2021 IEEE Intelligent Transportation Systems Conference (ITSC)
Indianapolis, USA. September 19-21, 2021

An Online Safety Guard For Intelligent Transportation Systems

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Abstract— **Intelligent transportation systems (ITS) become more and more sophisticated. They get equipped with different sensors to observe environmental as well as traffic conditions targeting to increase traffic flow and to improve roadway safety. At the same time, automated driving systems are hitting the road and their safety concepts become more and more mature. This raises the idea of what it would take to transfer advanced in-vehicle safety approaches into the roadside. In this paper, we discuss how Responsibility-Sensitive Safety can be applied as a safety guard within the infrastructure and show the incremental benefits for the ITS.**

I. INTRODUCTION

The transition of (static) traffic infrastructure towards intelligent transportation systems (ITS) has accelerated rapidly in the last decade. Gathering information on the current traffic state to plan and manage the traffic on the road allows improving traffic flow by e.g. applying variable speed limits, adaptive lane usage or dynamically controlling the phases of traffic signals. These solutions on active traffic management have become widely adopted state-of-the-art [1]. Another emerging trend of ITS it to deploy roadside sensors to monitor and potentially improve roadway safety, by detecting dangerous environmental or traffic conditions and providing early warnings to road users.

With the increase in the computational capabilities of roadside infrastructure, it is not only possible to display warning message using roadside signals, but also to rely on direct communication between the infrastructure and road users. Such cooperative systems and services in general [2], [3] and collision avoidance systems in particular are based on vehicle-to-vehicle (V2V) [4], vehicle-to-infrastructure (V2I) [5], [6] or generally on V2X technologies. Safety metrics like time-to-collision (TTC) [7] or other measures [8] are applied to detect dangerous situations. In addition, in future ITS it might even become possible to go beyond the scope of a single vehicle state, but to consider the interactions of drivers, vehicles and road [9].

However, an intelligent roadside system that can monitor the traffic, detect dangerous situations and then inform all involved road users with an appropriate (counter)-behavior is still missing. As respective communication protocols are getting standardized [10], it becomes possible to signal individual warnings to the vehicle (and a potential driver). Furthermore, such a system can provide many benefits over existing isolated in-vehicle safety solutions. For example, imagine an emergency situation on a multi-lane road, that could be bypassed, if all vehicles move one lane to the left (see Figure 5 at page 6). Such cooperative emergency maneuvers can only be performed, if all involved vehicles participate in the maneuver. An infrastructure safeguard that directly sends driving commands to each vehicle is able to enforce this. Another example is coordinated platooning, where the infrastructure ensures that all vehicles in the platoon have sufficient/individually-tuned following distances.

At the same time, such an infrastructure-based safety guard is not far away utopia. In fact, a lot of work is spent on the development of safety concepts for automated driving systems (ADS) of SAE levels 3–5, as they are actually hitting the road and will get deployed at larger scale in near future. Combining recent enhancements on in-vehicle safety [11], which promise advantages over classical surrogate safety measures [12], with infrastructure based safety systems by transferring these methodologies from the in-vehicle perspective into the larger infrastructure scope provides all traffic participants, not only ADS, with the ability from preventing hazardous situations, if they connect to the ITS.

Therefore, we propose in this work a novel infrastructure-based safeguard, that brings the safety benefits of the Responsibility-Sensitive Safety model (RSS) for ADS [11] into the roadside. We show how such a system can be architected and which challenges have to be taken into account for real-world deployments. An infrastructure based perception system is expected to provide higher accuracy and to suffer much less from occlusions than in-vehicle systems due to the increased field of view, but it has only limited knowledge on the concrete planned trajectories of the vehicles, for which an RSS-based safety envelope is calculated for. In addition, it has to cope with dynamically changing latency. RSS deployed as safety metric at the roadside will be able to identify areas or time intervals showing an increase in arisen dangerous situations and provides the basis to coordinate multi-agent safety behaviors. Finally, the results of this work are applied to *Providentia*++ [13] an intelligent road infrastructure project, that uses a test-bed near Munich, Germany comprising highway, rural and urban road segments and a digital twin enabling the analysis of such a comprehensive safety guard.

