Detection and Analysis of Lane Wandering and Cut-Out Scenarios in Naturalistic Driving Data for Automated Driving Safety Assessment

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***Abstract*— With the focus on data-driven scenario-based methods for the safety assessment of autonomous driving systems, there is a need to generate scenario databases from naturalistic driving data. In this study, we look at the lane wandering and the cut-out scenario, two scenarios that have received little attention to date. The paper is structured as follows: first of all, we model the two scenarios and define parameters necessary to accurately describe them. After that we show how algorithms can be used to detect the scenarios automatically in a large naturalistic driving database recorded on German highways using vehicles equipped with pre-series sensors. Following that, we analyze selected scenario parameters in detail and discuss the findings of the scenario data analysis to derive recommendations for the safety assessment of autonomous driving systems. We were able to show that lane wandering scenarios may in many cases lead to safety critical situations due to the significant lateral velocities and that cut-out scenarios are especially critical if they involve a lane change to the left lane.**

I. Introduction

A. Motivation

As the development of autonomous vehicles progresses, the validation of autonomous driving systems (ADS) is increasingly becoming the focus of research and legislation. While many different approaches exist for the validation of ADS, industry and academia agreed on the data-driven scenario-based testing approach. The development of the methods and processes required for this is the subject of various completed and ongoing research projects such as SAKURA [1], PEGASUS [2] and VVM [3], whose findings have also already been incorporated into the development of the first standards for scenario-based testing of ADS such as ISO 34502 [4].

The generation of scenarios that can prove the safety of an ADS is of central importance for scenario-based testing. A common scenario definition in this context is the subdivision of scenarios into functional, logical and concrete scenarios presented in [5]. While functional scenarios represent an abstract description of a scenario, logical scenarios define a scenario using descriptive parameters. By defining specific parameter values, the concrete scenarios are then derived from the logical scenarios. Since only concrete scenarios are distinct enough to be used as test cases, it is necessary to define the parameter values of logical scenarios to create test cases which can then be presented to an ADS in simulation, on proving grounds or in real traffic. As shown in [6], in particular data-driven approaches make an important contribution for scenario generation as they provide a method to define the parameter values needed to create concrete scenarios. Essential for the use of data-driven methods is the creation of scenario databases, for example by detecting scenarios in naturalistic driving data. For this purpose, this study detects and evaluates two functional scenarios from the highway domain for the realistic but safety-critical generation of concrete scenarios using a large naturalistic driving database of 81194 km recorded on German highways.

The first of these scenarios is the lane wandering scenario. Lane wandering refers to the behavior of vehicles that oscillate between lane markings while driving straight ahead within their own lane. While the scenario itself does not pose any significant potential danger to surrounding vehicles, it carries the risk of provoking incorrect decisions of an ADS. One example would be the misclassification of lane wandering as a lane change, which could cause an autonomous driving system to initiate unnecessary and potentially dangerous braking maneuvers.

The second scenario is the cut-out scenario. In this scenario, the vehicle in front of the vehicle under test (VUT) executes a lane change to the adjacent lane. Similar to the lane wandering scenario, this behavior is not directly safety-critical for the VUT. Instead, there is a risk that the lane change of the vehicle in front was triggered by an obstacle such as a stationary or significantly slower moving vehicle, which remains hidden from the vehicle under test. After the lane change and with the initial detection of the new lead vehicle, the VUT may have little time to react.

B. Related Work

While there are numerous publications in the literature on lane changes and their modeling, hardly any work has been published on lane wandering as defined in this study. A scenario with a similar definition was modelled in [7], motivated by the test cases defined in the UN R157 [8]. This standard regarding automated lane keeping systems, which is also the first on driving functions with SAE Level 3, takes lead vehicles which are swerving within their lane into account as part of the test cases defined therein. As the original version of UN R157 was only intended for the speed range up to 60 km/h, the modelling in [7] is limited

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to the speed range up to 70 km/h. It is also noted that data obtained by statically positioned sensors such as drones are not ideal for detecting swerving lead vehicles due to the long-term nature of that scenario. Since that study is based on the highD drone dataset [9], no detailled analysis of the scenario is therefore presented.

