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Virtual risk assessment for the deployment of autonomous shuttles

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Abstract

In recent years, autonomous shuttles have been deployed in many regions all over the world. Currently, there exists no generalized process model for conducting shuttle trials. Shuttle suppliers are using their developed procedures, making it difficult for public authorities to assess the risk of potential shuttle deployments. The Digibus® Austria flagship project, among other goals, develops an approach for the virtual risk assessment of identified critical spots along proposed shuttle paths. Embedded into the deployment process, this serves as a significant body of evidence regarding the safety assurance of shuttle trails. Conducted simulation studies optimizing the shuttle's trajectory for concrete maneuvres, along with derived requirements for the associated virtual environment, are part of the first noteworthy outcomes. Conclusively, by utilizing the restricted operational domain of the shuttle, the proposed virtual risk assessment is considered as the first step towards a general procedure for the safety assurance of automated vehicles.

Keywords:

autonomous shuttles, virtual validation, virtual risk assessment

Introduction

As of late, many different trials for autonomous shuttles have started (Guala et al., 2015; Hunsicker et al., 2017). Although first efforts regarding a standardized deployment process for such shuttle trials have been taken by Rehrl et al. (2020), there is still the open question of how to accurately assess the potential risk for a shuttle deployment, including associated validation procedures. This is an issue since public authorities are lacking those procedures as a basis for the decision regarding the allowance of shuttle trials. What is missing is a structured argument, supported by a body of evidence, providing a compelling and valid case that shuttle operation is safe for the given environment. Generally, this is referred to as a safety case (UK Ministry of Defence, 2007). Virtual validation provides significant support in the needed body of evidence. Especially in recent years, the required virtual environments have made a giant leap, enabling the necessary level of detail regarding the general road network, including surrounding elements (e.g., buildings and vegetation) as well as realistic environmental conditions.

Virtual validation is an approach taken by many research projects and initiatives in the industry, aiming for the development of verification and validation (V&V) processes for such automated driving systems

(ADS). For instance, automotive industry leaders have published a white paper (SaFAD, 2019), presenting different test strategies in response to critical challenges for V&V, like a statistical demonstration of system safety. Among other things, they propose a scenario-based testing approach, which includes the use of different test techniques, ranging from virtual testing to proving ground tests. This is partly based on the work carried out by the German research project PEGASUS (2019)[1], which developed criteria, tools and methods for the release of highly automated driving functions based on a highway chauffeur use case. Another framework for ADS, regarding testable cases and scenarios, was published by the National Highway Traffic Safety Administration (Thorn et al., 2018)[2], also proposing a mixture of test methods including virtual testing.

Although there is a consensus on the overall approach for the V&V challenges of ADS, the research work carried out so far focuses mostly on scenarios for highway-based use cases, resulting in limited applicability to the maneuver-based trials of autonomous shuttles. Additionally, the operational domain of such shuttles primarily consists of urban environments. The proposed approach in this paper is assessing the risk of an autonomous shuttle deployment, by adapting the developed methods in the mentioned research projects and initiatives for a maneuver-based urban use case and is, therefore, an effort towards the development of methodologies for one of the key areas for autonomous vehicle deployment. This is also supported by the fact that one of the two successor projects from PEGASUS, VV-Methoden[3], is also using a junction-based urban environment use case. The project develops methods, which should serve as a baseline for future homologation efforts (Galbas, 2018).

This paper is an effort to define a sophisticated approach for the virtual assessment of potential risks of a shuttle deployment to reduce the chances of hazardous events. The virtual risk assessment is embedded into a deployment process and supports the necessary safety case by providing a body of evidence that the proposed path can be successfully operated by the autonomous shuttle or recommend needed adaptions to responsible stakeholders. Additionally, the existing sensor setup of the shuttle can be evaluated for the planned trail, leading to already validated suggestions for risk reduction regarding the deployment.

