

Determination of the Environmental Conditions by the Evaluation of Test Drive Data

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Abstract—With taking full responsibility for the driving maneuvers automatically performed by the vehicles, the automobile manufacturers are responsible that the vehicles can handle the spectrum of possible traffic situations in the automated driving mode. The vehicles have to either cope with the traffic situations without the help of the human driver or to handover the control to the human driver in a safe manner. For the handover, a reasonable warning period is required, in which the automated driving has to be maintained. Therefore, the warning period depends on the distraction of the human driver and the current traffic situation. The time must be sufficient, so that the human driver can perceive the traffic situation and react appropriately. The testing of automated driving is considered as a major challenge for the automotive industry, because so far the human driver was considered as an immediate fallback level in traffic situations that cannot be handled by the vehicle software. Hence, robustness testing becomes more and more important to ensure a safe operation of the vehicles within different environmental conditions. This paper presents an approach that determines the environmental conditions encountered during test drives based on traffic theory. The approach provides metrics, which describe the traffic situations of test drives from an environmental point of view. Hence, the consideration of the metrics can ensure comparable traffic situations for the evaluation of the vehicle behavior between different versions of an automated driving system. Moreover, they can point to areas of the vehicle software that have not yet been tested and thus can be used to track the progress of the testing during the development.

Keywords—Automated Driving; Environmental Conditions; Test Drives.

I. INTRODUCTION

Driving in a dynamic environment is subject to a variety of cognitive demands of the human driver as shown in [2]. The human driver has to correctly perceive the traffic situation, interpret it, and derive actions from it. Moreover, she or he has to recognize new circumstances and make appropriate adjustments well enough in advance. Overall, driving is a complex task and offers the possibility to make mistakes. Approximately 94 % of the road accidents, as published in [3], are caused by the human driver due to incorrect performing of driving maneuvers, wrong decisions or carelessness. Therefore, the human driver is considered as the main cause of the majority of all road accidents, which offers a great potential to improve the traffic safety by the automation of driving. The automated driving relieves thereby the human driver of specific driving tasks in certain driving scenarios.

The road accidents statistic [1] based on the police reporting in Germany covers mainly road accidents with serious consequences and usually none with material damages or minor injuries. For each reported road accident, the police determine the main cause that led to the road accident, which is part of the statistic. The main causes provided by the Federal Statistical

Office of Germany [4], as summarized in Figure 1, shows that a large number of road accidents in urban environments (about 40 %) could not be assigned to one of the major causes listed in the summary. Collisions at intersections (32.8 %) are the main cause for road accidents in urban environments, whereas leaving the carriageway (32.3 %) is the main cause in non-urban environments. The main cause of almost half of all road accidents on the freeways that represent only a small percent of the entire road network of Germany, but with a high dwell time of the road users, are rear-end collisions followed by leaving the carriageway (27.5 %) and collisions during the lane change (13.5 %). Almost 90 % of all road accidents on the freeways can be assigned to three causes, which can be extensively tested by the automobile manufacturers. Hence, it is hardly surprising that they are going to provide their first automated driving functions for the use on freeways [5]. Freeways provide a manageable complexity, both in the tasks to be performed by the driver of a vehicle and in their construction. Simplified, it can be said that the vehicle control is limited to approaching and overtaking other vehicles. The characteristics of a freeway are usually clearly defined by the government, e.g., in the German Road Traffic Act as shown below:

- a) Only for motor vehicles
- b) Entry and exit only at marked locations
- c) Traffic on the continuous road has the right of way
- d) Turning and reversing are prohibited
- e) Stopping is prohibited

According to SAE J3016 [6], the currently available comfort functions for specific driving scenarios, i.e., an Adaptive Cruise Control or a Parking Assist, belong to the driving automation level "Partial Automation". In this driving automation level, the vehicle control is automated in the lateral and in longitudinal direction. Thereby, the human driver is considered as an immediate fallback level in traffic situations, which cannot be handled by the vehicle. The next generation of comfort functions will belong to the next higher driving automation level "Conditional Automation". After a warning of the system, the human driver has to react only within a reasonable time. The necessary time for the handover of the vehicle control, which is expected to be in the double-digit seconds range [7], differs depending on the degree of distraction of the human driver and the complexity of the current traffic situation. This means, e.g., that a handover just before a collision, in which the human driver has no possibility to avoid the collision, is not acceptable.