In contrast to the directly safety-critical cut-in scenario, only a few studies have been published to date on the cut-out scenario. In [10] very similar investigations of the cut-out scenario are conducted using a naturalistic driving database recorded on Japanese highways. In this study, they model and analyze parameter dependencies as well as evaluate possibilities for data extrapolation for the generation of safety-critical but realistic test cases. A further consideration of the cut-out scenario takes place in [11], where instead of data recorded with real vehicles, data recorded in a driving simulator is used to analyze the relevant parameters.

C. Main Contribution

With the lane wandering and cut-out scenarios, two scenarios from the highway domain were identified that have so far received little attention in the literature on safety assessment of ADS. Therefore we show real occuring parameter distributions based on 81194 km of German highway data as well as analyze and interpret their usage for data-driven test case generation. In particular, for the lane wandering scenario, this study addresses the difficulty of detecting longer lasting scenarios by using data collected using measuring vehicles. Further, we consider higher speeds up to 130 km/h which aligns with the updated speed limit of 130 km/h of UN R157 in 2023 [8]. To the knowledge of the authors, that leads to the first in-depth analysis of the lane wandering scenario for higher speeds.

For the cut-out scenario, the work in [10] is to be built upon. While the work carried out there in collecting the data by measuring vehicles and defining the scenario is very similar to this study, the consideration of German highways in contrast to Japanese highways creates the possibility for comparing the driving behaviour in cut-out scenarios and thus contribute to a possible international harmonization of future test standards.

II. Methodology

A. Modeling of the Lane Wandering Scenario

A schematic modeling of the lane wandering scenario is shown in Fig. 1. Since the lane wandering scenario in itself is not a scenario in which several vehicles interact with each other, only a single vehicle referred to as Ego is considered in this case.

The driving environment is a lane on a multi-lane highway. The boundaries of the lane are marked in the figure as left lane marking and right lane marking. While the type of lane marking is not explicitly defined in the case of the right lane marking, the left lane marking is a dashed lane marking. The vehicle under consideration can therefore be in any lane of the multi-lane highway except the leftmost lane. The reason for this definition is the significance of the lane wandering

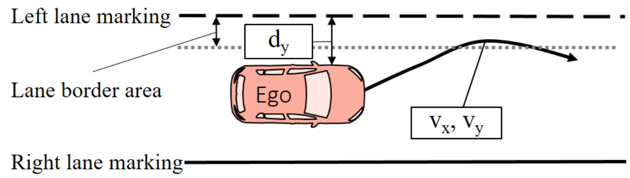

Fig. 1. Parameters of the Lane Wandering Scenario

scenario in combination with a faster vehicle overtaking on the left, which is not possible if the vehicle is positioned in the leftmost lane. Lane wandering in the form of an approach to the right lane marking will therefore not be considered further in this study.

At the beginning of the scenario, the vehicle is in the middle of it's lane and builds up a lateral velocity in the direction of the left lane marking. Accordingly, the vehicle moves into the border area near the lane marking, referred to here as lane border area. Within the lane border area, the lateral velocity to the left is reduced again and a lateral velocity to the right is built up. This causes the vehicle to move away from the lane marking and out of the lane border area.

Due to the single vehicle considered for the scenario and the focus on the left lane marking, there are a total of three parameters relevant to this study for this scenario. These are the longitudinal and lateral speed of the vehicle, referred to below as v_x and v_y, and the lateral distance d_y of the vehicle to the left lane marking.

B. Modeling of the Cut-Out Scenario

A schematic representation of the cut-out scenario can be found in Fig. 2. In contrast to the lane wandering scenario, in which only a single vehicle is involved, the cut-out scenario comprises a total of three interacting vehicles, which are referred to here as Ego, Obj1 and Obj2. The driving environment for the scenario is once again a multilane highway. The vehicles are all positioned in the same lane while the ego vehicle's view of the vehicle in front is obscured by Obj1.

