Integrated simulation of microscopic traffic flow and vehicle dynamics

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Abstract

This paper demonstrates a method for integrating microscopic traffic simulation and vehicle dynamics simulation using Simulation of Urban MObility (SUMO) and IPG CarMaker. The goal is to combine the specific strength of both types of tools and this goal is achieved using the Simulink interfaces that are available for both simulation tools. Two use-cases are presented to demonstrate these strengths and the potential of an integrated simulation of microscopic traffic flow and vehicle dynamics. In the first use case, the detailed vehicle dynamics simulation is used on a road stretch with high curvature to determine maximum speeds along the road. These speeds are afterwards transferred into the network of traffic flow simulation to achieve more realistic speed distributions. Within the second use case, the integrated simulation is used in order to test the detailed model of an automatic cruise control system with surrounding traffic that shows stochastic behavior and does not rely on deterministic maneuver planning.

Introduction

Many traffic control systems as well as vehicular systems are evolving from static systems to dynamic systems and are now moving towards connected systems. As an example, traffic signals relied on fixed-time signal plans in the beginning of their application. Today, stationary detection of vehicles is used for traffic responsive control. In the future, the connection of traffic signals and vehicles will enhance the data basis and enable speed advisory systems. The development of cruise control in the domain of driver assistance systems is comparable. Initially, static cruise control was brought to a dynamic level by introducing adaptive cruise control (ACC) with the usage of vehicular sensors. Again, further enhancements regarding safety, efficiency and comfort are to be expected by connecting vehicles, leading to a cooperative ACC. The increasing automation and connectivity of vehicles results in a closer integration of traffic control and vehicular systems. This leads, on one hand, to the further exploitation of traffic control actions that influence individual vehicles. On the other hand, vehicular systems can benefit from the close integration with traffic infrastructure and traffic control. Therefore, an increase of safety and efficiency for the individual vehicles as well as the overall traffic can be expected by connecting and automating vehicles.

Simulation tools are used to investigate such impacts and test vehicular systems and traffic control systems prior to their deployment. Due to increasing automation and connectivity of vehicles, not only vehicles and traffic systems are more integrated, but also an integration of simulation tools from both domains is required. Vehicle dynamics simulations represent the vehicle and its components with a high level of detail. They are mainly used to test and develop vehicular software. A typical use case is the parametrization of an electronic stability controller. On the contrary, microscopic traffic simulation tools rely on simplified vehicular models and can be used to simulate the behavior of a large number of vehicles in a road network.

Evaluating the impact of a new traffic signal control on travel times is a typical use case for microscopic traffic flow simulation.

Within this paper, an integrated simulation environment is created, in which the vehicle dynamics simulation software IPG CarMaker [IPG AUTOMOTIVE GMBH, 2016] is integrated with the microscopic traffic flow simulation tool Simulation of Urban MObility (SUMO) [KRAJZEWICZ ET AL., 2012]. Both simulations are run in a co-simulation mode so that visualization and results can be retrieved from both tools. The goal is to develop a methodology that enables the investigation of interdisciplinary research questions, such as the impact of a vehicular system on traffic flow or the traffic situations with which a newly developed vehicular system has to cope. This should ideally be done within an integrated workflow instead of the usually necessary simplification of vehicular software for testing within traffic flow simulation. Both, the suggested ideal as well as the typical workflow are shown in Figure 1. The simplification process of vehicular systems for traffic flow simulations (shown with a dashed arrow in Figure 1) does not only lead to a higher workload, but also limits the possibility of feedback from traffic impact assessment on the development of vehicular systems.

