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Risk minimisation for autonomous shuttles in suburban environments based on virtual validation

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Abstract

In recent years autonomous shuttles have been deployed worldwide. Currently, autonomous shuttle trials rely on safety operators monitoring the environment and intervening in critical situations. One of the next steps is to operate shuttles with remote human supervision only, which will require an extensive safety procedure before deployment. Using virtual validation for risk minimisation is an effort to address the current lack of resilient arguments regarding the safety case needed for autonomous shuttle deployment. In this paper, a virtual validation architecture specifically designed to assess autonomous shuttle deployments is proposed. A knowledge-based approach towards scenario generation was used, integrating safety-related key performance indicators for evaluation purposes. The executed test cases for a specific left-turn manoeuvre of the shuttle show the importance of correct vehicle orientation in critical situations. This research contributes towards a verifiable risk minimisation by virtually validated shuttle trajectories, taking location-specific static infrastructure into account.

Keywords:

Autonomous shuttles, virtual validation

Introduction

In recent years autonomous shuttles have been deployed worldwide (Hunsicker et al., 2017, Guala et al., 2015). First efforts have been conducted regarding creating a generalised deployment procedure for such shuttles (Rehrl et al., 2020). Such a procedure should provide all relevant stakeholders with the necessary information and guidelines to safely deploy autonomous shuttles on public roads. Currently, these trials rely on human safety operators in the shuttle monitoring the environment and intervening if critical situations occur. Therefore, these shuttles are currently only granted exceptional permits to be deployed on public roads. The next logical step in the development is to equip shuttles with autonomous driving systems (ADS) SAE Level 3+ (SAE J 3016, 2018) operating along a specific road section with remote human supervision only (without a human safety operator in the shuttle). However, when it comes to the risk assessment of such deployments, it will be required to provide an extensive safety case to justify the deployment (UK Law Commission & Scottish Law Commission, 2020). Virtual validation using a respective architecture to conduct virtual testing is needed to provide the required body of evidence to decide on the potential deployment (SaFAD, 2019). There are already existing approaches towards a generalised virtual testing framework (Leitner et al., 2020). This paper uses the described methods and applies a virtual validation architecture tailored towards an autonomous shuttle use case, combined with a scenario-based approach for virtual testing (Scholtes et al., 2020). Concretely, since no scenario databases for suburban environments are available, a knowledge-based approach towards scenario generation is used (Riedmaier et al., 2020). Additionally, relevant safety key performance indicators (KPIs) are defined, implemented, and evaluated on the derived scenarios, taking the shuttle's specific sensor setup into account. It needs to be mentioned that the focus of this evaluation lies in the assessment of potential shuttle trajectories for specific risk-prone manoeuvres.

Using virtual validation for risk minimisation is an effort to address the current lack of resilient arguments regarding the safety case needed for autonomous shuttle deployment. In this particular case, a left-turn manoeuvre is focused upon and assessed to choose the safest possible trajectory for crossing the opposite lane. Using a virtual validation architecture, with subsystems that meet the derived use case requirements, it can be shown that this is a valuable approach towards risk minimisation. It provides relevant input for public authorities and other stakeholders that need to decide on potential deployments of ADS equipped shuttles.

Real-world operation and deployment

In the Austrian flagship project Digibus® Austria, a consortium of 13 partners under Salzburg Research's coordination joined forces to develop methodologies and technologies for conducting safe operations of autonomous shuttles. The provided EZ10 shuttle from EasyMile (consortium partner) was deployed in different phases during the project duration in the suburban town Koppl, near the City of Salzburg (Austria). The main goal of the project was to investigate if such a shuttle can effectively bridge the last mile by incorporating it into the public transportation system. During these shuttle trials, various experiences were gained. Together with the developed methodologies, all of these aspects have been incorporated into a generalised deployment process (Rehrl et al., 2020). The generalisation stems from combining existing procedures from the shuttle supplier EasyMile and incorporates additional aspects beneficial for public authorities (e.g., feasibility checks).

