# Multi-Resolution Traffic Simulation for Large Scale High Fidelity Evaluation of VANET Applications

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***Abstract*—This paper presents an approach for coupling traffic simulators of different resolutions in order to conduct both large scale and high fidelity virtual evaluations of Advanced Driver Assistance Systems based on Vehicular Adhoc Networks. The emphasis is put on the need for such an attempt to satisfy the constraint of performing simulations in real time. Both, the methods to accomplish this as well as the resulting performance are described.**

## I. Introduction

Vehicular Adhoc Networks (VANETs) have attracted a lot of research attention over the last years due to the potential improvements in traffic safety, efficiency and driver comfort. A high variety of applications, commonly referred to as Advanced Driver Assistance Systems (ADAS), such as cooperative driving and subsequently automated driving, can only be enabled through wireless communication between the vehicles on the road.

Before deploying large-scale of such systems, which often exhibit safety-critical features, in series production on a large scale a lot of effort has to be put into testing and validation. Although real test drives using physical testbeds of prototype vehicles offer the highest degree of realism, the large amount of financial, material and human resources needed to perform large-scale and extensive testing of vehicular networks render their use rather impossible. Due to this, simulations are employed for obtaining a view of the performance of such solutions in large-scale virtual environments. As well, simulation-based evaluation techniques particularly allow testing of those complex systems in a wide variety of dangerous and critical scenarios without putting humans and material at risk while at the same time being less resource-intensive.

In the automotive industry the use of simulation is well established in the development process of traditional driver assistance and active safety systems. However, the current emphasis is primarily on the simulation of individual vehicles at a very high level of detail [1]. When investigating and evaluating the performance of ADAS based on vehicular communication, this isolated view of a single vehicle alone or a small number of vehicles in the simulation is not sufficient anymore. Potentially every vehicle equipped with wireless communication technology is coupled in a feedback loop with the other road users participating in the vehicular network and therefore the number of influencers which need to be taken into account is drastically increased.

These considerations lead to a trade-off between the accuracy in terms of the simulated level of detail of each vehicle and the scalability in terms of the number of vehicles that can be simulated with the computing resources available. In this paper we present an approach on how to solve this trade-off by coupling multiple resolutions of traffic simulations to get highly accurate simulation results where it is necessary and simultaneously achieving an efficient simulation of large scale scenarios.

The rest of this paper is organized as follows. The testing and evaluation of real-world implementations of ADAS imposes a certain set of additional requirements, which are discussed in section II before giving an overview of the related work. Section III describes the concept of our multi-resolution traffic simulation approach. In section IV we evaluate the performance by means of an exemplary scenario. In section V we discuss the limitations of the approach and conclude the paper in section VI.

## II. Background and Related Work

Before we proceed to the discussion of related work, it is essential to illustrate our scope and area of application. In order to evaluate and validate real implementations of ADAS in a simulated, virtual environment, both state and behavior of the vehicles must be modeled and simulated in high fidelity. We define the term *high fidelity* as a three-dimensional problem:

To substitute the real vehicle by its simulated counterpart, the virtual vehicle must provide its state variables in a *sufficient range*, in *sufficient precision* and in a *sufficient temporal resolution*. The concrete manifestations of these three requirements depend on the respective use case. For example a Cooperative Adaptive Cruise Control (CACC) system will need, among others, the dynamic state of the vehicle (e.g. speed, acceleration, position), powertrain state, RADAR sensor values as well as the input from the wireless communication channel at different sampling rates [2]. If any of these requirements is not met, e.g. a necessary state variable is not covered by the simulation model, simulative testing can not be performed.

Since the range of wireless communication technology is higher than what can be achieved through conventional sensors, even vehicles which are farther away can act as relevant information sinks and sources and therefore influence the driving assistance system as well as the road traffic system as a whole. In order to capture these effects in the simulation, a naive approach would be to simply scale existing, high detailed simulations by increasing the amount of vehicles in the simulated area. However, these high-detail simulations are extremely computationally intensive and hence are not suitable to perform evaluations of large-scale scenarios in a reasonable amount of time. This also prohibits their use in hardware-in-the-loop simulations where a real time constraint must be fulfilled [1].