Deployment process

Currently, there exists no standard deployment process for autonomous vehicles. Recently, Singapore has announced to open more than 600 miles of public roads for conducting tests with autonomous vehicles and is, therefore, one of the public administrations aiming towards standardized trial procedures (Smith & Ankel, 2019). Singapore's Land Transport Authority (LTA) has already issued a 4-part standard called TR68 (Enterprise Singapore, 2019), which covers key guidelines like basic behavior and safety principles for autonomous vehicles' ADS. As this standard aims at providing comprehensive guidance for deployment and testing of all types of autonomous vehicles on public roads, it can serve as

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[1] https://www.pegasusprojekt.de

[2] https://www.nhtsa.gov/

[3] https://www.ika.rwth-aachen.de/de/forschung/projekte/automatisiertes-fahren/3119-vv-methoden.html

a blueprint for future national guidelines. Although such instructions are a much-needed foundation for safe autonomous vehicle deployment, they typically lack a concrete process model including well-defined deployment and operation activities organized as consecutive steps with decisions and actors. The development of such a process model is one of the goals pursued in Digibus® Austria[4], the Austrian flagship project on integrating autonomous shuttles in public transport systems. A consortium of 13 partners, under the coordination of Salzburg Research, develops and evaluates methodologies and technologies for safe deployment and operation of autonomous L3-4 shuttles (Rehrl & Zankl, 2018). The proposed process model (Rehrl et al., 2020) recommends seven major activities with several sub-activities, being structured in four consecutive phases. The start phase includes a preliminary *feasibility check* as well as an *assignment* activity. The preparation phase continues with *risk assessment* and *preparation* followed by the deployment phase with *deployment* and *validation & approval* activities and finally, the operation phase defines the *operation* activity.

Risk Assessment

According to the previously introduced process model, the risk assessment is part of the preparation phase and one of the defined main activities in the process model for the deployment of autonomous shuttles. Currently, there is no widely accepted standardized approach for conducting such a risk assessment, especially for the deployment of autonomous shuttles. Part of the Digibus® Austria project is dedicated towards the development of such methodologies, which combines currently used approaches of shuttle suppliers, as well as national risk assessment standards and is carried out by the project partner AIT (Austrian Institute of Technology).

In the first step, the proposed uniform risk assessment methodology splits the intended path of the autonomous shuttle into different areas, based on pre-defined road network characteristics, as pictured in Figure 1. These characteristics distinguish between intersections and non-intersections, as well as pedestrian and bicycle crossings. Each of these categories presents different challenges for an autonomous shuttle and the split into different areas makes it easier to locate critical parts of the proposed shuttle path and identify necessary assessments regarding risk reduction.

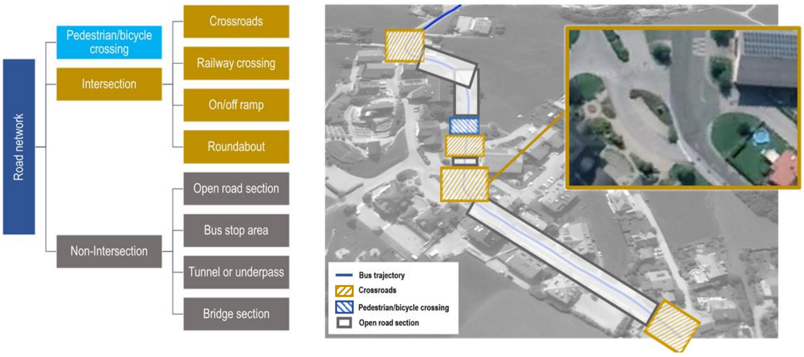

Figure 1 – Uniform risk assessment methodology developed by AIT (adapted from (Rehrl et al., 2020))

In the next step of the uniform risk assessment methodology, the risk potential of each identified area

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[4] https://www.digibus.at/

gets calculated, based on an established method for determining the general risk of road sections (BMVIT, 2012). This national guideline from the Austrian government categorizes each area into seven different sub-categories, for which the maximum risk potential is calculated. This maximum is determined from the various risk potentials of the elements belonging to the same sub-category. For example, the sub-category "*Road layout and visibility*" includes features like road slope, lane width and road curvature. Additional essential elements include properties of the proposed stopping points of the shuttle, like the general visibility of the vehicle for other traffic participants. The risk potential of each component is determined using a pre-defined evaluation table, based on the probability and the expected impact of an occurrence, leading to risk potentials between one (lowest risk) and five (highest risk). The highest risk value of all the different elements inside a category is chosen as the maximum risk potential of this very same category. In the last step, the total risk is determined as the highest value from the different maximum risk potentials of each group. Categories that do not apply to the assessed area are excluded.