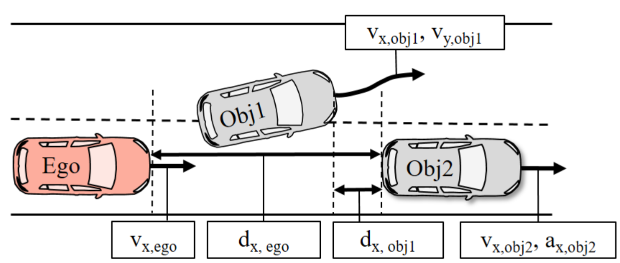

Fig. 2. Parameters of the Cut-Out Scenario

At the beginning of the scenario, all three vehicles are in the same lane. Obj1 then initiates a lane change to the left or right, whereby as a simplification Fig. 2 only shows the lane change to the left. The lane change finally makes Obj2 visible to the ego vehicle. Since there are no requirements regarding the direction of the lane change performed by

Obj1, this also results in a possible placement of the vehicles at the beginning of the scenario on all available lanes of the highway.

Due to the higher number of vehicles involved, various parameters relevant to this study can be defined for the cut-out scenario. These include the parameters $v_{x,Ego}$, $v_{x,Obj1}$ and $v_{x,Obj2}$ for the longitudinal speed of all vehicles involved. In the case of the middle vehicle, which also changes lanes during the scenario, the lateral speed $v_{y,Obj1}$ and, in the case of the vehicle in front, its acceleration $a_{x,Obj2}$ should also be considered.

Also relevant for the investigations of the cut-out scenario in this study are the distances $d_{x,Ego}$ and $d_{x,Obj1}$. The former is defined as the distance from the front vehicle to the rear vehicle, while the latter specifies the distance from the front vehicle to the middle vehicle. Overall, the choice of these parameters align with the scenario definition in [10].

C. Naturalistic Driving Database

The data basis for the scenarios detected in this study is an unpublished database primarily described in [12] with sensor data from European highways. The database was recorded from several manually driven vehicles equipped with pre-series sensors and includes data from both mid-range radars (MRR) and mono cameras. A large number of different drivers were used for the recording, who did not receive any additional instructions while driving.

The majority of the signals required for the detection and evaluation of the scenarios in this study are provided directly by the pre-series sensors. These include, for example, the measured distances to the surrounding objects and their velocities, which are provided by the radar sensors. The distances between the measuring vehicle and the lane markings as well as the type of lane markings are determined by the installed mono cameras. Other required variables such as the lateral velocities of the measuring vehicle relative to the lane markings and the lateral velocities and distances of the object vehicles relative to the lane markings are also calculated from the measurement data. In the case of the object vehicles, the measurement data from both sensor systems are combined with each other for this purpose. Additionally, kinematic parameters of the ego vehicle such as longitudinal speed and acceleration are available.

A more detailed overview of the database, process steps carried out during pre-processing and previous applications with the aim of scenario detection can be found in [12]. For the present study, an excerpt from this database was used exclusively from German highways with a measurement duration of 824 h and 81194 km.

III. Implementation

A. Detection of the Lane Wandering Scenario

In the case of the wandering scenario, only data relating to the ego vehicle itself and no data from object vehicles is used for detection and evaluation. The reason for this is the large amount of available measurement data and the relatively high frequency of the scenario, which already results in a sufficient number of lane wandering scenarios with the higher quality data relating to the ego vehicle. To detect the scenario, the measurement data of the ego vehicle is first searched for four events, which must occur one after the other in the defined order. First, the vehicle initially builds up a significant lateral velocity above the threshold value $v_{y,sig}$ to the left in the direction of the lane marking (event 1), approaches the lane marking and moves into the lane border area (event 2). Within the lane border area, the lateral velocity is reduced and instead a lateral velocity is built up in the direction of the lane center, which must again be above the threshold value $v_{y,sig}$ (event 3). The vehicle then moves out of the lane border area again (event 4). The width of the lane border area is defined by the parameter $d_{y,border}$. During this sequence of events, the vehicle must not change lanes.

