Examining the impact on road safety of different penetration rates of vehicle-to-vehicle communication and adaptive cruise control

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***Abstract*—In recent years, significant attention has been paid to the implementation of cooperative driving by means of the integration of Advanced Driver Assistance Systems (ADAS) and Vehicle-to-Vehicle (V2V) communication, which has led to a wide range of applications with the potential to enhance road safety and prevent traffic accidents. Prior to the implementation of these systems in vehicles, comprehensive analysis through exhaustive and realistic simulations is vital. Accordingly, this paper presents the effects on road safety of a variety of penetration rates of vehicles equipped with ADAS and V2V, either separately or combined, using the simulation platforms Scene Suite and Simulation of Urban Mobility (SUMO). A total of six simulation scenarios were developed, three for intersections and three for urban cases. The obtained results show that the ADAS Adaptive Cruise Control (ACC) requires combination with V2V communication in order to increase safety, especially in certain scenarios with side and rear-end collisions. However, V2V alone at the lowest penetration rate already provided a level of safety similar to the one reached by combining it with ADAS-ACC.**

***Index Terms*—V2X Communication, SUMO, Safety Applications, Scene Suite, ADAS, Simulation**

I. INTRODUCTION

Any research paradigm seeking to advance the boundaries of the automobile experience must focus on a few key mobility components, one of the most crucial being safety. Despite this emphasis on safety and research that goes into furthering road safety, an alarming number of road fatalities occur each year worldwide. Beyond the obvious injury and human tragedy these accidents represent, it is also inordinately costly. In 2015 alone the approximate cost to governments of road accidents has been reported as 3-5% of their Gross Domestic Product (GDP) [1]. The introduction of new Intelligent Transportation Systems (ITS) technology related to cooperative systems in the form of active and passive safety systems, particularly Automotive Inter-networks (AutoNet), promises to substantially contribute to a decrease in the number of road-related accidents [2], [3]. Evaluating a new system for implementation in the automotive industry usually takes place in two steps: simulation, used to analyze and evaluate technical developments at an early stage [4], [5], and operational testing (Field Operational Test (FOT)) using a set of simulated real-world scenarios [6]. As a contribution to the first state of evaluation, in this paper we analyze road safety by simulating different Vehicle-to-Vehicle (V2V) communication applications in combination with the Advanced Driver Assistance System Adaptive Cruise Control (ADAS-ACC). V2V communication enables vehicles to detect the velocity and acceleration of approaching vehicles and subsequently broadcast warning messages to neighboring vehicles. As a consequence, a timely deceleration of the surrounding vehicles in response to the message successfully prevents potential accidents. ADAS-ACC determines the speed of any vehicle in relation to the vehicle ahead of it.

For a comprehensive evaluation of the systems, we rely on the simulation tools Scene Suite [7] and Simulation of Urban Mobility (SUMO) [8]. We extend in this work the approach presented in [9], with three newly developed simulation scenarios for urban use cases, in addition to those for intersections. Our contribution consists of a comparative analysis of ADAS-ACC and V2V systems separately and combined in intersection and urban scenarios. To this end we formulated the following research questions:

- What are the main effects of different penetration rates (0%, 40%, 60%, 100%) of ADAS-ACC and V2V communication separately on road safety in the developed scenarios?
- What are the main effects of different penetration rates (0%, 40%, 60%, 100%) of V2V communication combined with ADAS-ACC on the level of road safety in the developed scenarios?

Road safety is determined by the number of accidents occurred. In order to investigate the research questions, the following hypotheses have been defined for both the intersections as well as the urban scenarios.

1) H1: The total number of accidents that occur when no system is applied is higher than when either V2V or ADAS-ACC is applied separately with different penetration rates (0%, 40%, 60%, 100%).
2) H2: The total number of accidents that occur when ADAS-ACC alone with 40%, 60% and 100% penetration rates is applied is higher than when V2V alone with

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40%, 60% and/or 100% penetration rates is applied.
3) H3: The total number of accidents that occur when ADAS-ACC alone with 40%, 60% and 100% penetration rates is applied is higher than when V2V and ADAS-ACC combined with 40%, 60% and/or 100% penetration rates is applied.
4) H4: The total number of accidents that occur when V2V alone is applied with 40%, 60% and 100% penetration rates is higher than when V2V and ADAS-ACC combined is applied with 40%, 60% and/or 100% penetration rates.

The remaining parts of this paper are organized as follows: Section II describes studies related to road safety and traffic efficiency considering V2V and ADAS-ACC technology. In Section III, the methodology is outlined. Results from the comparative analysis performed are presented in Section IV. Section V, summarizes important points, concludes the paper and defines future lines of work.

II. Related Work

In recent years, a large number of projects have been carried out to investigate Vehicle-to-Everything (V2X) and ADAS with respect to safety and traffic efficiency [10]. In this section, some related applications are described in two main categories: safety and traffic efficiency improvement.

A. Safety-Based Applications

The authors in [11] developed an Intersection Safety (INTERSAFE) application by detecting dangerous traffic situations. INTERSAFE combines sensor data with communication technologies to warn drivers to stop in order to avoid an accident. Results show that INTERSAFE could effectively prevent dangerous traffic situations in intersection scenarios.

Another application, the Cooperative Intersection Collision Avoidance Systems (CICAS) [12], utilizes information about surrounding vehicles as well as information obtained from the infrastructure in order to enhance the awareness of approaching vehicles. It enables drivers to avoid accidents by re-routing their trips or by influencing time-sensitive reactions like stopping, decelerating or accelerating. This system also has the capability of identifying pedestrians and cyclists in dangerous situations and informing the involved drivers.