The highest possible risk for the given example area is reached for the zoomed out area in Figure 1, which indicates that additional investigations are necessary, exceeding general risk assessment approaches. The proposed deployment process of the Digibus® Austria project suggests conducting detailed simulation studies for the identified critical spots, based on the uniform risk assessment methodology. This should lead to a more sophisticated assessment of the potential risks of an autonomous shuttle deployment, as well as recommendations for the different stakeholders (e.g., shuttle supplier, public authorities) in the deployment process to lower the risk of a potential shuttle trial.

Virtual risk assessment approach

The identified critical spots along the proposed shuttle path are associated with a significantly higher risk regarding the pursued safe operation of the vehicle and are, therefore, the key for successful deployment. Usually, the interaction with other traffic participants holds the most potential for unsafe behavior as it involves the correct interpretation of those objects. Therefore junctions, an important part of road networks, especially in urban environments, are one of the most risk-prone places, not only for autonomous shuttles. Due to the complexity of such junction-based urban use cases, many hazardous events, either known or unknown beforehand, can occur and affect the safety of the vehicle. The goal should, therefore, be to strive for the absence of unreasonable risk due to hazards, which are resulting from functional insufficiencies of the intended functionality. This is referred to as the safety of the intended functionality (SOTIF) and is defined in (ISO/PAS 21448, 2019). The proposed SOTIF workflow can be seen in Figure 2. In the first step, unknown hazardous events need to be revealed, moving them from the bottom left to the top left quarter of Figure 2. The second step is about making the correct adjustments so that hazardous events move to the top-right quarter, leading to a significant risk reduction.

The operational design domain (ODD) is defined by the Recommended Practice SAE J 3016 (2018) as the operating conditions under which ADS are specifically designed to function, therefore, also reflecting the technological limitations. To unveil critical situations in the ODD, scenario-based testing is one of the most promising approaches. Ulbrich et al. (2015) are defining the term scenario as a temporal sequence of scenes, which covers a specific time span and additionally defines all surrounding elements of the ego vehicle (along a multiple-layer model, initially defined by Schuldt et al. (2013)) so that a systematic coverage of the ODD at hand can theoretically be achieved. Additionally, by using a scenario-based approach, the derivation of sophisticated pass/fail criteria for evaluation can be obtained by defining appropriate key performance indicators (KPIs).

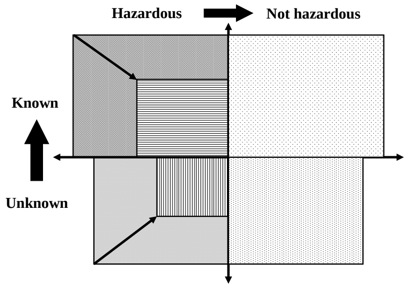

Figure 2 – Scenario-based testing supports the SOTIF flow (based on (ISO/PAS 21448, 2019))

Achieving the needed statistical coverage for ADS of SAE level 3 or higher, due to the enormous ODD, can only be done by an intelligent combination between different test methods. There is a consensus that simulation, next to the proving ground, is an essential component in reaching that goal. In case of an autonomous shuttle, even though it needs to have SAE level 4 for its business model to work, the ODD is nonetheless rather small, as the shuttle drives along a pre-defined path and should fulfill pre-defined maneuvers. Hence an autonomous shuttle use case serves as a perfect starting point for the development of methods for V&V. In case of risk assessments for the proposed autonomous shuttle path, the specific surrounding environment along the route, especially for the critical spots, is crucial. Consequently, the use of proving ground testing is not the ideal approach, as it is challenging to resemble such a specific environment for efficient assessment. In a simulation, however, creating matching virtual environments is still a difficult task, which needs to be embedded into the deployment process, but it is much more scalable in assessing the identified critical situations and derive appropriate measures afterward.

