Temporal Analysis of the Gate Concept as Enabler for Highly Automated Driving based on the Conduct-by-Wire Approach

Sebastian Geyer, Melanie Karg, Stephan Hakuli, Hermann Winner, Benjamin Franz, and Michaela Kauer

Abstract—Conduct-by-Wire (CbW) is an innovative vehicle guidance concept that shifts the vehicle control task from the stabilization level to the guidance level. Instead of continuous stabilization on a designated trajectory—using the conventional control elements for manual steering, braking, and accelerating—a CbW vehicle is controlled by means of maneuver commands. One important element on the way to realizing CbW might be the gate concept that consists in a segmentation of the vehicle guidance task and the identification of decision points during the execution of a driver’s maneuver command. This article introduces an approach for the analysis of the time available for decision-making in systematically derived scenarios. For the first time, the results offer the basis for a suitability evaluation of the gate concept and thus a fundamental contribution to the technical feasibility assessment of CbW.

I. INTRODUCTION

Modern Advanced Driver Assistance Systems (ADAS) have established a standard of driving comfort and safety unknown so far. Vehicles have become increasingly “intelligent” allowing the driver to delegate specific subtasks of vehicle guidance to these systems or to let the automation take over vehicle guidance completely in emergency situations. However, the scientifically proven advantages of ADAS [1] are accompanied by an important disadvantage: increasing complexity. Today, most ADAS are developed separately, with the consequence that each of these systems has its own user interface and interaction concept. This increasing complexity is contrary to the original goal to increase comfort and safety.

A solution for the described problem of an increasing user complexity when combining multiple assistance systems and a very important step towards fully automated driving might be innovative vehicle guidance concepts such as H-Mode [2] or Conduct-by-Wire (CbW). The idea of 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, as shown in Fig. 1.

Fig. 1. Maneuver-based vehicle guidance [3]

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 [4]. Thus, the driver of a CbW vehicle delegates the tasks of trajectory planning and vehicle stabilization to the automation. This concept allows a maximum degree of automation, while—unlike fully automated concepts—still keeping the driver responsible for the vehicle guidance according to the 1968 Vienna Convention on Road Traffic [5].

A research project at Technische Universität Darmstadt aims to provide a technical feasibility assessment of the Conduct-by-Wire concept focusing on the driver-vehicle interaction, the identification of the functionality the automation has to provide [6], and on the determination of the requirements for the environment detection system [7]. First promising investigations with test persons have
demonstrated the acceptance of maneuver-based vehicle guidance [8].

II. THE GATE CONCEPT

As described above, the CbW principle is based on a clear task assignment between the driver (maneuver command) and the automation (maneuver execution). The execution of a driver’s maneuver command implies several subtasks such as to check if the maneuver command can be executed in the actual driving situation, safe trajectory planning, detection of unsafe driving states, and surveillance of the system availability. When facing situations with increased collision risk due to crossing other priority trajectories, additional, cognitive tasks are becoming essential in order to guarantee a safe continuation of the driving mission. In [9] a new approach for the systematic analysis of information required for decision-making in different driving scenarios has been introduced. The key element of this approach is the so called “gate concept” that consists in a segmentation of the vehicle guidance task. The gates mark the points along a planned trajectory where a decision on the continuation of the driving mission has to be made. Each gate is assigned to an information cluster, which comprises different information needed at that point.

Fig. 2 shows the driver-vehicle interaction at the guidance level. The driver’s maneuver commands are transferred to the maneuver control that – depending on the actual driving situation – assigns, coordinates, and parameterizes the appropriate driving functions. When approaching a gate, the driver of a CbW vehicle can be cooperatively assisted by the automation in decision-making at different automation levels that range from the indication of upcoming gates to autonomous decision-making. In cases where no decision is made by the driver or the automation, the gate stays, metaphorically speaking, closed. In that case, the currently executed maneuver is put on hold and replaced by a gate-approaching maneuver. Common to all approaching strategies is that they stop the vehicle at the position of the gate according to the CbW safety concept. Once the gate is “unlocked”, the saved maneuver is reactivated from the memory.

Fig. 2. CbW driver-vehicle interaction at the guidance level

To date, the gate concept is a theoretical approach, motivated from the automation’s point of view. The idea is to shorten time-consuming decisions or to correct wrong decisions made by the automation in complex driving situations, as described for fully-automated concepts in [10], by integrating the human driver as additional decision instance. The gate concept has proven itself in different urban intersection scenarios. With respect to the assessment of technical feasibility and the realization of a prototype vehicle, it is unclear whether this concept is suitable for practical use. Besides the application of the gate concept to a high number of systematically identified driving situations, an analysis of the time available to the driver or the automation for the decision-making process builds the fundamental basis for the assessment. The approach proposed in this article allows both, for the first time. Moreover, a control strategy is presented that generates the required time for decision-making in situations that have been identified as being time critical by adapting the gate-approaching strategy.