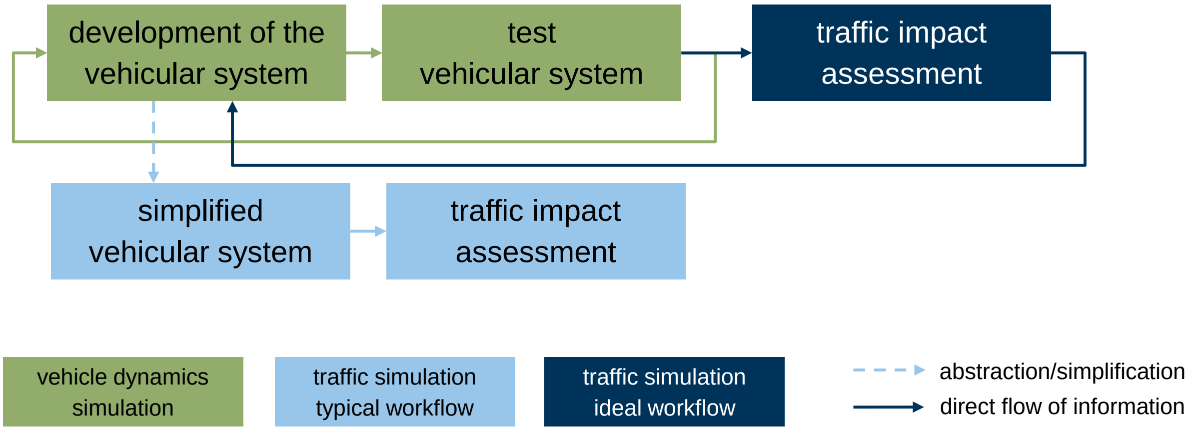

Figure 1 Ideal and typical workflow to investigate impacts of vehicular systems on traffic flow

Within the next chapter, the two simulation tools are described briefly. In chapter three, the integrated simulation model is explained in detail. In the fourth chapter, use cases for the newly developed integrated simulation are presented to demonstrate the potential of the chosen approach. The paper concludes with a summary and outlook.

Simulation of microscopic traffic flow and vehicle dynamics

Vehicle dynamics simulation tools that include a vehicular model with a high level of detail are used within automotive research and development. Examples of these detailed models include the kinematics of axles and steering and a tire model representing the driving dynamics of the vehicle. Vehicular software components, such as vehicle controllers, can be integrated and tested easily with the modelled hardware. Additionally, hardware-in-the-loop and software-in-the-loop allow for the testing of selected real components of vehicles in the virtual environment. To create a typical test run, the parametrized vehicle model, the road model as well as a maneuver definition are necessary. The maneuver definition requires input parameters such as desired speed, steering angle and desired braking force. Alternatively, a driver model can be chosen to follow a track. This type of maneuver definition leads to a deterministic behavior of the simulation where the same input parameters lead to the same results. Depending on the problem at hand, various tools exist to represent vehicle models and simulate their behavior in a virtual environment. Programming interfaces allow for the exchange of information during the run time and foster the integration of newly developed vehicular software. IPG CarMaker is one of the tools in this market and offers the aforementioned possibilities to the user.

For the simulation of traffic flow, detailed models of vehicle dynamics are not of major importance. In this type of simulation, accurate models describing the behavior of the drivers are priority. Within microscopic traffic simulation, single vehicles are the modelled entities and a large number of such vehicles can be simulated simultaneously. The underlying models represent human driving maneuvers and reactions to other drivers' behaviors, resulting in a realistic behavior of the overall traffic flow. This type of tools is mainly used to test traffic management strategies. Therefore, the resulting quantities include, for example, travel times, delay and capacity of a road. The traffic simulation is stochastic, all actions of a vehicle may influence the behavior of others and different random seeds lead to a statistical distribution of departure times and desired speeds of vehicles. The input to the simulation are traffic volumes and route choices in a road network as well as the basic distributions of vehicle speeds. The models of driving behavior can be parametrized and thus adapted to local conditions or calibrated to real measurements. Except for basic functions and limits of acceleration behavior and speeds, the vehicle dynamics are widely neglected in traffic simulations. SUMO is an open-source microscopic traffic simulation tool developed by the German research center DLR. It offers an interface for the external control of the simulation and the integration of external driver models. Within this work, the tool was used for the simulation of traffic and a programing interface was used for coupling the simulation with CarMaker.

Development of an integrated simulation model

The integrated simulation model was developed with Matlab/Simulink as both simulation tools offer the required interfaces. With CarMaker for Simulink an interface is available which provides access to the vehicle model and all quantities that are necessary in the traffic simulation. On the side of the traffic flow simulation, the programming interface TraCI4Matlab [ACOSTA ET AL., 2015] allows the interaction with SUMO using Matlab/Simulink.