The spectrum of possible traffic situations and their temporal sequences in the road traffic are challenges for the automated driving. In practice, they are usually not adequately considered by current test methods and thus it is hardly possible to draw any conclusions about the robustness of the vehicle

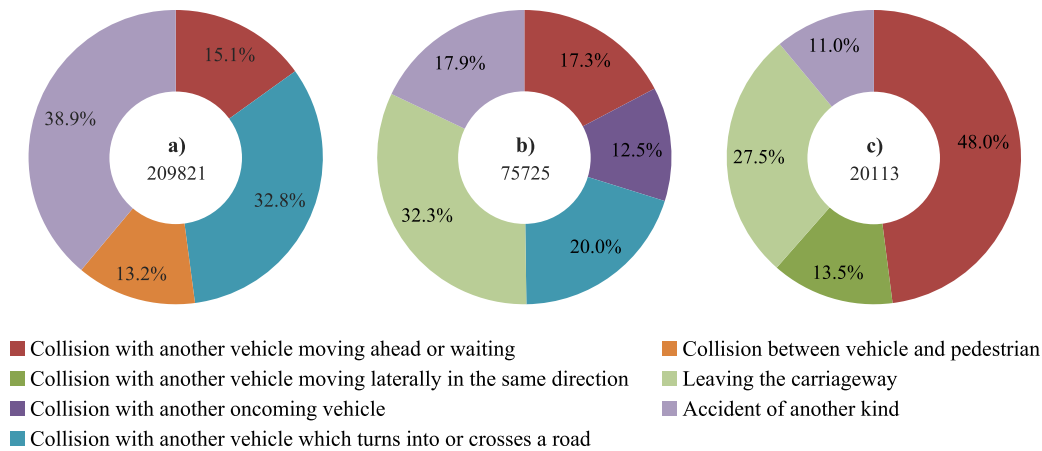


Figure 1. Summary about road accidents in Germany in 2015 [1] separated by the street location: a) urban environments b) non-urban environments c) freeways.

software. In contrast to a drive within a defined environment, an automated vehicle has to cope with a large number of different environmental conditions in the road traffic. Therefore, not only the starting point and the destination are critical factors of a drive, but also a combination of many factors unknown before. Drives between the same starting point and destination differ at least in the number of encountered road users and their driving behavior. In any case, the automobile manufacturers have to ensure that the vehicle reaches its intended destination or a safe state without endangering the occupants or other road users in compliance with the road traffic regulations.

The following section shows the related work. In Section III, an approach is presented, which determines the environmental conditions encountered during test drives based on traffic theory to provide metrics, which describe the traffic situations of the test drives from an environmental point of view. The metrics represent, among others, the complexity and the criticality of the coped traffic situations. Based on these metrics, the vehicle behavior can be evaluated in similar traffic situations to find deviations from the specification. The metrics can also point to areas of the vehicle software that have not yet been tested and thus they can be used to track the progress of the testing during the development. Finally, Section IV shows a case study to discuss the idea behind the presented approach on the example of a simulated drive on the freeway.

II. RELATED WORK

In [8], the authors claim that in relation to automated driving the definitions of the terms "scene", "situation" and "scenario" are often vague or even contradictory. To cope with this, they did a review of existing definitions including a detailed comparison between them. Moreover, the authors suggest their own definition and provide an example, which demonstrates the usage of the definition, for each term. According to these definitions, a scene describes a snapshot of the environment that is all-encompassing only in the simulation, whereas it is incomplete, incorrect, uncertain and subjective in the real world. A situation can be derived from a scene, which is defined as the entirety of circumstances and entails all relevant conditions, options and determinants. A sequence of scenes forms a scenario that describes the temporal development.