III. PROPOSED APPROACH FOR THE TEMPORAL ANALYSIS OF THE GATE CONCEPT

The proposed approach follows a five-step, top-down analysis illustrated in Fig. 3. These steps are explained in detail below.

Fig. 3. Top-down approach

A. Conduct-by-Wire catalog of driving situations

Known catalogs of driving situations either focus on the identification of relevant situations for potential new ADAS (e.g. [11]) or for driver behavior analysis (e.g. [12]). Both approaches do not present a preferred solution for the analysis of technical feasibility of CbW, because all potential situations a CbW vehicle has to cope with have to be considered. Therefore, a catalog of driving situations (shown in Table I) is developed, derived from German guidelines for road design [13] and traffic laws [14] and verified by systematically analyzing real traffic situations in the Rhine-Main-area in Germany. The situations of this catalog can be assigned to one of four situation classes. To limit the number of possible parameter variations, the set of relevant parameters that describe a situation can be adapted to the focus of investigation. To give an example, the direction markings on the road can be neglected for the gate identification but they are relevant for the determination of the requirements for the environment detection system.
Furthermore, as the catalog is based on legal guidelines, only admissible parameter combinations are considered, which again limits the number of analyzed situations. This catalog builds the basis of the approach proposed in this article.

### TABLE I

<table>
<thead>
<tr>
<th>Class</th>
<th>Situation</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection</td>
<td>X-intersection</td>
<td>Priority regulation</td>
</tr>
<tr>
<td></td>
<td>T-intersection</td>
<td>Direction of intersection</td>
</tr>
<tr>
<td></td>
<td>Star intersection</td>
<td>entrance</td>
</tr>
<tr>
<td></td>
<td>Traffic island</td>
<td>Number of intersection entries</td>
</tr>
<tr>
<td></td>
<td>Turning road</td>
<td>Number of intersection exits</td>
</tr>
<tr>
<td>Traffic circle</td>
<td>Traffic circle</td>
<td>Priority regulation</td>
</tr>
<tr>
<td>Traffic circle</td>
<td>Bypass</td>
<td>Priority regulation</td>
</tr>
<tr>
<td>Cross traffic</td>
<td>Crosswalk</td>
<td>Priority regulation</td>
</tr>
<tr>
<td>Parallel traffic</td>
<td>End of lane</td>
<td>One-sided/both-sided</td>
</tr>
<tr>
<td></td>
<td>Obstacle evasion</td>
<td>W/wo lane change</td>
</tr>
<tr>
<td></td>
<td>Restricted lane</td>
<td>Parallel/oncoming lane</td>
</tr>
<tr>
<td>Traffic lights</td>
<td></td>
<td>Left/right side</td>
</tr>
</tbody>
</table>

#### B. Identification of gate sequences

An analysis of the gate sequence is performed for each situation of the catalog shown in Table I. Similar gate sequences for different situations of one class are grouped to reduce again the number of situations for the temporal analysis. In reality, the situations shown in Table I rarely occur separately. For instance, crosswalks at an intersection is a common combination. In order to cover the most dominant part of situations in real road traffic, the elements of different situation classes have to be combined. Thus, using a matrix that contains all gate sequence groups mentioned above and that allows any combination of groups, new and more complex situations and gate sequences are identified.

This procedure finally allows identifying four representative scenarios, as a combination of driving situation and executed maneuver, where up to four gates have to be passed. These scenarios represent the “worst-case” gate sequences covering all other identified scenarios. Thus, the results of the temporal analysis for these four representative scenarios that reveals the time available for the decision-making is valid for nearly 400 different scenarios.

#### C. Parameter analysis

The next step of this approach consists in identifying the parameters that influence the time available for decision-making. These are the

- gate sequence
- position of the gates
- velocity
- approaching strategy
- time of gate unlock

The gate sequence corresponds to that assigned to one of the four representative scenarios. As a variation, consecutive gates could be combined. This might, for example, be the case due to the geometrical conditions of a driving situation, when two gates have the same position or if the area in front of the gate does not allow a safe stop of the vehicle.