As a preparation for the coupling of the tools, the road networks need to be identical in order to enable the exchange of position data. Two possibilities to create road networks for both simulation tools have been developed within this work. The first possibility relies on SUMO's functionality to import networks from OpenStreetMaps. A software script has been developed to translate the created SUMO network information, which is available in an XML format, into CarMaker's digitized road format. The second possibility uses information from KML files, which can be retrieved for example using Google Earth. The KML files can be directly read by CarMaker, but have to be translated into the SUMO XML format. Again, this transformation is achieved with a script. Apart from the road network, both simulation tools need their specific input values. These include the car setup and a basic maneuver for CarMaker and route choice and traffic flow for SUMO.

To establish the co-simulation, SUMO is used to simulate all vehicles within the network, including the ego vehicle that will be simulated by CarMaker. To enable the recognition of the ego vehicle in SUMO, this vehicle is given a unique ID. CarMaker simulates the movements of the ego vehicle and by retrieving the position, speed and angle of this vehicle these values are then updated within SUMO by using the TraCI command "moveToVTD". Therefore, all adjustments in the driving behavior of the ego vehicle or the integration of external controllers can be realized in CarMaker and are transferred into the SUMO environment. To enable traffic within the CarMaker environment, a fixed number of relevant surrounding vehicles is defined and named using their position, e.g. TFR for traffic front right. In total, nine vehicles are placed in the simulation as shown in Figure 2. Given the position of the ego vehicle, the surrounding vehicles can be identified by comparing the positions to that of the ego vehicle. During the simulation, the IDs, positions and speeds of the surrounding vehicles are retrieved and sent to CarMaker to update them within the CarMaker environment.

If no vehicle is found on either of the positions, the respective vehicle is moved outside of the network to its default position.

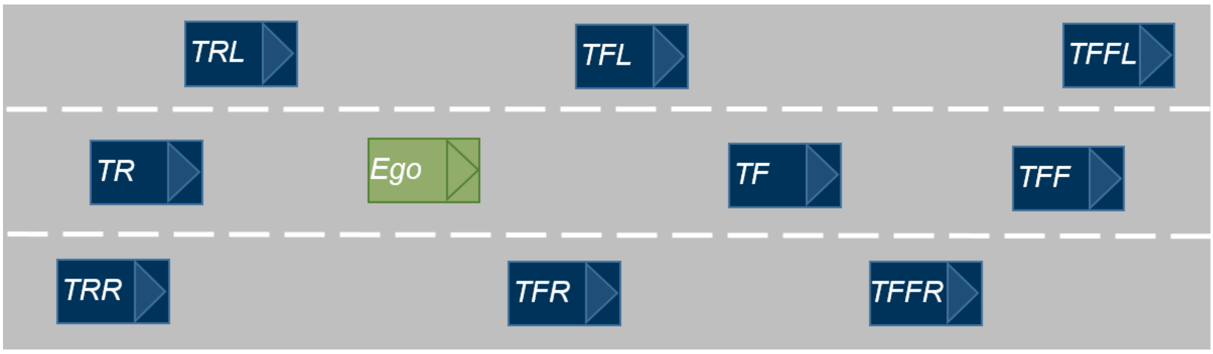

Figure 2 Position of surrounding vehicles for representation of traffic within the CarMaker environment

The different level of detail of the two simulation tools requires different simulation step sizes. While CarMaker for Simulink uses a step size of 1 ms, SUMO is usually run with a step size of 1 s since the underlying model is validated for this step size [KRAUß, 1998]. However, the step size of SUMO can be lowered for example to 0.1 s, which is done for this work. Therefore, the vehicle positions of surrounding vehicles within CarMaker will be updated only at these time intervals and interpolated in between using current speeds, positions and angles to prevent the vehicles from jumping. Accordingly, the position of the ego vehicle is updated within the SUMO simulation only at the interval of the SUMO simulation. In this way, CarMaker can be run with smaller simulation intervals compared to the SUMO simulation step size.

The simulation procedure is illustrated in the simplified flowchart given in Figure 3. To establish the communication with SUMO, Traci4Matlab is used and the necessary Matlab commands are coded within an S-Function to enable interaction with Simulink blocks such as the ones provided by CarMaker for Simulink.