It can be seen that the procedure shown for detecting lane wandering scenarios with $v_{y,sig}$ and $d_{y,border}$ is dependent on two parameters. The choice of these two parameters has a major influence on the detection results. If, on the one hand, for example the threshold value for the significant velocity $v_{y,sig}$ is set too high, only a small number of very dynamic lane wandering scenarios will be detected. If, on the other hand, $v_{y,sig}$ is chosen too small, a very large number of lane wandering scenarios are detected, the majority of which, however, only have very low lateral velocities and large minimal distances to the left lane marking. Similar effects can be observed when choosing the parameter $d_{y,border}$. For this reason, a parameter study was carried out in which the values of the two parameters were varied and different combinations were tested. A value of 0.2 m/s for $v_{y,sig}$ and a value of 0.5 m for $d_{y,border}$ proved to be a good compromise.

In addition to the actual detection of the lane wandering scenarios, the determination of the associated start and end times is also of great importance for the evaluation of the scenarios. The start time of the lane wandering scenario was selected for this study as the first time at which the lateral velocity in the direction of the left lane marking exceeds the defined threshold value of $v_{y,sig}$ at the beginning of the scenario. Similarly, the end time of the scenario is selected as the time at which the lateral speed away from the left lane marking falls below the threshold value of $v_{y,sig}$ towards the end of the scenario.

Following the detection, the lane wandering scenarios found are filtered. On the one hand, scenarios with a solid left lane marking are removed, as specified in the scenario definition. On the other hand, scenarios that do not have a minimum time interval of 5 s to a previous lane change of the vehicle are also removed. The reason for this is the lateral movement behavior of lane-changing vehicles. During the development of the detection algorithms it was possible to observe close approaches to the left lane marking at high lateral speeds performed by lane changing vehicles in their target lane. By maintaining the minimum distance in time to detected lane changes, falsification of the lane wandering data due to this effect is avoided.

In order to validate the algorithms developed in this study for the detection of lane wandering scenarios, randomly selected lane wandering scenarios were subjected to a manual check. Video recordings from the measurement vehicles served as the basis for this. The video recordings matching the timestamps of the detected lane wandering scenarios were automatically extracted and the detected scenarios were evaluated based on the extracted video recordings. In this way, a positive predictive value of 100% was achieved for a random selection of 50 scenarios.

B. Detection of the Cut-Out Scenario

To detect a cut-out scenario based on the radar data, a total of three criteria must be met. The first criterion is that the dataset used is first searched for all situations in which the object vehicle in front of the measurement vehicle changes lanes to the left or right. The second criterion is then to check whether another vehicle is detected in the lane in front of the measurement vehicle instead of the vehicle that has changed lanes. As it may not be possible to guarantee immediate detection of the vehicle in front due to the vehicle in the middle obscuring the vehicle in front, a maximum period of one second is allowed for the detection of the new vehicle in front from the time at which the vehicle in the middle crosses the lane marking.

As the cut-out scenario is only indirectly safety-critical, as described earlier, and potentially dangerous situations result from the difference in speed between the rear vehicle and the vehicle in front, the third criterion is to check whether the new vehicle detected in the lane of the measurement vehicle is at least 5 km/h slower than the measurement vehicle. The threshold value for the differential velocity was derived from expert knowledge. In this way, a minimum requirement is set for the criticality of the detected cut-out scenarios.

In order to determine the start and end times, the scenario is divided into two sub-scenarios, which can also overlap in time. The first sub-scenario corresponds to the lane change of the middle vehicle. The start time for this is defined as the time at which the lateral distance of the vehicle to the lane marking falls below 1.5 m for the first time as it approaches it. Similarly, the end time is defined as the time at which the lateral distance of the vehicle to the lane marking exceeds 1 m for the first time after crossing it.