The study [9] shows that there is currently a lack of metrics, which can be used to compare different versions of an automated driving system. In [10], it is assumed that a single metric has no significance and that comparability can only be achieved by using several independent metrics. Moreover, it is shown that reaching a statistical goal does not make a statement about the coped traffic situations during the test drives and therefore cannot be used as an appropriate metric. The authors argue that no real test drive is identical, even if it is performed between the same starting point and destination. Thus, test methods using systematic approaches, taking into account the time behavior, are required, which cover a wide spectrum of the system input and have a better performance than brute force. According to [11], simulation can offer a way to perform the expected number of tests.

Different data collection methods are explained in [12], which can be used to monitor the road traffic. Thereby the authors differ between trajectory data, floating-car data and cross-sectional data. The trajectory data is determined by recording the position of all vehicles within a defined area from one or more external observation points for a certain time. It allows the direct determination of the road traffic density and the lane changes. Floating-car data are captured from specially equipped vehicles, which are part of the road traffic. They record their location obtained from the GPS and their speed. In contrast to floating-car data, cross-sectional data are captured by detectors.

An approach is described in [13] that evaluates the criticality of traffic scenarios from the viewpoint of an external observer by using a parameterizable distance model. The model spans safety areas around the road users, which are dynamically adapted to the current traffic situation. Thereby, the dynamic behavior of the distance model allows, e.g., an increase in the size of the safety areas in specific directions depending on the velocity of the road users. The authors argue that the safe distance between road users depends on the traffic situation and cannot be specified by generally valid values. These values, which are considered as safe, vary, among others, with the driving direction or the environmental conditions. In the presented case study, the distance model was parameterized according to the two-second rule, which states that a driver of

a vehicle should stay at least two seconds behind the vehicle in front. Based on the information provided by the distance model, a classification of the current traffic situation was done using the three classes: "unsuspicious", "hazardous" or "event of damage".

III. APPROACH FOR TEST DRIVES

During the development, different versions of an automated driving system have to be evaluated to decide whether the changes made have only the desired and no unintended effects. Especially with real vehicles, it is difficult to reproduce the environmental conditions and the temporal development as specified in the test scenarios, and thus to decide if a test scenario was executed as specified and if the evaluation criteria are passed or not. Only if the test scenario was executed as specified, the behavior of the vehicle can be compared between different test runs. As discussed in [9], there is currently a lack of metrics, on the basis of which a decision can be made. The presented approach shall close this gap by providing metrics about the traffic situations of test drives that represent the encountered environmental conditions and the behavior of the test vehicle. With the help of such metrics, the approach allows the developers and testers not only to compare the data, but also to have a better understanding of the vehicle behavior within different environmental conditions. Moreover, the metrics can be used to track the progress of the testing by showing areas that have not yet been tested or areas that have an above-average coverage rate. An above-average test coverage rate does not necessarily increase the quality of the automated driving system, but rather reduces the efficiency of the testing.

The presented approach not only works with data from simulations, but also with data captured from real test vehicles. Within an all-knowing simulation, the entire data of the test drive are available, whereas the data from a real test vehicle only contains the information within the sensor range of the vehicle. The information outside of the sensor range is therefore considered as not relevant for the approach.

A. Evaluation of the Test Drive Data

The test vehicle and the other road users, also called objects, are both part of the road traffic and therefore they can influence each other. The trajectory data of the road users describe their dynamic behavior and possible influences on a high abstraction level from the viewpoint of an outside observer. In addition, information about the road characteristics is required to determine the orientation of the test vehicle on the road. Some information depends on the vehicle line. Other information is obtained from sensors of the test vehicle that provide physical quantities about the test vehicle itself and its environment. The road characteristics are obtained from vehicle-mounted cameras or high-definition maps. All the required information and data are stored within an internal representation of the test drive. Overall, the following information is evaluated by the approach:

- a) Test vehicle
 - 1) Length and width
 - 2) Mounting positions of the sensors
 - 3) Absolute velocity
 - 4) Absolute acceleration

- b) Environment
 - 1) Object sizes
 - 2) Relative object positions
 - 3) Relative object velocities
 - 4) Relative object accelerations
 - 5) Lane types
 - 6) Lane positions