Model-based testing framework

To virtually validate the behavior of the autonomous shuttle in the identified critical spots, model-based testing introduces appropriate models to represent the ADS in the *necessary* detail. Models are always abstractions from the real world and are, therefore, only accurate to a certain degree. The desired fidelity for each of the introduced models of the testing framework depends on the particular use case at hand and is, therefore, purpose-driven. The elements of the general structure used for the simulation framework can be seen in Figure 3 and have the following meaning:

- Driving function:

  In the case of an autonomous shuttle, a sequence of waypoints through a road network, forming a path, is pre-defined. The specific driving behavior is chosen in the "*Behavioural Layer*", taking perceived road users, obstacles and signage into account. This motion specification is an input for the "*Motion Planning*", which seizes the estimated pose, as well as the collision-free space, to calculate a reference path. The "*Local Feedback Control*" then determines the actuator commands based on a vehicle state estimation. (Paden et al., 2016)

- Vehicle dynamics:
  This model acts as the virtual representation of the actual vehicle in terms of the vehicle dynamics and executes the actuator commands from the driving function based on pre-defined interfaces. The model fidelity highly depends on the purpose of the intended simulation study.
- Sensors:
  Sensor models simulate the interaction between the driving function-related vehicle sensors and the virtual environment. These models are, therefore, a prerequisite for virtual testing of ADS. The actual state of the virtual environment (ground-truth) is forwarded to the sensor model, where it is modified based on the sensor model category. (Muckenhuber et al., 2019)
  These are:
  - *Ideal sensor models:* These models generate object-list data based on perfect ground truth data from the virtual environment. (Stolz & Nestlinger, 2018)
  - *Probabilistic sensor models:* These models establish a probabilistic relationship between the sensor output and the ground truth of the virtual environment, e.g., by adding statistical failure rates. (Hirsenkorn et al., 2015)
  - *Physical sensor models:* These models generate sensor data based on actual physical laws and require appropriate virtual environments, which enable the modeling of physical properties as well as material parameters. (Hirsenkorn et al., 2017)

  The output of these sensor models is then forwarded to the driving function.
- Virtual environment:
  In the virtual environment, all necessary elements for scenario generation, depending on the specific use case and the critical area, need to be represented (Figure 3). This includes all defined road users in the desired scenario, including their behavior, as well as the ego vehicle (dynamic environment). For the static environment, the road network, as well as the surroundings are necessary. Furthermore, the required input for the sensor models (ground-truth) needs to be generated.

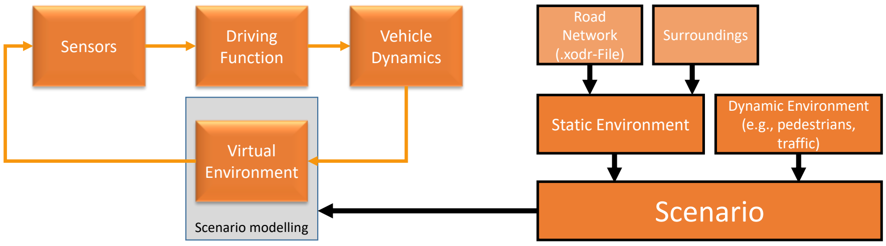

Figure 3 – Model-based testing architecture and virtual environment structure

Since virtual testing environments are a crucial element for successfully conducting simulation studies to support a general safety case for autonomous vehicles, many different environments are available. In general, the different simulators consist of a graphic (for realistic 3D rendering) and a physics engine (for realistic movements) (Rosique et al., 2019). Kang et al. (2019) published an overview of currently relevant virtual testing environments to develop algorithms for self-driving vehicles.

The requirements for testing the ADS of vehicles are similar and can be conducted summarizing the first chapters of this paper. This leads to a list of requirements that the virtual environment needs to fulfill to use simulation for V&V procedures, see Table 1 effectively. The most important elements of the road, as well as the surrounding environment, need to be represented accordingly in the virtual environment in order to make a meaningful contribution towards lowering the risk in the critical area, which was identified via the uniform risk assessment methodology. Additionally, the simulation of different environmental effects, like different weather and lighting conditions, concerning the ODD of the vehicle, is essential, as these are common sources of risk-prone situations. For a specific use case, the characteristics of high-risk categories need to be represented in the virtual V&V framework. The values of the important and applicable risk potential categories for the identified areas during the uniform risk assessment methodology can be seen in the far-right column of Table 1, together with the identified requirements for the respective V&V subsystems.

