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SUMO in SPACE: Combining SUMO and dSPACE for Advanced Traffic Simulation

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Abstract. Microscopic traffic simulation tools enable the simulation of various traffic demands and their impacts. By implementing realistic traffic models, they are commonly used to analyze traffic engineering measures. Since microscopic traffic simulations focus more on the network than on individual small-scale scenarios, such frameworks are appropriate for efficiency studies. In this respect, SUMO allows only a limited investigation of efficiency measures at the vehicle level, as the underlying vehicle models, such as Krauss, Gipps, or IDM, do not regard vehicle dynamics constraints. To encounter this disadvantage, SUMO is enriched by the elements of the submicroscopic simulation tool ASM from dSPACE, including a highly detailed vehicle dynamics model for the ego vehicle. Combining the elements of microscopic and submicroscopic simulation in a co-simulation framework, the effectiveness assessment of efficiency measures can be broken down to vehicle level. Besides the efficiency aspect, the proposed co-simulation bridge also offers the possibility to simulate sensing technology in a 3D environment with AURELION, where SUMO provides realistic traffic situations.

Keywords: SUMO, dSPACE, Co-Simulation, Microscopic Simulation, Submicroscopic Simulation

1. Introduction

Microscopic traffic simulation represents the cornerstone of analyzing approaches for the ongoing mobility transformation and evaluating future traffic measures. In this sense, the open-source simulation tool SUMO (Simulation of Urban Mobility) offers the possibility of being used in different target applications. As outlined in [1], research topics such as vehicular communication, navigation, evaluation of traffic light algorithms, and traffic surveillance systems represent typical fields of interest, with SUMO as the simulation environment. Besides, SUMO is commonly used for calibrating and implementing realistic traffic demand, as exemplified in [2].

Despite the wide range of applications, microscopic traffic simulation has limitations. Pechinger and Lindner [3] highlighted the positional inaccuracies of vehicle models like Newell or IDM, as it was described in [4] and [5]. Furthermore, these models do not consider any vehicle dynamics constraints when following the desired speed course, leading to an ambiguous interpretation of emission and efficiency results. As microscopic simulation simplifies the environment to a 2D perspective, it additionally lacks the capability to analyze aspiring traffic algorithms based on sensing technology.

However, SUMO represents a base platform for efficiency studies, as microscopic traffic simulations focus more on large-scale than individual small-scale scenarios. Concerning this, SUMO also allows the investigation of efficiency measures at the vehicle level by applying emission models, though it neglects any vehicle dynamics. To encounter this disadvantage, this paper describes an extension of SUMO enriched by the elements of the submicroscopic simulation tool ASM (Automotive Simulation Model) from dSPACE [6], including soft electronic control units and a highly detailed model of vehicle dynamics for the ego vehicle. Combining the elements of microscopic and submicroscopic simulation in a co-simulation framework, the effectiveness assessment of efficiency measures can be broken down to vehicle level. Consequently, this framework allows to validate an algorithm by simulation at the early stage of development. Besides the efficiency aspect, the proposed co-simulation bridge also offers the possibility to simulate sensing technology in a 3D environment, with SUMO providing realistic traffic situations. Consequently, this framework eliminates all the disadvantages of the microscopic traffic simulation environment and combines the strengths of both simulation levels. The remainder of this paper is organized as follows. Section 2 gives an overview of the related work. In Section 3, the proposed methodology is presented. Section 4 demonstrates the co-simulation framework in a concrete case study. Finally, a conclusion and outlook are given in Section 5.

2. Related Work

2.1 Microscopic Simulation For Efficiency Analysis

Microscopic traffic simulation is commonly used for efficiency analysis, as large-scale traffic scenarios can be implemented in such frameworks. Validi et al. [7] investigated different logistics strategies for trucks in the city of Linz, analyzing two different scenarios with SUMO: a) one single truck with two containers supplying two locations, and b) two trucks with one container, each of them supplying one delivery point. As a result, the single-truck scenario showed less fuel consumption and CO_2 emissions, underlining the need for shared concepts.