The application Intersection Priority Management (IPM), whose goal is the safe movement of vehicles through intersections without using traffic lights or signs, has been presented in [13]. A distributed predictive control approach was proposed.

The Intersection Collision Avoidance Support System relying on V2I communication was introduced in [14] and aimed to prevent intersection crashes and accidents that involve cars and pedestrians or cyclists, which are often a cause of casualties in Japan. The obtained results confirmed a good performance of the system.

In line with the work presented in this paper, Cooperative Adaptive Cruise Control (CACC) was tested in [15], providing optimal levels of acceleration or deceleration in order to prevent collisions in intersections. The proposed CACC system determined the existing acceleration or deceleration of vehicles and transmitted this information through the intersection controller to vehicles in the proximity.

In [16] the authors evaluated the safety and traffic efficiency of ITS applications using a real-world dataset. The vehicles communication system used V2X simulation runtime infrastructure (VSimRTI) to conduct the simulation. For simulating traffic networks, the SUMO traffic simulator was adopted. The evaluation results showed that applying Vehicle to Infrastructure (V2I) communication resulted in significant benefits, such as improvements in safety, reduced travel time, better average speed and more efficient fuel consumption.

In a further work the PARAMICS [17] traffic simulation tool was used to analyze the effects of connected vehicles on safety. In this study 0%, 10%, 20%, 30% and 40% penetration rates of vehicles equipped with V2V communication capabilities were defined. The authors showed that V2V improves both mobility and safety by reducing the number of accidents [18].

B. Traffic Efficiency and Management Applications

Among the many traffic efficiency and management applications, one of the more frequently studied is the Green Light Optimized Speed Advisory (GLOSA), which in [19] was examined with different penetration rates in a simulation to analyze traffic efficiency in an urban area. The penetration rates were 0%, 20%, 40%, 60%, 80% and 100%. At the three highest penetration rates, the stop time, trip time and fuel consumption decreased. A similar study also analyzed GLOSA with V2X penetration rates of 10% to 100% in intervals of 10% [20]. According to the reported results, at a penetration rate of 100% CO2 emissions and stop time were reduced by 10% and 100%, respectively. Furthermore, at a 40% penetration rate, the CO2 emissions and stop time decreased by 5% and 30%, respectively. In a similar line of research, in [21] the authors retrieved the traffic light timing program within a range in order to calculate the optimal speed while approaching an intersection, which was then used to recommend a velocity based on the vehicle's current acceleration and speed, phase state of the traffic light and remaining phase duration. Results showed an increased driving efficiency by reducing traffic flow, gas emissions, delays and accidents.

Enhancing the traffic flow in intersections by reorganizing the nearby vehicle platoons was the goal of the approach in [22]. The authors relied on V2X communication to develop an algorithm that was tested with 9 vehicles. Results showed an increase in the number of vehicles that were able to reach the green phase in the intersection, thereby contributing to a better traffic flow.

A further study aimed at improving traffic efficiency by developing and evaluating an approach based on V2X communication [23]. The penetration rates of V2X communication in this study varied in intervals of 5% starting from 0% to 100%. The implemented approach was capable of broadcasting and receiving the average travel speeds of vehicles and presented reliable results in terms of reducing the travel time. The results of this study show a 50%

TABLE I
KRAUSS MODIFIED VALUES TO ENABLE COLLISIONS

	Driving Behavior		
Metric	Aggressive	Normal	Courteous
Acceleration (m/s^2)	3.13	2.31	2.51
Deceleration (m/s^2)	5.52	4.41	4.52
Max. Speed (m/s)	30	20	15

improvement in travel time at V2X penetration rates of 80% or higher.

These studies and a review of further related literature reveal that while a considerable number of reported research focused on improving traffic efficiency, travel time and waiting time, fewer studies focus specifically on improving road safety by adopting different penetration rates of V2X and ADAS. By focusing on the prevention of pre-defined road accidents, this paper contributes to this gap in knowledge. Furthermore, in this paper we contribute to the state of the art by also considering driving behavior (aggressive, normal and courteous), as well as ADAS-ACC and V2V systems alone and combined.

III. Developed Methodology

The developed system architecture for the proposed simulation-based methodology is presented in Figure 1.

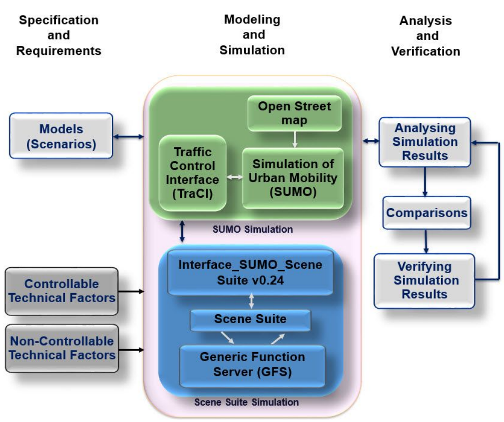

Fig. 1. System architecture of the proposed methodology

It consists of three main phases: Specifications and Requirements, Modeling and Simulation and Analysis and Verification. Each of the three phases consists of different steps that are briefly introduced in the following sections.

A. Specifications and Requirements

1) Scenarios: Two main real-world traffic situations are considered for modeling and simulation: urban and intersections. To define the driving behavior for lane-changing, we relied on the validated general model for car-following known as Minimizing Overall Braking Induced by Lane Changes (MOBIL) [24]. The behavior was defined by using the ”vType-Distribution” [25] parameters and applying related sets of attributes in the SUMO simulation. For each of these traffic situations, three different models corresponding to scenarios with various types of accidents were developed to investigate the extent to which the implementation of V2V and ADAS-ACC (separately and combined) would affect the level of road safety.