Deployment process

The deployment process contains activities organised in four phases (*start, preparation, deployment, operation*). In the first phase (*start*), a general feasibility check is done (e.g., checking all necessary permissions), followed by a planning activity (e.g., defining responsibilities, cost estimation). In the second phase (*preparation*), a risk assessment, as well as general preparation steps (e.g., planning of mobility services) are conducted. The last two phases include the actual *deployment* and the (daily) *operation*.

The focus of this paper is on the risk assessment activity, embedded in the second phase. During this activity, it needs to be estimated if the potential deployment risk is acceptable. In the first step, a general risk assessment of a shuttle route (following the pre-defined procedure) is conducted. This could already lead to an adverse decision, for example, if individual requirements of the shuttle supplier (e.g., necessary lane width) cannot be met. This general risk assessment could also lead to identify risk hot spots, where it is estimated that the shuttle is exposed to an increased risk. These hot spots may be further investigated using virtual validation, which in this paper is done for a specific shuttle manoeuvre, as discussed later.

ODD specification

The operational design domain (ODD) defines conditions for the safe operation of an automated driving system (ADS). Based on the specification PAS 1883:2020 (2020) the ODD is divided into the main categories *scenery* (non-movable elements of the operating environment), *dynamic elements* (all movable elements in the ODD), as well as *environmental conditions* (weather and atmospheric conditions).

The ADS incorporated in the shuttle needs to be able to operate in the defined ODD safely. In the Koppl deployment, specific weather aspects are excluded from the *environmental conditions,* which means the shuttle only operates in clear weather conditions (heavy rain, snowfall or slippery roads are avoided). The *scenery* essentially consists of the respective road layout in Koppl, which was derived from highly accurate environmental sensing data (mobile mapping system RoadSTAR, provided by the project partner Austrian Institute of Technology (AIT). From the sensed data, AIT extracted georeferenced road features as well as additional features from the scenery. From the road features, the project partner Prisma solutions created a high-definition (HD) road map in the ASAM OpenDRIVE® format. Static elements from the scenery such as trees or fences, represented as bounding boxes, were included in the HD map as well (see Figure 1). For the *dynamic elements,* all relevant traffic participants need to be considered. The executed simulations focus on vehicles with speeds up to 50 km/h, which is the legal speed limit in Austrian villages.

The initial situation concerning the left-turn manoeuvre of the autonomous shuttle can be observed in Figure 1. For starting the simulation, two different shuttle trajectories have been provided by project

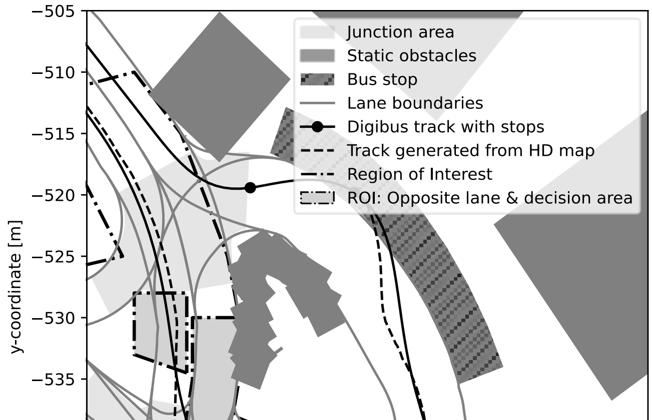

Figure 1: Digital map of Koppl centre (near Salzburg, Austria)

partners. One is the manually generated trajectory from the shuttle supplier EasyMile (solid line in black) during the deployment process, the other one (dashed line in black) is the trajectory which was automatically generated by Salzburg Research as the centreline of the physical and virtual driving lanes being modelled in the georeferenced HD road map. The algorithm for generating centrelines for driving lanes is part of the Graphium project[1], an open-source software platform for working with (HD) road maps. After generation, the centreline along the shuttle route is exported as GPX file.

