45 to 1.13 m, were present due to the way roundabouts are represented in SUMO as small straight segments.

The findings highlight that incorporating detailed vehicle dynamics into traffic simulations could enhance realism, particularly in maneuvers involving higher lateral acceleration and significant steering inputs. This demonstrates the importance of using more sophisticated vehicle models to improve the accuracy of traffic simulations, especially in complex driving scenarios.

Future work will involve a more comprehensive analysis with additional scenarios, including interactions between multiple vehicles such as an emergency braking chain, sudden lane closure, multiple vehicles in a crowded multi-intersection scenario, merging and diverging flows on on-ramps and off-ramps, cut-in and cut-out maneuvers in dense traffic, vehicle platoon formation and dissolution. These complex scenarios will enable the evaluation of cooperative maneuvers, reaction-time propagation, and the cumulative effects of simplified vehicle dynamics on overall traffic. Additionally, the impact of discrepancies on traffic metrics will be investigated. For instance, incorporating more realistic vehicle dynamics could affect cornering behavior, where a slight slide off the trajectory might result in longer cornering times, potentially causing delays in reaching subsequent intersections.

Also carrying out this comparison study using a high-fidelity commercially used vehicle dynamics simulator – such as IPG Carmaker or AVL VSM – would be interesting. The Simulink model was good for highlighting the simplifications of the SUMO traffic simulator but comparing it to a more sophisticated vehicle dynamics software could reveal deeper discrepancies.

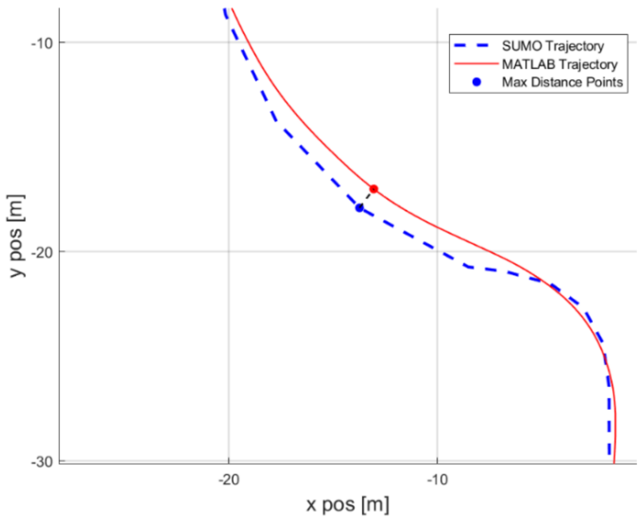

Fig. 8 Roundabout scenarios

Table 4 Summary of the results. At the highway overtake maneuver the SUMO heading is 0, therefore the *VM* returns an invalid value

Scenario	Max. trajectory deviation [m]	*VM* - Velocity	*VM*-Heading
Roundabout exit 1	0.45	9.44	9.61
Roundabout exit 2	1.04	9.67	9.29
Roundabout exit 3	0.8	9.53	9.74
Roundabout exit 4	1.13	9.25	9.84
Turning right with low speed	0.46	7.75	9.79
Turning right medium speed	0.71	9.06	9.7
Turning right high speed	0.71	9.55	9.68
Highway overtake	3.76	4.74	-
U-turn	2.36	9.76	9.52

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