The remainder of this paper is organized as follows: Section II briefly discusses special requirements of safety monitoring systems executed within the ITS. Section III provides an architectural overview of an RSS-based monitoring system integrated with a real-time digital twin framework. Our reference implementation, developed within the *Providentia*++ project is discussed in Section IV. And Section V provides an analysis on value-added benefits compared to in-vehicle systems. Finally, Section VI concludes the paper.

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Fig. 1. Live view from one of the measurement points of the *Providentia++* test-bed. Sensors (i.e. cameras, radars, LIDARs) observe the highway all the time from which a digital twin of traffic is created providing the tracks of the detected objects (white squares and object IDs). Our approach performs continuous online safety checks based on RSS. Vehicles can receive the check results which show how to escape from potential hazardous situations (sketched overlapping safety envelopes) and get guarded by the system.

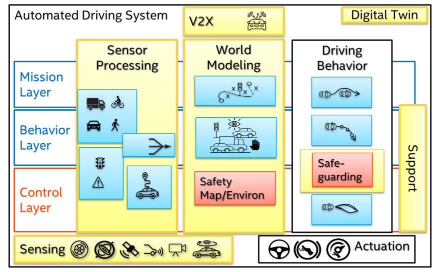

Fig. 2. Integration of a safety guard component into an ADS architecture, loosely based on upcoming SAE J3131 recommended practice [17]. The sensing system (i.e. cameras, LIDAR, RADAR), the sensor processing and the world modeling functional blocks (highlighted in yellow) are required to build up the digital twin of the ITS, while the driving behavior is not. Based on safety-grade map and environment data the safety guard validates the planned trajectory of the vehicles to prevent from violating safety goals.

II. SPECIAL REQUIREMENTS OF AN INFRASTRUCTURE SAFETY GUARD

Figure 1 depicts a live view from the *Providentia++* test-bed for which the safety guard functionality is designed for. The development of vehicle safety monitors encompass many mandatory requirements on the reliability and integrity of the overall system [14], [15]. However, this Section discusses the additional requirements that arise from the application of the safety guard within the infrastructure exceeding the scope of a safety module running within an ADS.

A. Independence from planned trajectory

From an abstract point-of-view the safeguarding task seems similar at the infrastructure scale or within a vehicle. Both require a reliable representation of the world model as input to evaluate if the trajectory of the vehicle is safe. Figure 2 sketches a generic functional reference architecture of an ADS. The functional blocks in yellow are also mandatory for the digital twin of an ITS. One major difference is that while an ADS, in general, contains a trajectory planner module providing its plan for the near future as an input to the safety guard module, an ITS does not have this information. A possible solution would be a trajectory prediction module that provides multiple options for each observed vehicle with assigned uncertainties. In the long run, an ITS might even provide this trajectory planning functionality based on the digital twin as a add-on service to some of the road users which then hand over the complete driving task to the ITS under certain conditions and constraints e.g. for a limited period of time or a limited geo-fenced area, but such implementation is currently limited in practical application. The safety guard shall be able to support all vehicles connected to the system. Human driven vehicles will not be able to provide a concrete trajectory or even a route they intend to take in a reliable manner. Also, without clear standards and regulatory practices, there could be the case where a particular ADS implementation isn't able to access a shareable representation of the future trajectory, for example if they apply Perception-To-Control deep neural networks [16]. Section III-B discusses in more detail how this affects the proposed RSS based safety guard.

B. Reliable Communication and Latency

Adding safety mechanisms to an ITS with the purpose to inform the respective vehicles in case the safety guard detects a dangerous situation requires reliable, safe and secure communications providing time guarantees. If a reliable communication channel between ITS and vehicles cannot be guaranteed, the safety guard service has to stop its operation. Because of this, ADS vehicles should not rely on the ITS safety guard alone in order to drive safely, but these can benefit like other vehicles from additional reliable information from the infrastructure enhancing the overall safety of the traffic. But even if a dependable communication chain is in place, the safety guard must be able to cope with the latency introduced by the communication overhead.