Design of scenarios and key performance indicators

A model-based testing architecture suitable for the specific use case needs to be derived. For the shuttle deployment in the Digibus® Austria project, a detailed investigation of all necessary aspects of such an architecture was already conducted by Weissensteiner et al. (2020). For the identified subsystems (*sensors, vehicle dynamics* and *virtual environment)* of the model-based testing architecture, requirements were derived. Additionally, the appropriate virtual environment of Koppl was generated, based on a road layout generated from real-world data (available in the ASAM OpenDRIVE® format), with added static elements of the road surroundings (e.g., vegetation) where necessary. The concrete implementation of sensor and vehicle dynamics models for conducting the simulation studies is presented in the *virtual validation architecture* section.

The most important step after defining the general structure and necessary submodules of the model-based testing architecture is to decide which scenarios are relevant and therefore need to be tested using the developed simulation framework. Since for the suburban use case at hand, no specific scenario database exists (compared to highway-based use cases where different databases already emerged, e.g., Saigol et al. (2020)) a similar approach as used in de Gelder et al. (2020) is taken. The categorisation of potential scenarios is done in different classes (*scenario categories)* based on the scenario's similarity. This method of using scenario categories for classification can also be compared to the idea of logical scenarios, as described in Scholtes et al. (2020), where they use an ontology-based 6-layer model.

For the shuttle deployment in the Digibus® Austria project in Koppl, five challenging shuttle

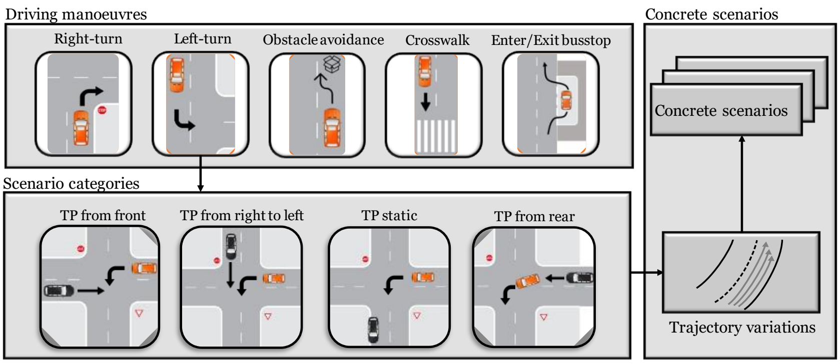

Figure 2: From driving maneuvres to concrete scenarios

manoeuvres along the proposed path were identified using a uniform risk assessment methodology, considering location specific aspects like road layout and condition (Rehrl et al., 2020). These five

[1] https://github.com/graphium-project/

driving manoeuvres can be seen at the top of Figure 2. While Weissensteiner et al. (2020) are having the right-turn manoeuvre as a specific example, this paper focusses on the left-turn manoeuvre. In the next step, the relevant scenario categories are defined. This is done by acknowledging specific aspects of the junction area in the centre of Koppl where the left-turn should be executed. Concretely, it is evaluated from which sides (from the shuttles perspective) traffic participants (TP) can approach the shuttle while preparing or executing the manoeuvre. This specific case led to four different categories since vehicles can approach from the front, from right to left (crossing the road in front of the shuttle) and from the rear (trying to overtake the shuttle). Additionally, a stationary vehicle on the road where the shuttle is supposed to turn into was considered as well. Considering individual trajectory variations for the approaching vehicles is the last step needed before generating concrete scenarios for each of the defined categories. The concrete scenarios are generated automatically in the ASAM OpenSCENARIO® format for each of the scenario categories using a Python wrapper available on GitHub[2]. It needs to be noted that a combination of the different scenario categories would be possible as well, however, for evaluating the left-turn manoeuvre, focussing on one scenario category each, seems sufficient.

After having decided upon the different scenario categories and types of concrete scenarios which need to be tested to evaluate the shuttles' trajectory before the deployment, specific key performance indicators (KPIs) need to be defined to assess the simulated test cases in the next phase. The assessment could be for *safety, comfort, performance,* or *efficiency* aspects, each on the ego-vehicle level. While the safety category merely focusses on the safe execution of the scenario, other aspects that might be important for shuttle operations (but not exclusively) like ride comfort for passengers or energy efficiency of the shuttle are evaluated in the other categories. In this paper, the KPI category *safety* is considered. Concretely, various KPIs have been defined which are then used for evaluation of the simulated test cases. Firstly, the duration in specific areas (region of interest, ROI) is measured during a simulation run. These areas are the junction area itself, the decision area, which is the area the shuttle enters before the turn manoeuvre and the opposite lane, that the shuttle needs to cross during turning. Secondly, a specific variant of a time-to-collision (TTC) calculation, based on Jiménez et al. (2013), was implemented and used to evaluate the second simulation study, the shuttle turn-manoeuvre without dedicated stopping point. Furthermore, an oncoming vehicle's duration inside such a defined ROI is measured (using ground-truth information) and used for evaluation purposes.