To generate collisions for a later evaluation of the performance of the relevant system, three different driving behaviors based on acceleration and deceleration patterns as well as maximum speed were defined after modifying the parameters of the adopted Krauss car-following model [26] as shown in Table I. According to these values we classified driving into “normal”, “aggressive” and “courteous”.

Each of the generated scenarios is designed to characterize some specific aspects of the relevant traffic situation. To this end the following general key specifications are developed:

- High traffic flow with the number of vehicles ranging from 21 to 40 and a maximum speed of 30 m/s.
- Low traffic flow with the number of vehicles ranging from 5 to 20 and a maximum speed of 30 m/s.
- Distributed vehicle types as explained in section III-B1, the definition of routes and vehicle types at runtime from a given distribution.
- Set of random trips for a given network automatically generated by SUMO.
- Vehicle accident type (rear-end and side).
- Single-hop V2V communication based on the IEEE 802.11p WAVE standard.
- Devising the ACC attributes such as Headway, the measurement of the distance or time between vehicles.

In addition to the listed general key specifications, the following particular features (compiled in Table II) were implemented with 40%, 60% and 100% penetration rates for each scenario:

- Generation of vehicle collisions (rear-end and side). According to [27] rear-end crashes are considered the most frequent with a rate of 70% under low-visibility night conditions and 30% during day-light conditions. Further research [28] indicated that side-on collisions are the major cause of deadly and serious damage accidents. Based on the conducted microscopic accident analysis in [29], maladjusted speed and insufficient safety distance are the main causes of road accidents. Figure 2 illustrates the various generated accidents for our study.
- Generation of a specific number of vehicles according to low or high traffic flow conditions.
- Definition of the number of accidents per scenario. To measure the level of safety by the number of prevented pre-defined accidents.
- Definition of the simulation time.
- Determination of the V2V and ADAS-ACC penetration rates separately and combined.
- Determination of the ADAS-ACC penetration rates.
- Adjustment of SUMO and Scene Suite attributes.
- Implementation of the WLAN, crash sensors and actuators on the simulated vehicles.

2) Controllable Technical Factors: The controllable technical factors are defined as all the available capabilities

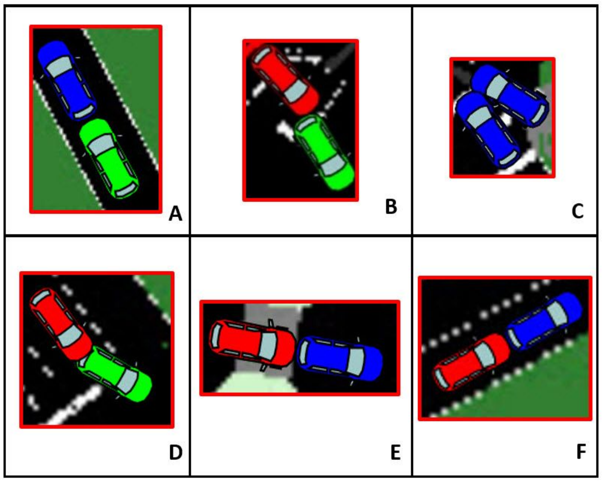

Fig. 2. Generated accidents in intersection and urban scenarios. A: "rear-end" collision in intersection scenario I. B: "rear-end" collision in intersection scenario II. C: "side" collision in intersection scenario III. D: "rear-end" collision in urban scenario I. E: "rear-end" collision in urban scenario II. F: "rear-end" collision in urban scenario III.

TABLE II
PROPERTIES OF THE DEFINED URBAN AND INTERSECTION SCENARIOS

Intersections Scenarios			
#	**Defined Vehicles**	**Defined Collisions**	**Simulation Time (sec.)**
I	19 Vehicles Aggressive: 2 Normal: 7 Courteous: 10	1 rear-end Fig. 2 (A) Between N & C	33.90
II	32 Vehicles Aggressive: 5 Normal: 13 Courteous: 14	2 rear-end Fig. 2 (B) Between A & C, A & N	42.90
III	25 Vehicles Aggressive: 4 Normal: 10 Courteous: 11	1 side Fig. 2 (C) Between N & N	31.25
Urban Scenarios			
#	**Defined Vehicles**	**Defined Collisions**	**Simulation Time**
I	21 Vehicles Aggressive: 3 Normal: 9 Courteous: 9	1 rear-end Fig. 2 (D) Between A & C	33.90
II	35 Vehicles Aggressive: 3 Normal: 17 Courteous: 15	2 rear-end Fig. 2 (E) Between A & C, A & N	29.90
III	26 Vehicles Aggressive: 1 Normal: 7 Courteous: 18	1 rear-end Fig. 2 (F) Between A & N	35.50

of the simulation platforms that enable the generation of the intersection and urban scenarios. The controllable factors allow the creation of desired scenarios with different specifications.

3) Non-Controllable Technical Factors: Non-controllable technical factors are defined as limitations on the process of generating different scenarios. Table III shows the defined non-controllable technical factors in the SUMO and Scene Suite simulation platforms.

B. Modeling and Simulation

The second phase of the methodology deals with two main simulation platforms that interact with some other applications and sources.

