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VEHICLE-IN-THE-LOOP (VIL) AND SCENARIO-IN-THE-LOOP (SCIL) AUTOMOTIVE SIMULATION CONCEPTS FROM THE PERSPECTIVES OF TRAFFIC SIMULATION AND TRAFFIC CONTROL

Márton Tamás Horváth [1]***, Qiong Lu*** [2]***, Tamás Tettamanti*** [3]***, Árpád Török*** [4]***,***
Zsolt Szalay [5]

[1,2,3] *Budapest University of Technology and Economics,*
Department of Control for Transportation and Vehicle Systems,
Stoczek J. u. 2., Budapest, H-1111, Hungary,
{horvath.marton, lu.qiong, tettamanti}@mail.bme.hu

[4,5] *Budapest University of Technology and Economics,*
Department of Automotive Technologies,
Stoczek J. u. 6., Budapest, H-1111, Hungary,
{arpad.torok, zsolt.szalay}@gjt.bme.hu

As highly automated and autonomous vehicles (AVs) become more and more widespread, inducing the change of traffic dynamics, significant changes occur in traditional traffic control. So far, automotive testing has been done mostly in real-world or pure virtual simulation environment. However, this practice is quite obsolete as testing in real traffic conditions can be quite costly, moreover purely simulation based testing might be inadequate for specific goals. Accordingly, a hybrid concept of the Vehicle-in-the-Loop (ViL) was born recently, in accordance with the Hardware-in-the-Loop concept, i.e. in the ViL concept the vehicle is the 'hardware' within the simulation loop. Furthermore, due to the development of software capabilities, a novel approach, the Scenario-in-the-Loop (SciL) concept evolves based on the ViL approach. The paper defines the main purposes and conditions related to implementing ViL and SciL concepts from the perspective of traffic simulation and traffic control.

Keywords: Scenario-in-the-Loop, Vehicle-in-the-Loop, traffic simulation, automotive simulation

1. Introduction

Autonomous vehicles (AVs) are core elements of future's transportation, and it is not only a vision anymore since Waymo got the license to test their driverless cars in real traffic with no human observation in the vehicle (Reuters, 2018). These kinds of road tests focus only on the behaviour of single vehicles without exploiting the advanced ability of AVs considering the relevancy of cooperation among the infrastructure and other vehicles. For example, it is no longer needed to visually see each other, it is enough to get a sign from other vehicles or the infrastructure to know what is happening. Currently, the so called “in-the-loop” concept seems to be the most efficient methodology to test the interaction of AVs and the control environment. The Vehicle-in-the-Loop (ViL) concept, which is already in use, was directly developed to test ADAS functions (Bock, 2018). In this configuration the vehicle itself is real but all the other elements of traffic are simulated. The next step is using Scenario-in-the-Loop (SciL) testing environment (Szalay *et al.*, 2018), where not just the physical attributes of the vehicle are tested but also its sensors via the virtual twin realisation. In this case the investigated scenario is simulated and fully or partly realised in parallel.

ViL represents the state when the vehicle is moving on the real surface or on a test bench, and the full environment is simulated, the actuators of the vehicle get their input signal directly from the traffic simulation software, i.e. sensor spoofing is applied. It can be considered as a Hardware-in-the-Loop approach. SciL is one step closer to realistic environment simulation, because not only the vehicle and the surface are real but some elements of traffic control can also be installed physically. This means that the vehicle has to use some of its own sensors, depending on the type of the test, to realise the traffic situation (Rosenberger *et al.*, 2018). SciL covers all the intermediate simulation states between ViL and real-traffic test approaches. For example, if the signal head or some other vehicles or objects representing vulnerable road users are also real, then these simulations are considered as SciL simulations. Apart from the test vehicle, the road surface, and the traffic simulator, the elements of SciL can either be real or simulated, depending on the current simulation configuration. The concept realises a virtual twin technology practically (shown in Fig. 1).