Table 1: Requirements for the virtual environment in V&V procedures

V&V Subsystem	Requirements	Risk Potential
Static Environment	Road Network: Lanes (e.g., width, curvature), lane markings, pedestrian crossings, sidewalks, junctions, slope, logic road network description	4
	Surroundings: Objects (e.g., buildings, trees, vegetation, street signs)	
Dynamic Environment	Environment (incl. weather, lighting), road users (cars, trucks, pedestrians, bicycles)	5
Sensor Models	Representation of the used sensor setup of the vehicle in terms of FOV, range (including other effects based on model fidelity)	N/A
Vehicle Dynamics	Ability to represent the essential physical effects of the vehicle up to 20 km/h	N/A
Driving Function	Needs to reflect the essential ADS of the vehicle	N/A

Virtual risk assessment in the Digibus® Austria flagship project

In the Digibus® Austria flagship project, the virtual testing environment CARLA (Dosovitskiy et al., 2017)[5] is used. It is based on the Unreal Engine, which enables the possibility of creating highly realistic 3D environments. In general, this environment fulfills the identified requirements for the autonomous shuttle use case (Table 1) by providing features like the import of road networks, defined in ASAM OpenDRIVE (2019)[6] and scenario descriptions (ASAM OpenSCENARIO (2017)[7]). Additionally, changes to the weather, including the lighting conditions, can be applied.

To investigate the risk of a potential shuttle deployment, the necessary models for the simulation framework of Figure 3 are derived. To model the LiDAR sensors of the shuttle, ideal sensor models, using the field-of-view (FOV) and the range of the respective sensor, are used. The information about objects, including other road users, in the FOV is provided as ground truth data by the simulator. As the

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[5] http://carla.org/

[6] https://www.asam.net/standards/detail/opendrive/

[7] https://www.asam.net/standards/detail/openscenario/

autonomous shuttle is driving with cautious speed (< 20 km/h), the vehicle dynamics model is kept simple, only changing simple parameters like the total mass and adding rear-wheel steering, in comparison to the standard vehicle model available in CARLA. The driving function enables the shuttle to follow the path. In case of obstacles on the road, it can either re-plan the trajectory for avoidance or stop. Such a decision is based on the input of the relevant sensors.

For the virtual environment, the structure, which can be seen in Figure 3, was derived. The static environment includes everything that does not change its position and orientation during the execution of a concrete scenario. This includes most importantly, the road network, which defines how the inserted road users of the scenario can move, based on the ASAM OpenDRIVE standard. Project partners of the Digibus® Austria project already provided a first section of the proposed path of the autonomous shuttle trial. The road network description was derived from a uniform process chain for the generation of such high definition digital map formats and is also part of the Digibus® Austria project. In the future, it is planned to include certain aspects of the surroundings (see the right part of Figure 3), like houses and trees, as well in the chosen digital map format (Rehrl et al., 2020). This would further enhance the usage of the process chain for virtual validation purposes. The dynamic environment contains everything that changes its location and orientation during the scenario execution, including most importantly traffic participants like pedestrians and road users. The combination of the static and dynamic environment leads to the possibility of scenario descriptions, which is necessary for conducting scenario-based testing.

Right-turn maneuver analysis

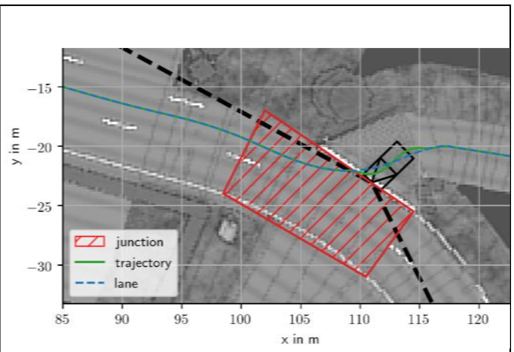
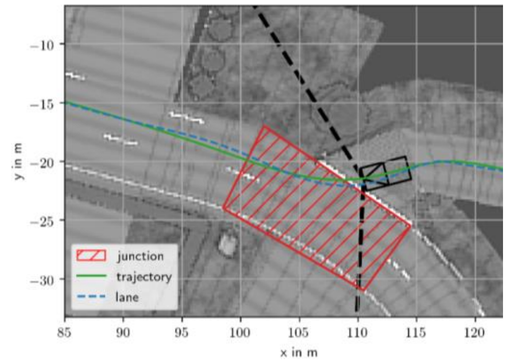
In the Digibus® Austria project, six different driving maneuvers were identified, which inherit a potential risk for the planned deployment of an autonomous shuttle along the proposed path. Out of these six maneuvers, two are happening at a junction (turning left and right). The maneuver of turning right on to the main street at the specific junction, relevant for shuttle deployment, was analyzed further with the help of the previously explained virtual testing environment.