Communication within the ITS is not limited to the vehicles participating in the safety service. The latency between the infrastructure sensors installed at the measurement points and the road-side units (RSU, infrastructure compute unit) varies, because the natural surrounding has to be taken into account on the planning of the measurement system. Latencies of in-vehicle sensors to the in-vehicle compute unit (ECU) is smaller and bounded as part of the operational design domain of the vehicle automation. *Providentia++* is deploying 5G to provide guarantees on the message transmission latency between the ITS and the respective vehicle. The latency of the measurement systems has to be determined as part of the system setup and the safety guard might have to support varying latency values in different regions of the serviced area.

Furthermore, while the safety system in a vehicle can be optimized for a fixed configuration, an infrastructure-based system needs to cope with a variety of different vehicles. It has to consider the complete range of driving performance parameter values of different types of AD or ADAS vehicles, such as breaking and acceleration parameters, reaction times and beyond, it must be able to cope with maneuver execution differences performed by individual human drivers in vehicles equipped with or even without warning systems. Section III-C describes how the approach based on RSS copes with different reaction times and varying latency to ensure the safety maneuvers can be executed on time to prevent from potential collisions.

C. Accuracy

Similar to in-vehicle systems, the accuracy and uncertainty of the infrastructure based digital twin will not remain constant over time. While this is common for all perception systems [18], an infrastructure based system is expected to show reduced uncertainties: The sensors are fixed in the world frame and static parts of the environment and dynamics entities of the roadside, like the state of the traffic lights, are well known. Furthermore, the scene is observed from different measurement points with different field-of views such that occlusion are reduced to a minimum [19] and can be reduced further by the installation of additional measurement points if required. Another advantage of the digital twin over an in-vehicle setup is its independence from power consumption and therefore, gives more flexibility on the computational resources to be deployed. While the infrastructure is supposed to provide better perception accuracy and have less problems on tracking than on-board perception in most of the covered area, the accuracy will be lower in other areas with less redundancy or even partial blind spots due to light/atmospheric conditions and the safety guard needs to operate on all areas equally. Therefore, errors and inaccuracies of the digital twin world model have to be taken into account on the implementation of the safety guard (see Section III-D).

D. Roaming of vehicles

Vehicles entering the region of the safety guard operating on a local roadside unit might have been tracked and evaluated at an adjacent node of the ITS before. While the periphery is less relevant for an in-vehicle safety guard, the ITS safety guard shall work without gaps, so that relevant safety check states have to be preserved while the vehicles are roaming through different ITS nodes when deployed on a large scale. While the issue of coverage gaps is a generic problem for intelligent infrastructure to be solved within the digital twin framework, the safety guard application will add additional data requirements to be monitored and passed between transitions.

III. DESIGN BASED ON RESPONSIBILITY-SENSITIVE SAFETY

This Section describes our proposed approach based on RSS as safety metric in form of a doer/checker and discusses why RSS is well-suited to fulfil the special requirements towards an online safety guard at infrastructure scope.

A. Responsibility-Sensitive Safety as safety guard

RSS [11] continuously monitors the current state of the environment, in order to determine if the ego vehicle is in a safe state. If the ego vehicle is not in a safe state, according to [11] definitions, RSS provides a response action that will bring the car back into a safe state, so that the ego vehicle is not causing a collision with another road actor, if the other behaves as expected. If this so called proper response is deployed by the respective ego vehicle the RSS safety model acts as a safety guard.

On structured roads a state is considered dangerous, if both the longitudinal as well as the lateral safety envelope are compromised. Thereby, the positive longitudinal safety distance $d_{\min}$ in a vehicle following scenario is e.g. defined by the distance, the ego vehicle at speed v_{r} in the back covers while accelerating with $\alpha_{\max}$ during its response time ρ, plus the distance the ego requires when starting to brake after response time with a deceleration of at least $\beta_{\min}$, minus the distance the front vehicle at speed v_{f} requires when braking immediately with a deceleration of at most $\beta_{\max}$. The parameters ρ, $\alpha_{\max}$, $\beta_{\min}$ and $\beta_{\max}$ of Equation (1) must be selected wisely to cover reasonable worst case assumptions. Selecting the global worst case for a vehicle braking in front would require to assume maximum possible deceleration of any vehicle allowed on the road; for the ego vehicle in the back a global worst case might have to consider there could be oil or mud on the road and the braking forces are limited. This would lead to overly conservative safety distances which would limit the usability in daily traffic.

