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.

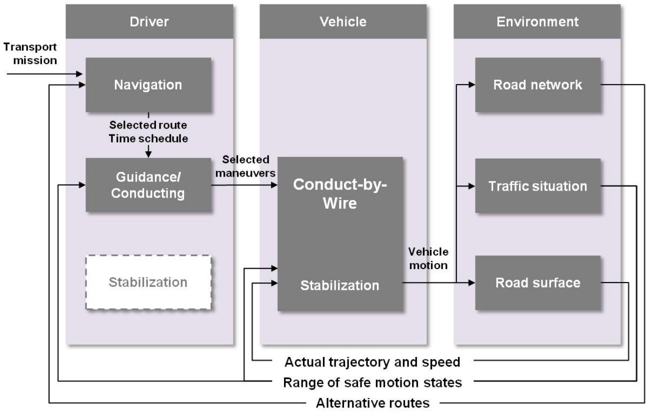

Fig. 1. Maneuver-based vehicle guidance [3]

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

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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
CONDUCT-BY-WIRE CATALOG OF DRIVING SITUATIONS

Class	Situation	Parameters
Intersection	X-intersection T-intersection Star intersection	Priority regulation Direction of intersection entrance Number of intersection entries Number of intersection exits
	Traffic island Turning road	Priority regulation
Traffic circle	Traffic circle Bypass	Priority regulation
Cross traffic	Crosswalk Railroad crossing	Priority regulation
Parallel traffic	End of lane	One-sided/both-sided Right/left
	Obstacle evasion	W/wo lane change Parallel/oncoming lane
	Restricted lane Traffic lights	Left/right side

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_V 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 Δs_G 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 Δs_G, d_{G2}, and the acceleration performance of the vehicle a_V.

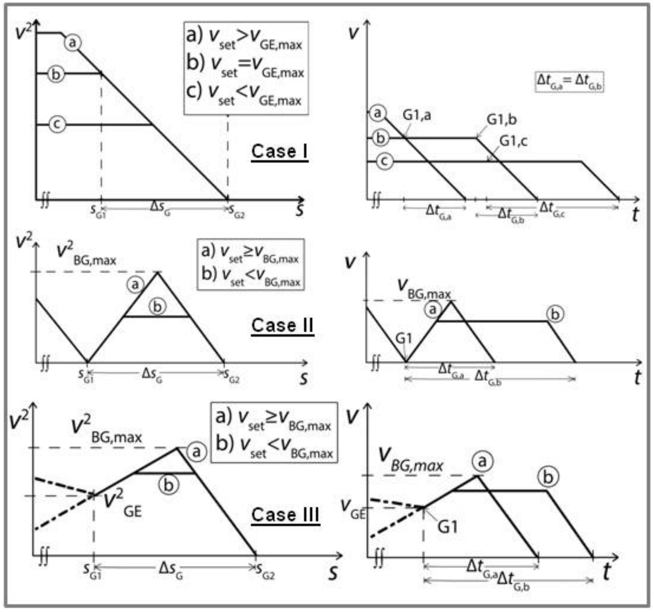

Fig. 4. Possible cases for the time of gate unlock

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 Δs_G, d_{G2}, a_V, and v_{GE}. The influence on the time available Δt_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[1].

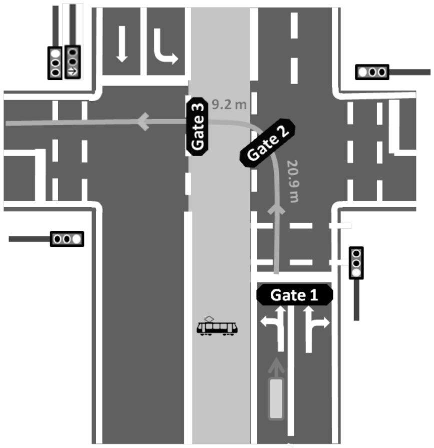

Fig. 5. Example for passing the three gates assigned to the turning left maneuver at a X-intersection

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 II
CONSTANT SIMULATION PARAMETERS

Parameter	Variable	Value
Distance between the gates	Δs_{G12}	20.9 m
	Δs_{G23}	9.2 m
Velocity	v_{set}	50 km/h
Acceleration of the vehicle	a_V	2 m/s²

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

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[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
VARIATION OF THE TIME WHEN GATES ARE UNLOCKED

<table>
<tr><th>Sequence</th><th colspan="2">Gate 1</th><th colspan="2">Gate 2</th><th colspan="2">Gate 3</th></tr>
<tr><td rowspan="2">1</td><td colspan="2">stopped</td><td colspan="2">stopped</td><td colspan="2">stopped</td></tr>
<tr><td colspan="3">Case II</td><td colspan="3">Case II</td></tr>
<tr><td rowspan="2">2</td><td colspan="2">stopped</td><td colspan="2">passed</td><td colspan="2">stopped</td></tr>
<tr><td colspan="3">–</td><td colspan="3">Case III</td></tr>
<tr><td rowspan="2">3</td><td colspan="2">passed</td><td colspan="2">passed</td><td colspan="2">stopped</td></tr>
<tr><td colspan="3">–</td><td colspan="3">Case I</td></tr>
<tr><td rowspan="2">4</td><td colspan="2">passed</td><td colspan="2">stopped</td><td colspan="2">stopped</td></tr>
<tr><td colspan="3">Case I</td><td colspan="3">Case II</td></tr>
</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
SIMULATION RESULTS

	d_G = -3 m/s²		d_G = -5 m/s²	
	Δt_{G12}	Δt_{G23}	Δt_{G12}	Δt_{G23}
Sequence 1	5.7 s	3.8 s	5.3 s	3.6 s
Sequence 2	(4.6 s)	2.3 s	(4.6 s)	**1.8 s**
Sequence 3	(1.9 s)	2.4 s	(1.6 s)	**1.8 s**
Sequence 4	3.6 s	3.7 s	2.8 s	3.5 s

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 m/s². 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).

$$\Delta t_{G,I} = \frac{\Delta s_G}{v_{GE}} - \frac{v_{GE}}{2d_G} \qquad (1)$$

with $0 < v_{GE} \le v_{GE,\max} = \sqrt{-2d_G \Delta s_G}$

$$\Delta t_{G,II} = v_{BG}\left(\frac{1}{2a_V} - \frac{1}{2d_G} + \frac{\Delta s_G}{v_{BG}^2}\right)$$
$$\text{with } 0 < v_{BG} \le v_{BG,\max} = \sqrt{\frac{2\Delta s_G a_V d_G}{d_G - a_V}} \tag{2}$$

$$\Delta t_{G,III} = \frac{v_{BG} - 2v_{GE}}{2a_V} - \frac{v_{BG}}{2d_G} + \frac{\Delta s_G}{v_{BG}} + \frac{v_{GE}^2}{2a_V v_{BG}}$$
$$\text{with } 0 < v_{GE} < v_{set} \cap 0 < v_{GE} < v_{GE,\max} = \sqrt{-2d_G \Delta s_G} \tag{3}$$
$$\text{with } v_{GE} < v_{BG} \le v_{BG,\max} = \sqrt{\frac{2a_V d_G\left(\Delta s_G + \frac{v_{GE}^2}{2a_V}\right)}{d_G - a_V}}$$

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 Δs_G there are at least two variables that can be modified at a time in order to get a time gap Δt_G 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 $v_{GE,max}$ 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.

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