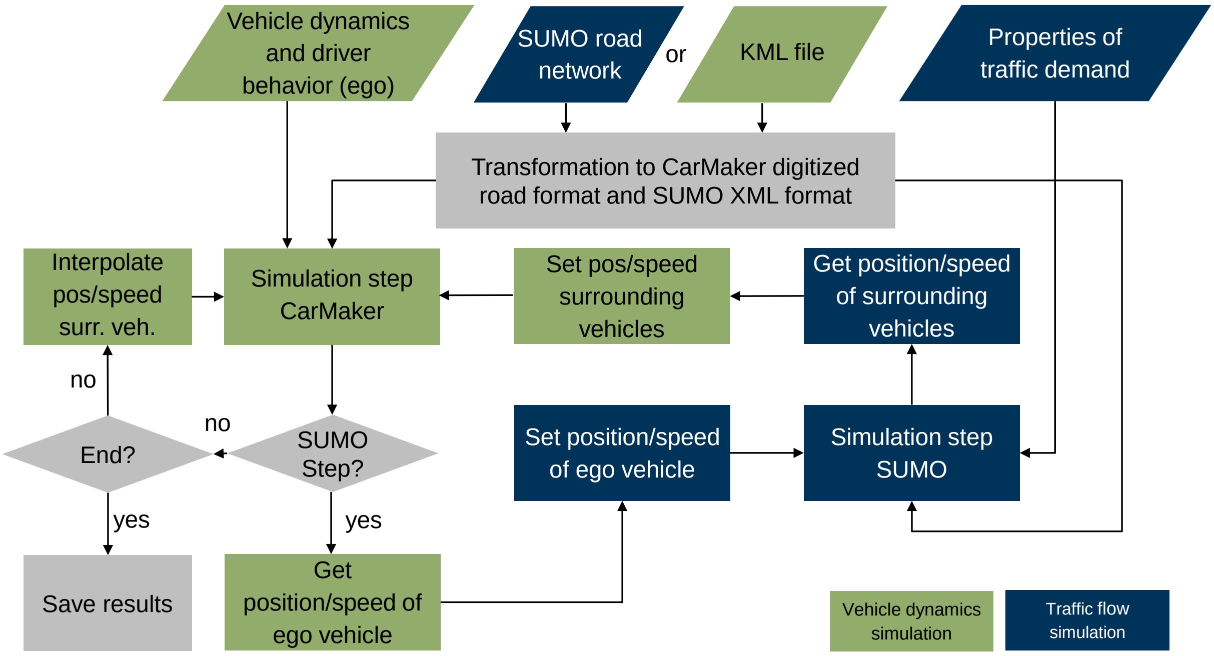

Figure 3 Flowchart of the integrated simulation environment

Use cases for the integrated simulation

The integrated simulation of traffic flow and vehicle dynamics makes it possible to combine the advantages of both types of simulation. It enables the simulation of a vehicle with a high level of detail including the dynamic behavior, sensors and driver assistance systems among others. On the other hand, with the traffic flow simulation it is possible to create traffic scenarios, making it possible to test the ego vehicle with its integrated vehicle controllers in traffic scenarios that are not pre-defined by setting up vehicle specific maneuvers. This makes it possible to test, for example, an assistant system such as the congestion assistant in dense traffic conditions without having to determine the maneuvers of all vehicles within the simulation. The traffic flow simulation defines the behavior of all traffic participants in the scenario and all vehicles will react to other vehicles' actions. The stochastic nature of the traffic flow simulation can lead to unplanned, but realistic events such as congestion, slower or faster vehicles in front, lane changes, etc. On one hand, the stochastic behavior together with a sufficient number of simulation runs guarantees statistically sound results regarding traffic impacts. On the other hand, unplanned events can produce valuable input for the development of vehicular systems that react to surrounding traffic. However, simulation scenarios can be reproduced exactly if necessary by setting a fixed random seed for the traffic flow simulation.