This additional timing requirement conflicts with the aforementioned three dimensions of simulative high fidelity. There are numerous references that deal with similar issues in the fields of traffic simulation, VANET simulation and multi-resolution simulation. In the following we give a brief overview of those research areas in order to state the fundamentals of this investigation:

### A. Traffic Simulation

Road traffic simulations can generally be subdivided into the following four categories according to the level of detail [3], [4]: Macroscopic, mesoscopic, microscopic and nanoscopic. While macroscopic flow models describe traffic at a high level as aggregate flows, microscopic simulations model the behavior and interactions of each simulated entity individually with specific state variables such as position, speed and acceleration. Mesoscopic models are medium-detailed models where traffic is usually represented by queues of vehicles. In nanoscopic models, which are also referred to as submicroscopic models, an even higher level of detail is achieved through the subdivision of each vehicle in multiple subunits. This allows to model for example the vehicle dynamics, complex decision processes of the driver or the interaction with the vehicle surroundings more accurately. The necessary amount of computation time for the traffic simulation rises considerably with the increasing degree of detail.

### B. VANET Simulation

The usual strategy to simulate VANETs found in literature is to bidirectionally couple a network simulator and a microscopic traffic simulation. Following this approach the interactions between road traffic and network protocols are represented and the mutual impact can be explored [5], [6]. The majority of research publications focuses on the investigation of low level networking subjects such as medium access [7] or rather high level concepts of applications such as reducing $CO_2$-emissions [8]. For this kind of studies it is sufficient to apply realistic mobility patterns originating from the microscopic traffic simulation. In this bird's eye view of the overall system it is not necessary to model individual cars in the high level of detail mentioned above because the accuracy of the vehicle representation has a negligible influence on the simulation results of the vehicular network. Therefore the three requirements of high fidelity in terms of modeling and simulation individual vehicles need not be considered when simulating VANETs on such an abstract level.

### C. Multi-Resolution Simulation

Multi-Resolution Modeling (MRM) is defined as the combination of different models of the same phenomenon at different levels of resolution which are then executed together [9]. This methodology allows to find a good balance between simulation accuracy and computing resources. High resolution models, which provide accurate simulation results at the cost of high computational efforts, are only applied in limited areas of interest whereas the major part of the simulation is handled by less acurate but also less resource consuming low resolution models. However, not only the difference in execution speed can be exploited but also the fact that low resolution models tend to give a better overall understanding of the system under examination because of their rather abstract view of the big picture.

MRM has been successfully applied in road traffic simulation. In [10] a combination of a microscopic simulation modeling the inter-vehicle interactions and a computationally less expensive macroscopic simulation applied to freeways is described. This allows a scalable, yet accurate investigation of traffic flow in large scale networks. This approach is not applicable for VANET simulations since due to the flow-based simulation in macroscopic models accurate vehicle positions are missing which is crucial when simulating vehicular networks. In [11] a coupling of two different microscopic traffic simulators of different accuracy is implemented for VANET simulation to exploit the difference in execution speed. In [11] and in [12] the areas of interest are fixed throughout the simulation, for example road intersections are simulated at a higher level of detail than freeways. In contrast to that, the areas of interest are not statically fixed in [13] but rather depending on the simulation context.

### D. Combining Traffic and Driving Simulation

A rather recent research direction is the combined simulation of both traffic and driving simulation. A co-simulation of a microscopic traffic simulation and a driving simulator [14] respectively a robotics simulator [15] has been investigated. In these approaches the behavior of a fixed subset of all vehicles is "remote controlled" through an external simulator, which allows to have a predefined number of detailedly simulated vehicles to be surrounded by a large number of microscopically simulated vehicles.

## III. Novel approach for Multi-Resolution Traffic Simulation

### A. Dynamic Spatial Partitioning of Simulated Area

Our approach aims to couple traffic simulation models of different resolutions at dynamic regions of interest. Contrary to conventional traffic simulation we are not interested in investigating a large number of vehicles from a bird's perspective but the focus is rather on a single vehicle or a limited number of vehicles which are used to conduct a test drive in a virtual environment. In the following we will refer to this kind of vehicle as the EGO car. The ADAS under investigation is imagined to be on board of such an EGO car. The simulated measurements and sensor values are fed into the ADAS.Depending on its type and its use case, the respective ADAS directly or indirectly influences the vehicle's state and behavior.