The authors of [8] used SUMO to analyze the environmental impact of urban scenarios generated by the OSM Web Wizard tool and scenarios configured with different vehicle characteristics such as vehicle types and driving styles. For the vehicle under test, the results showed a deviation of about 14% for fuel consumption and CO_2 emissions, emphasizing the variance of simulation results based on different settings.

Since intelligent vehicle solutions will become essential for future traffic, Schweizer et al. [9] evaluated the impact of platooning for connected automated vehicles (CAVs) in comparison to conventional cars for the area of Bologna. Precisely, the CAVs are tactically controlled in SUMO by the *SIMPLA* algorithm [10], orchestrating the formation of platoons, whereby the integrated CACC (Cooperative Adaptive Cruise Control) model calculates the vehicle distances within the platoon. The analysis shows a slight increase in fuel consumption and emissions for CAVs compared to regular cars, assuming the same engine technology is applied. Similarly to the work mentioned above, the effect of specific control algorithms for CACC and ACC (Adaptive Cruise Control) on traffic efficiency was examined in the work of [11], showing improved traffic flow even at a low penetration rate for each technology compared to manually driven cars.

Despite the great potential of microscopic traffic simulation for efficiency studies, the mentioned works do not model the vehicle dynamics with its powertrain in very high detail, allowing imprecise results and conclusions. The need for accurate vehicle dynamics modeling was highlighted in [12]. For this reason, extensions of microscopic traffic simulation are inevitable, especially for efficiency use cases.

2.2 Microscopic Simulation Extensions

The idea of extending microscopic traffic simulation by submicroscopic elements has been widely discussed in academia. This section gives an overview of different approaches to coupling microscopic with submicroscopic simulation tools. As the authors give a condensed description of the naturally complex methods, further explanations can be found in the corresponding references.

Pechinger et al. [13] investigated the potential of roadside Intelligent Transport System Stations (ITS-S) in intersection scenarios with limited visibility. ITS-S was used as an instrument of collective perception, recognizing hidden vulnerable road users for affected vehicles. The authors introduced a simulation framework, combining the software tools Aimsun Next and PreScan. In this context, Aimsun Next was used as a microscopic traffic simulator to generate the surrounding traffic as input for the 3D environment PreScan, providing the necessary sensing capabilities of the roadside ITS-S.

Sumonity [3] provides an interface between SUMO and Unity, utilizing the advantage of SUMO in terms of traffic modeling. Concerning this, the vehicles' reference velocity and reference position are calculated by SUMO as input for the longitudinal controller of the vehicle system based on the Unity asset *Realistic Car Controller Pro*. This library contains powertrain models (e.g., engine, clutch). On the other hand, lateral control is realized by the *Pure Pursuit Path Tracking* algorithm of Coulter [14], calculating the steering angle based on the so-called look-ahead distance.

In addition, Lizenberg et al. [15] validated cooperative driving functions by coupling traffic flow simulation from SUMO with the vehicle dynamics of CarMaker. In this context, SUMO spawns large-scale traffic and initiates the generation of small-scale scenarios with CarMaker. Hereby, the scenario generation trigger is controlled by a machine learning module called *OverWatch*, with the cooperative driving functions running in ROS.

3. Methodology

As mentioned in the previous section, co-simulation frameworks between microscopic and submicroscopic simulation have already been developed, particularly comprising SUMO. For this reason, the authors of this work do not claim exclusive ownership of this methodology but rather present a new framework that integrates SUMO as a traffic simulator. In this sense, the following sections describe the general architecture of the simulation platform ASM from dSPACE and the approach of its coupling with SUMO.