$$d_{\min} = \left[v_{\mathrm{r}}\rho + 0.5\alpha_{\max}\rho^2 + \frac{(v_{\mathrm{r}} + \alpha_{\max}\rho)^2}{2\beta_{\min}} - \frac{v_{\mathrm{f}}^2}{2\beta_{\max}}\right]_+ \tag{1}$$

B. RSS requires no trajectory

The requirement on independence from the vehicle's actually planned trajectory discussed in Section II-A makes it hard to transfer AD safety systems designed tightly around actual trajectories like e.g. [20]. Since the RSS safety checks [11] are based only on the current (instantaneous) state of the ego-vehicle and the state of the other traffic participants, RSS can be applied as a metric in the context of ITS. Applying RSS from each vehicle's perspective individually allows the calculation of their respective safety envelopes. Furthermore, the RSS safety model provides guidance of what countermeasures an individual vehicle must take to escape from a hazardous situation. This enables the safety guard to not only warn the vehicles when getting in danger, but also to proactively compute optimal responses to each vehicle for the situation providing maneuvers to the affected vehicles to prevent collisions.

C. RSS supports customizable latency

The mathematical model of RSS explicitly considers the response time ρ of a traffic participant in all equations defining the safe distances [11]. Varying latency values of traffic participants as discussed in Sections II-B can be addressed by customizing individual response times as an input to the safety guard for each vehicle accordingly. This allows to select the model parameters in a situation specific manner. For example, the ITS and the vehicles within the system could negotiate parameter settings such as response time to customize for early warnings or compensate for temporary environmental events such as bad visibility.

D. Inaccuracies can be handled by RSS

The RSS safety model itself doesn't define how a concrete implementation of RSS must cope with inaccuracies and uncertainties. Shalev-Shwartz et. al [11] discuss the effect of errors and inaccuracies in the sensing state on the driving policy and propose to consider Probably-Approximately-Correct sensing data in the learning phase of the driving policy. Our proposed approach in the context of the digital twin is not based on machine learning techniques. It is based on the publicly available implementation of RSS [21] and its integration into CARLA driving simulator [22]. Therefore, inaccuracies of the digital twin as discussed in Section II-C have to be taken into account by other means, like e.g. deploy confidence metrics of the provided world model, consider uncertainty estimation or reasonable worst case considerations based on fused contextual information when calculating the safety envelopes:

1) Handle occlusions: Most of the remaining false negatives observed at the digital twin can be mitigated, by considering occlusions as defined by [11], Definition 26. Therefore, in this implementation we extend the RSS library to be able to inject artificial vehicles and pedestrians. The creation of reasonable parameterized artificial vehicles/pedestrians in occluded areas leads to more cautious driving behavior in areas with limited visibility, as the safety guard will report a dangerous situation for a potential safety critical hidden vehicle/pedestrian.

2) Consider measurement uncertainties: The current open-source implementation of *RSS Open Library* intended for research on the RSS safety model is already considering inaccuracies in the transformation from the Cartesian coordinate frame into the lane-based system if curved lanes are considered. Within a curve the distance between two vehicles depends e.g. on which side of the curve the distance is measured (see also the discussion on the selected lane-based coordinate system [21]). The implementation at *RSS Open Library* overcomes this issue by turning the length of the lane segments l into intervals of $[l_{\min}; l_{\max}]$ and the actual transformation into the lane-based system considers the reasonable worst case for the actual safety calculations.

Infrastructure based uncertainties on the estimated object pose, extent or speed can be modelled to be coverage dependent (i.e. region specific) and temporary (e.g. under certain light/weather conditions). These can be faced in a similar manner as the inaccuracies on the coordinate transformation. Within the *RSS Open Library* the pose and the dimension of the vehicles are represented in form of *occupied regions* within the lane-based system. The exemplary implementation at *RSS map integration* performs map-matching of the vehicles with their pose and dimension to calculate these occupied regions. Inaccuracies in pose and dimension can be considered by increasing these occupied regions respecting the reference point of the detections. Inaccuracies in speed can be taken care by turning the speed v into an interval $[v_{\min}; v_{\max}]$. This way, the core RSS calculations consider the respective reasonable worst case and ensure that errors within the provided input ranges are mitigated. As measurement uncertainties are present within ITS as well as in vehicles, any appropriate solution like e.g. [23] can be applied to consider these, too.