First, the virtual environment was derived, using the digital map for the road layout, provided by partners of the Digibus® Austria project, as a foundation. The surroundings, belonging to the static environment, were derived from measurements provided by the project partner Austrian Institute of Technology (AIT), using a reference measurement system, including different LiDAR sensors and stereo cameras. The virtual environment relevant to the right-turn maneuver can be seen in Figure 4.

Figure 4 – Real (left) and virtual (right) environment for the risk assessment of critical maneuvers

For the maneuver analysis, two possible paths, which are contrary to each other, were derived and simulated. The paths can be seen in Table 2. Case 1 describes a path with an optimal FOV for the autonomous shuttle during the right-turn maneuver. This means the path was optimized for the ideal orientation at the stopping point (right at the entry of the junction), including optimization boundary conditions for the path curvature (respecting the physical limits of the shuttle while turning). Keeping a safe distance to the opposite lane was considered as well. The objective of case 2 was to minimize the curvature of the proposed path while keeping safe distances to the roadside and opposite lane.

Table 2 – Two possible paths for the autonomous shuttle in the critical area

Case 1	**Optimal field of view for the proposed path**	
Optimized for:	Orientation at the stopping point φ_{stop}	
Boundary conditions:	Path curvature $\kappa < 0.35\ m^{-1}$	
	Distance to opposite lane $t_{safe} \geq 0.26\ m$	
Needed time to clear the junction: 15.82 s		
Case 2	**Minimized curvature of the proposed path**	
Optimized for:	Path curvature $std(\kappa)$	
Boundary conditions:	Distance to the roadside/ opposite lane: $\lvert t_{safe} \rvert \geq 0.26\ m$	
Needed time to clear the junction: 9.81 s		

The results of this path optimization can be seen in Table 2. In each of the subfigures, one optimization case is displayed, including the relevant sensor FOV, as well as the orientation of the shuttle at the junction entry and the trajectory of the shuttle. Additionally, the dotted line represents the center of the respective lane. The background of the figures shows a bird view of the created virtual environment, with the critical junction area highlighted in red. Only analyzing the shuttle during an identified high-risk maneuver, shows great optimization potential regarding the proposed path, but also a conflict of objectives. While the first case provides the best view into the junction, especially regarding approaching road users, it takes nearly 16 seconds for the shuttle to clear the marked junction area, as can be seen in Table 2. That is because of the high curvature of the calculated path, resulting in a low rotation rate of the shuttle. In contrast to that, the second case provides significantly less relevant FOV into the junction but leaves it slightly under 10 seconds.

Conclusion and Outlook

By utilizing the restricted ODD of autonomous shuttles, the first step towards a V&V methodology, depending significantly on the use of virtual testing, has been made. The proposed virtual risk assessment approach provides significant decision criteria for the deployment process of a potential autonomous shuttle trial. In the Digibus® Austria flagship project, the developed procedure is used to derive alternative shuttle paths for an identified critical spot. The right-turn maneuver the shuttle is supposed to execute at this location can, therefore, be adapted based on the specific parameters, like the exact sensor setup of the autonomous shuttle. Furthermore, critical parameters, which can act as important KPIs in future simulation studies, including junction-based maneuvers, are identified and used as criteria for the risk assessment. This serves as valuable feedback for the whole deployment process and addresses the needs of several actors involved in the process. For public authorities, the simulation studies of critical spots serve as a foundation for decision making concerning the approval of trials, especially if specific changes of the surrounding environment (e.g., adding traffic lights or changing the speed limit) are solely carried out for the shuttle trial. These changes can be validated using the proposed virtual risk assessment approach. The shuttle supplier gets important feedback from the analyzed maneuvers, which could be fed into the development process of future shuttle generations, concerning both software (ADS) and hardware adaptions (sensor setup).