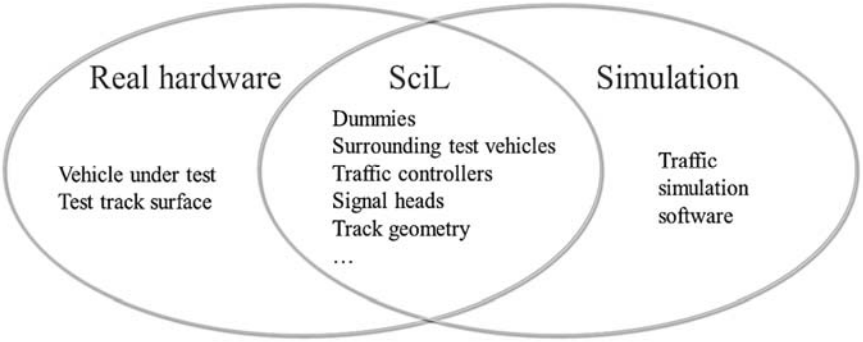

Figure 1. The relation of real, simulated, and SciL elements. Possible SciL elements are in the middle

As previous researches (Németh *et al*., 2018), (Szalay *et al*., 2017a) have stated, the core component is the control software which dynamically redefines the scenario adapting to the continuously changing input parameters of the tested vehicle and the proving ground environment. To show the concept of SciL an example is introduced to support the understanding of the novel approach. A vehicle approaches a signalised intersection in different conditions. Only the signal head and the vehicle is real the other elements are simulated. Different simulated conditions can be included by the given test scene: the area can be metropolitan or rural, and the weather conditions can be foggy, rainy, sunny etc. The next step can be for instance to include some real vehicles too, but the scenario itself can be freely constructed by the test personnel. Test vehicles or other dummies, e.g. test-pedestrians or test-animals are coordinated by the traffic management centre. The traffic management centre has a significant role in moving these vehicles and dummies in different ways in scenarios as requested by the tester, e.g. next to a simulated school test-pedestrians are much more likely to make unexpected movements, representing the behaviour of schoolkids. The behaviour of pedestrians has been investigated by (Hartmann *et al*., 2018) using a Pedestrian-in-the-Loop approach. Another important aspect of SciL tests is that many manufacturers apply their own specific objects which also requires a high-level coordination from the centre, accurately controlling each object what to do and when to do. In connection with that (Schramm *et al*., 2018) has described the mathematical equations of the movement of objects considering them as complex multibody systems. That is also a relevant difference compared to ViL, where it is not necessary to apply such a central management system since there are only one object and the simulator. In SciL the traffic management centre has therefore much more complex tasks. The concept of SciL is presented in Figure 2.

ViL is an existing concept, several manufacturers offer their products worldwide, and research institutes have also developed their solutions and use it for various tests, e.g. (AVL, 2019; IPG Automotive, 2017; Tettamanti *et al*., 2018). On the other hand, SciL is not that widespread. Researchers (Butenuth *et al*., 2017) mentioned the concept of SciL first in 2017 fall as a next step in the future. The PEGASUS project (PEGASUS, 2018) has exactly the same proposal; it aims to create relevant traffic scenarios for testing highly automated vehicles. It has also been highlighted by (Zlocki *et al*., 2017) that there is no accepted evaluation methodology available for automated driving above SAE Level 3 (SAE International, 2016b).

