Abstract— Conduct-by-Wire (CbW) is a research project which breaks away from today’s vehicle guidance by shifting the vehicle control task from a stabilization level to a conducting level. Instead of continuous stabilization on a designated trajectory – using the conventional control elements for manual steering, braking, and accelerating – a Conduct-by-Wire vehicle is controlled by means of maneuver commands. By keeping the driver in the loop, the vehicle guidance is cooperatively shared between the driver and the automation.

This article introduces an approach for the analysis of realizable automation levels and the design of a cooperative system behavior depending on the interaction concept between the human driver and the automation. Following a top-down approach, different driving scenarios are systematically analyzed as to the information needs that occur. This approach builds the basis for assessing the technical feasibility of a maneuver-based vehicle guidance concept based on the Conduct-by-Wire principle.

I. INTRODUCTION

Vehicle guidance can be represented by three cascaded control loops [1]. On the highest level, the navigation level, the route and possible modifications are planned. On the next lower level, the guidance level, the realization of the route is planned by means of driving maneuvers and trajectories depending on the current situation. These output the set values for the stabilization task, which consists of minimizing the difference between actual and planned trajectory. Today the dominant part of vehicle guidance is done at this stabilization level.

The idea of Conduct-by-Wire (CbW) is to shift vehicle guidance from the stabilization level to the guidance level by means of a maneuver-command-based interaction between the driver and the automation. Thus the conventional and continuous interaction between driver and vehicle at the stabilization level is replaced by an event-based communication by means of maneuvers at the guidance level.

The driver assigns maneuver commands via the so-called maneuver interface, which also allows the parameterization of the chosen maneuvers and interaction at the stabilization level if desired. This maneuver interface represents the human machine interface as well as the interaction concept itself [3]. The next element of the system architecture described in Fig. 2 is the maneuver control that – depending on the current driving situation – assigns a driver’s maneuver command to a pair of exactly one longitudinal and exactly one lateral driving function [4].

Thus the driver of a CbW vehicle delegates the tasks of trajectory planning and vehicle stabilization to the automation. Nevertheless, the driver still has to make decisions on route planning and maneuver selection and stays responsible for the vehicle guidance according to the 1968 Vienna Convention on Road Traffic [5]. By keeping the driver in the loop, his/her situation interpretation capabilities can be integrated, resulting in a higher system performance compared to autonomous driving concepts, where all decisions have to be made by automation that must
satisfy high safety demands and consequently often limits overall system performance. First promising investigations with test persons have demonstrated the acceptance of maneuver-based vehicle guidance [6].

The basis for CbW system design and the elementary task of the automation is to guarantee the safe continuation of a driving mission; for trajectory planning this is first of all collision avoidance. Therefore, automation follows a strict safety strategy, permanently looking for reasons not to continue the driving mission. This decision is made at all times under the precondition to be able to stop at a safe stopping distance within the driving corridor. In cases where the automation is able to find such reasons, it will transfer the vehicle to a safe state. This safe state depends on the current driving situation and may follow different strategies, such as reducing speed, stopping the vehicle at the end of the safe stopping distance or a sequenced combination of both. In this context, it is important to mention that if the automation is not able to find reasons to stop the driving mission, this does not automatically imply absolute safety. An incorrect interpretation of the current driving situation by the automation or the driver – who according to the CbW concept has the possibility to intervene at any time – cannot be excluded.

II. FROM AUTOMATED DRIVING TO COOPERATIVE VEHICLE GUIDANCE

When driving a conventional vehicle using the steering wheel and the gas and brake pedal, the car reacts to driver inputs following a clear pattern. The behavior of the human driver develops with time from knowledge-based to skill-based behavior according to a mental model of the vehicle guidance task [7]. In the context of conventional vehicle guidance only the driver is responsible for any decision made during vehicle guidance and the interaction with the environment.