1) SUMO Simulation: The main simulation tool SUMO [8] relies on OpenStreetMap (OSM) data. SUMO prepares the simulation and waits for the main tool Scene Suite to connect and take over control in order to replicate real traffic conditions. The purpose of using SUMO is to generate road networks, vehicle networks and different types of accidents in order to test the effects of V2V and ADAS-ACC accurately. The process for generating the desired SUMO simulation is presented in Figure 3. To generate the road networks we applied the commands NETCONVERT, POLYCONVERT and NETEDIT [30] on the OSM data [31]. By applying NETCONVERT to the imported OSM data, all the road network features were generated, such as road types with different attributes. Furthermore, by adopting POLYCONVERT additional environmental features such as buildings and green areas were added to the imported road network. Through NETEDIT different lane connections were edited and modified to make the network more closely reflect the real world.

In order to simulate different characteristics for each scenario there are some properties that we considered and added to the network:

- Definition of vehicle types in SUMO
  Vehicle types (vType) and their attributes were defined using "vType" command line [32].
- Vehicle type distribution in SUMO
  As previously mentioned, by generating different types of accidents it is possible to test the effects of different penetration rates of V2V and ADAS-ACC. Considering this, we developed rear-end and side collisions by creating interrelated effects in random trip generation, manipulating the "vTypeDistribution" attributes, rou.xml and net.xml generated files.
  By defining the vehicles in SUMO through the alternative way vehicle type distribution (vTypeDistribution), SUMO is able to define routes and vTypes at runtime from a

TABLE III
NON-CONTROLLABLE TECHNICAL FACTORS

Non-controllable Technical Factors			
SUMO Simulation	**Scene Suite Simulation**		
SUMO (sumo-0.25.0)	**Scene Suite (0.17.2_92)**	**Interface SUMO Scene Suite (v0.24)**	**Generic Function Server**
Limited defined ways for generating different types of accidents	High-level computational capacity is required	Limited period of time for simulation	High number of steps required to reach the result
	Limited size of the background image	Limited number of exported vehicles	

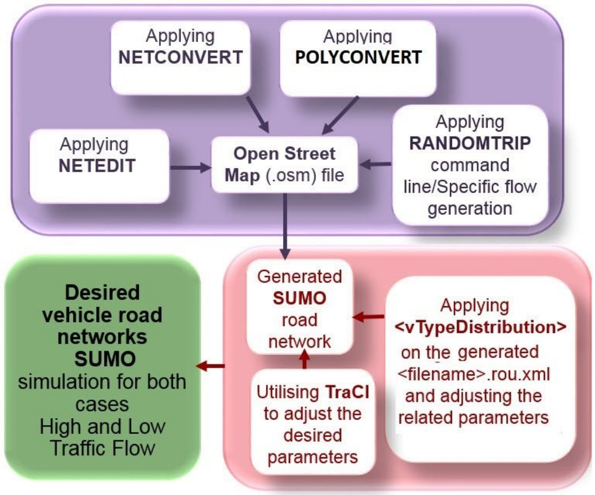

Fig. 3. Sumo simulation process to generate the vehicle and road networks. OSM is the input for NETCONVERT and POLYCONVERT. NETEDIT makes it possible to fix the generated net and additional files, and finally, the RANDOMTRIP script can be used with the final network definition.

given distribution instead of defining them explicitly for each of the vehicles through the flows definition. The ”vTypeDistribution” and its attributes are specified in the SUMO documentation [25]. We additionally defined the probability of the distributed vehicles and visualized driver behavior by configuring the desired maximum speed, acceleration and deceleration of vehicles as attributes of “vTypeDistribution” (see Table I). Color coding has been used to characterize driving behavior so that red, blue and green denote aggressive, normal and courteous drivers, respectively.

2) Scene Suite Simulation: The main simulation tool Scene Suite interacts with the SUMO-SceneSuite-Interface and Generic Function Server (GFS), two interfaces developed by IAV GmbH. The vehicle networks have been imported from SUMO using the SUMO-SceneSuite-Interface. This interface is only able to import vehicle networks to Scene Suite without any road maps. In order to generate a complete vehicle and road network in Scene Suite, the related road networks were added as an image background. This image background has been generated using the terrain background feature embedded in Scene Suite. Scene Suite has been used to finalize the simulation scenarios and to investigate the effects of different penetration rates of V2V and ADAS-ACC (separately and combined) on road safety. The two interfaces have been optimized and improved by:

- Generating complete vehicle networks in Scene Suite with their related road networks.
- Generating reliable networks of vehicles (exported from SUMO-SceneSuite-Interface) that are adjustable to the generated road networks.
- Developing a method to visualize the effects of V2V in Scene Suite.
- Developing an application in GFS, which is able to detect the time of a specific accident and simultaneously identify the involved vehicles.

3) V2V Implementation: In this paper V2V communication has been considered with 40%, 60% and 100% penetration rates according to the most common rates investigated in previous works [33], [34], [35], [18]. Although penetration rates higher than 40% are rarely considered, we additionally studied rates of 60% and 100%. To this end we developed two different approaches that relied on two message types, Cooperative Awareness Message (CAM) [36] and Decentralized Environment Notification Message (DENM) [37]. Both CAMs and DENMs use a single networking device to travel from source to destination (single hop system) relying on the IEEE 802.11p WAVE standard [38]. CAMs provide information related to the presence and position of vehicles and are distributed periodically to other vehicles in the vicinity. The frequency of CAMs transmission ranges from 1Hz to 10Hz. DENMs on the other hand are event-related messages and are broadcast in specific situations such as detection of high speed or acceleration.

In the first approach Scene Suite was used to implement V2V communication and visualize the related consequences of the information dissemination between vehicles. In order to implement and visualize the effects of CAM and DENM, the first step is to identify the time of the accidents in the related scene. This is then followed by mounting the necessary sensors and actuators on the simulated vehicles and manipulating the forward sequences of the related vehicle movements (in the generated scenes in Scene Suite) based on the time of the accident. Consequently, the involved vehicles are able to stop or decelerate by receiving the DENM messages before crashing. Figure 4 illustrates the steps.