B. Determination of the Environmental Conditions

Based on the internal representation, a determination of the environmental conditions is performed by the approach. Therefore, it is sufficient to analyze only the information within the sensor range of the test vehicle as described before. Objects outside of the sensor range have no direct influence on the current behavior of the automated driving system and only play a role, when they are coming into the sensor range at a later point in time or have an influence on objects within the sensor range. The approach provides the following data about the environmental conditions:

- a) Velocity of the road users
- b) Acceleration of the road users
- c) Jerk of the road users (third derivative of the displacement)
- d) Distance between two road users
- e) Time to the preceding road user
- f) Time to the following road user
- g) Collisions between road users
- h) Traffic density (number of road users within a road segment at a point in time)
- i) Traffic flow (number of road users that cross a point on the road within a period of time)

If necessary, the road users are expanded around the center of gravity and thus collisions with other road users are checked. In case of a road with several lanes, a separate analysis is performed for each lane.

For a first overview of the traffic situations, the spatio-temporal context, which reflects the place and the time, is used to characterize the type and the properties of motion [14] as commonly applied in the traffic theory. In this way, aggregated values (e.g., for the density, the velocity and the acceleration) are provided for defined road sections at certain periods of time. This is followed by a detailed analysis of the dynamic behavior of the test vehicle, which can be experienced directly by its passengers. Therefore, the approach analyzes the third derivative of the displacement, named jerk, to find points in time with rapid changes in the dynamics that exceed a limit.

Metrics are provided by the approach for the complexity and the criticality of a traffic situation, and how the test vehicle handles the traffic situation. The complexity metric is determined on the basis of the road characteristics, as well as on the traffic density and the traffic flow in the surroundings of the test vehicle. The criticality metric is calculated based on the evaluation of the distances to other road users and their changes, as well as on the position of the test vehicle within its own lane. Usually rapid changes in the dynamics are not desired for comfort functions and are mainly caused by emergency functions, e.g., the Collision Mitigation System, or malfunctions of the vehicle software. Rapid changes in the dynamics of the test vehicle can be indicators for interventions

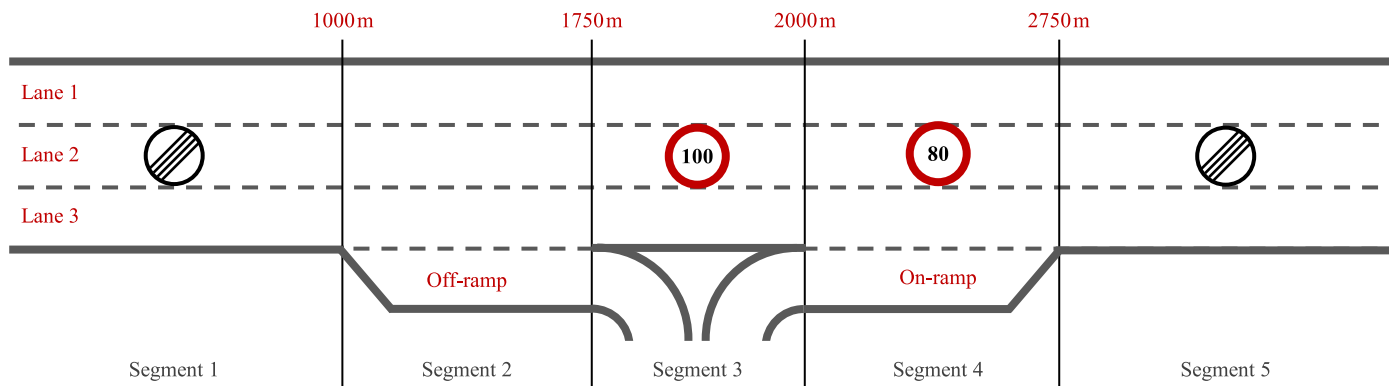


Figure 2. Schematic representation of the road characteristics.

of the automated driving system, which are necessary to prevent collisions with other road users or obstacles. Otherwise, rapid changes can be caused within a certain range to comply with legal requirements, e.g., to maintain the safety distance or the speed limit. Thus, the dynamic behavior of the test vehicle is used to define the metric for how the automated driving system copes with the traffic situation. If an unusual behavior of the test vehicle is found at the system-level, further efforts are necessary to ensure that the traffic situation is within the operating limits of the automated driving system and, if this is confirmed, to find the cause of the issue at lower levels.