The discussed KPIs are all focussed on the performance (e.g., in terms of safety) of the ego-vehicle. Additionally, KPIs on a scenario level can be defined, which could be defining specific metrics regarding the scenario space coverage. Since a knowledge-based approach in generating the scenario is used, no further investigation in terms of coverage was made.

ODD-based virtual validation potentials

Considering the defined ODD of the autonomous shuttle enables to specify the potentials of virtual validation further. By mapping the ODD specification to the respective ADS subsystems, concrete

[2] https://github.com/pyoscx/pyoscx

requirements for a framework used for virtual validation were derived. Now, these requirements serve as a baseline for the generation of a suitable validation architecture for virtual testing. This architecture is then used to conduct the virtual risk assessment on the defined test cases.

Virtual validation architecture

Considering the requirements for the ADS subsystems, an architecture for conducting virtual testing is derived and can be seen in Figure 3. It consists of two main building blocks, an internal simulation framework (left side) and several external modules necessary for simulation purposes (right side).
The simulation workflow starts with the generation of test cases (defined as an external module in Figure 3). In the test case description, a specific stopping point (for the left-turn at the junction) and a concrete trajectory are assigned to the autonomous shuttle. Furthermore, the road layout is defined referring to a separate ASAM OpenDRIVE® file. Additionally, a concrete scenario (in the ASAM OpenSCENARIO® format), which most importantly describes other traffic participants' behaviour, is referenced in the test cases description. All these parameters, directly or indirectly (via other files) defined in the test case, are used as input for the scenario engine's initialisation. The task of this module is to execute the given scenario based on its described content. In the specific case of virtually validating a turning manoeuvre of an autonomous shuttle, other traffic participants' behaviour in the scenario is most important. Therefore, the scenario engine interprets the given scenario description and controls the simulation process by initialising the respective vehicles and assigning them their target trajectory defined by the scenario. The spawning of these vehicles happens based on pre-defined triggers, which are based on simulation time. The scenario engine is a further development of the scenario runner, which is a submodule of the autonomous driving simulator CARLA (Dosovitskiy et al., 2017). This was necessary since the required interfaces to the internal simulation framework had to be added. The scenario engine transfers all vehicles' pose information in the scenario (e.g., the shuttle, other traffic participants) to the environment simulator. For this specific setup, since the scenario engine is based on the mentioned scenario runner, CARLA was used for visualising the static and dynamic content of the scenario. The static content is represented as 3D-model, mostly based on an ASAM OpenDRIVE® map generated from real-world data (Weissensteiner et al., 2020). For the dynamic content, a realistic 3D-model of the autonomous shuttle was imported. For the other vehicles of the scenario, available vehicle models in CARLA were used.