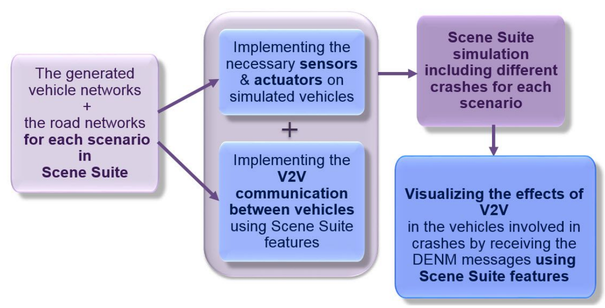

Fig. 4. First approach in applying V2V and visualizing the effects

The second approach for simulating V2V is using GFS (see Figure 5). Crash sensor capabilities have been applied to the simulated vehicles in Scene Suite. Detecting the accidents in the output file of the Scene Suite simulation enables their subsequent dissemination through V2V with the purpose of preventing potential accidents. To this end, an application in GFS was developed which obtains the “.xml” output file of the Scene Suite simulation. It determined the time of the accidents and the vehicle IDs involved. The obtained information is delivered through the V2V application in GFS and the system visualizes the effects of the message exchanges. Algorithm 1 describes the procedure.

4) ADAS-ACC Implementation: In order to implement the ADAS-ACC in the simulated vehicles, we adopted the SUMO car-following model. SUMO uses the Krauss model by default,

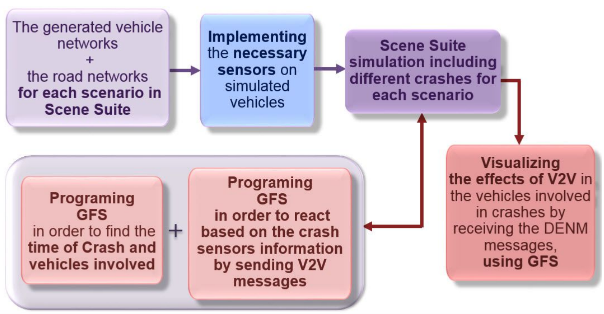

Fig. 5. Second approach in applying V2V and visualizing the effects using GFS.

Algorithm 1: Application in Generic Function Server (GFS)

input : SensorOutput i;
output: Crashed VehicleIDs cv;

Reading the nodes in the rootNodes;
for *all attributes of the SensedObjectList* **do**
  if *SensedObjectList* $\leftarrow$ *0* **then**
    No vehicle involved in accident;
  end
  else if *SensedObjectElement* $\leftarrow$ *theSENSEDOBJECT* **then**
    identifying CrashTimes and VehicleIDs ;
  end
end

which is an extension of the stochastic car-following model introduced in [26]. In the Krauss model the leading and following vehicles adjust their speeds in order to prevent a collision [39]. Other car-following models such as the Intelligent Driver Model (IDM) [40] and Gipps [41], for example, perform reasonably under steady-state and mixed traffic conditions. However, the Krauss car-following model is proven to perform better under non-steady-state conditions [42]. Considering the mentioned factors, the simulation platforms used in this work, as well as the simplicity and high execution speed of the Krauss model, we adopted it to perform the pertinent tests.

C. Analysis and Verification

The final phase of the developed methodology is analyzing and verifying the outcomes obtained from the modeling and simulation phase. Comparisons depending on the penetration rate have been conducted for the intersection and urban scenarios I, II and III (see Table II) based on the formulated hypotheses in Section I.

IV. Results

In order to organize and comprehend the effects of our simulations, we made a comparative analysis of the intersection scenarios, a comparative analysis of the urban scenarios, and examined the results from the quantitative analysis of both.

A. Comparative Analysis of Intersection Scenarios

Depending on the tested hypothesis, the results from the comparative analysis under different penetration rates of ADAS-ACC and V2V separately and combined in terms of their capability in preventing potential accidents in intersections are presented here. As an example, Figures 6 and 7 show the visualization for the intersection scenarios I and II.

1) H1: No system vs. 40%, 60% and/or 100% of vehicles equipped with ADAS-ACC or V2V:

0% (No system)	**vs**	40% ADAS-ACC

The relevant scenarios to test the implementation of ADAS-ACC (alone) were I, II and III as they include rear-end and side collisions (see Table II). With 40% of vehicles equipped, the results showed that in scenario III it was not possible to avoid accidents. In intersection scenario III the ADAS-ACC implementation, with the capability of longitudinal controlling, has been proven incapable of preventing side-on accidents. Accidents defined as “rear-end” as in intersection scenarios I and II were, however, prevented by ADAS-ACC alone.

0% (No system)	**vs**	60% ADAS-ACC

An increased ADAS-ACC penetration rate from 40% to 60% in intersection scenario III shows no improvement in preventing “side” collisions.

0% (No system)	**vs**	100% ADAS-ACC

The highest penetration rate of ADAS-ACC (100%) on the simulated vehicles, shows no improvement in the level of safety in intersection III.

0% (No system)	**vs**	40% V2V

In addition to testing the effectiveness of V2V (alone) in scenarios I and II with “rear-end” collision, scenario III with “side” collision was also tested. The lowest penetration rate of V2V (40%) proved to be enough to prevent all three types of accidents in the three intersection scenarios.