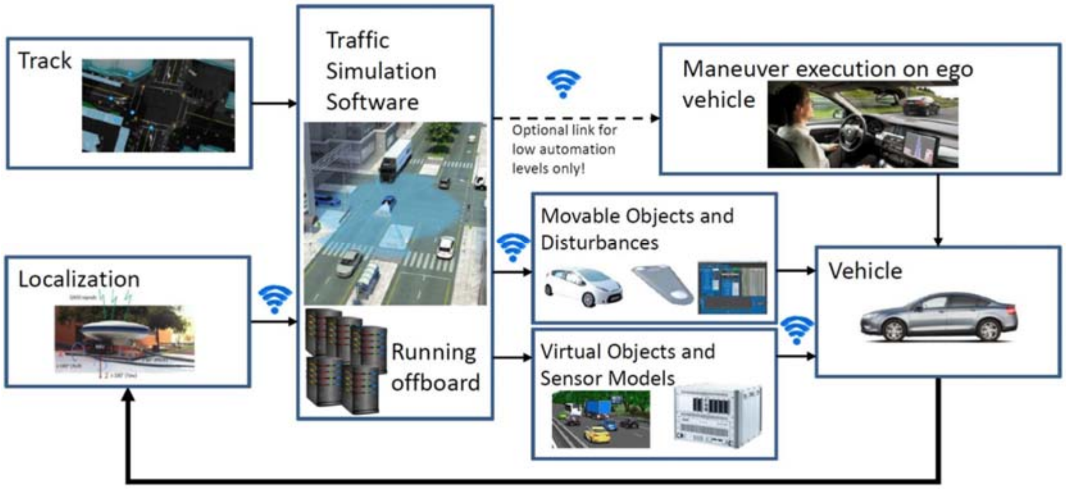

Figure 2. The concept of SciL (Szalay, 2017b)

Unlike ViL, the concept of SciL has rarely been applied so far. But this situation is expected to change in the near future in accordance with the development trends of autonomous vehicle technology. The main considerations of designing a test track for AVs have been described by (Szalay *et al*., 2017a). In the article the principles of SciL are among the requirements of test track and vehicle configurations. The practical considerations of SciL have been presented by (Németh *et al*., 2018), including its benefits and critical elements. The SciL approach is able to provide a realistic test environment, where test runs and results are reproducible. The configuration of tests is flexible and scalable, therefore it is easy to define and redefine scenarios. These make SciL a cost-effective testing method. On the other hand, communication is a critical element: the fastest wireless technologies have to be applied to avoid latency. Another drawback is that there are no standard testing methodologies for providing non-real test information for test vehicles, nevertheless, there some initiatives, e.g. (Hartmann *et al*., 2018). Finally, a central control software is required that manages the scenario, receives the data from localisation units, and automatically triggers virtual signals for all the disturbance elements in the scenario.

This article presents the basics for ViL and SciL concepts from the perspective of traffic simulation and traffic signal control (especially for autonomous vehicles). The remaining part of this paper is composed as follows. The preliminaries of traffic control and standards are written in Section 2. Traffic control elements of the SciL test environment are described in Section 3. The building blocks of tests and an implementation example are introduced in Section 4. Concluding remarks are written in Section 5.

2. Preliminaries

The test environment should be functioning as a re-configurable urban area to be able to test any scenario with real vehicles, traffic signal devices, traffic sensors, and simulated traffic conditions. This requires a novel approach for installing and designing the signal, measurement, and control devices of the test track.

2.1. Traffic control technology

Traffic light control aims at ensuring safe and disturbance-free traffic flow. The main element of this technology is the traffic controller unit that directly controls the operation of traffic lights. The basic elements of local intersection control are the banned stage matrices of simultaneously allowed movements in an intersection and intergreen matrices of the minimum times (intergreen times) required to elapse between any two consecutive movements.

Traditional traffic controllers contain these matrices permanently in a dedicated, protected memory (e.g. flash EPROM). Hence, the worst-case is a fail-safe situation which means that the traffic signal switches to flashing amber light mode or goes completely dark. In practice, traffic signal heads and local traffic controllers are connected to each other with wire-based technologies. Therefore, it is not a straightforward task to move these installations from one location to another. This approach is not applicable if one aims at building a re-configurable test environment for AVs.

AVs make new technologies possible to use in traffic control. AVs do not necessarily get information of signal heads and the environment visually; they can be provided this information via a communication protocol. This way AVs can also be involved in traffic control. Vehicle to Infrastructure (V2I) communication increasingly involves communication with traffic control units, in our case local signal heads and certainly the traffic management centre are involved by V2I communication.