However, in the presence of uncertainty, we still need to provide an answer to the question of how much confidence intervals need to be increased to ensure safety? Mathematically the uncertainties are distributions spanning over the whole value range. Therefore, every interval selected like e.g. 3σ will introduce also a residual error, which decreases by increasing the interval. But the more the interval increases, the larger the safety envelope becomes; which from the pure safety point-of-view might look great, but on the other hand comes with the cost of undesired large safety distances. Therefore, the selection of the confidence interval has to be performed wisely. In ITS it is expected that variances will be local and can be accurately modeled, therefore the negative effect of confidence variations should be reduced, compared to on-board system implementations. Finally, to reduce the impact of the remaining residual error, an additional minimum safety margin in longitudinal ($d_{\min}^{\mathrm{lon}} >= 0$) as well as in lateral direction ($d_{\min}^{\mathrm{lat}} >= 0$) might be applicable. An additional consideration of minimum safety margins is that they could be combined or considered to provide individual safety comfort preferences which would be customized by the vehicles themselves through interactions with the road infrastructure (comparable to the individual configuration of desired distance in an ADAS adaptive cruise control).

In the extended digital twin of the *Providentia++* project, providing information on measurement uncertainties is not established yet due to lack of practical measurements. The accuracy of the predecessor *Providentia* digital twin [19] was reported with a root-mean square error of the spatial position in longitudinal direction of $\sigma_{\mathrm{lon}} = 3.27\,\mathrm{m}$ and $\sigma_{\mathrm{lat}} = 0.53\,\mathrm{m}$ laterally. At this, the vehicles dimensions were not taken into account and the positions were either at the front or the rear of the vehicles while the ground truth positions actually were the centers of the vehicles. Therefore, these values incorporate a displacement of about half a vehicle length of $2.3\,\mathrm{m}$ in average, leading to approximately $\sigma_{\mathrm{lon}} = 0.97\,\mathrm{m}$. Considering a 3σ interval on expanding the safety envelope on the safety guard would lead to a longitudinal extension of $3\sigma_{\mathrm{lon}} = 2,91\,\mathrm{m}$ at front and back of the vehicles and a lateral extension of $3\sigma_{\mathrm{lat}} = 1,59\,\mathrm{m}$ at both sides which would make the safety guard extremely conservative. Therefore, this will be evaluated based on the upcoming *Providentia++* digital twin once increased accuracy and robustness is enabled.

3) Consider classification uncertainties: The RSS model provides a variety on parameters in terms of braking and acceleration values (see Section III-A), that go beyond the reaction time parameter already discussed in Section III-C. The safety guard is affected by inaccuracies in object classification only if the parameterization of the considered traffic participant classes actually differ from each other. In such cases, additional artificial vehicles can be injected using different parameters to cover all relevant cases, similar to the injected ones suggested in Section III-D.1.

IV. EXEMPLARY IMPLEMENTATION

In Section III-B we explained that the RSS model doesn't require the trajectory of the vehicles to perform the safeguarding. While that's true, the exemplary *RSS map integration* analyses the intended high level route of the ego-vehicle to create all required so called constellations between ego and other vehicles to be checked [22]. Therefore, in case the extended infrastructure safety guard isn't aware of the planned high level route of the respective ego-vehicle, it analyses all possible routes at once and provides RSS check results for each of the possible routes. It's then up to the respective ego-vehicle to decide on which of the routes reported it should react upon.

A driver assistance system might use this information to trigger a warning to the human driver immediately if the active route of the in-vehicle navigation system is getting unsafe. It also could provide a different warning if any of the possible available routes becomes unsafe, e.g. a turn to the right. This information might provide tactical guidance on restrictions to the driver following a route proposed by the navigation system or even in the case no active route is being followed (see also Figure 3).