As stated before, all surrounding vehicles both near and far away from the EGO car need to be taken into consideration because of the wide range of transmission on the wireless communication channel. However, we can distinguish between highly relevant and less relevant vehicles. This distinction is based on the criterion of the respective distance between the vehicles to the EGO car. Nearby vehicles are inherently of more relevance because they pose a higher danger in terms of possible collisions and because their messages transmitted on the vehicular network are of higher importance due to the vicinity of their origin.

Based on this distance criterion an area of interest is defined which is centered around the EGO car and in which the defined simulative high fidelity requirements must be fulfilled. Since the EGO car is driving continuously through the virtual environment, this area of interest is being moved along likewise. We therefore partition the global area of the simulation dynamically into a High Resolution Area (HRA) and a Low Resolution Area (LRA). Figure 1 shows a schematic view of the dynamic spatial partitoning. There the HRA is defined as the area of a circle which is centered around the EGO vehicle. Red vehicles are within that circle and are therefore simulated in high resolution by the nanoscopic simulator, whereas the green vehicles are outside of the circle and are consequently simulated in low resolution by the microscopic simulation. All vehicles exist in the microscopic simulation but in the nanoscopic simulation only the high resolution vehicles are contained and their movements are applied to their "proxy counterparts" in the microscopic simulator.

Due to the dynamic nature of road traffic the EGO car, the high resolution vehicles as well as the low resolution vehicles are permitted to move continuously. The classification of the assigned resolution mode is therefore performed after each time step of the simulation. Vehicles for which the classification has led to a change in resolution are transferred to the appropriate simulator. This change of resolution is possible in both directions at every time step. However, since the HRA is defined to be centered around the EGO car, it is always simulated in high resolution.

In order to prevent vehicles which are close to the boundary between HRA and LRA from oscillating very frequently between the two resolution areas, a hysteresis controller as depicted in figure 2 is applied in the classification process. As shown in figure 1 the two thresholds $R_{in}$ and $R_{out}$ are defined. A vehicle is transferred into the high resolution simulation only if its distance to the EGO car falls below the value of

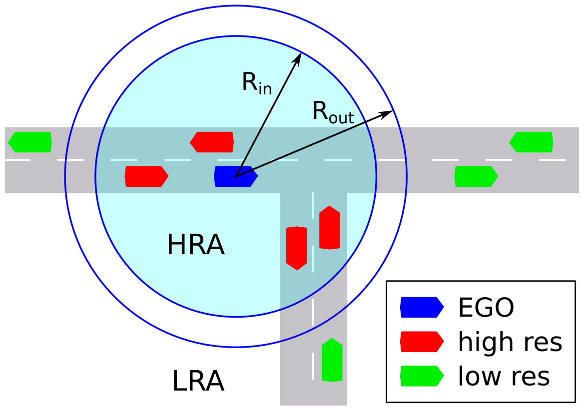


Fig. 1. Dynamic Partitioning of Simulated Area

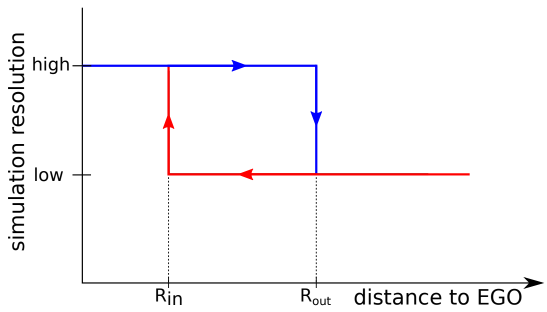


Fig. 2. Hysteresis control of the simulation resolution

$R_{in}$. The exchange back to the low resolution simulation is carried not out until the threshold $R_{out}$ is exceeded.

The difference in simulation resolution switching is shown in figure 3 by an exemplary trajectory. Without the hysteresis the change in resolution is performed multiple times, whereas when applying the hysteresis controller the vehicle stays in the high resolution model while being close to the boundary.

