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Communication Between Drivers in a Road Bottleneck Scenario

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ABSTRACT

Automated vehicles must be able to recognize behavioral intentions of human road users to act in an expectation-compliant way, particularly in situations in which the right of way is not clearly defined. An example of such a situation is a bottleneck with equal rights, where road users must negotiate who will pass the bottleneck first. In the present study, video observation was used to examine the communication behavior of drivers in a bottleneck scenario. The results reveal a dominance of implicit communication signals and show that drivers who pass the bottleneck first show more offensive behavior than drivers who pass second. For both driver groups (passes first vs. passes second) characteristic communication sequences were identified. The communication sequences represent a first indication of the behavioral strategies drivers use to negotiate the right of way in a bottleneck scenario, and therefore provide the basis for behavior recommendations for automated vehicles.

Keywords: Road bottleneck, Implicit communication, Explicit communication, Communication sequences

INTRODUCTION

With the introduction of automated vehicles, communication between automated and human road users is becoming increasingly important. A particular challenge will be the communication between automated vehicles and conventional road users in situations that are not clearly defined by traffic regulations. In Germany, an example of such a situation is a bottleneck with equal rights, in which drivers must communicate with each other who will pass the bottleneck first. In general, human drivers communicate their intentions using explicit and implicit communication signals (Schaarschmidt et al., 2021). Explicit communication signals (e.g., hand gestures, horn, turn signal) are defined as intentional actions which are explicitly sent to communicate (Schaarschmidt et al., 2021). Implicit signals, on the other hand, include the driving dynamics (lateral and longitudinal movement) of a road user (Hensch et al., 2019). Accordingly, every movement of a vehicle has an implicit communication character. Focusing on the bottleneck scenario with equal rights, Imbsweiler (2019) showed that explicit communication seems to play a minor role in this situation and that the observed communication behavior of the drivers can be divided into offensive (acceleration, constant speed) and defensive (deceleration, stop) strategies. According to Rettenmaier et al. (2019), drivers who arrive and pass the bottleneck first show an offensive behavioral strategy, whereas drivers who arrive and pass second tend to behave defensively to cede the right of way. According to Imbsweiler (2019), drivers' exhibited behaviors primarily consist of a combination of two signals (e.g., deceleration and stop). However, the reported studies are limited because they do not attempt to provide information on drivers' lateral movements, which means that implicit communication has not been fully considered. It is also unclear into which sequences (temporal sequence of signals) the displayed communication patterns (combination of signals) can be clustered.

OBJECTIVES AND RESEARCH QUESTION

Given the limitations in previous research, this work aimed to analyze the explicit and implicit communication behavior of drivers when driving through an equal rights bottleneck by additionally considering lateral vehicle dynamics and the temporal order of communication signals, to understand the communication behavior of drivers in more detail. The analysis was based on video recordings of real traffic and guided by the following research questions: Which communication signals do human drivers use to negotiate the right of way at an equal bottleneck, and how often are explicit and implicit signals used for this purpose? Which communication patterns (combination of signals) can be derived from the observed explicit and implicit communication signals? In which sequences (chronological order of the signals) can the identified communication patterns be clustered?

METHOD

Video recordings were collected at an equal rights bottleneck with a speed limit of 30 km/h in Braunschweig (Germany) in September 2019. At this location, the roadway is narrowed by almost 2 m due to an extension of the sidewalk on both sides (see Fig. 1), which makes it difficult for two drivers to pass the bottleneck at the same time. Data was collected via stereo cameras mounted on two masts (part of DLR's Application Platform for Intelligent Mobility, Knake-Langhorst & Gimm, 2016). The two masts were placed on both sides of the road bottleneck to capture both directions. Based on the detection performance of the stereo cameras and following previous research (Imbsweiler, 2019; Rettenmaier et al., 2019) an observation area of 30 m to both sides of the bottleneck was chosen. The area was divided into phases (Fig. 1) to allow a spatial tracking of the drivers' communication behavior and to control infrastructural influences (side street).