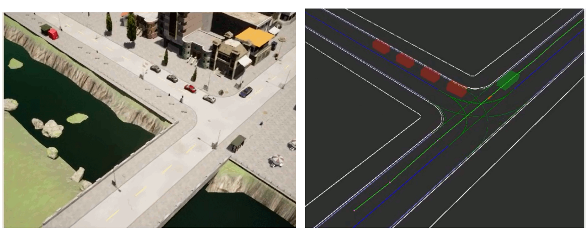

Fig. 3. The driving ego vehicle (green) in this situation has two possible routes to take: turn right where road is blocked by other vehicles stopped (in red) and RSS reports unsafe or drive straight where RSS reports safe. As long as the driver follows the planned route and drives straight, no warning needs to be issued.

A human driven vehicle deploying the safety guard results for active collision prevention might perceive a braking reaction in case any of the routes becomes unsafe as overly conservative in a situation as depicted in Figure 3. A collision prevention system should only intervene if the collision tends to become unavoidable. Therefore, the system might only react actively if none of the possible routes is safe anymore, while a passive warning still could be issued if any of route becomes unsafe. But in this case, one might have to enforce, that the driver is not leaving the last safe route by accident. Otherwise, it would be possible that the driver leaves the safe route, being already much too close to an obstacle on the unsafe route, so that braking in time wouldn't be possible anymore. One implementation solution on RSS guard side could be the possibility to introduce virtual objects which can be placed at the lane boundaries. Then, these virtual objects can be handled within *RSS Open Library* in a similar way as any other vehicle or object. As a result, the ITS will detect that a route is to be left soon, and the safety guidance provided from the ITS to the individual vehicle will enforce to keep that particular safe route (Figure 4 describes an example). It is assumed that the on-board collision prevention system would also have to ensure, the vehicle is able to follow at least one of the safe routes without exceeding the physical limits of the vehicle when being forced to intervene (e.g. by pushing the vehicle into the last viable route which could be the turning one).

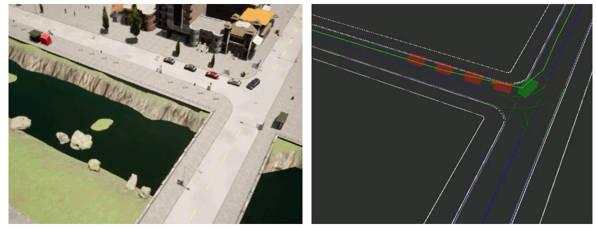

Fig. 4. The driving ego vehicle (green) again has two possible routes: turn right into the blocked unsafe road or drive straight safely. In this experiment, the vehicle RSS restrictor is configured to react on the last route to become unsafe and the ego-vehicle tries to turn to the right. Like this, the straight route would never become unsafe and the crash couldn't be prevented. By considering the lane borders of the routes, the straight route becomes unsafe, at the point in time the ego starts its movement to the right. The RSS response of the straight route indicates to countersteer and is able to prevent from the accident.

The above discussion suggests that the safety guard has to provide different operation modes for different use-cases which must be negotiated with the vehicles participating in the ITS safety guard service: If the vehicle provides a high level route (as it's e.g. always the case for ADS), the safety guard only observes that particular route. In addition, intelligent warning and/or prevention systems can benefit from the selection of the mode on how to handle lane/road borders to cope with the aforementioned situations. The final implementation of such in-vehicle systems would naturally require further research considering human factors.

One side effect of the multiple potential routes r to be observed, is an expected increase in run-time compared to an in-vehicle variant of the safety guard. In combination with the number of ego-vehicles n participating in the safety guard service, the actual number of checks N sums up to $N = rn$. Therefore, our exemplary implementation is designed to reuse intermediate results of expensive operations, like e.g. vehicle map matching and route predictions, where feasible. Furthermore, the infrastructure safety guard is usually responsible only for a local subset of the map (e.g. a few kilometers of highway, one single intersection) and is able to restrict calculations to these local lanes. But in general, the expected reasonable worst case of these run-time effects can be estimated and mapped to an increase on the overall latency, and therefore mitigated, as already discussed in Section III-C.