The second sub-scenario involves the approach of the rear vehicle to the newly detected front vehicle. The starting point here is defined as the first point in time at which the vehicle is detected by the measurement vehicle after the middle vehicle has crossed the lane marking. The end time, on the other hand, is defined as the time at which the differential speed between the measuring vehicle and the vehicle in front becomes positive or the vehicle in front is no longer positioned in front of the measuring vehicle.

Finally, the detection algorithms developed for the cut-out scenario were also validated manually using automatically extracted video recordings. After manually checking a total of 164 scenarios, a PPV of 88% was determined for the detection of the cut-out scenario.

IV. Scenario Analysis

A. Analysis of the Lane Wandering Scenario

By applying the detection method described above and using the detection parameters determined in the parameter study, a total of 8068 cases of the lane wandering scenario were identified in the entire data set. An overview of the analysis of relevant parameters is shown in Fig. 3.

The histogram a) shows the distribution of the mean longitudinal velocities during the detected lane wandering scenarios. It can be seen that the mean longitudinal velocities are approximately normally distributed. The median of the distribution is 114.20 km/h, the 5% percentile is 80.19 km/h and the 95% percentile is 142.87 km/h. The distribution of the longitudinal velocities of the detected scenarios thus corresponds to an expected distribution of typical cruising speeds on the highway. It can therefore be concluded that lane wandering scenarios generally occur at all speeds relevant to the highway.

Histogram b), on the other hand, shows the distribution of the minimum lateral distances to the lane marking measured over the course of the detected lane wandering scenarios. The median of the distribution is 0.34 m, the 5% percentile is 0.00 m and the 95% percentile is 0.47 m. There is a clear accumulation of the minimum lateral distances at 0.5 m, as the histogram is limited at this point by the defined width of the lane border area. This observation again illustrates the effect of the choice of parameter value for the width of the lane border area. In contrast, the frequency decreases rapidly towards lower values for the minimum lateral distance.

Several conclusions can be drawn from the distribution of the minimum lateral distances. Firstly, lane wandering scenarios with a close approach to the lane marker are relatively rare. However, due to the frequency of the scenario, a large number of scenarios with a close approach could still be detected in absolute terms. It can also be seen that the lateral distance assumes a negative value in approx. 5% of the scenarios. This corresponds to a slight overshooting of the lane marking with the left side of the vehicle and thus a swinging into the adjacent lane. These scenarios represent particularly critical manifestations of lane wandering and are therefore of particular interest for the creation of test cases and the development of lane change detectors.

Histogram c) finally shows the distribution of the mean lateral speeds of the detected lane wandering scenarios compared to the lane change during the cut-out scenarios described in the following section. For the lane wandering scenarios, the median is 0.16 m/s, the 5% percentile is 0.11 m/s and the 95% percentile is 0.28 m/s. This shows that while significant lateral speeds occur during the lane wandering scenarios, these can still be clearly distinguished from lane changing maneuvers.

B. Analysis of the Cut-Out Scenario

Based on the definition of the cut-out scenario and the detection method described above, a total of 906 cases of the cut-out scenario were detected within the entire data