2) H2: ADAS-ACC alone vs. V2V alone: Results from testing the previous hypothesis showed that the lowest penetration rate of 40% for V2V communication prevented all types of accidents in the three intersection scenarios, including scenario III, side collisions. This is in stark contrast to ADAS-ACC alone, which did not prevent side collisions even with 100% penetration rate.

3) H3: ADAS-ACC alone vs. V2V and ADAS-ACC combined:

40%-100% ADAS-ACC	**vs**	40% ADAS-ACC & V2V

Through the combination of ADAS-ACC and V2V with 40% of the vehicles equipped, all types of accidents were prevented in the three intersection scenarios.

Fig. 6. Intersection scenario I; an example of the developed intersection scenarios (with an average area of about $2km^2$).

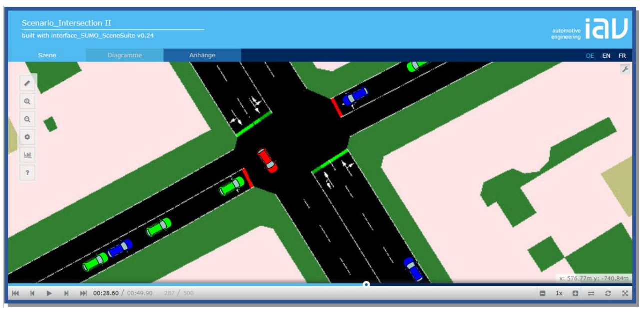

Fig. 7. Intersection scenario II; an example of the developed intersection scenarios (with an average area of about $800m^2$).

4) H4: V2V alone vs. V2V and ADAS-ACC combined:

40% V2V	**vs**	40% ADAS-ACC and V2V

Considering the previous results, testing H4 to examine the total number of accidents that occurred using V2V alone with different penetration rates and with V2V and ADAS-ACC combined did not seem necessary. Previously obtained results showed that the lowest 40% penetration rate in each system already prevented all accident types defined in our study.
When no system was applied to the vehicles the crash rate was 10.53%, 12.50% and 8% for scenarios I, II and III, respectively. The results regarding vehicles equipped with ADAS-ACC and V2V separately and combined are summarized in Table IV.

Summarizing the results for the intersection scenarios, ADAS-ACC alone did not prevent the “side”-type of accident even at 100% of penetration rate in intersection III. However, ”rear-end” accidents in intersection scenarios I and II were prevented when 40% of vehicles were equipped with ADAS-ACC alone. 40% of vehicles equipped with V2V communication prevented all types of accidents in the tested scenarios.

B. Comparative Analysis of Urban Scenarios

The comparative results of testing the four defined hypotheses through adopting different penetration rates of the systems on three generated urban scenarios are presented in this section. As an example, Figure 8 shows the visualization of urban scenario II:

TABLE IV
INTERSECTION COLLISIONS RESULTING FROM THE PROPOSED SYSTEMS

Intersection	**Scenario I**	**Scenario II**	**Scenario III**
No System	10.53%	12.50%	8%
40% penetration rate			
ADAS-ACC	0.00%	0.00%	8%
V2V	0.00%	0.00%	0.00%
Combined	0.00%	0.00%	0.00%
60% penetration rate			
ADAS-ACC	0.00%	0.00%	8%
V2V	0.00%	0.00%	0.00%
Combined	0.00%	0.00%	0.00%
100% penetration rate			
ADAS-ACC	0.00%	0.00%	8%
V2V	0.00%	0.00%	0.00%
Combined	0.00%	0.00%	0.00%

1) H1: No system vs. 40%, 60% and/or 100% of vehicles equipped with ADAS-ACC or V2V:

0% (No system)	**vs**	40% ADAS-ACC

Having 40% of vehicles equipped with ADAS-ACC resulted in an improvement in the level of road safety. Unlike with the intersection scenarios, even at the lowest penetration rate (40%) of ADAS-ACC alone, all types of accidents were prevented in the three urban scenarios.

0% (No system)	**vs**	40% V2V

Even the lowest penetration rate (40%) of V2V successfully prevented all defined types of accidents.

2) H2: ADAS-ACC alone vs. V2V alone; H3: ADAS-ACC alone vs. V2V and ADAS-ACC combined and H4: V2V alone vs. V2V and ADAS-ACC combined:

40% ADAS-ACC	**vs**	40% V2V

40% ADAS-ACC	**vs**	40% ADAS-ACC and V2V

40% V2V	**vs**	40% ADAS-ACC and V2V

For the hypotheses H2, H3 and H4, since a 40% penetration rate of V2V alone already prevented all accident types, combining it with ADAS-ACC did not result in any change. When no system was applied, the crash rates were 9.52%, 11.43% and 7.69% for scenarios I, II and III, respectively.

In contrast to the intersection scenarios, ADAS-ACC and V2V separately or combined were able to reduce rear-end collisions to 0% in all three scenarios with the minimum 40% penetration rate. Increases in the penetration rates for separate and combined systems resulted in no changes to the 0% crash rate, as one would expect.