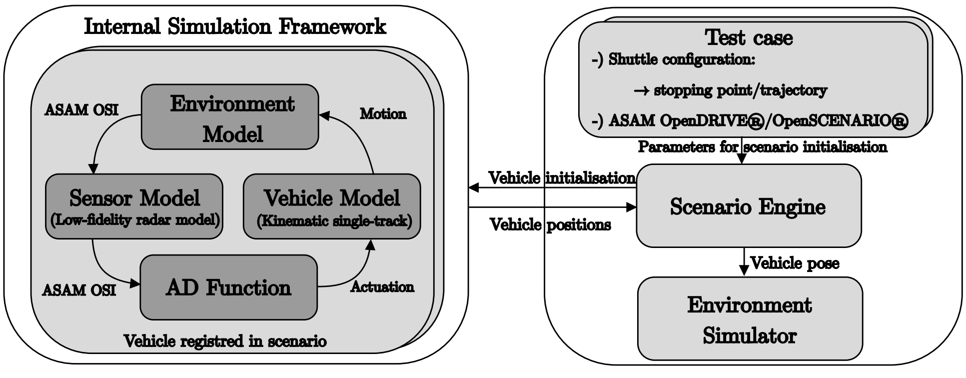

Figure 3: Simulation architecture for virtual validation of shuttle manoeuvres

Furthermore, the scenario engine initialises all vehicles in the internal simulation framework using the embedded interfaces. This simulation framework is developed internally and purely based on Python. Each vehicle registered in the scenario (via the scenario engine) gets assigned the necessary ADS subsystems. For the autonomous shuttle, various submodules have been integrated. As a sensor model, a low-fidelity radar model, based on the concepts of Muckenhuber et al. (2019), is embedded, which incorporates a realistic occlusion calculation. For the in- and output of the sensor model the ASAM OSI interface is used, as described in van Driesten & Schaller (2019). As vehicle model a kinematic single-track model is implemented (Schramm et al., 2014). The automated driving (AD) function is implemented as trajectory following, taking potential stopping points and other traffic participants into account. The environment model is a 2.5D representation of the virtual environment imported into CARLA. It uses 2D bounding boxes for the vehicles (used for occlusion and collision calculation) and the static obstacles. For the static obstacles, the height of the respective bounding box is also used as information for the integrated sensor model, which has a horizontal and vertical field of view (FOV). Each traffic participant defined in the scenario gets assigned to a separate instance of this internal framework, making it a multi-agent simulation. The traffic participants are also using a trajectory following AD function and a kinematic single-track vehicle model.

Virtual risk assessment of generated test cases

In the following, the results of the conducted simulation studies are presented. The simulations were carried out using the simulation setup described in Figure 3. The sensor setup was modelled using the described low-fidelity radar models, implementing a specification for standard automotive radars. Those radars usually have two different configurations, for short- and long-range applications, with a much narrower FOV in long-range mode. The horizontal FOV was approximated using two triangles (20m/60m range and 120°/74° angle for the short-range; 150m/190m and 19°/8° angle for the long-range), which is a conservative estimate of the real horizontal FOV depicted in (Liebske, 2019). The vertical FOV of all sensors was set to 20°. The autonomous shuttle is configured with three front-facing radars (one on each side in short-range and one in the middle in long-range configuration) and one facing the back of the vehicle (long-range configuration). The vehicle model was parametrised using available data from the shuttle supplier for the EZ10 (3^{rd} generation).

Using the drivable area, derived from the HD-map, as a boundary condition of a trajectory optimisation leads to the variations seen on the left side of Figure 4. Depending on the weighting, the trajectory can either be minimised in terms of curvature (red dotted line) or staying as close as possible to the centre of the respective lane (green dotted line). A balanced option between these two was also considered (blue dotted line). It can be observed that the trajectory with focus on minimising the curvature is very similar to the original shuttle trajectory generated by the shuttle supplier. On the other hand, the centre-based trajectory is closest to the automatically generated lane. It cannot be directly matched since the boundary condition of being as close as possible to the original stopping points would be violated. However, evaluating these three trajectory options, a general statement which weight option (min. curvature or centre-based) to favour becomes possible.

The trajectories of possible traffic participants for all relevant scenario categories can be seen on the right side of Figure 4. Traffic participant velocities between 30 km/h and 50 km/h were considered. The vehicles' trajectories were generated based on the given road layout (using the ASAM OpenDRIVE® file) and calculated in such way that they arrive at a particular location (approximately were the shuttle crosses the opposite lane) in a specific point in time. This arrival time is then extended to a time range that is uniformly distributed. Additionally, for traffic participants coming from the front, a varying offset from the lane's centre was added. For the static traffic participant, the red dotted line's beginning is relevant since this vehicle has no velocity. This vehicle placement is varied across the road's length until the marked stopping point of the original shuttle trajectory in the bottom of Figure 4 (right side).