3.1 Architecture of dSPACE ASM

The submicroscopic simulation tool ASM is based on Simulink and is capable of offline and real-time simulation. In detail, ASM models are structured in a modular design, describing precisely the powertrain and environment of the ego vehicle [16]:

- Electrical System: describes the low- and high-volt periphery in the case of electrically driven vehicles.
- Engine: characterizes the engine torque as a function of the engine speed and accelerator pedal position.
- Drivetrain: transmits the engine torque to the wheels, modeling drivetrain components (e.g., clutch, transmission, differential, and drive shafts).
- Vehicle Dynamics: represents a multi-body system of the vehicle, extended by subsystems for tire, aerodynamics, and suspension.
- Driver: given a reference velocity and position, the driver follows those target values by adjusting the pedal position and steering wheel. A longitudinal and lateral controller implements the control strategy.
- Environment: describes the maneuver, road characteristics, the movement of the fellow vehicles as well as sensors.
- Domain Control: contains a model for an ACC controller, among other things.

The architecture of the ASM models and the control of the ego vehicle depending on the reference velocity and position are illustrated in Fig. 1.

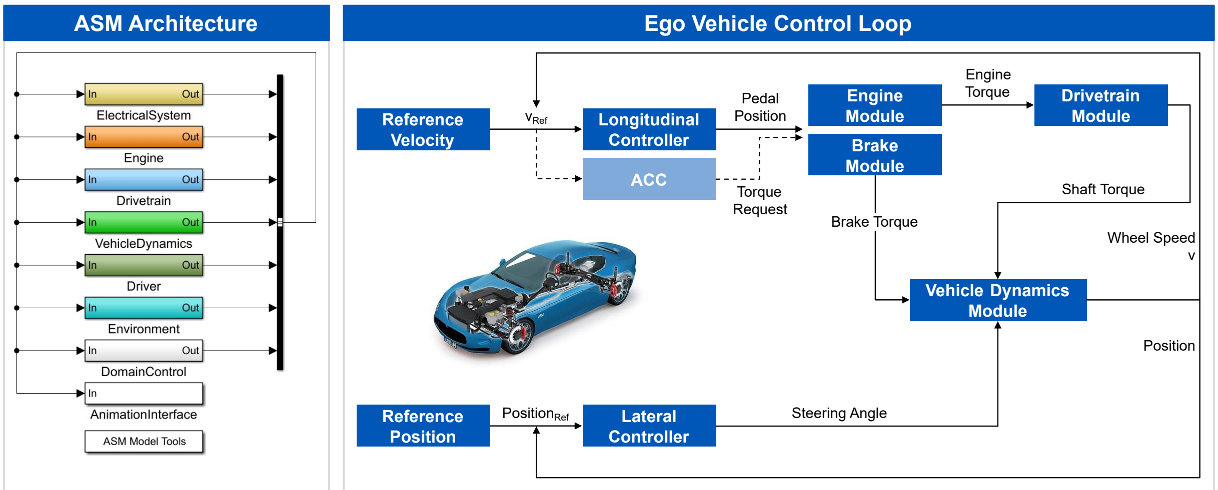


Figure 1. *ASM Architecture and Ego Vehicle Control Loop.*

The reference velocity is generated by the dSPACE traffic driver model, which detects traffic signs and traffic lights and complies with the corresponding traffic rules. The difference between reference velocity v_{ref} and the velocity of the vehicle dynamics module v is monitored by a longitudinal controller via accelerator and brake pedals. The regular gasoline engine model of a mid-sized car is controlled by a soft ECU (electronic control unit), and the engine torque is transmitted through a drivetrain model with a 5-gear manual transmission. The resulting shaft torques are the input of a multi-body vehicle dynamics model with 25 degrees of freedom. The brake pedal request is the input for a brake hydraulic model, leading to a corresponding brake torque at the wheels. A *TM Easy* tire model represents the tire-road interaction. In the case of an active soft ECU for ACC, the velocity of the vehicle is controlled based on the torque requests of the corresponding engine and brake soft ECUs. Based on a required distance defined as distance time (time gap) and a minimal distance, the ACC controls the distance to a leading vehicle. The soft ECU also includes an autonomous emergency brake (AEB) functionality, executing an emergency brake in critical situations. The maximal and minimal values of acceleration and deceleration are set dynamically by the soft ECU ACC and comply with the definitions of ISO 15622 [17].