IV. CASE STUDY

In this section, an example that was done as a case study is discussed to show the idea behind the presented approach to determine the environmental conditions by evaluating the data captured during a simulated test drive.

A. Generation of the Test Drive Data

The test drive data for the evaluation was generated with a microscopic traffic simulator [15] that provides different

car-following and lane-changing models. For the other road users, the "Enhanced Intelligent Driver Model" (ACC) [16] and the "General Lane-Changing Model" (MOBIL) [17] were used, whereas a custom car-following model was implemented for the test vehicle. The car-following model behind the test vehicle has the functionality of an autonomous cruise control system, which maintains a distance to the preceding vehicle on the same lane by automatically adjusting the velocity.

The traffic scenario of the example represents a freeway constructed with five straight road segments, as shown in Figure 2. Each road segment has three lanes by default with the exceptions of the second and the fourth road segment, which have an additional lane on the right side as off-ramp and on-ramp respectively. There are speed limitations in the third and the fourth road segment, which facilitate the lane change of the entering vehicles from the on-ramp lane. Both the off-ramp and the on-ramp cause an increased occurrence of lane changes in their road segments. On the one hand, there is a lower traffic density in the road segment of the off-ramp. On the other hand, there is an increased traffic density in the road segment of the on-ramp. The number of vehicles entering the freeway is

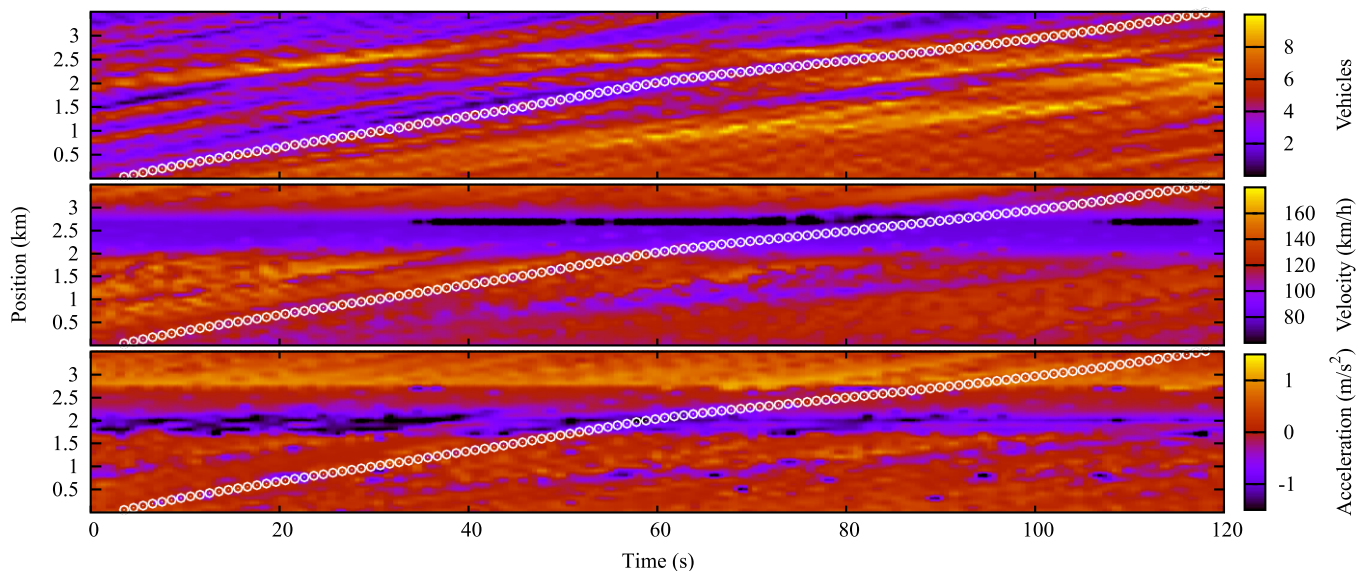


Figure 3. Spatio-temporal diagrams of density, velocity and acceleration including the trajectory of the test vehicle.