To demonstrate the potential of the co-simulation an ego vehicle was equipped with the ACC system that is provided in the CarMaker example library. A motorway stretch on A96 between Munich and Landsberg with a length of 12 km and two lanes per direction is chosen to perform simulation runs with an average traffic volume of 1400 veh/h. Figure 4 shows the speed profile of the ego vehicle for two simulation runs with a selected ACC speed of 44.44 m/s (160km/h). An initialization period of 200 s is used to fill up the simulation network with vehicles at random start positions. At that point the ego vehicle accelerates and its speed is adjusted due to the surrounding traffic that is simulated by the SUMO traffic simulation and recognized by the ACC system of the ego vehicle. Overtaking is enabled and activated by the IPG driver model if necessary.

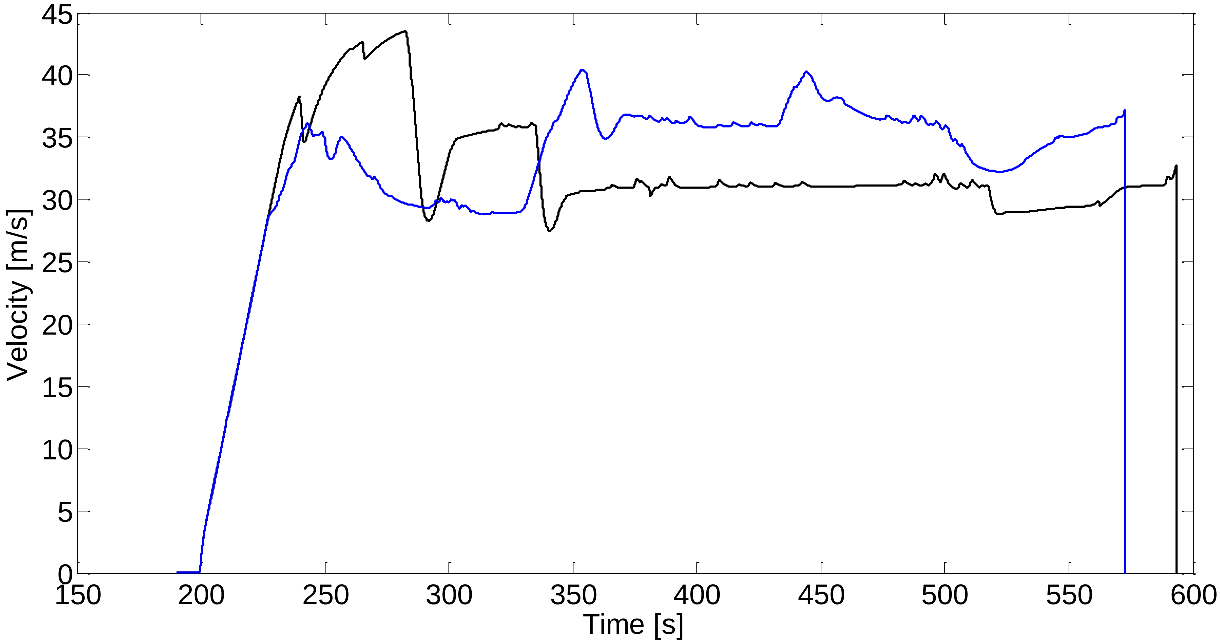

Figure 4 Speed profiles of the ego vehicle with enabled ACC in two different simulation runs

Besides the co-simulation discussed above, the traffic flow simulation can also benefit from the integrated vehicle dynamic simulation. Since both traffic flow simulation and vehicle dynamics simulation share the same road network, driving dynamics can be of great value to improve the behavior of the vehicles in SUMO. Usually dedicated measurements, manual counts or available data from infrastructural sensors are used to calibrate microscopic traffic flow simulation. Prior to the calibration process, often only speed limits are used to determine speed distributions of vehicles. Since the simulated vehicles generally do not consider the curvature of roads and lateral acceleration, their driving behavior is not adapted automatically. Hence, the vehicles in a traffic simulation will always try to reach a desired speed and only adapt it to other vehicles or infrastructural components such as traffic lights or speed limits. To avoid unrealistic behavior, areas of lower speeds can be included manually with significant workload. However, detailed speed measurements along a certain track are often missing, since usually only aggregated data on certain cross-sections (e.g. from loop detectors) or section based data (e.g. travel times) is available from infrastructural sensors. To ease the process of calibration, the vehicle dynamics simulation can be used. The ego vehicle is provided with a high desired speed and is driving along the network without considering traffic. Afterwards the minimum of the legal speed limit and the achieved speed of the ego vehicle can be used as the maximum speed for the traffic flow simulation, resulting in a more realistic traffic flow simulation.