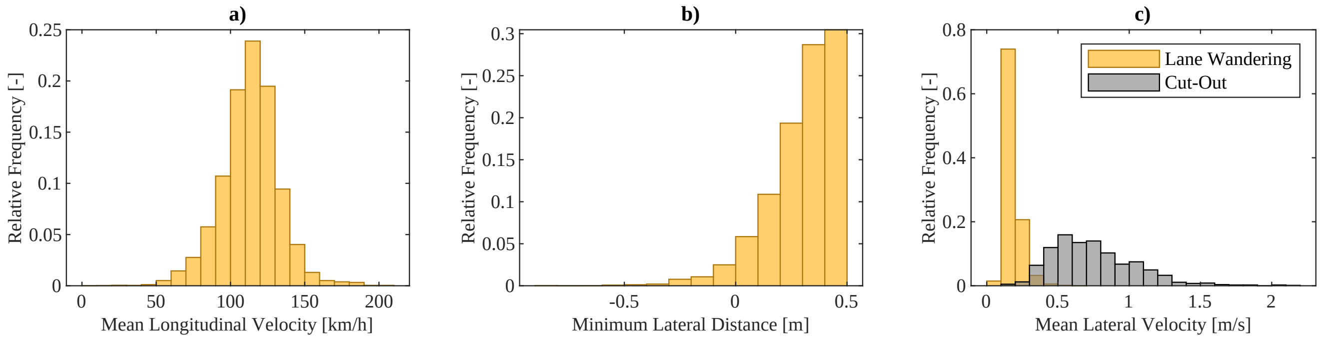

Fig. 3. Distribution of the parameters mean longitudinal velocity, minimum lateral distance and mean lateral velocity of the lane wandering scenario

set used. For the evaluation, further filtering was carried out and scenarios were removed that had a TTC of more than 15 s between the newly detected vehicle in front and the measurement vehicle and therefore only had very low criticality. Some identified data errors were also removed. This results in a total of 829 detected cases of the cut-out scenario, of which 719 involve a lane change to the left into the faster lane and 110 involve a lane change to the right into the slower lane. This breakdown thus confirms the expectation that vehicles tend to switch to the left lane to avoid a slower vehicle. Excerpts from the evaluation of the detected cut-out scenarios are shown in Fig. 4.

The histogram a) shows the distribution of the longitudinal accelerations of the newly detected Obj2 at the first detection time, whereby only objects detected immediately after the lane change were taken into account. The longitudinal accelerations show an approximately normal distribution. The median of the distribution is -0.01 m/s^2, the 5% percentile is -0.55 m/s^2 and the 95% percentile is 0.45 m/s^2. Consequently, there is no particular accumulation of braking maneuvers of the newly detected vehicle that would lend additional criticality to the respective scenario. Furthermore, no conspicuously large deceleration values that would correspond to emergency braking were found in the data.

Histogram b), on the other hand, shows the distribution of the mean lateral speeds during the lane change maneuver of the vehicle in front, divided into the directions of the lane change. For the lane change to the left, the median of the distribution is 0.74 m/s, the 5% percentile is 0.40 m/s and the 95% percentile is 1.26 m/s, for the lane change to the right respectively 0.46 m/s, 0.25 m/s and 0.94 m/s.

It can be seen that lane changes to the left within the cut-out scenarios are significantly more dynamic than lane changes to the right. The lane changes were also compared with the cut-in scenarios detected in [12], whereby practically identical distributions of the mean lateral velocity were found for the lane changes to the left in both scenarios. The observation that lane changes to the left and therefore faster lane are usually more dynamic than lane changes to the right is also consistent with other literature sources such as [13].

Finally, the histogram c) shows the distribution of time-to-collisions (TTC) within the detected cut-out scenarios, divided into the direction of the lane change. The TTC is calculated between the lane-changing vehicle Obj1 and the vehicle in front Obj2 due to the higher assumed criticality compared to the ego vehicle. Here we use the alternative TTC metric proposed in [14] and calculated using (1).

$$InverseTTC = \frac{1}{TTC} \tag{1}$$

Using the inverse TTC results in continuity across the negative and positive value range, whereby a small or negative value represents lower criticality and a large or positive value represents greater criticality. For the lane change to the left, the median of the distribution is 0.18 1/s, the 5% percentile 0.05 1/s and the 95% percentile 0.42 1/s, for the lane change to the right respectively 0.01 1/s, -0.07 1/s and 0.18 1/s.

Thus, from the perspective of the middle vehicle Obj1 and to a lesser extent also for the ego vehicle, cut-out scenarios in which the lane change occurs to the left are more critical. This is also consistent with the observation that lane changes to the left are more dynamic than lane changes to the right. On the basis of the recorded video data, this could be explained, among other things, by the fact that the cut-outs with lane changes to the left occur more frequently in the context of overtaking maneuvers and thus at significant differential velocities. The cut-outs with lane changes to the right, on the other hand, primarily occur at highway exits where the middle vehicle Obj1 changes lanes to the deceleration lane.