V. INCREMENTAL VALUE OF AN INFRASTRUCTURE SAFETY GUARD

The previous sections discussed the requirements, design and the implementation of an infrastructure based safety guard and how it differs from an in-vehicle safety guard. In the following, we describe opportunities which arise when a safety guard system is deployed system wide within an ITS.

A. Multi-agent safety maneuvers

The vehicles participating in the safety guard service of the Intelligent Infrastructure are evaluated and receive the safety results with included proper response guidance. If the RSS rule 5 "If you can avoid an accident without causing another one, you must do it.", is implemented on ITS level, this includes so called evasive maneuvers [11] to prevent collisions due to unexpected behavior of others. But there are situations where a single ego-vehicle isn't even able to perform an appropriate evasive maneuver in an emergency situation because any potential evasive path might be blocked by other vehicles. A big advantage on ITS-level safety guards is the possibility to execute a controlled and coordinated safety maneuver involving several vehicles that would eliminate the possibility of vehicles blocking the evasive path. Figure 5 depicts an emergency situation which cannot be resolved by a single vehicle on its own. The safety guard at infrastructure level, if connected to all relevant vehicles, can provide a coordinated collective safety maneuver. In this manner, the critical situation can be resolved and the collision prevented, which would not be possible without a well coordinated multi-agent maneuver. An added benefit for this use-case, comparing to other proposed solutions in coordinated maneuvers (e.g. in ETSI [10]) is that the ITS system can converge on the right solution for each of the vehicles avoiding long negotiation periods by simply considering the mathematically proven RSS rules.

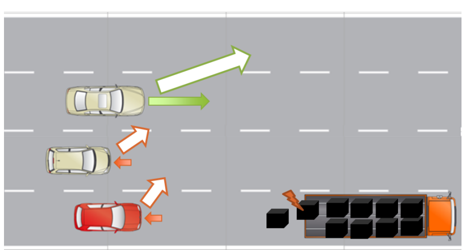

Fig. 5. Boxes are dropping from the orange truck driving at the rightmost lane on a four lane road. Even if the red vehicle driving behind always keeps the required safety distance, it cannot foresee, that something is dropping from the truck out of the sudden. An immediate braking maneuver with maximum possible baking force will not come to a stop in time. Therefore, the red vehicle has to perform an evasive maneuver to escape from this situation. But since the lane to its left is not free, it can't do so without causing a collision with that vehicle. In case the left most lane is free, the leftmost vehicle could accelerate and change to the leftmost lane (indicated by green arrows). The vehicle in the middle as well as the red vehicle on the rightmost lane could brake and switch to the lane on their left (indicated by orange arrows), which shortly becomes free because of the evasive maneuver of the other vehicles.

B. Analysis of traffic behavior

Beyond active safe guarding, continuous safety measures of the current traffic under different weather, time and lighting conditions can be collected throughout the year. This gives the operator of the ITS the opportunity to analyse and judge the safety of the road layout based on near-collision events, not only after actual accidents happened. In general, the planning and management of the traffic on the road will benefit if a metric continuously provides some means of the level of safety within a given region and time.

To demonstrate the potential of our proposed method we've run a simple analysis on the RSS check results of about 2 h traffic on a Friday afternoon on the *Providentia* digital twin [19]. During that time more than 7500 vehicles were considered driving with a headway of less than 6 seconds behind each other. The vehicles stayed about 9 seconds within the measurement area at an average speed of $32.5\,m/s$. Around 20% of all considered measurements showed a headway of less than 0.9 s (Fig. 6 right), which on German highways would already lead to a temporal loss of the driver's license. The RSS evaluation of the safety guard (Fig. 7) shows that applying a RSS parameter set describing rather aggressive driving style observed on German highway, only 5% of the measurements are actually rated dangerous. One of the benefits of RSS over classical surrogate safety

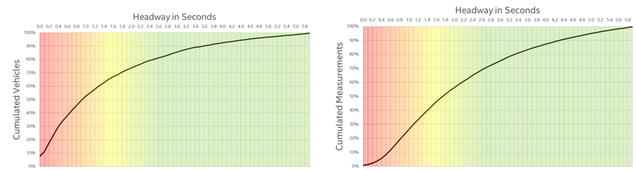

Fig. 6. Graph of the cumulative vehicles (left) in percent in relation to their minimum headway in seconds towards its nearest vehicle in front on the same lane while driving through the area. 50% of the vehicles got at least for some time below the 0.9s threshold. The right graph shows the cumulative measurements of the same showing that only a portion of 20% of the measurements was actually below the 0.9s threshold: not all vehicles have been below the threshold all the time.