A curvy stretch of rural road with a length of approximately 5 km on St2063 south of Munich is used as an example. The maximum speeds along the road are set to a maximum of 100 km/h or the maximum speed achieved during the test run with a single vehicle of CarMaker. This is done for two scenarios, one with a high friction coefficient (μ=1) and one with lower friction coefficient (μ=0.5) with activated electronic stability control to avoid instable driving conditions and to achieve lower speeds when necessary. The accepted lateral acceleration of the driver is set to 3 m/s². It should be noted here, that besides the curvature, also changes in road friction and the activation of electronic stability control cannot be easily represented in traffic flow simulation. The resulting speeds of the ego vehicle that are used as an input for the following simulation study are shown in Figure 5.

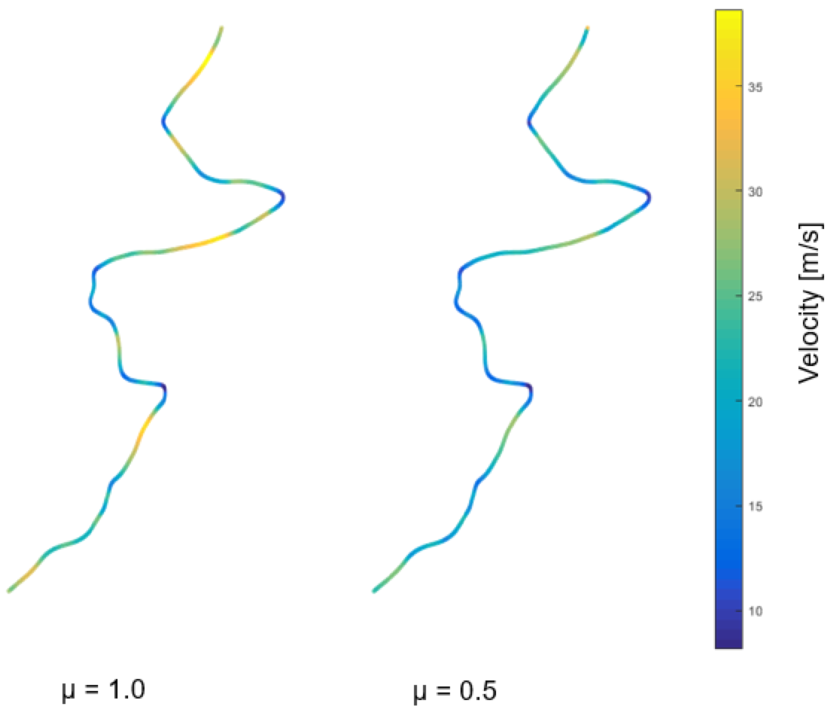

Figure 5 Curved road with achieved speeds of ego vehicles displayed in different colors

Afterwards, a microscopic traffic flow simulation study is performed with high traffic volume (ca. 1800 veh/h) and low traffic volume (ca. 500 veh/h) for each of the following three scenarios:

- default speed (100 km/h)
- achievable speeds with µ=1.0 capped at 100 km/h
- achievable speeds with µ=0.5 capped at 100 km/h

A total of ten simulation runs with a length of 7200 s per scenario have been performed with different random seeds. After 3600 s for filling the network, the travel times along the road stretch are measured and the results are shown in Figure 6.

It can be seen that the travel times increase considerably when using the information about the achievable speed due on the road stretch. The effect gets more relevant when raising traffic flow to 1800 veh/h since congestion is generated upstream of tight curves where speeds are low. However, the lower friction coefficient does not lead to a considerable increase in travel times.