V. Discussion and Outlook

The evaluation of the detected scenarios carried out in the previous section has several implications for the safety assessment of ADS. With regard to the lane wandering scenario, it was found that lane wandering scenarios with often significant lateral velocities occur across the entire speed range typical for highways. This results in a considerable potential for the occurence of safety-critical scenarios due to incorrect decisions by the ADS. We therefore recommend that the lane wandering scenario be taken into account in the safety assessment for ADS and be further investigated. To this end, as part of future work, we are planning to evaluate rearward traffic on the basis of data from the rear radars installed in the measurement vehicles with the aim of detecting breaking maneuvers by overtaking vehicles which were provoked by the lane wandering scenario.

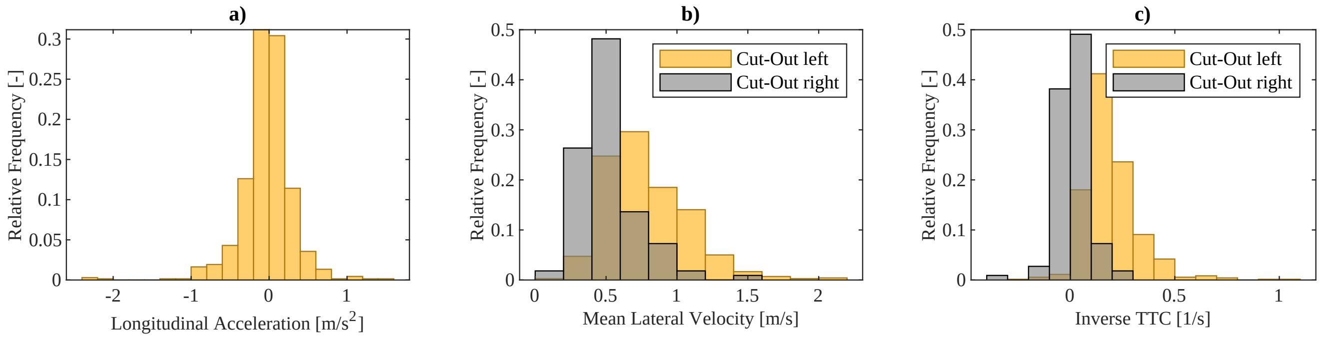

Fig. 4. Distribution of the parameters longitudinal acceleration, mean lateral velocity and inverse TTC of the cut-out scenario

In addition to the use of lane wandering scenario data in the area of safety assessment, there are also potential applications in the area of ADS development. An important example of this is functions for predicting lane changes. While various approaches for predicting lane changes of surrounding vehicles exist in the literature, for example [15] and [16], the approaches typically require the collection of data of the classes lane change and lane keeping. Finally, a classifier is developed or trained based on this data. By including the lane wandering scenarios, the borderline cases of the class lane keeping could be specifically included and thus the quality of the classifiers could be improved.

With regard to the cut-out scenarios, it was found that in Germany these are both considerably more dynamic when changing lanes to the left in terms of the lateral velocities as well as more critical in terms of the TTCs to the new lead vehicle. We therefore recommend to focus on cut-out scenarios to the left for the safety assessment of ADS. However, it was not possible to detect truly safety-critical cut-out scenarios in the data. The reason for this is most likely the rarity of the combined scenario of a cut-out maneuver and a slower vehicle in front. Considering the already very comprehensive database used, we therefore recommend to investigate the possibility of generating critical cut-out scenarios from a combination of individually detected cut-out and deceleration maneuvers and plan to address this as part of future work.

VI. Conclusion

The study in this paper analysed lane wandering and cut-outs, two scenarios that have not been discussed much in the literature so far, in regards to safety assessment of ADS. First, we modelled the two scenarios and defined the parameters necessary to describe them. We then showed how the two scenarios can then be detected automatically in a large naturalistic driving database recorded on German highways. Subsequently we performed an analysis of the scenarios which were detected by the developed algorithms. The data gathered supports the importance of considering lane wandering and cut-out scenarios for the safety assessment of ADS and leads to recommendations on where to focus further work regarding those two scenarios.

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