In the future, it is planned to analyze all the identified critical maneuvers the shuttle endeavors during the proposed path of the trial. For this purpose, the maneuver-based concept, helping to determine the critical spots along the route, will be extended towards a scenario-based concept. Such an enhancement enables even more efficient use of simulation studies to reduce the risk of certain maneuvers by aiming at statistical significance regarding the coverage of the restricted shuttle ODD. Using the layer-model for scenario-based testing, a methodical approach for potential changes in the static environment along the shuttle path, which would lead to reduced risk, is also possible by combining the methods for the creation of virtual environments with the scenario-based concepts. Furthermore, the use of real-world data from controlled shuttle test runs along the proposed path, serve as an essential source for quantifying and arguing model accuracy. This is mainly critical for the sensor models, as the vehicle dynamics model will stay low fidelity, considering the shuttle motion.

Acknowledgments

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References

1. BMVIT. (2012). *Road Safety Inspection* (RVS - Richtlinien Und Vorschriften Für Das Straßenwesen 02.02.34). Bundesministerium für Verkehr, Innovation und Technologie. http://www.fsv.at/shop/produktdetail.aspx?IDProdukt=4a2fbc6f-ff67-4e17-9643-efb121d85c2b

2. Dosovitskiy, A., Ros, G., Codevilla, F., Lopez, A., & Koltun, V. (2017). CARLA: An Open Urban Driving Simulator. *ArXiv:1711.03938 [Cs]*. http://arxiv.org/abs/1711.03938
3. Enterprise Singapore. (2019). *Technical Reference for autonomous vehicles* (Part 1-4; TR68). https://www.singaporestandardseshop.sg/Product/SSPdtDetail/1cd3d49e-e896-4f33-b1d0-dda96f55bf74
4. Galbas, R. (2018). *Validierung und Verifikation für hochautomatisiertes Fahren*. Symposium „Testen -Automatisiertes und Vernetztes Fahren“. https://www.dlr.de/fs/Portaldata/16/Resources/veranstaltungen/2018/VV-Methoden_DLR_Symposium_09_2018_V04.pdf
5. Guala, L., Alessandrini, A., Sechi, F., Site, P. D., Holguin, C., & Salucci, M. V. (2015). *Testing Autonomous Driving Vehicles in a Mixed Environment with Pedestrians and Bicycles*. *22nd ITS World Congress Proceedings*, 12. https://trid.trb.org/view/1413005
6. Hirsenkorn, N., Hanke, T., Rauch, A., Dehlink, B., Rasshofer, R., & Biebl, E. (2015). A non-parametric approach for modeling sensor behavior. *2015 16th International Radar Symposium (IRS)*, 131–136. https://doi.org/10.1109/IRS.2015.7226346
7. Hirsenkorn, N., Subkowski, P., Hanke, T., Schaermann, A., Rauch, A., Rasshofer, R., & Biebl, E. (2017). A ray launching approach for modeling an FMCW radar system. *2017 18th International Radar Symposium (IRS)*, 1–10. https://doi.org/10.23919/IRS.2017.8008120
8. Hunsicker, F., Knie, A., Lobenberg, G., Lohrmann, D., Meier, U., Nordhoff, S., & Pfeiffer, S. (2017). Pilotbetrieb mit autonomen Shuttles auf dem Berliner EUREF-Campus. Erfahrungsbericht vom ersten Testfeld zur integrierten urbanen Mobilitaet der Zukunft. *Internationales Verkehrswesen*, *69*(3). https://trid.trb.org/view/1513396
9. ISO/PAS 21448. (2019). *Road vehicles—Safety of the intended functionality* (Edition 1; p. 54). ISO/TC 22/SC 32 Electrical and electronic components and general system aspects. https://www.iso.org/standard/70939.html
10. Kang, Y., Yin, H., & Berger, C. (2019). Test Your Self-Driving Algorithm: An Overview of Publicly Available Driving Datasets and Virtual Testing Environments. *IEEE Transactions on Intelligent Vehicles*, *4*(2), 171–185. https://doi.org/10.1109/TIV.2018.2886678
11. Muckenhuber, S., Holzer, H., Ruebsam, J., & Stettinger, G. (2019). *Object-based sensor model for virtual testing of ADAS/AD functions*. IEEE International Conference on Connected Vehicles and Expo (ICCVE), Graz, Austria.
12. Paden, B., Cap, M., Yong, S. Z., Yershov, D., & Frazzoli, E. (2016). A Survey of Motion Planning and Control Techniques for Self-Driving Urban Vehicles. *IEEE Transactions on Intelligent Vehicles*, *1*(1), 33–55. https://doi.org/10.1109/TIV.2016.2578706
13. PEGASUS. (2019). *PEGASUS Method—An Overview*. https://www.pegasusprojekt.de/files/tmpl/Pegasus-Abschlussveranstaltung/PEGASUS-Gesamtmethode.pdf