To analyze the collected video material, videos were annotated using the annotation software ELAN (version 5.8). The investigated variables were the phase (P1, P2, P3; see Fig. 1) in which a vehicle was located, the longitudinal vehicle dynamics (constant speed, deceleration, acceleration, stop), the lateral vehicle dynamics (movement to the side of the road, movement to the middle

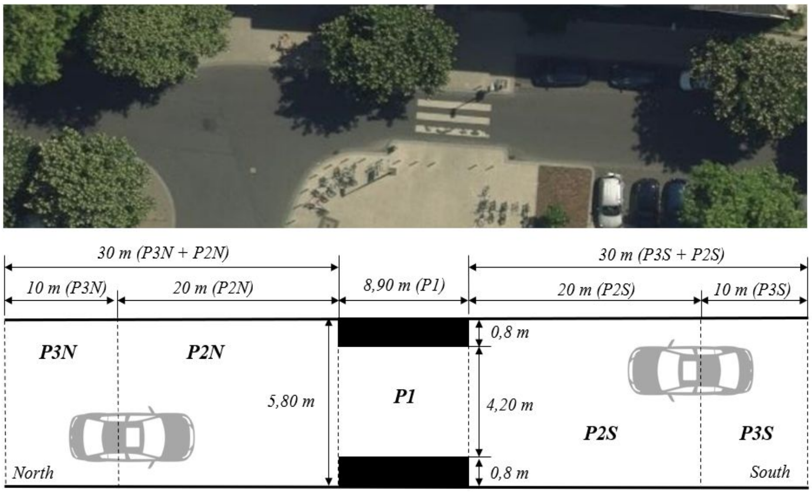

Figure 1: Road bottleneck caused by an extension of the sidewalk. P = Phase; S = South; N = North.

of the road, movement straight ahead), the activation of the headlight flasher and the turn signal (on/off) as well as the execution of hand gestures.

Only cases that met the following conditions were considered: a) both road users were cars, b) drivers did not turn off or onto the side road, c) max. 5 s difference between the points in time at which the two drivers crossed the center of the bottleneck. The final analysis consisted of N = 100 encounters. Each annotation process started as soon as a driver entered P3 and ended as soon as the first driver left the bottleneck (P1). For quality assurance of the method, two independent raters coded one third of the situations, showing substantial interrater reliability (Cohen's Kappa $\kappa = .77$; Landis & Koch, 1977).

RESULTS

For descriptive analysis of the collected data, drivers were subdivided into the groups *passes first* (n = 100) and *passes second* (n = 100). This classification was made because in 60% of the encounters the driver who arrived second was the first to pass the bottleneck.

In a first step, the beginning of a communication process was examined by analyzing the first behavioral change. In three encounters, none of the drivers showed a behavior change. In 82% of the remaining encounters (N = 97), the first behavioral change was shown in P3. Drivers who passed the bottleneck second initiated the first behavioral change in 77% of the encounters. Overall, defensive signals (deceleration or movement to the side of the road) were significant the most frequently (89% of all encounters) observed first behavioral changes ($\chi^2(1, N = 97) = 57.99, p = <.001, \Phi = .77$).

To identify which explicit and implicit communication signals were used for communication, the quantity of all observed signals (N = 838) was analyzed in a second step (Fig. 2). The results show that implicit communication signals were significant predominant in the observed

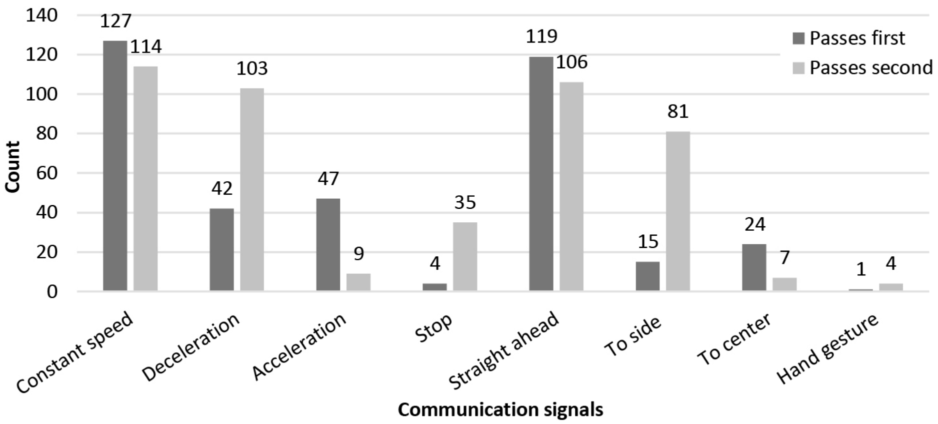

Figure 2: Type and number of communication signals at the bottleneck.

encounters ($\chi^2(1, N = 838) = 818.12, p = <.001, \Phi = .99$). The only detected explicit communication signal were hand gestures, of which three were observed after passing and therefore interpreted as a gesture of acknowledgment. Differences between the two driver groups exist especially for offensive *(acceleration, to the center)* and defensive (*deceleration, to side, stop*) communication signals ($\chi^2(1, N = 367) = 103.14, p = <.001, \Phi = .53$). The signals *constant speed* ($\chi^2(1, N = 241) = .70, p = .402$) and *straight ahead* ($\chi^2(1, N = 225) = .75, p = .386$), however, show no significant difference between the driver groups.