With increasing degree of automation, parts of the vehicle guidance task are transferred from the driver to the vehicle and the automation respectively. With upcoming interaction between the systems “driver” and “vehicle”, which were assumed so far to be independent, the boundary of the overall system involved in vehicle guidance can be drawn around the driver and the vehicle. Known automation problems such as “mode awareness” and “situation awareness” [8] become more and more important. Using today’s advanced driver assistance systems (ADAS) such as Adaptive Cruise Control (ACC) the interaction between driver and automation is limited to driver inputs (e.g. desired speed) and system information (e.g. target object detected). Although the driver delegates longitudinal guidance to the automation, he/she has to monitor the execution of this task. When reaching system limits or in the event of unsatisfactory executed assistance functions, the driver has to intervene and to take over complete vehicle guidance. Therefore, the driver needs to develop a mental model of the system behavior that allows him/her to predict system actions and thus to be able to react in time.

For autonomous vehicle guidance, interaction between driver and automation mainly occurs at navigation level. The driver completely assigns the subsequent steps of vehicle guidance to the automation, which has to guarantee safe accomplishment of the driving mission. Therefore automation has to make any decision by itself without relying on the driver, who according to the concept of autonomous driving is not in the loop. This implies high performance in terms of perception and cognition abilities of the environment detection system. While interpreting a driving situation two potential error types have to be avoided: false positive (also known as alpha error) and false negative (also known as beta error). Whereas for false positives automation detects an object where in reality there is none, for false negatives automation fails to detect an existing object. The challenge in developing system architecture is that measures to reduce the probability of occurrence of one type of error automatically increase the probability for the other type. System architectures for autonomous vehicles are mostly based on a complex safety concept as described in [9] and on conservative decision strategies admitting more false positives. Hereby, autonomous error handling strategies become quite time-consuming, because different alternatives with increasing potential risk have to be assessed sequentially [10].

This decision process could be significantly shortened by integrating the human driver whose abilities in deciding whether a positive detection is true or false are superior to those of the automation. Moreover, the human driver is able to quickly analyze complex driving situations and if necessary to derive alternatives. Thus the integration of the human driver is the motivation for cooperative vehicle guidance concepts [11]. Interaction between driver and automated systems and the analysis of the system behavior are often considered from an ergonomic point of view, concentrating on the driver, analyzing his/her abilities to understand and predict the behavior of the automated system and his/her capabilities of intervening correctly in case of reaching system borders. Even though this is a key factor for a successful cooperation between driver and automation, the relevance of a clearly defined system behavior for the vehicle-related design of the overall system architecture is mostly neglected. Depending on the driving functions executed and the current driving situation, the elementary trajectory planning strategy described above reaches its boundaries when facing situations with increased collision risk due to crossing other priority trajectories. These driving situations require that additional information be taken into account within the decision process in order to guarantee a safe continuation of the driving mission. As the CbW principle is based on a clear task assignment between the two acting partners, arbitration [12] does not present a preferred solution. Rather, automation levels and system behavior
strategies have to be analyzed based on the information needs occurring for combinations of maneuvers and driving situations. The main goal is to identify system behavior strategies that are consistent for different driving situations in order to enable the driver to develop a mental model. The approach proposed below primarily focuses on technical-driven aspects. Ergonomic assessment criteria such as driver acceptance and comfort are not taken into account.

III. PROPOSED APPROACH FOR THE DEVELOPMENT OF A COOPERATIVE CBW SYSTEM BEHAVIOR

The proposed approach follows a five step top-down analysis illustrated in Fig. 3. The information required for the decision to continue a driving mission is analyzed in systematically derived driving scenarios. Based on this analysis decision points, so called “gates” are identified. Moreover, this analysis reveals the technical requirements for the realization of different automation levels. The following steps consist of assessing possible system behavior strategies for different automation levels and to make a consistency check. These steps are explained in detail below.