The extent of $R_{in}$ defines the circumcircle in which vehicles are simulated by the nanoscopic simulator. This value needs to be determined separately for each application scenario, for example in an urban scenario due to the expected low traffic speed a lower value can be used than what is suitable for a freeway scenario. As an alternative to the definition of a fixed size the value of $R_{in}$ can be determined dynamically at simulation runtime, for example based on traffic speed, volume of traffic or even depending on the currently available computing capacities.

The gap $R_{out} - R_{in}$ defines the size of the hysteresis window for the dynamic change between the two simulators. $R_{out}$ can be selected in both absolute and relative terms in relation to $R_{in}$ and exhibits a lower dependence with regard to specific scenarios and traffic speeds.

Our approach of dynamic spatial partitioning of the simulated area enables us to allocate the processing resources between the simulators. As the focus is only on a relatively small region of the simulated area we achieve both a simulative high fidelity in this region of interest and the simulation of

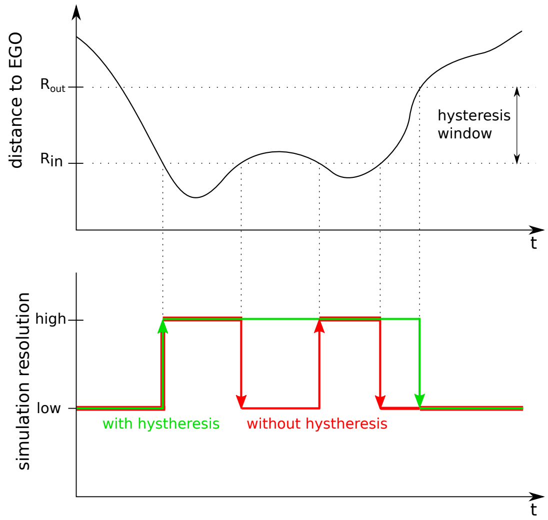


Fig. 3. Comparison of simulation resolution switching

large scale scenarios.

### B. Utilized Simulators

In the following we describe the concrete manifestations of the simulators which we combine using the above described concept to achieve a multi-resolution traffic simulation.

*1) Microscopic Traffic Simulator - SUMO:* We chose to use Simulation of Urban MObility (SUMO) as the traffic simulator responsible for the simulation of the LRA. SUMO is a microscopic, space-continuous and time-discrete simulator. While it is employed in a wide range of research domains, its most notable use is shown in a high number of research papers regarding VANET simulations [16]. SUMO is well known for its high execution speed as well - being open source - its extensibility. In [17] it is reported that it can handle 200,000 vehicles in real-time when using timesteps of 1 second. Due to its efficiency, which is partly achieved through its simplified driver model[18], SUMO is ideally suited to simulate a high number of vehicles residing in the LRA.

*2) Nanoscopic Traffic And Vehicle Simulator - VIRES Virtual Test Drive:* We employ the nanoscopic traffic and vehicle simulator VTD for the simulation of the high resolution vehicles. VIRES Virtual Test Drive (VTD) has been developed for the automotive industry as a virtual test environment used for the development of ADAS [19]. Its focus lies on interactive high-realism simulation of driver behavior, vehicle dynamics and sensors. VTD is highly modular, so any standard component may be exchanged by a custom and potentially more detailed implementation. Its standard driver model is based on the intelligent driver model [20], however an external driver model may be applied if necessary. The same concept applies to the vehicle dynamics simulation, where the standard single-track model can be substituted by an arbitrarily complex

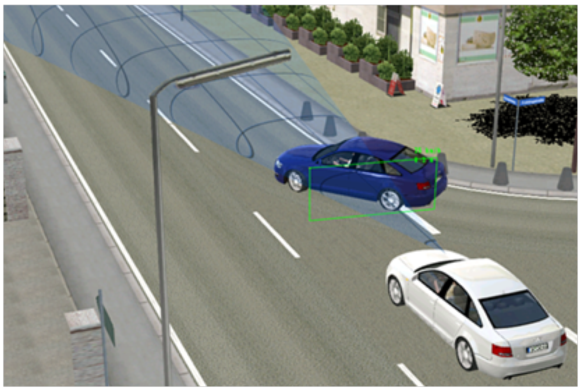

Fig. 4. 3D visualization of a simulated RADAR sensor in VTD

vehicle dynamics model adapted for specific vehicles. Each simulated vehicle can be equipped with arbitrary simulated sensors, for example a RADAR sensor, which is shown in figure 4.