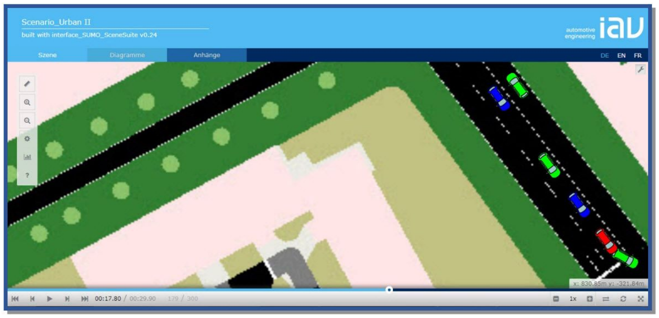

Fig. 8. Urban scenario II; an example of the developed urban scenarios (with an average area of 1 km^2)

V. Conclusion and Future Work

A proper testing environment is essential to develop and evaluate cooperative systems. This paper studied accident prevention resulting from equipping different vehicles with ADAS-ACC and V2V communication at different rates by using the SUMO and Scene Suite simulation tools. On the basis of the obtained results, H1 was rejected, as ADAS-ACC alone was not able to prevent all accidents. Consequently, H2 and H3 were accepted. H4 was rejected as the combination of both systems was not necessary to prevent the number of accidents. The obtained results from intersection and urban scenarios showed that even the lowest penetration rate (40%) of V2V, it prevented all types of accidents. These findings also proved it unnecessary to combine it with ADAS-ACC to acquire the same results. On the other hand, ADAS-ACC necessitates a combination with V2V communication in order to increase safety, especially in certain scenarios with side collisions.

As shown in Table III the possibilities that SUMO offers in term of creation of different types of accidents is very limited. Particularly the generation of side collisions in intersections was hard to achieve. In an urban environment in which the vehicles move in the same direction the generation of side-on collisions was not possible. Therefore, we decided to focus on rear-end collisions.

A comparison of our findings with related works that used different approaches, simulation tools and penetration rates confirms the impact of V2V communication on preventing rear-end collisions (i.e. [28], [18]). For example 50% of vehicles equipped with V2V reduced the collision rate by 20% to 30% [35].
Future lines of work aim at extending this study by first providing a safe and accurate interaction between vehicle networks and infrastructure. This will require different implementations in the simulation scenarios. Secondly, future work should develop different V2X communications that ultimately secure and increase the level of road safety on a larger scale. Last but not least, the number of experiments and vehicles involved in collisions should be increased and include more scenarios to account for the variety of real life situations encountered on the road.

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References

[1] T. Pietrasik. (2016) Road traffic injuries. (accessed on: 19.12.2017). [Online]. Available: http://www.who.int/en/news-room/fact-sheets/detail/road-traffic-injuries
[2] T. Kosch, C. Schroth, M. Strassberger, and M. Bechler, *Automotive internetworking*. John Wiley & Sons, 2012, vol. 4.
[3] O. Altintas, F. Dressler, H. Hartenstein, and O. K. Tonguz, "Inter-Vehicular Communication–Quo Vadis (Dagstuhl Seminar 13392)," in *Dagstuhl Reports*, vol. 3, no. 9. Schloss Dagstuhl-Leibniz-Zentrum für Informatik, 2014.
[4] S. G. Henderson and B. L. Nelson, *Handbooks in operations research and management science: simulation*. Elsevier, 2006, vol. 13.
[5] C. Campolo, A. Molinaro, and R. Scopigno, "Vehicular ad hoc Networks," *Standards, Solutions, and Research*, 2015.
[6] M. Emmelmann, B. Bochow, and C. Kellum, *Vehicular networking: Automotive applications and beyond*. John Wiley & Sons, 2010, vol. 2.
[7] IAVGmbH. (2015) Driver Assistance Systems. (accessed on: 02.10.2017). [Online]. Available: https://www.iav.com/node/8018
[8] D. Krajzewicz, J. Erdmann, M. Behrisch, and L. Bieker, "Recent Development and Applications of SUMO - Simulation of Urban MObility," *International Journal On Advances in Systems and Measurements*, vol. 5, no. 3&4, pp. 128–138, December 2012.
[9] A. Validi, T. Ludwig, and C. Olaverri-Monreal, "Analyzing the effects of V2V and ADAS-ACC penetration rates on the level of road safety in intersections: Evaluating simulation platforms SUMO and Scene Suite," in *International Conference on Vehicular Electronics and Safety (ICVES)*. IEEE, 2017, pp. 38–43.
[10] C. Weiß, "V2X communication in Europe–From research projects towards standardization and field testing of vehicle communication technology," *Computer Networks*, vol. 55, no. 14, pp. 3103–3119, 2011.
[11] K. C. Fuerstenberg, "A new European approach for intersection safety-the EC-Project INTERSAFE," in *Intelligent Transportation Systems, 2005. Proceedings.* IEEE, 2005, pp. 432–436.
[12] M. Maile, F. Ahmed-Zaid, S. Bai, L. Caminiti, P. Mudalige, M. Peredo, and Z. Popovic, "Objective testing of a cooperative intersection collision avoidance system for traffic signal and stop sign violation," in *Intelligent Vehicles Symposium (IV)*. IEEE, 2011, pp. 130–137.
[13] A. Katriniok, P. Kleibaum, C. Ress, and L. Eckstein, "Automation of Road Vehicles Using V2X: An Application to Intersection Automation," SAE Technical Paper, Tech. Rep., 2017.
[14] M. Fukushima, "The latest trend of V2X driver assistance systems in japan," *Computer Networks*, vol. 55, no. 14, pp. 3134–3141, 2011.
[15] I. H. Zohdy, R. K. Kamalanathsharma, and H. Rakha, "Intersection management for autonomous vehicles using iCACC," in *15th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2012, pp. 1109–1114.
[16] N. Ekedebe, C. Lu, and W. Yu, "Towards experimental evaluation of Intelligent Transportation System safety and traffic efficiency," in *International Conference on Communications (ICC)*. IEEE, 2015, pp. 3757–3762.
[17] PARAMICS. (2018) Quadstone paramics. (accessed on: 05.5.2018). [Online]. Available: http://www.paramics-online.com/
[18] E. Paikari, S. Tahmasseby, and B. Far, "A simulation-based benefit analysis of deploying connected vehicles using dedicated short range communication," in *Intelligent Vehicles Symposium Proceedings*. IEEE, 2014, pp. 980–985.
[19] M.-A. Lebre, F. L. Mouël, E. Ménard, A. Garnault, B. Bradaï, and V. Picron, "Real scenario and simulations on GLOSA traffic light system for reduced CO2 emissions, waiting time and travel time," *arXiv preprint arXiv:1506.01965*, 2015.
[20] K. Katsaros, R. Kernchen, M. Dianati, D. Rieck, and C. Zinoviou, "Application of vehicular communications for improving the efficiency of traffic in urban areas," *Wireless Communications and Mobile Computing*, vol. 11, no. 12, pp. 1657–1667, 2011.
[21] C. Olaverri-Monreal, J. Errea-Moreno, and A. Díaz-Alvarez, "Implementation and Evaluation of a Traffic Light Assistance System in a Simulation Framework based on V2I Communication," *Journal of Advanced Transportation*, 2018.
[22] B. Liu and A. El Kamel, "V2X-based decentralized cooperative adaptive cruise control in the vicinity of intersections," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 3, pp. 644–658, 2016.