![Fig. 3. Five step analysis](image)

A. Development of a catalog of driving situation characteristics

A catalog of driving situation characteristics is developed according to [13]. This catalog contains systematically identified parameters that can be assigned to one of the following three groups:

- **Static Parameters**
  Group of parameters characterizing the basic invariable set-up in which a driving scenario takes place (e.g. road topology, static obstacles, road traffic regulations, sight obstructions, etc.).

- **Dynamic Parameters**
  Group of parameters characterizing the variable components of a driving situation (e.g. moving traffic members, traffic lights, etc.).

- **Diverse Parameters**
  Group of parameters influencing driving conditions (e.g. road condition, weather, etc.) or characterizing irregular events (e.g. suddenly appearing obstacle)

In line with the high number of possible parameter combinations, this catalog makes it possible to generate nearly every conceivable driving scenario.

B. Analysis of information needs for maneuver execution

The information required for the decision to continue a driving mission depends on the combination of driving scenario and driving maneuver. A systematic analysis of these combinations reveals which information is relevant at which point. Similar to the description of driving scenarios, information required can be grouped into static and dynamic information. In this way, information clusters, which comprise different information needed at the same point, so-called “gates” are identified. These gates mark the points where – with respect to the basic trajectory planning strategy described above – additional information has to be taken into account for the decision on a safe continuation of the driving mission. In order to be able to pass a gate and thus to safely continue the driving mission, automation and/or the driver need to have all required information assigned to that gate available to them.

C. Analysis of realizable automation levels

The third step consists of analyzing at which of the following automation levels (AL) the driver can be cooperatively assisted in decision making in order to pass the gate:

- **AL 1:** Indication of upcoming gate, decision is made by the driver
- **AL 2:** Automation makes proposal, decision is made by the driver.
- **AL 3:** Share of responsibility where automation makes a proposal on decision with a potential alpha error, the decision is made by the driver. A decision with a potential beta error is made by the automation while informing the driver about the decision and future action.

The automation level that can be realized depends on the information available to the automation. This allows the determination of the technical requirements the automation has to fulfill. For AL 1 the automation has to fulfill the requirements for the position of the gates to be available, whereas the next higher automation levels require additional information, e.g. the trajectory of other traffic members, in order to be able to make a proposal or a decision.

D. Analysis of possible system behavior strategies

The next step consists of assessing possible system behavior strategies during the decision process when approaching a gate and of analyzing cooperative interaction between the driver and the automation. The gates that have to be passed during a driving mission are metaphorically speaking closed unless the required information and the decision on the continuation of the driving mission based on that information is available. Thus, common to all approaching strategies is that they stop at the gate if no decision is made by the driver or the automation, because a safe continuation of the driving mission cannot be guaranteed.

Fig. 4 shows four different strategies for speed reduction when approaching a closed gate. Strategy 1 represents emergency braking, stopping the vehicle with maximum deceleration from $x_{EB}$, the latest possible point. Following
strategy 2, comfortable braking – with speed-dependent deceleration of 3.5-5.0 m/s² as with today’s FSR-ACC systems [14] – is initiated. The third strategy first slows down the vehicle to a low speed, e.g. walking speed, creeping towards and finally stopping at the gate. Strategy 4 reduces vehicle speed in multiple steps.

The approaching strategy and the required speed reduction influence the point at which the deceleration is initiated. The distance between that point and the gate increases from strategy 1 to 4 and with increasing initial speed. However, the time available for the interpretation of the current situation and thus for decision making increases from strategy 1 to 4. The suitability of these strategies is assessed following a process of elimination, where strategies that reveal to be unsuitable for a specific combination of driving maneuver and driving situation are eliminated.