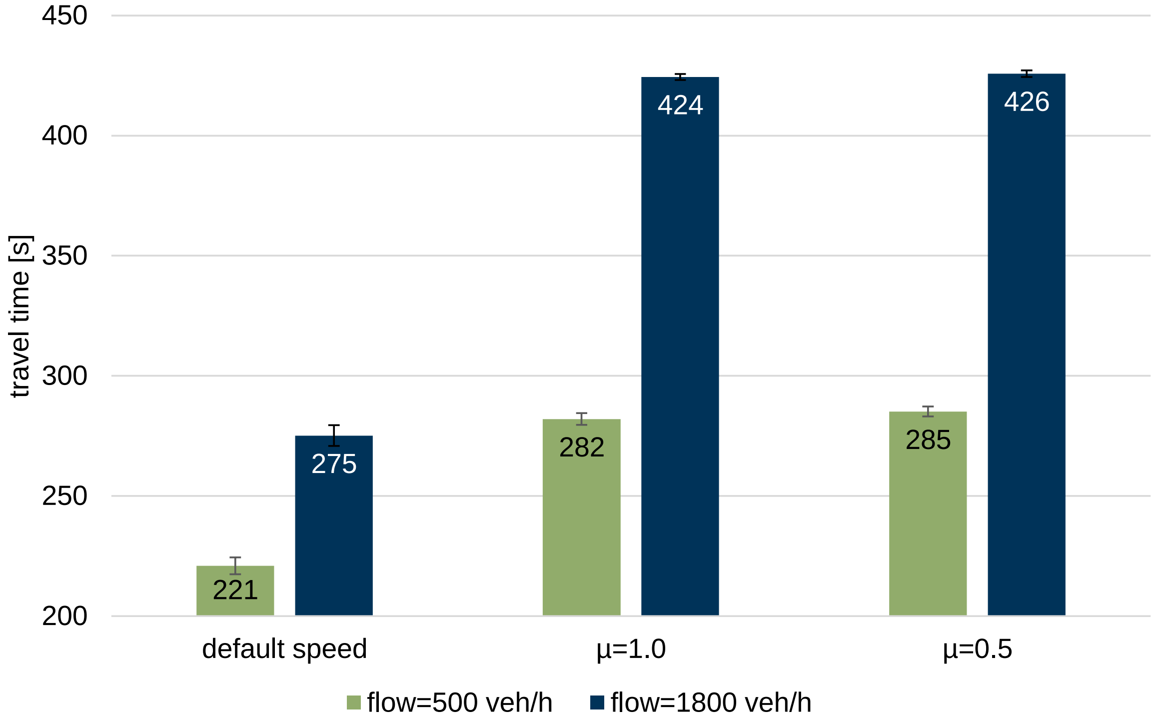

Figure 6 achieved travel times on a rural road for different traffic flows and different friction coefficients

Summary and Outlook

In this paper, an integrated simulation environment of microscopic traffic flow and vehicle dynamics is described. This is done in order to deliver a tool for interdisciplinary research questions that address both vehicular and traffic systems. The microscopic traffic simulation tool SUMO is used for simulating the traffic flow. The vehicle dynamics of a single vehicle are modeled and simulated with the help of IPG CarMaker. The simulations were run in co-simulation mode and exemplary use cases were identified to show the potential benefit of an integrated simulation.

The integrated simulation of traffic flow and vehicle dynamics shows major advantages for users of both tools. Within traffic flow simulations, where vehicle dynamics are widely neglected, improvements can be made for a more realistic driving behavior of vehicles based on the results from a vehicle dynamics simulation. Within the vehicle dynamics simulation, where the representation of traffic is mainly done by defining driving maneuvers for each of the vehicles in the simulation, the integrated simulation model helps representing random traffic.

As such, it is possible to identify new and unplanned events, which can result in valuable feedback for the development process of vehicular systems, which could not be found with the pre-defined maneuvers. The integration of the two types of simulation tools helps to solve interdisciplinary problems.

The simulation results presented in this paper demonstrate possible use-cases and the resulting benefits for automotive and traffic engineering. However, it would be meaningful to validate the achieved results with field measurements. Another interesting addition to the work described in this paper would be the integration of more than one vehicle from a vehicle dynamic simulation into a traffic simulation. Additionally, further improvements could be made by considering the newly developed Road 5.0 representation of road networks from IPG. As a result, it would be possible to represent urban traffic infrastructure such as complex intersections and different traffic signal control systems in CarMaker by making use of the data basis of the traffic flow simulation. The traffic flow simulation, which uses models to describe the behavior of vehicles at conflict points among others, would make it possible to create more realistic traffic scenarios even in a complex urban environment.

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