[23] J. W. Wedel, B. Schünemann, and I. Radusch, "V2X-based traffic congestion recognition and avoidance," in *10th International Symposium on Pervasive Systems, Algorithms, and Networks (ISPAN)*. IEEE, 2009, pp. 637–641.

[24] U. Khan, P. Basaras, L. Schmidt-Thieme, A. Nanopoulos, and D. Katsaros, "Analyzing cooperative lane change models for connected vehicles," in *International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE, 2014, pp. 565–570.

[25] SUMO-vTypeDistribution. (2016) vtypedistribution. (accessed on: 24.11.2017). [Online]. Available: http://sumo.dlr.de/wiki/Definition_of_Vehicles,_Vehicle_Types,_and_Routes

[26] S. Krauss, "Microscopic modeling of traffic flow: Investigation of collision free vehicle dynamics," Ph.D. dissertation, 1998.

[27] J. M. Sullivan and M. J. Flannagan, "Risk of fatal rear-end collisions: is there more to it than attention?" 2003.

[28] G. Bulumulle and L. Bölöni, "Reducing Side-Sweep Accidents with Vehicle-to-Vehicle Communication," *Journal of Sensor and Actuator Networks*, vol. 5, no. 4, p. 19, 2016.

[29] T. Richter and P. Gilka, "Improving the safety on motorways with I2V-communication," in *15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual MeetingITS AmericaERTICOITS JapanTransCore*, 2008.

[30] SUMO-NETEDIT. Sumo.dlr.de/wiki/netedit. (accessed on: 11.05.2018). [Online]. Available: http://sumo.dlr.de/wiki/NETEDIT

[31] SUMO-NETCONVERT. (2016) Networks/import/openstreetmap. (accessed on: 10.10.2017). [Online]. Available: http://sumo.dlr.de/wiki/Networks/Import/OpenStreetMap

[32] SUMO-randomTrips. (2016) Tools/Trip-randomTrips.py. (accessed on: 01.10.2017). [Online]. Available: http://sumo.dlr.de/wiki/Tools/Trip

[33] R. Bauza and J. Gonzálvez, "Traffic congestion detection in large-scale scenarios using vehicle-to-vehicle communications," *Journal of Network and Computer Applications*, vol. 36, no. 5, pp. 1295–1307, 2013.

[34] J. Argote-Cabañero, E. Christofa, and A. Skabardonis, "Connected vehicle penetration rate for estimation of arterial measures of effectiveness," *Transportation Research Part C: Emerging Technologies*, vol. 60, pp. 298–312, 2015.

[35] K. Shah and E. M. Parentela, "A Case Study on Potential Benefits of V2V Communication Technology on Freeway Safety," *California State University, Long Beach*, 2016.

[36] T. ETSI, "Intelligent Transport Systems (its); Vehicular Communications; Basic Set of Applications; Part 2: Specifications of Cooperative Awareness Basic Service," *ETSI*, vol. 302 637-3 V1.2.1, 2011-3.

[37] E. ETSI, "Intelligent Transport Systems (its); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service," *ETSI*, vol. 302 637-3 V1.2.2, 2014-11.

[38] IEEE802.11PWorkingGroup *et al.*, "Part11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," *ANSI/IEEE Std. 802.11*, 1999.

[39] L. Bieker-Walz, M. Behrisch, M. Junghans, and K. Gimm, "Evaluation of car-following-models at controlled intersections," in *ESM 2017 European Simulation and Modelling Conference*, vol. 31, 2017, pp. 247–251.

[40] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Physical review E*, vol. 62, no. 2, p. 1805, 2000.

[41] P. G. Gipps, "A behavioural car-following model for computer simulation," *Transportation Research Part B: Methodological*, vol. 15, no. 2, pp. 105–111, 1981.

[42] V. Kanagaraj, G. Asaithambi, C. N. Kumar, K. K. Srinivasan, and R. Sivanandan, "Evaluation of different vehicle following models under mixed traffic conditions," *Procedia-Social and Behavioral Sciences*, vol. 104, pp. 390–401, 2013.

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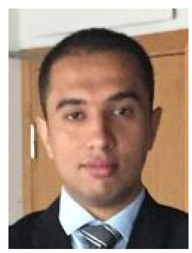

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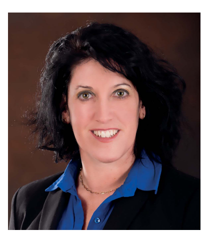

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