In a third step, the spatial occurrence of the communication signals was examined based on the three phases. Drivers passing the bottleneck first started 19% of all communication signals in P3, 78% in P2, and 3% were started within the bottleneck (P1). In contrast, drivers passing second started 60% of all signals already within P3 and 40% of the signals were started in P2. Thus, drivers who passed the bottleneck second communicated more often at a greater distance (30 - 20m) from the bottleneck than drivers who passed first ($\chi^2(1, N = 347) = 118.76, p = <.001, \Phi = .59$).

In a fourth step, it was analyzed which communication signals occurred together, looking for common communication patterns (the temporal order of the signals will be considered in the next step). The signal *hand gesture* was excluded from further analysis due to its low occurrence. Moreover, the signals *constant speed* and *straight ahead* were only considered in cases where they were shown during the whole encounter and will further be referred to as "no behavioral change". A total of N = 14 different communication patterns for drivers who passed first as well as N = 13 for drivers who passed second were found. For each driver group, two representative communication patterns were identified. Forty two percent of the drivers who passed the bottleneck first showed no behavioral change during the encounter and 21% showed a combination of decelerating and accelerating. Drivers who passed second communicated mainly by decelerating and a movement to the side of the road (41%) or by decelerating, side movement and an additional stop (25%). Fifty-five percent of all observed encounters (N = 100) show a combination of the two most frequent communications patterns of the two driver groups. All remaining communication patterns were shown by a maximum of 5% of the drivers in both driver groups, resulting in a large variety of combinations in the observed encounters, which is why a detailed description is omitted here.

In the last step, all the identified communications patterns of both driver groups were further mapped into communication sequences by including information about the temporal order and frequency of communication signals shown by a driver. The identified communication sequences are shown in Fig. 3 as a sequence diagram. Each path in the diagram corresponds to a communication sequence shown by drivers who passed the bottleneck first or second. The signals are listed hierarchically in terms of their temporal order, whereby the listed order refers to the detected start time of the signals. The numbers at the paths show the quantity of drivers that behaved according to the respective sequence.

For both driver groups, two characteristic communication sequences were identified. The predominant communication sequences for drivers passing first were a) passing straight ahead at a constant speed and b) decelerating and subsequently accelerating. Drivers passing second, on the other hand, showed an initial decelerating maneuver or lateral movement to the side of the road followed by a stop in some cases.

DISCUSSION

This work focused on the communication behavior of drivers encountering an equal rights bottleneck, with special interest in comparing drivers who passed first vs. second. By analyzing video recordings, it was shown that implicit communication played a primary role in the observed encounters, which is in line with previous findings from Imbsweiler (2019) and Rettenmaier et al. (2019). Drivers showed both longitudinal and lateral movement signals, complementing the state of knowledge from previous studies in which only longitudinal communication signals were analyzed (cf. Imbsweiler, 2019; Rettenmaier et al., 2019). Accordingly, longitudinal and lateral vehicle dynamics seem to be an essential component in the communication process at an equal rights bottleneck.

Moreover, the presented findings confirm a difference in communication signals shown by drivers passing first vs. second, which was already reported by Imbsweiler (2019) and Rettenmaier et al. (2019). This difference was shown by not only considering the occurrence of communications signals, as previous research has done (Imbsweiler, 2019; Rettenmaier et al., 2019), but also by including the temporal order of the signals. More offensive communication sequences, in which the driver either drove at a constant speed straight ahead or showed a decelerating maneuver followed by acceleration, were associated with drivers who passed the bottleneck first. In comparison, more defensive communication sequences, consisting of decelerating and driving to the side of the road as well as an additional standstill, were characteristic for drivers who passed the bottleneck second. The results indicate that different behavioral strategies might be used to signal a driver's intention to pass