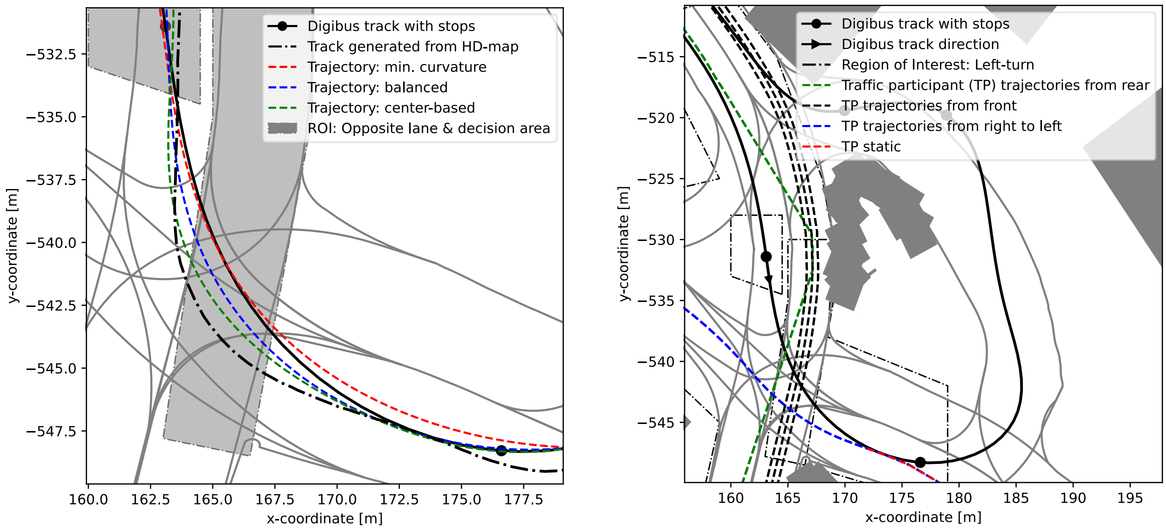

Figure 4: Shuttle trajectory variations (left) and possible trajectories of traffic participants (right)

The described trajectory variations for the traffic participants in all the relevant scenario categories combined with the proposed shuttle trajectories (also including three different locations along the trajectory path for the left-turn stopping point) lead to nearly 1700 simulated test cases.

Table 1: Results of simulated test cases

		Shuttle left-turn manoeuvre variations									Unit
Optimized based on:		min. curvature			balanced			centre-based			
Stop position (along path):		45	48	52	45	48	52	45	48	52	m
Duration in region of interest (ROI):		28.4	28.48	**28.33**	28.6	28.6	28.53	28.8	28.77	28.73	s
Duration in opposite lane:		4.97	5.63	8.77	4.73	5.26	7.03	**4.3**	4.7	5.97	s
Scenario category:	KPIs (mean values):										
TP from front	first TP detection	29.57	29.5	29.68	29.78	30	**29.33**	29.38	29.4	29.8	s
	TP undetected in ROI	2.9	2.83	3.02	3.12	3.33	**2.67**	2.72	2.73	3.13	s
TP from rear	first TP detection	28.76	28.71	**28.54**	29.08	29.01	28.81	29.28	29.25	29.1	s
	TP undetected in ROI	0.23	0.17	**0.01**	0.55	0.48	0.27	0.75	0.72	0.55	s
TP static	first TP detection	29.97	28.57	23.42	28.47	26.87	16.32	27.97	26.07	**15.72**	s
	TP undetected in ROI	29.9	28.5	23.35	28.4	26.8	16.25	27.9	26	**15.65**	s
TP from right to left	first TP detection	28									s
	TP undetected in ROI	0									s
Two TPs from front	timesteps with two detected TPs	115	109	63	149	142	145	**271**	203	256	#