While VTD is designed for online operation, it is however not suited to simulate a large number (i.e. thousands) of vehicles with respect to real time due to the details and complexity of the simulation. Therefore only the EGO car as well as the vehicles residing in the HRA are simulated by VTD.

### C. Coupling concept

*1) offline preprocessing:* Both simulators rely on different data formats representing the modeled road network. In order to be able to run a co-simulation of both simulators the underlying data basis has to match. VTD uses the OpenDRIVE[1] format to specify the road network. This specification models the road geometry as realistically as possible by using analytical definitions. SUMO on the other hand approximates the road network by line segments. There are additional differences in the modeling of intersections and lane geometries. To achieve a matching database we convert the road network in an offline preprocessing step from OpenDRIVE to the file format SUMO supports. This causes a loss of precision, whose impacts are described in the following section.

*2) online coupling and synchronization:* The coupling of the simulators at simulation runtime is based on the master-slave-principle. Figure 5 shows this sequence of operations during a single simulation step, in which VTD und SUMO can operate with different temporal resolutions. $s_{VTD}$ is the length of a time step for the HRA, whereas $s_{SUMO}$ is the length of a time step for the LRA. Typically, the nanoscopic simulation is run at a higher frequency than the microscopic simulation. $t_{VTD}$ respectively $t_{SUMO}$ denote the local simulation time in each simulator. At the beginning of each simulation step a new time step is simulated in VTD. If the next time step has been reached for SUMO and therefore the condition $t_{VTD} \geq t_{SUMO} + s_{SUMO}$ is fulfilled, the state of the high resolution

[1] http://www.opendrive.org

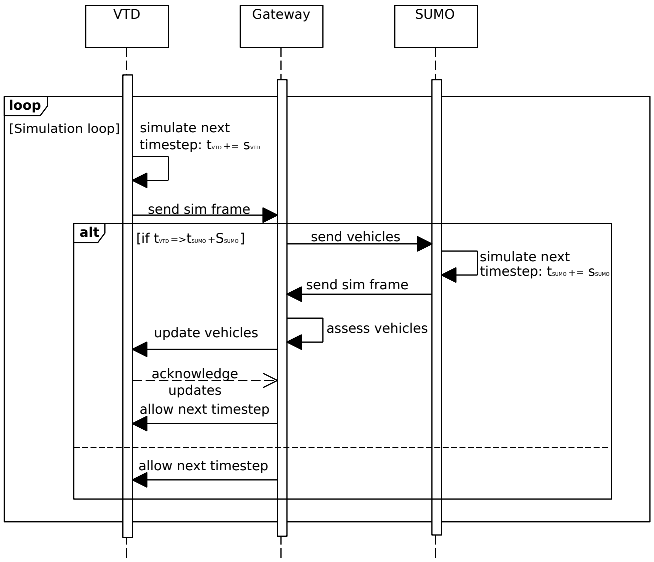


Fig. 5. Synchronization

vehicles is sent to SUMO through a gateway. It then triggers the simulation of the next timestep in the low resolution model and as a result the positions of the low resolutions vehicles are passed back. These vehicles are now classified according to section III-A and, if applicable, the change of resolution is performed for individual vehicles. When an exchange of a vehicle between the simulators happens, the previously mentioned inherent difference in the underlying road network may cause problems if a vehicle can not be mapped based on its position on a specific lane due to difference in accuracy. This is especially true for complex intersections which are modeled quite differently.

After all resolution changes have successfully been completed the simulation is unblocked again and the next time step can be simulated. This synchronization is very important to ensure reproducible simulation results across multiple simulation runs.

### D. Implementation

The gateway depicted in Figure 5 is implemented as a dynamic plugin for VTD written in C++. It uses the TraCI network interface [21] provided by SUMO to control the vehicles of the microscopic simulation.