14. Rehrl, K., Schwieger, C., Piribauer, T., Weissensteiner, P., & Sedlacek, N. (2020, May 18). *Towards a uniform process model for deploying and operating autonomous shuttles on public roads*. Submitted for 14th ITS European Congress, Lisbon.
15. Rehrl, K., & Zankl, C. (2018). Digibus©: Results from the first self-driving shuttle trial on a public road in Austria. *European Transport Research Review*, *10*(2), 51. https://doi.org/10.1186/s12544-018-0326-4
16. Rosique, F., Navarro, P. J., Fernández, C., & Padilla, A. (2019). A Systematic Review of Perception System and Simulators for Autonomous Vehicles Research. *Sensors*, *19*(3), 648. https://doi.org/10.3390/s19030648
17. SAE J 3016. (2018). *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems* (p. 35). SAE International, On-Road Automated Driving (ORAD) committee. https://doi.org/10.4271/J3016_201401
18. SaFAD. (2019). Safety First for Automated Driving. *Connected Automated Driving Europe*. https://connectedautomateddriving.eu/mediaroom/framework-for-safe-automated-driving-systems/
19. Schuldt, F., Saust, F., Lichte, B., & Maurer, M. (2013). *Effiziente systematische Testgenerierung für Fahrerassistenzsysteme in virtuellen Umgebungen*. Gesamtzentrum für Verkehr (GZVB). https://www.tib.eu/de/suchen/id/tema%3ATEMA20130600993/Effiziente-systematische-Testgenerierung-f%C3%BCr-Fahrerassistenzsysteme/
20. Smith, L. M., & Ankel, S. (2019). *Singapore is opening up more than 600 miles of public roads to test self-driving cars*. Business Insider. https://www.businessinsider.com/600-miles-public-roads-close-singapore-test-self-driving-cars-2019-10
21. Stolz, M., & Nestlinger, G. (2018). Fast generic sensor models for testing highly automated vehicles in simulation. *E & i Elektrotechnik Und Informationstechnik*, *135*(4–5), 365–369. https://doi.org/10.1007/s00502-018-0629-0
22. Thorn, E., Kimmel, S., & Chaka, M. (2018). *A Framework for Automated Driving System Testable Cases and Scenarios* (Technical Report DOT HS 812 623; p. 180). National Highway Traffic Safety Administration. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13882-automateddrivingsystems_092618_v1a_tag.pdf
23. UK Ministry of Defence. (2007). *Safety Management Requirements for Defence Systems* (Issue 4; Defence Standard 00-56, p. 22). https://www.skybrary.aero/bookshelf/books/344.pdf
24. Ulbrich, S., Menzel, T., Reschka, A., Schuldt, F., & Maurer, M. (2015). Defining and Substantiating the Terms Scene, Situation, and Scenario for Automated Driving. *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 982–988. https://doi.org/10.1109/ITSC.2015.164
25. VIRES Simulationstechnologie GmbH. (2017). *OpenSCENARIO*. http://www.openscenario.org/download.html
26. VIRES Simulationstechnologie GmbH. (2019). *OpenDRIVE- Open Dynamic Road Information for Vehicle Environment*. http://www.opendrive.org/download.html