The previously mentioned factors require a new type of traffic control architecture to be installed with new generation of signal heads and local traffic controllers using wireless technologies as much as possible. An innovative concept of intelligent signal heads with wireless distributed traffic control has been introduced by (Tamaskovics *et al*., 2016), where the energy consumption was served with solar cells for each signal head. The intelligence means that the signal head is not only used to show the specific signal but it also has an own logic that serves control and communication tasks. This solution enables to minimise installation and maintenance costs and provide a high level of flexibility when it is needed to change the position of signal heads. This makes it also possible to have a distributed traffic control system, where local traffic management in junctions is done directly by the control unit of signal heads.

2.2. Communication standards from traffic control aspects

Communication is a key element of effective realisation of the SciL concept: vehicles, signal heads, other infrastructure elements, and the traffic management centre have to be able to communicate with all other hardware elements in the test track. This has to be independent of manufacturers, so no matter what type the cars or the signal heads are, they should be able to communicate with each other. This requires a standardised interface that is open for everyone. Every manufacturer has to decode the messages from other participants exactly in the same way.

Technical specifications only exist at the level of human communication: created by DATEX II (DaTa EXchange (European Commission, 2011)) and TPEG (Transport Protocol Expert Group (TPEG, 2014)) communities. Both DATEX II and TPEG are combined with the specific C-ITS technical specifications developed under ETSI mandate. DATEX II is the electronic language used in Europe for the exchange of traffic information and traffic data, primarily among roadside stations and traffic management centres. The main thought of DATEX II is to avoid the potential misunderstandings of human communication, e.g. when two people of different nations talk to each other. Therefore, standardised messages have been constructed. By means of DATEX II, traffic information and traffic management information is distributed in a way that is not dependent on language and presentation format. This means that there is no room for misunderstandings and / or translation errors by the recipient, but the recipient can choose to include spoken text, an image on a map, or to integrate it in a navigation calculation. The increasing scale on which ITS services are being dimensioned, as well as the new digitisation requirements arising from self-driving cars, make the increased use of standards necessary and thus also challenge the DATEX II community (European Commission, 2011). The next step is to create such a standard in the 'language' of machines.

TPEG aims communication at a lower level, between the vehicles themselves and roadside stations. TPEG technology was originally motivated by the desire to develop a 21st century multimodal travel and traffic data protocol for delivering content to the end-user. Already TPEG has proved that it can satisfy an even wider remit, covering other application areas such as weather information and perhaps some content exchange requirements. Language independence was a prime principle in the design. Various location referencing methods were developed to allow any client device to take advantage of the content with no prior installation of a location database (TPEG, 2014).

The technical specification for Signal Phase and Time and Map Data (SPaT/MAP (Amsterdam Group, 2019)) offers a potential channel for detailed information exchange between traffic systems and road users. The function of Signal Phase and Time (SPaT) informs drivers about the current status and change of the traffic signal ahead as well as when the next signal stage change. It also provides information about approaching traffic to optimise the signal system. Map Data (MAP) describes the physical geometry of one or more intersections. In connection with SPaT/MAP the ISO/TS 19091:2017 (ISO, 2017) is also important to mention as it defines the message, data structures, and data elements to support exchanges between the roadside equipment and vehicles. In all, through these standardised data exchange safety, mobility and environmental efficiency can be raised.

Finally, the guidance of the SAE International is worth mentioning (SAE International, 2016a). Under the code SAE J2735_201603 the Dedicated Short Range Communications (DSRC) Message Set

Dictionary was published. The aim of this document is to provide a message set, and its data frames and data elements, specifically for use by applications intended to utilise the 5.9 GHz DSRC for wireless access in vehicular environments.

Apart from the previously mentioned specifications, there are several on-going research projects as well for developing C-ITS communication, the specific goals of the European Union research activities are presented in (Marilisa *et al*., 2018).

3. Traffic Control Elements for SciL Test Environment

This chapter introduces the basic necessary elements of the test scene, focusing on the requirements of a manufacturer-independent, re-configurable environment for operating traffic control and recording information. These are the core elements of successful SciL simulations (see Fig. 2 again).