The positioning of the gates depends on the geometrical representation of the considered driving situation and the planned trajectory. Parameters that describe the driving situation might, for example, be the relative position of the connected roads of an intersection, the width of the traffic lanes or the positioning of crosswalks. These parameters are chosen in accordance with real traffic situations. The German guidelines for road design [13] give a rough overview of dimensions, such as lane width or corner rounding, but they are not sufficient to fully determine the position of the gates. As a solution, the position of the gates is determined for real traffic situations in Germany that correspond to the representative situations and are measured using Google Earth [15]. For this purpose, a trajectory is chosen that keeps the vehicle in the middle of the path, limited by the lane width. Thus, it is possible to measure both the geometrical dimensions of the driving situation and the distance between the gates.

Another parameter that has an impact on the time available for decision-making is the velocity at which the vehicle approaches the gate and the approaching strategy. While the former primarily depends on the velocity chosen by the driver $v_{set}$, the latter depends on the acceleration performance of the vehicle $a_f$ and the deceleration strategy assigned to the gate. This can be a continuous deceleration that ranges from comfortable to maximum braking or a strategy that reduces the velocity in multiple steps.

Finally, the time when the driver or the automation decides to “unlock” a gate influences the velocity with which the vehicle passes the gate, and thus the time that is available to make a decision on the continuation of the driving mission at the following gate. Three different cases can be distinguished, qualitatively shown for two consecutive gates in Fig. 4 assuming constant acceleration. The left side shows the velocity-displacement courses. By plotting the square of the velocity over displacement, constant accelerations are shown as straight lines with the acceleration as slope. The right side shows the same courses over time.

In case I, the first gate is unlocked before the approaching strategy of the first gate is executed. The velocity at the entrance of the first gate $v_{GE}$ depends on the chosen velocity $v_{set}$. Moreover, $v_{GE}$ is automatically limited to the maximum velocity $v_{GE,max}$ as a function of the distance between the two gates $d_{G1}$ and the deceleration $d_{G2}$ assigned to the approaching strategy of gate 2. This means that the deceleration for gate 2 begins before (I.a) or after (I.c) gate 1 is passed or at gate 1 (I.b) respectively. In case II the first gate is unlocked after the vehicle has stopped. The velocity between the two gates $v_{BG}$ up to which the vehicle accelerates after gate 1 is unlocked depends on $v_{set}$ and is...
limited to \( v_{BG,max} \), that depends on \( \Delta s_G \), \( d_{G2} \), and the acceleration performance of the vehicle \( a_V \).

Fig. 4. Possible cases for the time of gate unlock

In case III, \( v_{GE} \) is lower than \( v_{set} \), which can be the case when the decision to pass gate 1 is made after the deceleration for gate 1 has started or when the distance to the gate is too short to reach either \( v_{set} \) or \( v_{GE,max} \). Thus, the cases I and II represent the extremes of case III. The time available between the two gates primarily depends on the velocity at the first gate \( v_{GE} \). The cases where the acceleration performance and the distance to gate 1 is sufficient to reach either \( v_{set} \) or \( v_{GE,max} \) are similar to case I. If \( 0 < v_{GE} \leq v_{GE,max} \), \( v_{BG} \) depends on \( v_{set} \) and is limited to \( v_{BG,max} \) as a function of \( \Delta s_G \), \( d_{G2} \), \( a_V \), and \( v_{GE} \). The influence on the time available \( \Delta t_G \) between the two gates is qualitatively shown on the right side of Fig. 4.

D. Simulation with IPG CarMaker

The vehicle simulation tool IPG CarMaker [16] is used as first test environment for CbW functions. Besides a completely parameter-based and validated vehicle model, a driver, and a road network model, CarMaker also offers the possibility to integrate the CbW driving functions realized in MATLAB/Simulink and the position of the gates as road marks. Thus, it is possible to design completely reproducible test scenarios in a virtual environment of increasing complexity. Moreover, a systematic parameter variation can be performed using the functionality of the CarMaker TestManager.

IV. RESULTS

This section describes exemplary results for the application of the approach. In the chosen scenario – one of the four representative scenarios – the CbW vehicle turns left at a X-intersection with traffic lights while a tram lane and two crosswalks have to be passed, as shown in Fig. 5. Because the area in front of the second crosswalk does not allow a safe stop of the vehicle the decision to pass this crosswalk is made at gate 3. Thus, the resulting gate sequence consists of three gates with a relative distance of 20.9 m and 9.2 m.