### E. Generalization of the Approach

While the description in section III-A focuses on the simulation of a single EGO car, the concept can be generalized as follows. Generally speaking multiple EGO cars can be simulated analogously and can exist either in separate or in joined areas of high resolution. The dynamic spatial partitioning concept is not necessarily limited to having only two different simulators forming the multi-resolution simulation but even more simulators could be added to the synchronization scheme in figure 5.

The definition of the area of interest is also not limited to a circle. The circle was chosen due to its simple definition and fast distance calculations in the classification process, but the HRA could be represented by arbitrary complex shapes. As another generalization, the classification process need not only be based on pure geometrical calculations but could also be enriched with logical conditions, for example on a freeway vehicles driving on oncoming lanes could be excluded due to their limited relevance to the EGO car.

## IV. Evaluation

### A. Scenario and Simulation Setup

A synthetic scenario was created for testing the coupling concept and evaluating its performance. It consists of a single straight road running west to east with a length of 50 kilometers and two lanes, one for each direction. Each lane is configured to have a constant inlet of 1000 vehicles per hour heading either east or west. The EGO car is located near the start of the road. It drives from west to east and is followed by a traffic flow and heading to the oncoming traffic flow. This artificial road was first modeled in the OpenDRIVE format and was then converted to the SUMO road network format.

We performed two series of experiments. In the first series, the nanoscopic traffic simulator VTD was applied to the whole simulated area. In the second series we used the described multi-resolution concept to partition the simulation area between VTD and SUMO. We chose a timestep of $t_{VTD} = 20\ ms$ for the high resolution area in VTD and a timestep of $t_{SUMO} = 1\ s$ for the low resolution area in SUMO. The hysteresis thresholds which define the dynamic area of interest were set to $R_{in} = 500\ m$ and $R_{out} = 550\ m$.

Both simulators are executed on the same computer which is equipped with an Intel Xeon CPU E5-1620 at 3.60 GHz and 16 GB of RAM. The operating system is Ubuntu Linux 14.04 with a 3.13 64bit kernel. We used VTD version 1.4.1 with 3D rendering disabled and a custom branch of SUMO v0.21 that incorporated an in-work version of the methods needed to exchange vehicles between VTD and SUMO.

### B. Performance Evaluation

We measured the duration it takes to perform each simulation step over the simulation period of 1800 seconds while the number of vehicles is constantly being increased. Each series consists of five separate simulation runs to account for fluctuations in the measured execution times. To illustrate the trends of the measurements more clearly the moving average is also displayed in the following figures.

Figure 6 shows the performance development of the nanoscopic simulation while increasing the simulated vehicle count over the simulation period. The duration of each simulation step is almost constant up to a count of 70 vehicles. Until then, the duration is around 12 ms, which is less then the timestep length of 20 ms and therefore yet fulfills the real time constraint. At around 150 vehicles, the duration is beyond these 20 ms and real time simulation is not possible anymore. With increasing vehicle count the duration for each