Specific road traffic control architecture

The test track's road traffic control system consists of a Traffic Control Centre (a control room practically) and road side units, i.e. Traffic Light Controller (TLC), traffic signal heads, variable message signs, traffic sensors. All road side units are monitored and controlled by the Traffic Control Centre.

Specific Traffic Control Centre (TCC) features

TCC consists of specific hardware and software tools, as well as communication technology. At all times the control centre monitors and controls the test track's traffic as well as logs and stores all events.

Road side units (RSUs)

Road side units include those hardware elements that are in connection with collecting or giving information to vehicles and enabling also the information exchange between the TCC and RSUs. These are traffic sensors, traffic lights, variable message signs (VMS) and other components being responsible for communication. The role of VMS components might be different as fully autonomous cars appear.

Control and communication of road side units

Traffic lights should be able to communicate with each other and with the TCC by using wireless communication channels. Therefore, communication cables can be eliminated. Beside vendor specific local traffic light controllers (generally one TLC at each intersection), customisable PLC (Programmable Logic Controller) based control is applied in the system, i.e. one PLC is integrated into each traffic signal head. Thus, signal heads can be directly controlled and monitored from the TCC.

Communication protocol between traffic control centre (server) and local units (traffic lights)

UDP (User Datagram Protocol) is suggested as communication protocol between the traffic control system and local units (PLC components). UDP can be much faster than TCP/IP (Tamaskovics *et al*., 2016) which is very important in real-time traffic control processes. Even though UDP itself does not contain security elements, the sender and the receiver can guarantee security, and the protocol can be used in a secure way.

Communication technology

The communication is preferred to be wireless, but sometimes it is not feasible. In these cases optical fibre cable communication technology is preferred among units and the traffic control centre. This is much less flexible. RSUs can be connected with cable, but mobile units (vehicle under test, dummies etc.) cann't.

Communication security

Communication security is a very important issue in transportation, especially if penetration of connected vehicles continuously increases. Encrypted channels have to be used to avoid malicious interventions.

Re-configurable traffic control system provided by the TCC

The traffic control system must be dynamically re-configurable, e.g. changing the test field geometry induces the reprogramming of traffic signal phases in an appropriate software environment.

V2I functions

Road side units must be capable of V2X technology, i.e. broadcast to and receive signals from cars.

Traffic control strategies

TCC, TLCs, and the PLC based road side units are capable of performing arbitrary traffic control strategies. Main traffic control methods are: fixed, traffic-responsive (adaptive), pro-active. Traffic control must be ensured in two levels: local (road side) level and central control level.

Safety requirements concerning the whole traffic control system

The careful and secures implementation of safety critical functions of the system (according to the European norm EN 12675:2002) must be ensured at all levels (TCC, TLC, PLC) and must satisfy the following requirements basically:

- recognition of prohibited (conflicting) or false signals;
- in case of inside errors, it switches to fail-safe position state (depending on the error type);
- checking the right green light combination, i.e. prohibited greens cannot be on at the same time (check the existence of the intermediate times);
- checking the failure of the signal components.

4. ViL and SciL Testing Methodology with Traffic Simulation

This chapter introduces how the ViL and SciL concepts can be integrated with a microscopic traffic simulation software environment, focusing especially on the traffic control and the traffic simulation software environment, which is in our case based on SUMO (Lopez *et al*., 2018). In the example we consider a real test track in Hungary, the ZalaZONE, implemented in SUMO. We show how the real elements are connected to the virtual reality of the software.

4.1. Building blocks of ViL and SciL tests

Integration of hardware elements and the software is based on the concept presented in (Tettamanti *et al*., 2018). The building blocks of ViL and SciL test environments are similar to each other, the difference is that ViL includes only the ego car while SciL also includes other real elements such as traffic control lights, sensors, dummy cars etc. The added value of SciL compared to ViL is that the sensors of vehicles can be tested among real conditions, and they get real impulses, and have to decide about the future control. In ViL, sensors get only software impulses (e.g. sensor spoofing).