3.2 Architecture of Co-Simulation Framework: SUMO in SPACE

The architecture of the co-simulation framework is illustrated in Fig. 2. On the right side of the figure, SUMO is shown, simulating the traffic on a given road network with an integration step size of 100 ms. The left side represents the detailed vehicle dynamics model calculated with a 1 ms step size, as described in section 3.1. Additionally, ASM is coupled with AURELION for 3D visualization and sensor raw data simulation. The interface between ASM and SUMO is based on ethernet communication, using the Traffic Control Interface (TraCI) of SUMO. The challenges for the co-simulation are mainly the synchronization and real-time capability as well as the interpretation of the shared road network. To achieve a synchronous and real-time capable simulation, a Gauß-Seidel schema is used. This schema allows for the integration of a multi-rate co-simulation and is represented by the movement synchronization block in Fig. 2. In this schema, the state of the ego vehicle is extrapolated 100 ms and sent to SUMO to calculate the next 100 ms integration step. The resulting state of the traffic simulation is subsequently sent to ASM, where the position of the traffic participants is interpolated between times t + 100 ms and t + 200 ms. Thus, when simulating in real-time, SUMO has 99 ms to calculate the next integration step of 100 ms. In case this time is missed, the traffic participants from SUMO are not used. To optimize performance, only vehicles and pedestrians within a region of interest (ROI) around the position of the ego vehicle are sent to ASM. The region of interest is shown as a red circle in Fig. 2, with a distance norm used to filter for relevant traffic participants. This filter can be extended by additional weights, such as excluding vehicles on opposing lanes in a highway use case. On the ASM side, the traffic participants calculated in SUMO are represented as fellows, which can be detected by simulated sensors. In contrast, a corresponding object in the SUMO simulation represents the ego vehicle. To avoid any misinterpretation of the road network, an OpenDRIVE road is used as a common exchange format. In contrast, using geospatial data in both tools might lead to a different interpretation of the coordinate systems, e.g., using an Open Street Map import to both tools leads to a mismatch in coordinates. The simulation setup described above can run on different platforms and operating systems. Thereby, SUMO is executed on a host PC or virtual machine/container running Linux or Windows. ASM on the other side can be calculated on the following platforms:

- directly in Simulink on Windows for model in the loop (MIL) simulation,
- in the code-based offline simulation environment *VEOS* on Linux and Windows for software in the loop (SIL) simulation or
- on a real-time PC *SCALEXIO* for hardware in the loop (HIL) and real-time simulation, respectively.

In addition to the simulation of traffic participants, SUMO also simulates the signal phases of the traffic lights of a road network. Fig. 3 gives an overview of the synchronization of signal phases between the co-simulation instances, which is based on a mapping. This mapping relies on the definition of traffic lights for the road network. Both ASM and SUMO are required to have the same basis for the road network. As mentioned above, OpenDRIVE is used, wherein the traffic lights are defined by signals with an individual ID. Based on these IDs, traffic sign objects and signal groups are generated on the ASM road, whereas SUMO adds traffic signals to the corresponding junction. Based on the ID, a mapping from traffic sign objects to the SUMO junction ID is used to identify the relevant signals. During a simulation, the traffic sign object in front and along the route of the ego vehicle is identified, with a context subscription created for the corresponding junction in SUMO. The signal phases from the subscription