In Table 1, the results of the simulated test cases can be observed. The three different proposed shuttle trajectories, with three different stop positions along their path, can be seen at the top. Down below the duration in the junction area (defined as ROI) and in the opposite lane for each shuttle trajectory configuration is displayed. It can be observed that the time in the opposite lane is minimised if the stopping point is earlier (more time to accelerate for the turn manoeuvre) and a centre-based trajectory is chosen since this represents a geometrically shorter path across the opposite lane (see the left side of Figure 4). The whole junction area is left the fastest with the minimised curvature option, since once again this represents, geometrically, the shortest path. In the second half of Table 1, each scenario category is evaluated based on the first detection of the traffic participant and the time this vehicle is undetected inside the ROI. For the scenario category, *TP from front* the balanced trajectory and for *TP from rear* the minimised curvature is evaluated as the best option. For the static traffic participant, the centre-based trajectory is the best option. It detects the vehicle much sooner, which is otherwise occluded by static obstacles in the middle of the junction. All the proposed shuttle configurations can detect the approaching vehicle in the scenario category *TP from right to left* as soon as it enters the ROI. In case of two traffic participants approaching the shuttle (with a pre-defined gap in-between) the amount of timesteps where both vehicles are detected is evaluated. In this case, the centre-based trajectory presents the best option.

All simulations so far have been conducted with a dedicated stopping point of the shuttle before turning left. This stopping point is for the shuttle operator to monitor the environment and indicate the shuttle once a turn manoeuvre is safely possible. Since in the future the shuttle should be deployed without a dedicated operator, evaluating the proposed shuttle trajectories (on the left side of Figure 4) without stopping points for concrete scenarios of approaching traffic participants (scenario category *TP from front*) seems reasonable. Predominantly, the already described TTC is used as a safety KPI to evaluate if a turn manoeuvre would be possible considering the current assumption for the sensor suite. Concretely, it is evaluated if an approaching vehicle is detected during the shuttles time in the defined

Table 2: Testcase results for left-turn manoeuvre without stopping

		Shuttle left-turn manoeuvre variations (without stop)									Unit
Optimized based on:		min. curvature			balanced			centre-based			
Shuttle velocity:		3	5.55	6.95	3	5.55	6.95	3	5.55	6.95	m/s
Duration in opposite lane:		4.27	2.27	2.10	4.23	2.27	2.07	3.97	2.10	**1.90**	s
View specification:	Unit	Cases of safe left-turn manoeuvres: (Traffic participant velocity = 50 km/h)									
100	%	0									%
200	%	0*	12*	12*	0	22	22	0	**33**	**33**	%
		Cases of safe left-turn manoeuvres: (Traffic participant velocity = 30 km/h)									
100	%	0	14*	23*	0	25	78	0	**100**	**100**	%
*contains scenarios where the traffic participant is not detected during the decision area (highly safety critical)											

decision area (Figure 1) and if that vehicle TTC is greater than the duration the shuttle needs to cross the opposite lane. If both are the case, the turn manoeuvre is possible and classified as non-critical. Otherwise, it is categorised as unsafe turning (in case the vehicle is detected in the decision area, but the TTC is too small) or highly critical (when the vehicle is not detected at all by the shuttle during its time in the decision area). It needs to be mentioned that this only evaluates the suitability of the shuttle trajectory and the sensor suite for a specific scenario category and turn manoeuvre but does not evaluate the implemented AD function.

Table 2 presents the results from the simulation study of the left-turn manoeuvre (without a dedicated stop point). At the top of the table, the shuttle's duration in the opposite lane for the three different trajectory options with varying shuttle velocity is displayed. It can be shown that, like the general simulation study of Table 1, the centre-based trajectory is the best option (for all velocities) for crossing the opposite lane. To evaluate in how many test cases an unsafe turning would occur, two different traffic participant velocities were considered. The traffic participants' trajectories were varied based on the time they arrive in the opposite lane area (see Figure 1). It can be observed that no safe turning would be possible for the defined sensor configuration, no matter the shuttle velocity or trajectory if the approaching vehicle has a velocity of 50 km/h. If the ranges of the sensor configuration were doubled (keeping the same angles for the FOV), cases of safe turn manoeuvres would occur. If velocities are kept below 30 km/h, safe left-turns are possible. In all cases, the centre-based trajectory configuration (with the highest evaluated shuttle velocity) presents the best option for a stop-less turn manoeuvre. For the minimised curvature option, highly critical scenarios occur, as the shuttle is not detecting the approaching vehicle inside the decision area (while doing so in the other two configurations).