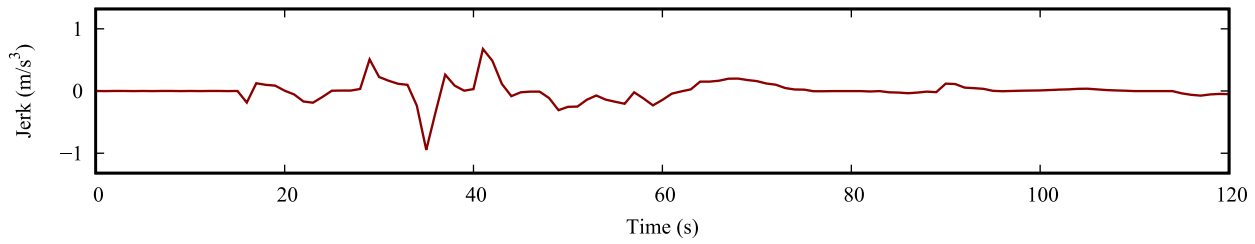


Figure 4. Jerk of the test vehicle during the test drive.

determined by the inflow rate of the traffic simulation. Based on the traffic composition configuration, previously defined vehicle classes are created, which can differ in the parameter set used for the simulation. Overall, there are two classes of vehicles used in the example, a slower and a faster one.

B. Applying the Approach

According to the presented approach, the spatio-temporal context of the captured test drive is firstly analyzed to obtain an overview, in this case an all-knowing overview due to the simulated test drive, about the encountered traffic situations. The spatio-temporal context, as visualized in Figure 3, shows an increasing of the vehicle density over the entire freeway with advancing time in the density diagram, and the speed limitations and the resulting backlog of the traffic with an aggregated velocity, lower than the specified speed limitation in the velocity diagram. The acceleration diagram finally shows road sections on the freeway, where there was a strong acceleration or deceleration of the road users. The position of the test vehicle and its sensor range are simply marked as a circle in the three diagrams, whose area represents the surroundings of the test vehicle and thus the environmental conditions processed by the automated driving system. Since the example is a straight road, the color within the circles of the density diagram illustrates the value of the complexity metric.

The evaluation is continued with an analysis of the movement of the test vehicle. Based on the jerk, as displayed in Figure 4, points of interest are searched in the test drive with an absolute value greater than a specified limit, on which a closer look could be worthwhile. At time 35 s, a significant change in the signal sequence of the jerk occurred followed by a reaction in the opposite direction only a few seconds later. In the remaining time, the value of the jerk changes only slightly. The significant change can be an indicator for an intervention of the automated driving system to prevent a collision.

Finally, the environmental conditions encountered during the test drive are analyzed to check whether a reaction of the automated driving system was necessary and if it was within the specified limits. For this purpose, Figure 5 shows the objects within an assumed sensor range of 100 m ahead of the test vehicle for each lane of the freeway. The color of an object represents the relative approaching between the test vehicle and the object. The object comes closer with a positive value and moves away with a negative value. A trajectory of an object starts after entering a sensor range of the test vehicle at a specific lane. The trajectory ends, if the object leaves the sensor range of the test vehicle or after a lane change. After a lane change within the sensor range, the trajectory has to start at the new lane. In the example, only the third lane has a relevance to the movement of the test vehicle when driving straight ahead.