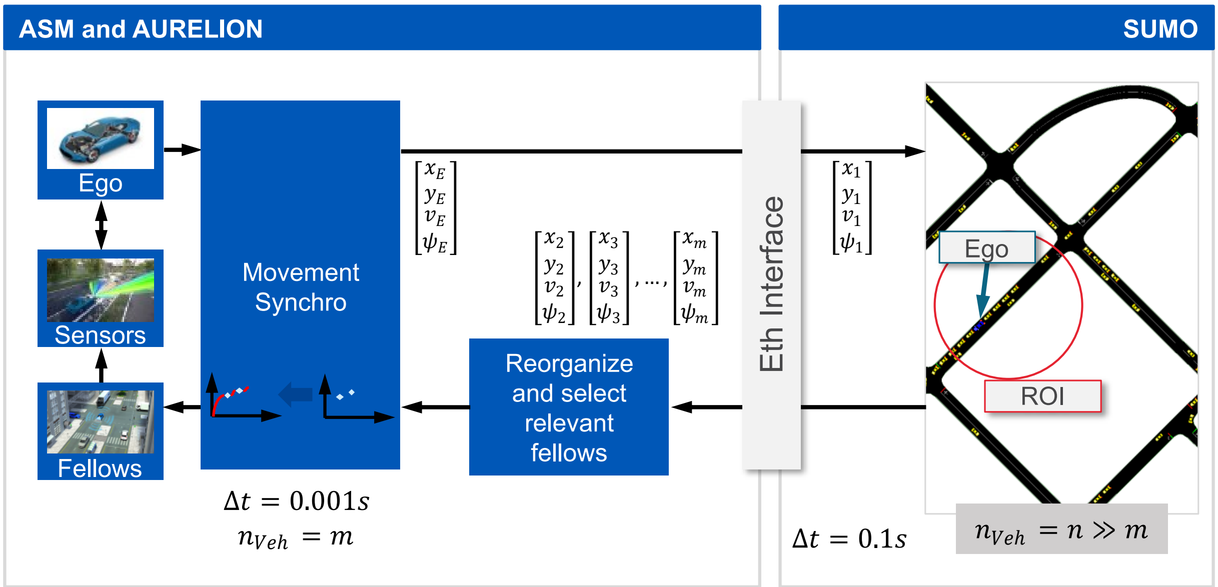


Figure 2. *Co-Simulation Framework Between ASM, AURELION and SUMO.*

results are subsequently mapped to the object data streams of the corresponding ASM traffic sign object. Additionally, this stream is connected to the so-called signal groups of the ASM junctions. This way, the signal phases can be sent via vehicle-to-everything (V2X) communication to a connected ECU.