The final step is to combine suitable approaching strategies with the automation levels specified for the particular driving scenario. For automation levels 1 and 2 all decisions are made by the driver, in the latter case possibly based on proposals made by automation. If no decision is made by the driver, the automation would automatically decelerate the vehicle when reaching the point where the escalation of the approaching strategy is initiated. Fig. 5 shows possible choreographies for the case where automation identifies gate passage as not being possible. Based on the proposal of the automation to stop at the gate, the driver has three possibilities. By confirming the proposal (1), automation would stop the vehicle at \( x_{Gate} \). The driver’s second option is to correct a potential alpha error by denying automation’s proposal and thus to open the gate (2). If the driver does not react until reaching \( x_{EAS} \), which denotes the corresponding coordinates shown in Fig. 4, the escalation of the approaching strategy is initiated (3). Moreover, the driver has at all time the possibility to abort the deceleration of the vehicle, e.g. because of changed traffic situation, by assigning the passage through the gate (4).

If the automation would decide to pass the gate for AL 3, the driver would be informed about that decision and future action by the automation. By not reacting the driver implicitly agrees. In the case of a beta error, the driver has the possibility to overrule automation’s decision by assigning a target braking maneuver.

E. Consistency check

Following the approach above, different system behaviors for different automation levels are developed for a driving scenario class, e.g. intersection scenarios, in combination with assignable driving maneuvers. Thus, the final step of the proposed approach is to make a consistency check with driving scenarios belonging to another class and representing possible state transitions of the maneuver control unit, e.g. approaching traffic lights or stopping behind an obstacle. It has to be checked whether a combination of system behaviors independently defined for a driving scenario class leads to contradictions. Therefore, realizable automation levels and approaching strategies have to be adapted for gates occurring at the same position or for succeeding gates that can be combined to one gate. Moreover, this step influences the assessment of technical feasibility.

IV. RESULTS

This section describes exemplary results for the application of the approach to intersection scenarios.

A. Analysis of information needs

Table I shows four different intersection scenarios that have been derived from the catalog of driving situation characteristics. To demonstrate this method only two parameters have been modified, namely the priority regulation at the intersection and the direction from which the ego vehicle is approaching the intersection.

The analysis of information needs for the combination of these scenarios and the possible driving maneuvers “turning left”, “driving straight through the intersection”, and “turning right” is shown in Table I using the nomenclature of Fig. 6.
The analysis of only four different driving scenarios reveals explicit differences regarding information needs for the three maneuvers but also for same maneuvers assigned in different driving scenarios. The analyzed intersection scenarios only have in common that gate 1 has to be passed for all combinations.

### B. Analysis of realizable automation levels

The analyzed differences in occurring information needs and the position of the gates can only be taken into account, if static information, in particular priority regulation, is known by the automation, e.g., by using digital map or traffic sign recognition. Thus all three automation levels would be realizable, passing only the identified gates.

Without this information automation would have to act based on a worst case assumption. In case of AL 1 the automation would assume the maximum number of gates for the assigned maneuver and inform the driver when approaching them. Hence for turning left this would be gate 1 and gate 3, for going straight through gate 1, and for turning right gate 1 and gate 2. In case of AL 2 and AL 3 the automation would have to take into account each identified gate for one kind of maneuver, assuming maximum information needs without having static information available. For example to drive straight through the intersection of scenario II without knowledge of priority regulation, automation would check the required information against that required for the same maneuver in scenario IV, whereby oncoming traffic members from directions A, B, and C would be taken into account. This would lead to a high number of false positives.

This analysis reveals the knowledge of priority regulation as being a necessary condition for the realization of AL 2 and AL 3 for intersection scenarios. Although AL 1 can be realized without that information available to the automation, due to the restrictions described above this type of assistance does not seem very desirable.

To realize AL 2 and AL 3 the automation has to have available not only the position of the gates but also the dynamic information assigned to each gate for the current combination of driving maneuver and driving scenario. As shown in Table I the occupancy of the intersection area and of the intersection exit as well as oncoming traffic members from lateral or longitudinal direction and having priority have to be taken into account. Thus this analysis builds the basis for assessing the technical feasibility of different environment detection systems or car-to-x communication.