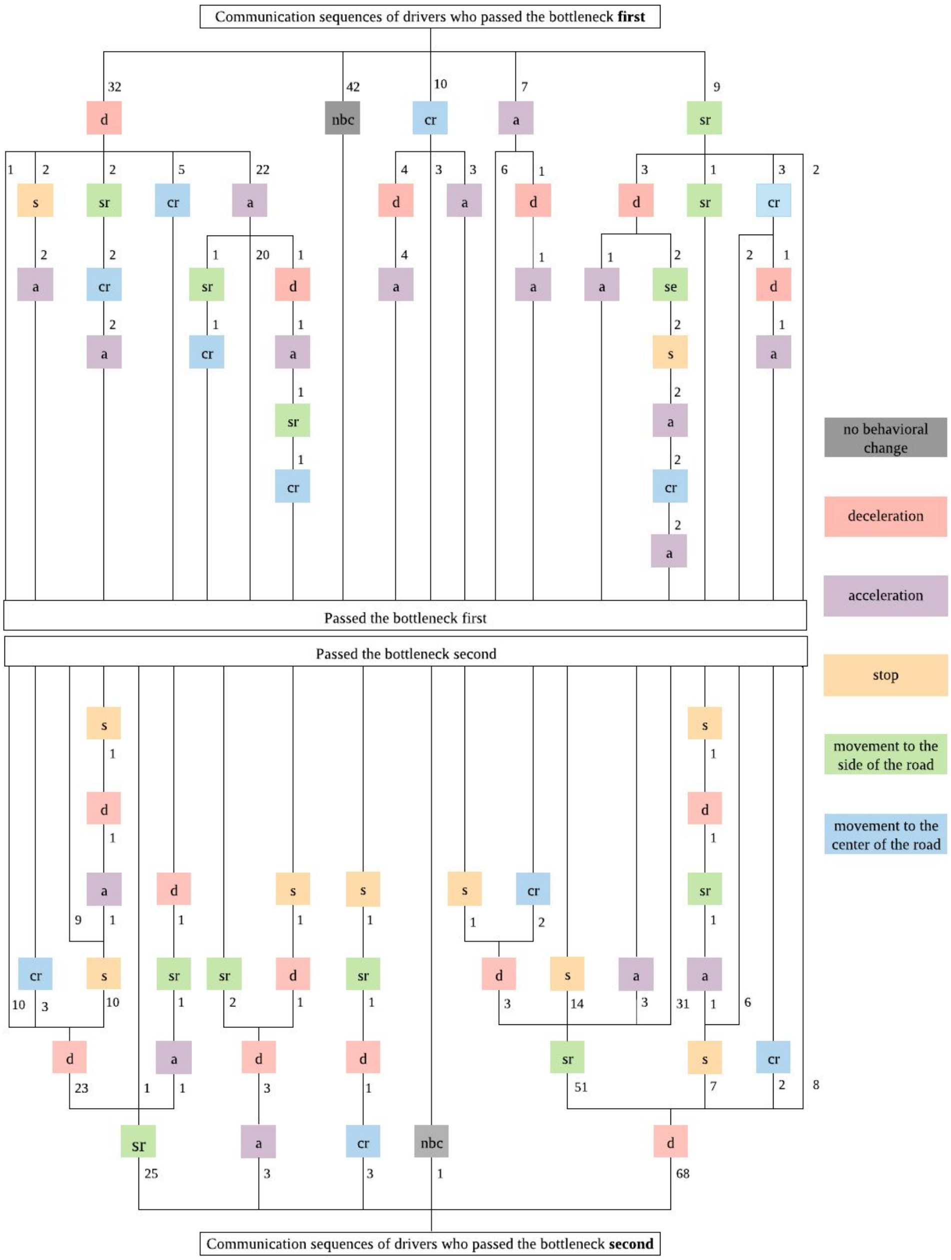

Figure 3: Communication sequences of drivers who passed first or second in the bottleneck scenario.

a two-sided bottleneck first or second. Further research is needed to address whether signals are intentionally shown to negotiate the right of way.

In contrast to previous work (Rettenmaier et al., 2019), it was not observed that the driver who arrived first was most often the one to pass first. The results of this study rather indicate that the passing order of the two drivers is related to the communication signals and sequences shown by a driver. This rather contradictory result could be due to the contextual dependence of communication behavior of drivers in road traffic (Markkula et al., 2020). At the selected location, there was a side road north of the bottleneck, which may have caused drivers from the north to slow down in front of the side road to be able to give way to traffic coming from the right if necessary. Since the present study was not interested in what caused a given behavior but in the identification of communication signals which are associated with passing the bottleneck first vs. second, the interference caused by the side road was neglected. Nevertheless, this result shows that local characteristics influence traffic behavior and informal rules might emerge, which could pose further challenges for automated vehicles. It is therefore important to also include non-prototypical scenarios when analyzing communication behavior.

The communication sequences identified in this work provide initial guidance on what behavioral strategies might be used to signal a driver's intention to pass an equal rights bottleneck first or second. The results can be considered as a first basis for the realization of expectation-compliant communication behavior of automated vehicles in a bottleneck scenario.

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