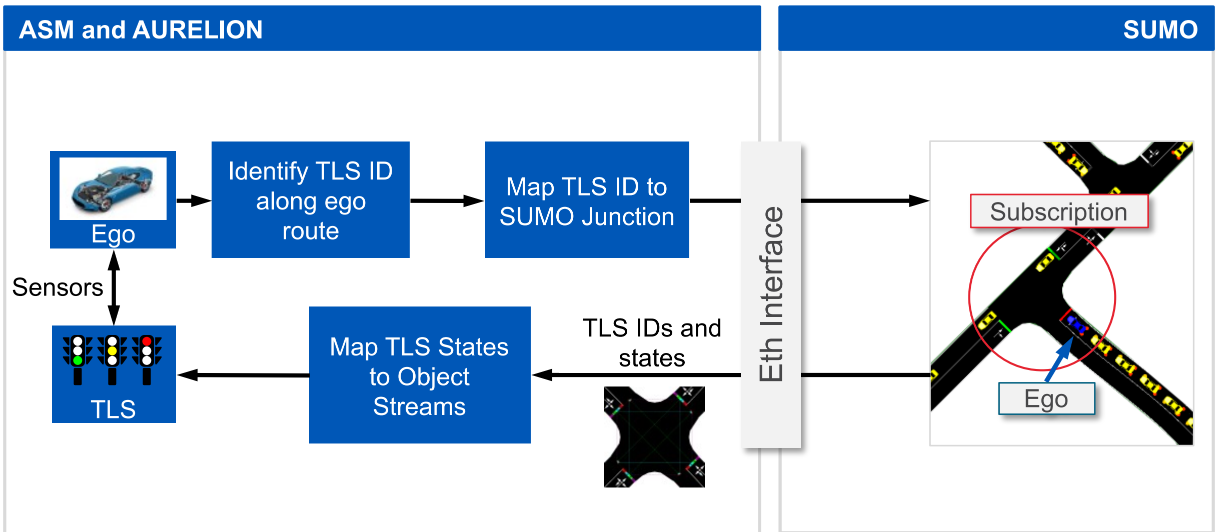


Figure 3. *Traffic Lights Synchronization Between ASM, AURELION and SUMO.*

4. Case Study

The presented interface between ASM and SUMO is used for an efficiency study, optimizing the parametrization of the soft ECU for the ASM-internal ACC. In particular, the threshold of the minimal distance between ego and leader vehicle as control input for the ACC varies within the interval 15$\pm$10 meters with a step width of 2 m. This parameter variation is conducted in a synthetic, suburban network, as shown in Fig. 4. In this respect, the ego vehicle is driving on the route colored in blue, with the traffic density varied in two different steps (low, high) and generated by SUMO. For each parametrization of the distance threshold, the same random seed for each traffic demand is used, generating reproducible and comparable simulations. Since this sensitivity analysis is performed in a synthetic network with artificial traffic demand, the authors propose extending this work to a calibrated network to obtain more conclusive results. This allows optimized parameter tuning considering real-world conditions. Nevertheless, the case study demonstrates the possibilities of using the framework, especially for the initial controller design in the early stages of development.

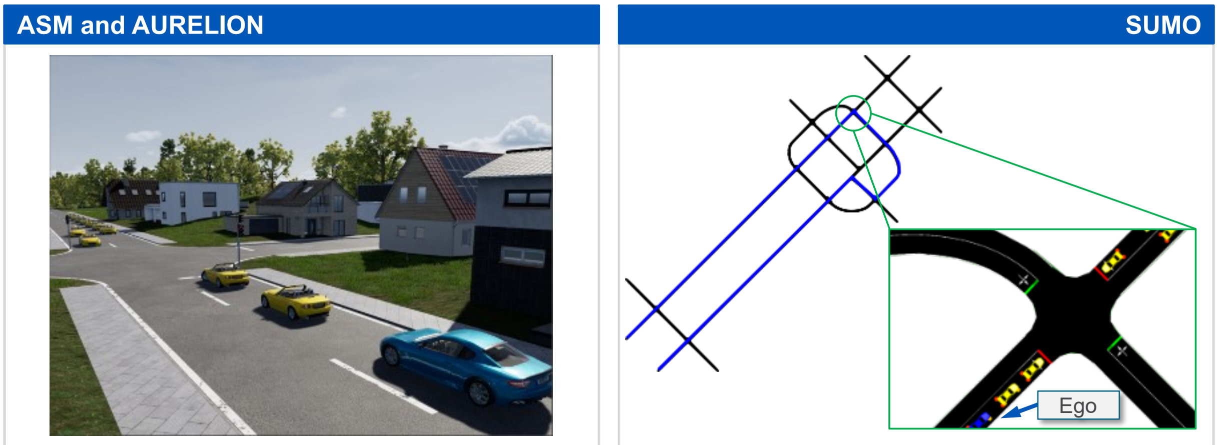
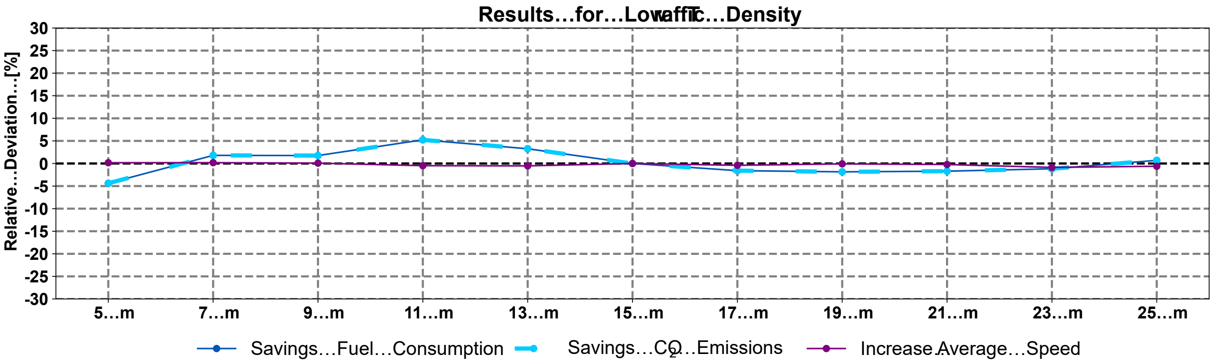
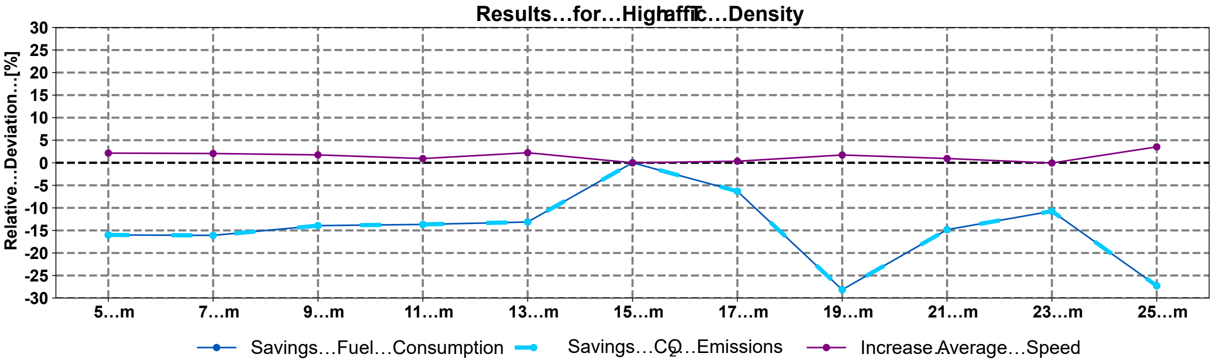