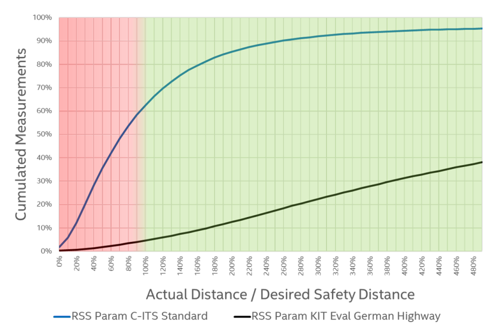

Fig. 7. Graph showing the cumulative measurements in percent in relation to the quotient of the vehicles actual distance towards its nearest vehicle in front divided by the desired safety distance calculated by RSS. For this experiment two different parameter sets for RSS were applied with different values (see Section III-A). The blue line depicts the China-ITS Standard [24] ($\beta_{\max} = -6.1 m/s^2$, $\alpha_{\max} = 1.8 m/s^2$, $\beta_{\min} = -3.6 m/s^2$, $\rho = 0.2s$): about 60% of all measurements were below 100% quotient and so being identified as dangerous situations. Using more aggressive parameterization like the ones identified by an KIT evaluation on German highways [25] ($\beta_{\max} = -11.0 m/s^2$, $\alpha_{\max} = 0.0 m/s^2$, $\beta_{\min} = -10.5 m/s^2$, $\rho = 0.1s$) show only about 5% of the measurements being dangerous.

measures is its high flexibility in terms of parameterization while the safety is not comprised as long as the parameters still consider a reasonable worst case to be expected. The parameters can easily be adapted to different operational design domains, different vehicle classes or in conjunction with an analysis different use-cases.

VI. CONCLUSIONS

In this paper we discussed the special requirements for implementation of a global safety guard within an intelligent transportation system that provides safety guarantees for the vehicles subscribed to the service. We outlined limitations of applying existing on-board safety models to the infrastructure and elaborated how the Responsibility-Sensitive Safety model overcomes these since it doesn't require to know the trajectories of the vehicles, it supports agent-based customizable latency settings and is able to cope with inaccuracies. RSS is well-suited to fulfil the ITS safety guard special requirements. Vice-versa, the application of a global safety guard feeds back a set of requirements to the underlying digital twin.

Furthermore, we introduced our exemplary implementation to realize a global safety guard for the digital twin of the *Providentia++* project and showed that a large variety of traffic participants can benefit from the deployment of the safety guard results: from passive driver warning systems via active in-vehicle collision prevention systems towards the augmentation of existing safety modules in ADS vehicles. Furthermore, we illustrated the great potential of a global safety guard to increase the safety within the supervised area with the ability to trigger coordinated multi-agent safety behaviors and the continuous analysis of current traffic safety.

When the extended digital twin of *Providentia++* will be available a thorough evaluation will be performed to evaluate if the achieved perception accuracy and real-time capabilities are sufficient to avoid over-conservative safety envelopes for the road-users. In addition, rural intersection areas with vulnerable road users like bicycles and pedestrians will be included in future experiments.

We propose that an ITS equipped with such a safety guard can be used for test and validation of AD-vehicles. Even the development phase of new ADS functionality might be supported by ITS based safety guards: given a safety-box within the vehicle, sitting in between the AD-development system and the vehicle actuation system which intervenes if the ITS safety guard detects a dangerous situation.

VII. ACKNOWLEDGMENTS

This research was partially funded by the Federal Ministry of Transport and Digital Infrastructure of Germany in the project *Providentia++* (01MM19008F).

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