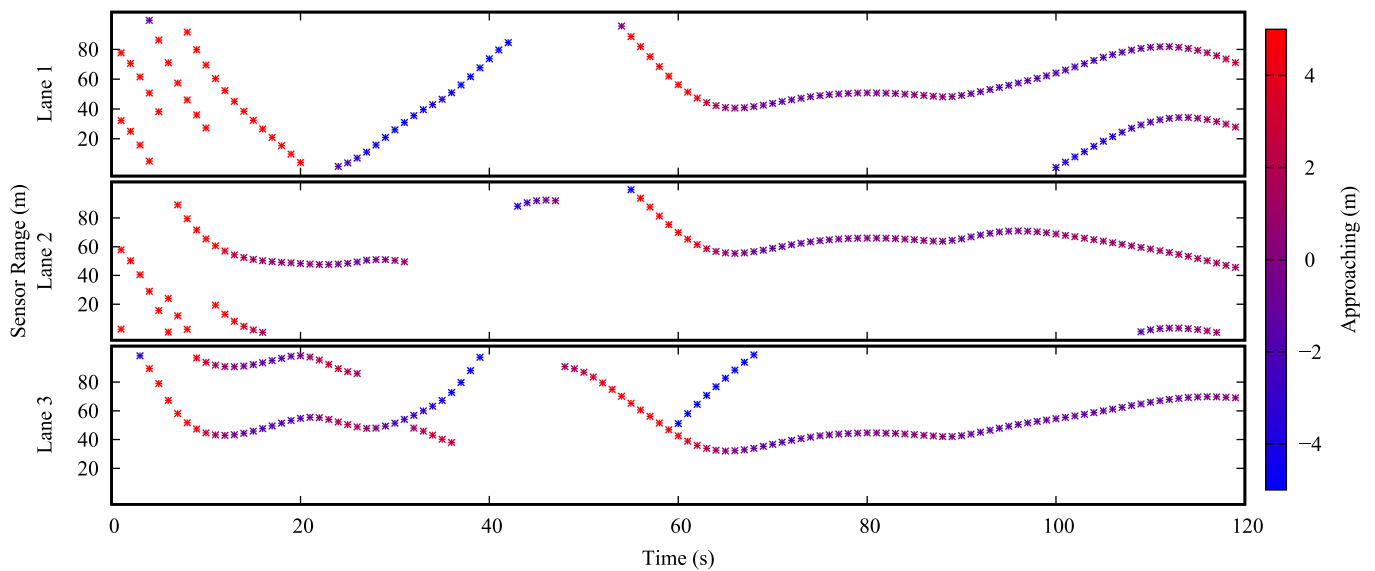


Figure 5. Objects within the sensor range of 100m ahead of the test vehicle separated by lanes.

The analyzed data shows that the point of interest was caused by a lane change of a road user, who wanted to leave the freeway at the off-ramp. For this purpose, the road user has used the safety gap between the test vehicle and the preceding road user to move from the second lane to the third lane and at last to the off-ramp. Therefore, the automated driving system slowed down the test vehicle to restore the safety distance. At the point of interest, the value for the criticality metric is high due to the fast approaching of the preceding road user on the same lane as the test vehicle. After the road user had left the freeway, the test vehicle was able to strongly accelerate.

V. CONCLUSION AND FUTURE WORK

The paper has discussed that robustness testing is necessary to ensure a safe operation of an automated driving system within different environmental conditions. With reaching the driving automation level "Conditional Automation", the full responsibility for the vehicles and possible damages lies with the automobile manufacturers until the takeover of the vehicle control by the human driver. The warning period for the handover will increase due to the allowed distraction of the human driver towards the surroundings of the vehicle. This means that the automated driving system must never get into a state, starting from its activation to the completion of the handover, in which the human driver is needed to cope with a traffic situation. In contrast to the currently performed testing, which only show that the human driver is rarely needed as an immediate fallback level, the testing for those systems should cover the spectrum of possible traffic situations.

It has been shown that the presented approach contributes to the testing of automated driving systems. Based on the evaluation of the test drive data, the environmental conditions can be determined and further analyzed. The analysis provides metrics about the environmental conditions, from which the complexity and the criticality of the traffic situations can be derived. The approach can be used with both data from real test drives and with data obtained from simulations. Therefore, it must be taken into account that the data captured during a real test drive can be inaccurate and incomplete, and data recorded from the simulation might be not realistic. A sufficient imitation of the real-world system is supposed to be precise enough for the simulation, so that it is usually not necessary to consider all eventualities in the simulation.

It is left for future work to evaluate, how significant the determined environmental conditions and the derived metrics are, and how the approach can be integrated in the development process. Particularly in the field of testing, application areas are seen in the search for comparable traffic situations, in the detection of software areas that have not yet been tested and thus to track the progress of the testing, as well as in the test optimization to contribute to an effective testing. In the next step, the approach shall be used to evaluate traffic situations of a staged test drive captured from a real test vehicle to compare the determined and the real environmental conditions.

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