Figure 4. *Left: ASM Ego Vehicle (Blue) in AURELION for Visualization and Sensor Simulation, Right: SUMO Network With the Route of the Ego Vehicle Highlighted in Blue.*

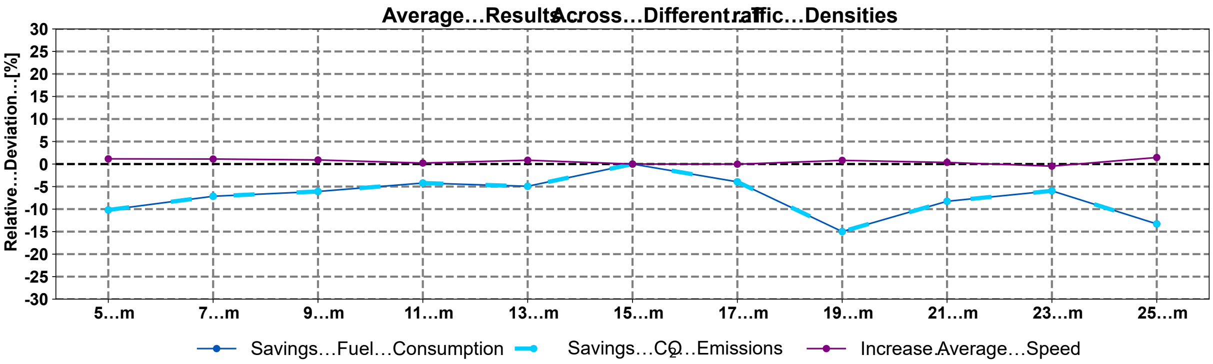
As metrics for the evaluation, the savings in fuel consumption, CO_2 emissions, and the increase in the average speed of the ego vehicle are defined by referring to the medium value of 15 m. Positive values imply efficiency savings and increased speed. The results of the sensitivity analysis depending on the different parameters of the distance control are shown in Fig. 5a–b for low and high traffic density. For the sake of clarity, the average deviation across the different traffic densities is computed for all three evaluation metrics, as illustrated in Fig. 5c. Thereby, the two levels of traffic density are weighted equally. The sum of all three metrics with the previously averaged deviations defines the final key performance indicator (KPI) *Total Average Deviation* for the optimization process. The resulting KPIs for each distance threshold are used for a cubic spline interpolation to generate a continuous function that is maximized. Referring to Fig. 5d, the optimization provides the best value for a distance of ca. 15 m. Please note that the extended ACC functionality, which is capable of driving in suburban areas, is still at an early stage of development. Together with the randomly generated traffic, collisions may occasionally occur.