The main elements of the loop are the following:

- real hardware elements, depending on the scenario, e.g. vehicles, traffic controllers, dummies;
- traffic simulation software, e.g. SUMO;
- obtaining information of hardware elements, e.g. via CANCaseXL;
- feeding the hardware elements with information, e.g. via AutoBox;
- core software that manages the entire scenario by connecting all software, e.g. Matlab (Tettamanti *et al*., 2018).

For such test processes, a microscopic traffic simulation software is needed. There are more options available on the market, each of them have their advantages and drawbacks depending on what the user needs. SUMO was chosen for realising our purposes. SUMO offers XML based configuration through of which one can design the geometry of any type of road networks and set up simulations in a simple way. With the additional SUMO TraCI (Traffic Control Interface) it is possible to control and modify simulation processes online. It uses TCP communication that can be programmed in several languages, e.g. Java, Matlab, Python. It is possible to give and get information from the elements of the simulation network such as links, intersections, vehicles, signal heads, traffic controllers etc.

The next building block we mention is the communication protocol of hardware elements taking part in the SciL simulations. Most vehicle manufacturers use the CAN protocol for in-vehicle communication processes (e.g. sensors, ECUs), therefore, the traffic simulation has to be connected with the vehicle using this protocol. Matlab, also being capable of integration with SUMO, has an internal CAN communication module. The connection between the CAN bus of the car and Matlab can be realised with the Vector CANCaseXL. This device with multi-channel communication acts as a node on the network that receives and sends all messages with any identifier (Tettamanti *et al*., 2018). Some signal controller manufacturers, e.g. Siemens (2018), Swarco (2018) also use CAN for internal communication processes or have CAN interfaces for external communication.

Commands for hardware elements can be given by the Autobox device. This might also require some of the parts of the original car to be modified, if the misses some by wire functionalities.

4.2. SUMO integration with implementation example

The specific example shows how the interaction of a real vehicle, a real signal head, and a traffic controller is implemented into SUMO software environment. The remaining elements of traffic (road geometry, other cars etc.) are modelled in the virtual SUMO environment. In this subsection this framework is introduced from the perspective of SUMO.

The elementary tasks that can be created in the SciL test environment are classified into the following main categories:

- adapting vehicle speed according to external factors (e.g. weather, traffic conditions, etc.);
- test vehicle operation at traffic light (e.g. accelerating, decelerating, turning, etc.);
- emergency brake simulation by interference (e.g. unexpected hazard);
- keeping small headway distance compared to the vehicle ahead (e.g. traffic jam pilot function);
- platooning situation with two or more real autonomous vehicles.

A simulation environment has been created to fulfil these tasks. The smart city area of ZalaZONE test track has been chosen as the simulation environment. The vision of ZalaZONE is to establish a full-range validation facility for vehicles and communication technologies of the future enabling multi-level testing opportunities from prototype tests till serial product developments. The proving ground provides dynamics tests for conventional vehicles as well as validation tests for AVs and electric vehicles.