Key findings based on virtual risk assessment

Analysing the two conducted simulation studies, various distinct outcomes can be observed. For the left-turn manoeuvre with stopping, no clear indication can be made which of the proposed shuttle trajectories represent the best option. Firstly, the time differences between the options are most of the time (not taking the particular case of the stationary vehicle into account) very small. Secondly, it depends on the individual weighting of the scenario category. For example, vehicles approaching the rear could be defined as more critical than those coming from the front. Furthermore, the presence of a dedicated stopping point influences this decision even further. The generated data suggests that stopping later is more favourable in most of the cases (two approaching vehicles from the front being the exception). This not because the stopping itself occurs later (this is rather negative as it leads to a longer time in the opposite lane) but because the trajectory is planned differently, knowing the stop point's location in advance.

In removing the stop point from the trajectory and evaluating the shuttle trajectory and the sensor setup in general, the second simulation study shows a much clearer picture than the first one. In both cases (high and low velocity of the approaching vehicle) the centre-based trajectory would present the best option for safe left-turn manoeuvres. While also being the fastest option through the opposite lane, which additionally supports choosing centre-based trajectories, most importantly they differ in terms of shuttle orientation in the decision area (left side of Figure 4). In general, much more of the relevant parts of the opposite lane is covered with the sensor FOVs, leading to not only sooner detections, but also to the fact that detected obstacles are longer inside the sensor's view. The described effect is even further enhanced since the modelled radar sensors have very narrow horizontal FOV in long-range configuration, which is needed for detecting approaching vehicles in time.

These findings present essential information for various stakeholders in the whole deployment process. For shuttle operators, such detailed considerations could be used as input to further develop the shuttle. In this specific case, this concerns mostly the sensor setup and concrete shuttle trajectories in junction areas. However, the results can also be used for the decision-making process of the shuttle, as it provides a priori risk assumptions on the potential trajectories. Using the deployment process described in Rehrl et al. (2020), the presented results support the argument of using automatically generated shuttle trajectories, with the caveat that in specific situations certain (small) changes in the path, could lead to significant differences in performance. Furthermore, using the proposed virtual validation architecture enables statements regarding potential infrastructure-related issues before the actual shuttle deployment. In the presented simulation study, the vegetation in the middle of the junction area could be blocking the view towards a stationary vehicle, which makes it a critical area to investigate further.

Conclusion and Outlook

Utilising the restricted ODD of an autonomous shuttle enables to assess the potential risks along a proposed shuttle route in a detailed manner. Using virtual validation, simulations can be conducted that provide concrete guidelines for the decision-making processes during the planning phase of a potential deployment. A comprehensive risk assessment is performed with valuable output for all relevant stakeholders by deriving a case-specific virtual validation architecture with all necessary subsystems. Using measurable safety KPIs effectively contributes to a verifiable risk minimisation by choosing the shuttle trajectory suggested by virtual validation, taking location-specific static infrastructure into account. The executed test cases for a specific left-turn manoeuvre of the shuttle show the importance of the correct vehicle orientation in critical situations, most notably for trajectories without dedicated stopping point before turning. Modelling the vehicle's relevant sensors made it possible to make such considerations and efficiently use the available sensor setup of the shuttle. Furthermore, these results can be used as input for shuttle operators to improve sensors position and orientation.

There are various ways to extend the conducted research in this paper further. The next step is to export the most suitable shuttle trajectory, which is possible since the used virtual environment is precisely georeferenced and use it for real-world testing. This was already conducted in a proof of concept with the shuttle operator EasyMile (project partner). Feedback from real-world tests is valuable for further validation of the available simulation architecture. Another potential extension would be to gather the relevant junction area's traffic data, either using static sensors or drones (Bock et al., 2019). Using the presented KPIs as a baseline for search criteria in the gathered data would extend the knowledge-based scenario generation used in this paper, towards a data-driven scenario generation to increase the tested scenarios' representativeness. Furthermore, this would strengthen the respective safety case arguments.

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