### C. Development of system behavior strategies

Applying the four approaching strategies to these scenarios reveals them all as being suitable. However strategies 3 and 4 – both enabling more time for decision making – might be advantageous when considering situations where information on other traffic members is available just shortly before reaching the gate, as might occur in the event of sight obstruction, for example. Moreover, in situations where neither the driver nor the automation is able to make a decision because of missing information when having reached the gate, by taking over manual control the driver could obtain more information by slowly continuing and passing the gate. Initiating strategies 1


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**Table I**

Analysis of Information Needs for Different Intersection Scenarios

<table>
<thead>
<tr>
<th>Driving Maneuver</th>
<th>Scenario I</th>
<th>Scenario II</th>
<th>Scenario III</th>
<th>Scenario IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection Type</td>
<td>X Intersection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of exits</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of entries</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of lanes per direction</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Priority Yield-to-right</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupancy intersection area</td>
<td>G1</td>
<td>G1</td>
<td>G1</td>
<td>G1</td>
</tr>
<tr>
<td>Occupancy exit G3</td>
<td>G1</td>
<td>G2</td>
<td>G3</td>
<td>G1</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

Static information is assumed as being relevant in advance of arrival at the intersection, whereas dynamic information is assigned to one of the three identified gates (G1 to G3).
and 2 in these situations might occur unexpectedly for following traffic members and cause confusion.

D. Consistency check

The consistency check is exemplarily demonstrated for the combination of intersection scenarios with the driving scenario “approaching traffic lights”. Compared to the large number of different intersection scenarios, the analysis of this driving scenario is quite simple. The gate that has to be passed is located on the stop line. The decision that has to be made consists of deciding whether passing traffic lights is allowed.

To realize AL 3 in this context would mean that automation decides on the passage through the gate when green light is detected while informing the driver. When the automation detects red light it will make a proposal to stop the vehicle at the stop line. The decision on orange light is assigned to the automation or the driver depending on the ability to stop the vehicle at the stop line. Hence, the realization of AL 2 and AL 3 requires information on the traffic lights status, e.g. using video-based traffic light recognition or car-to-infrastructure communication. To indicate upcoming traffic lights for AL 1 it would be sufficient for the automation to know of the existence of traffic lights, e.g. using digital map.

When approaching green traffic lights, speed reduction is disadvantageous because lights may change to red. When approaching red traffic lights a human driver would comfortably stop the vehicle at the stop line. Thus, strategies 3 and 4 are unsuitable for both cases and hence can be eliminated. As a result of the consistency check, these two strategies have also to be eliminated for the first intersection gate. In both cases the deceleration of the vehicle would start before passing the traffic lights gate and thus be conflictive to the suitable strategies defined for approaching traffic lights. Moreover the consistency of the approaching strategies is a precondition for combining the first intersection gate and the traffic lights gate. However, this combination influences the realizable automation level at this new gate. Whereas the availability of e.g. a digital map is still sufficient to realize AL 1 for intersection scenarios in combination with traffic lights, the requirements for the next higher automation levels have to be extended.

This example reveals the relevance of the consistency check as the final step of the proposed approach. A simple sequence of the driving situations and their respective identified gates and suitable approaching strategies is not acceptable because of their mutual interference.

V. CONCLUSION

The proposed approach allows a top-down analysis of realizable automation levels and system behavior strategies for highly-automated vehicle guidance based on the Conduct-by-Wire principle. Applying this method to a high number of systematically derived driving scenarios is the basis for important upcoming steps toward the theoretical feasibility assessment of CbW. Knowledge gained will be introduced in the driving functions development process using IPG CarMaker. Moreover, identified strategies and driver-automation interaction have to be assessed from an ergonomic point of view in order to evaluate the suitability of maneuver-based vehicle guidance for different application areas. This assessment will mainly be focused on the analysis of the time available to the driver for the decision making process. Besides, the results of this approach will help to determine the requirements of an environment detection system for the highest automation level. These upcoming steps will have a fundamental influence on the development of the system architecture and the safety concept of a future prototype vehicle.

REFERENCES