Fig. 5. Example for passing the three gates assigned to the turning left maneuver at a X-intersection

A. Parameter variation

As mentioned above, there are different time-influencing parameters. To demonstrate this method, only two parameters have been modified, namely the deceleration \( d_G \) (-3 m/s² and -5 m/s²) that is the same for all gates of a sequence and the time when the gates are unlocked. The constant simulation parameters are shown in Table II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between the gates</td>
<td>( \Delta s_{G12} )</td>
<td>20.9 m</td>
</tr>
<tr>
<td></td>
<td>( \Delta s_{G23} )</td>
<td>9.2 m</td>
</tr>
<tr>
<td>Velocity</td>
<td>( v_{set} )</td>
<td>50 km/h</td>
</tr>
<tr>
<td>Acceleration of the vehicle</td>
<td>( a_s )</td>
<td>2 m/s²</td>
</tr>
</tbody>
</table>

Based on the three different cases when a gate can be unlocked shown in Fig. 4, there are 27 variations for a sequence of three gates. Taking into account that one case for two consecutive gates is represented in several sequences, this number can be reduced significantly. Based on a worst-case assumption for the time available between two consecutive gates, the time when the gate is unlocked for case III is set to the time when the approaching strategy is initiated. Therefore, depending on the other parameters – primarily the distance to the next gate – the cases I and III are represented. Moreover, for this study only those sequences are of interest where a need for decision-making occurs. Sequences where the decision is made before reaching the gate can be neglected. Thus, there are four sequences left, shown in Table III. The indication “stopped” means that the gate is unlocked after the vehicle has stopped at the gate, while “passed” means that the gate is unlocked.

1 The geometrical dimensions are taken from an intersection in Darmstadt, Germany [49°52'03.42" N 8°39'50.28" E]
before the approaching strategy is initiated. Moreover, the sequence of two following gates is assigned to one of the three cases of Fig. 4.

### Table III

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Gate 1</th>
<th>Gate 2</th>
<th>Gate 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>stopped</td>
<td>stopped</td>
<td>stopped</td>
</tr>
<tr>
<td></td>
<td>Case II</td>
<td>Case II</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>stopped</td>
<td>passed</td>
<td>stopped</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>Case III</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>passed</td>
<td>passed</td>
<td>stopped</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>Case I</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>passed</td>
<td>stopped</td>
<td>stopped</td>
</tr>
<tr>
<td></td>
<td>Case I</td>
<td>Case II</td>
<td></td>
</tr>
</tbody>
</table>

#### B. Simulation results

The results for the four sequences and a variation of the deceleration \( d_G \) are shown in Table IV. The time available between two gates varies from 1.8 to 5.7 s, while as expected, the longest time is reached for case II where the vehicle stops at each gate and the time generally decreases with \( d_G \). The results put in parentheses are those cases where the decision on passing the gate is made before reaching that gate. In the case of sequence 3 for example, the decision has been possible before reaching gate 2 and thus the time between gate 1 and gate 2 is not critical. Although most of these early decision cases have been neglected in the previous section, some of them are relevant as they influence the subsequent two gates. Moreover, these results might be of interest when analyzing the time available for changing a made decision. Depending on the actual situation, this time may possibly be useful for making a decision on the subsequent gate.

### Table IV

<table>
<thead>
<tr>
<th>( d_G = -3 \text{ m/s}^2 )</th>
<th>( d_G = -5 \text{ m/s}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta t_{G12} )</td>
<td>( \Delta t_{G12} )</td>
</tr>
<tr>
<td>5.7 s</td>
<td>5.3 s</td>
</tr>
<tr>
<td>( \Delta t_{G23} )</td>
<td>( \Delta t_{G23} )</td>
</tr>
<tr>
<td>3.8 s</td>
<td>3.6 s</td>
</tr>
</tbody>
</table>

### C. Result evaluation

The aim of this investigation is to analyze the suitability of the gate concept for highly automated maneuver-based driving by identifying the time available for decision-making in different driving scenarios. The application of the methodology presented in this article led to the results shown in the previous section for an exemplary intersection scenario. As a final step, the calculated time available between two consecutive gates has to be compared with the time need of a human driver or the automation.

In the literature, many different studies can be found concerning the time between perception and reaction of a human driver. This time varies between 0.5 s and 3.5 s or is sometimes even above this value [17]. According to Green [18] “expectation” has the most important influence on the perception-response time. Of course, these studies are only valid for conventional vehicle guidance and cannot simply be transferred to the CbW concept. These studies focus on a driver’s reaction to one single event, which does not represent the whole variety of information that has to be taken into account when making a decision about the passage of a gate. Moreover, it can be assumed that the driver of a CbW vehicle is aware of decision-making when approaching a gate. However, these studies allow a rough estimation of a driver’s time need for decision-making that is set at the mean value of 2.0 s for the result evaluation in this article.