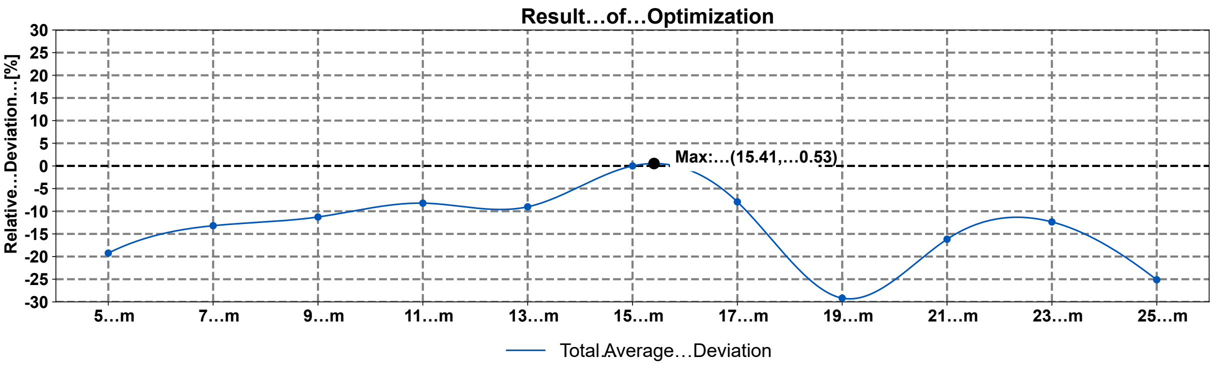
(a) *Results of Parameter Variation for Low Traffic Density.*



(b) *Results of Parameter Variation for High Traffic Density.*



(c) *Average Results Across Different Traffic Densities.*



(d) *Result of Optimization.*

Figure 5. *Results of Parameter Variation for Different Traffic Densities and Optimization.*

5. Conclusion

This paper presented a methodology extending the limitation of microscopic traffic simulation in the field of efficiency analysis while considering complex vehicle dynamics in combination with a soft ECU. For this purpose, SUMO was coupled with the submicroscopic tool ASM from dSPACE. Having addressed the need for detailed modeling of the powertrain and introduced existing frameworks, the authors presented the developed co-simulation framework. First, the essential elements of the ASM architecture were described, followed by the method of movement orchestration between both simulation environments. As a significant part of traffic simulation, the approach of traffic light synchronization was outlined, matching the corresponding traffic signal phases between ASM and SUMO. In addition, the framework is structured to allow for the implementation of MIL, SIL, and HIL simulations.

The proposed framework was applied to a case study investigating parameter optimization of the distance threshold of an ACC controller. The study was conducted using a sample network with different traffic demands. As this study is considered a demonstrator for a possible application of the framework, the authors do not claim generalized transferability of the results but rather emphasize the possibilities of this approach. Besides the efficiency aspect, the proposed co-simulation bridge also offers the possibility to simulate sensing technology in a 3D environment, with SUMO providing realistic traffic situations.

Data availability statement

The presented analysis is not based on data.

Author contributions

Christopher Stang – conceptualization, formal analysis, investigation, visualization, writing-original draft, writing-review and editing

Dennis Roeser – conceptualization, formal analysis, investigation, methodology, software, validation, visualization, writing-original draft, writing-review and editing

Competing interests

The authors declare that they have no competing interests.

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