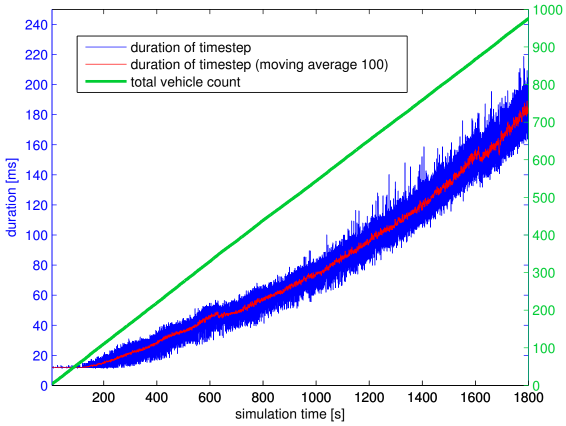


Fig. 6. Simulation Performance - nanoscopic simulation only

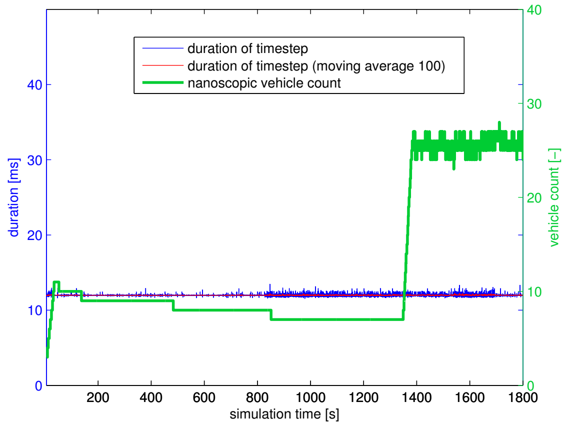


Fig. 7. Simulation Performance - multi-resolution simulation

timestep also considerably increases and reaches 180 ms at the end of the simulation period. This results in an increase of factor 15 compared to the amount of computation time at the beginning of the simulation. The overall simulation took over 120 minutes to complete, which is 4 times more than the simulated time.

Figure 7 shows the performance development of the multi-resolution simulation in the same simulation scenario over the same simulation period. While the total vehicle count is increased the same way as in the pure nanoscopic simulation, the separately plotted nanoscopic vehicle count illustrates the amount of cars which are within the high resolution area. It shows that reducing the nanoscopic model's area of interest fulfills the aim of reducing the overall simulation time. After a local maximum of 11 nanoscopic cars is reached this count decreases slowly since slower vehicles are left behind the faster moving EGO car. At around simulation time 1350 seconds the two traffic flows from each end of the road meet in the middle of the road, which then increases the nanoscopic vehicle count. However, due to the limited extent of the HRA the nanoscopic vehicle count does not exceed a certain limit, which for the given configuration is at around 27 vehicles. The duration for the time steps stays on average constant around 12 ms, so it can be seen that the overhead resulting from the coupling of the two simulators is negligible as is the execution time of the microscopic simulator due to its less detailed yet much more efficient simulation model. The overall simulation took less than 18 minutes to complete, so the simulation is faster than real time by factor 1.66. The real time constraint is fulfilled throughout the whole simulation period.

## V. Discussion

The above shown performance evaluations state that the multi-resolution approach leads to the desired goal of a highly detailed simulation in the region of interest while maintaining a high overall performance. However, there are additional concerns, which we cover in the following.

When switching between resolutions and simulators, maintaining simulation consistency is of utmost importance [22]. The change of resolution from high to low can generally be handled rather simply by losing information through a transformation function. The opposite direction though is problematic. The presented approach will face a consistency problem when using vehicle dynamics models with a higher level of detail. When switching from low to high resolution only a minimal subset of the state variables (position and speed) is available. The remaining state variables (pitch and roll angle of the car body, engine torque, current gear, etc.) must be somehow interpolated to reach a valid state in the simulation model.

Additionally, simulating using the nanoscopic traffic simulator naturally requires a high resolution representation of the simulated area, especially the road network, but furthermore a 3D model of the environment if this is necessary for the employed sensor models. Microscopic simulation usually works with rather coarse road networks, which are available publicly from sources like OpenStreetMap[2]. Nanoscopic simulation however has additional requirements, e.g. the continuity between road segments due to the vehicle dynamic simulation, which need to be satisfied. Obtaining the data basis in the necessary detail is not always directly possible and can cost an additional amount of time and money.

## VI. Conclusion

In this paper we proposed a concept for coupling traffic simulators of different simulation resolutions to achieve a multi-resolution traffic simulation which focuses on a dynamically determined area of interest. The presented methodology partitions the simulation area into a variable, highly detailed region of interest represented by a nanoscopic model and the surrounding area simulated at low resolution by a microscopic model. The evaluation shows a dramatic reduction of computation time in comparison to a pure nanoscopic simulation of the same simulation dimensions, which even makes real time simulation possible. This divide-and-conquer strategy enables accurate, realistic and large scale testing and validation of

[2]http://openstreetmap.org

real implementations of driver assistance systems based on vehicular networks in a virtual environment. As the next steps, we are investigating the application of the multi-resolution simulation methodology for the other domains relevant for the simulation of vehicular networks, namely network simulation and application emulation, to model the whole system across all domains efficiently at high fidelity.

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