The time need for decision-making by the automation depends on different parameters such as the configuration of the environment detection system or the implementation of decision algorithms. Regardless of whether the driver or the automation makes the decision on passing a gate, the driver is the bottleneck of the decision process – because of the time need on the one hand for making the decision by him/herself, and on the other hand for understanding the decision made by the automation. For this reason, the initial focus of this article lies on the driver’s time need for decision-making. However, the conclusions drawn can be transferred to the automation.

Based on the assumptions above, sequences where the time available between two consecutive gates is lower than 2.0 s are estimated as being time-critical. As explained above, this distinction is only made for those gate sequences where a need for decision-making exists. For the exemplary scenario, critical times – marked in bold in Table IV – occur in sequence 2 and sequence 3 between the gates 2 and 3 for \( d_G = -5 \text{ m/s}^2 \). For all other parameter variations, the simulated times are not critical.

### V. Implementation of an Adaptive Gate-Approaching Strategy

Based on the approach and the simulation results presented in this article, a control strategy is presented that generates the required time for decision-making in situations that have been identified as being time critical by adapting the gate approaching strategy. Assuming constant acceleration, the time available between two consecutive gates can be calculated for the three cases shown in Fig. 4 using the equations (1)-(3).

\[
\Delta t_{G,j} = \frac{\Delta s_G}{v_{GE}} - \frac{v_{GE}}{2d_G}
\]

with \( 0 < v_{GE} \leq v_{GE,\text{max}} = \sqrt{-2d_G\Delta s_G} \).
\[
\Delta t_{G,ii} = v_{BG} \left( \frac{1}{2d_v} - \frac{1}{2d_G} + \frac{\Delta s_G}{v_{BG}^2} \right) \\
\text{with } 0 < v_{BG} \leq v_{BG,\text{max}} = \sqrt{\frac{2\Delta s_G}{d_G} - \frac{1}{d_v}} \tag{2}
\]

\[
\Delta t_{G,iii} = \frac{v_{BG} - 2v_{GE}}{2d_v} - v_{BG} + \frac{\Delta s_G + v_{GE}^2}{2v_{BG}} \\
\text{with } 0 < v_{GE} < v_{set} \cap 0 < v_{GE} \leq v_{GE,\text{max}} = \sqrt{-2d_G\Delta s_G} \tag{3}
\]

\[
\text{with } v_{GE} < v_{BG} \leq v_{BG,\text{max}} = \sqrt{\frac{2a_Gd_G}{d_G} \left( \frac{v_{GE}^2}{2d_v} + \Delta s_G \right)} \\
\]

Of course, this linear approach does not present the preferred solution for a control algorithm, but it allows a worst-case assumption on the time available for decision-making. Using these equations the values for the different influencing variables can be deduced depending on the actual case. The equations show that for a given scenario with constant \(\Delta s_G\) there are at least two variables that can be modified at a time in order to get a time gap \(\Delta t_c\) that meets the criticality criterion. For sequence 3, this would mean that the criticality limit of 2.0 s could be reached either by reducing \(v_{GE}\) to 25 km/h for \(d_G = -5\) m/s² or by increasing \(d_G\) as shown in Table IV, which automatically reduces \(v_{GE,\text{max}}\) according to equation (1). The other cases offer the possibility to modify three (case II) and even four variables (case III) at a time.

Thus, the decision for the parameter setting should be based on a cost function with respect to the relevant optimization goal. Besides general optimization goals such as comfortable or energy efficient driving that could, for example, be reached with a smooth acceleration profile, a gate-specific optimization criterion might be where the additional time for decision-making is generated when passing a gate sequence. Thus, referring to the example scenario the information needed for making a decision on passing gate 2 might occur relatively late – e.g. due to sight obstructions at the intersection entrance – and close to the gate. Therefore, by only reducing \(v_{GE}\) at gate 1, the additional time is generated for the passage of the whole gate sequence, while by increasing \(d_G\) this time is primarily generated at the end of the gate passage.

VI. CONCLUSION AND OUTLOOK

The proposed approach allows a top-down analysis of the time available for decision-making in systematically derived driving situations when applying the gate concept. The combination of the gate concept with an adaptive approaching strategy seems to be a promising solution. The results are a fundamental contribution to the assessment of technical feasibility of Conduct-by-Wire. Although the gate approach is motivated from the automation’s point of view, it builds the basis for further engineering challenges – e.g. the development of suitable decision algorithms for the automation – and for ergonomic studies – e.g. on the acceptance of the gate approach or the determination of a driver’s time need for decision-making. The latter would allow a new evaluation of the results presented in this article.

REFERENCES