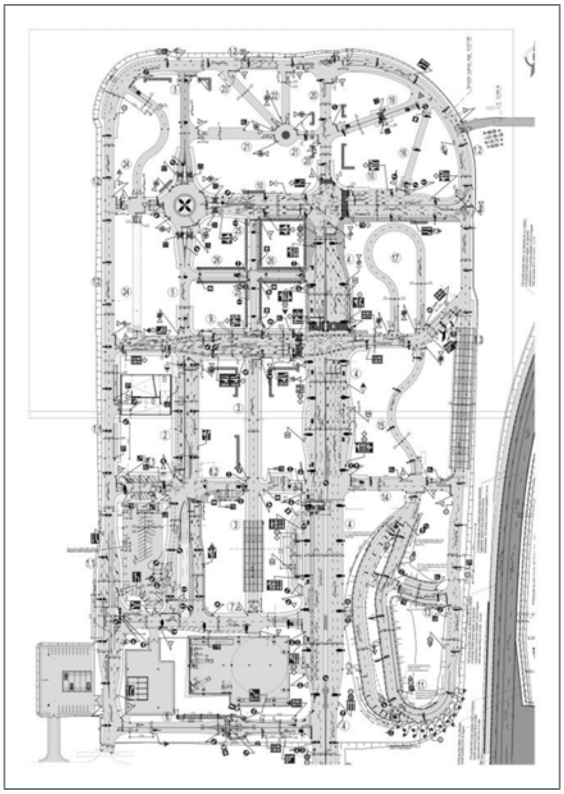

Figure. 3. Smart city network of ZalaZONE

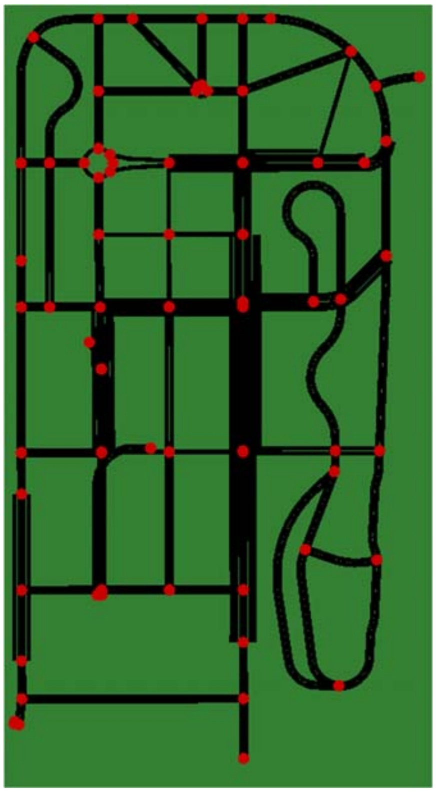

Figure. 4. Smart city road network in SUMO

As shown in Figure 3 the Smart City Zone is a city-like area to provide realistic traffic circumstances in a closed area that contains more environmental, engineering, traffic, and vehicle dynamics elements. There are different types of lanes, surfaces and road geometries. Different types of buildings and facades will be placed next to the street grid of the Smart City Zone. All of the communication technologies will be available in this area like WiFi, cellular technology (5G test network) and intelligent transportation systems.

The real environment can be implemented into SUMO, based on a simple AutoCAD file. The map of the real environment was in an AutoCAD file, which also contained the central lines of the roads. Then the file was saved as a DXF file. With the help of the DXF2GPX converter, the DXF was converted as an Open Street Map (OSM) file. The road types and their attributes were edited in an extensible OSM editor named JOSM. At last, the improved OSM file was transferred into a SUMO road network, as shown in Figure 4. Then the SciL simulation could be carried out in the road network.

One of the greatest advantages of this SciL testing method is its flexibility. Obviously, there is no need to build all types of traffic control systems, only a re-configurable environment with different control strategy is needed. It is also important to emphasize the safety of simulations, since during the experiments the physical safety of the participants or the proper functioning of a real transport system are not endangered.

There are also some limitations of the work at the moment, for example, the shapes of the roads are not very accurate because of the rough way of the road central lines generation. Besides, the slope in the smart city part cannot be well simulated because the road network is only two dimensional. The scalability of the smart city network is also very limited.

5. Conclusions

The SciL concept provides a new type of testing method by combining simulation software and real-world elements. The main advantage of this approach is that one can run many simulation variants, i.e. scenarios only by a relatively small adjustment between two simulation runs. SciL and ViL have the same basis; therefore, in this article the possible ways of implementation have been introduced together. ViL is already used in practice, but SciL is only at the beginning phase. This article has summarised the basic needs of a SciL test track configuration and introduced the first step of implementation. The testing methodology has been shown in connection with the newly developed real test track, ZalaZONE. Before SciL will be more and more widespread, the possible drawbacks should also be taken into consideration. One should not forget that applying new type of simulation methods also invokes new types of failure modes that have to be detected (Zhao *et al*., 2018). For example, the vehicle should be able to differentiate between a dummy-pedestrian or a real test-engineer being coincidentally on the track. Thorough failure mode analysis should be done when implementing such scenarios. The other critical factor is determining the very precise location of the vehicle in real time. These are definitely the tasks of the near future.

Acknowledgements

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