Methods

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Trajectory-based traffic observation of cooperation at a road narrowing

Trajektorienbasierte Verkehrsbeobachtung von Kooperation an einer Fahrbahnverengung

Implications for autonomous driving

Auswirkungen auf das autonome Fahren

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Abstract: Understanding human interactions in today's transportation system is a prerequisite for developing well-accepted cooperatively interacting autonomous vehicles. This paper is devoted to the two-sided narrow passage scenario and uses trajectory data to investigate drivers' interaction behavior when encountering each other from opposite directions. Trajectory data of 209 encounters at a road narrowing were analyzed in terms of drivers' approaching behavior and arrival order. The exploratory analysis has shown that in this specific location an informal traffic rule has developed: It was not the order of arrival but the direction of travel that primarily determined who passed the road narrowing first. This result shows that informal rules can influence drivers' interaction behavior and should accordingly be considered in the development of autonomous vehicles to ensure safe and efficient encounters with human road users.

Keywords: driver cooperation; informal traffic rules; narrow passage; road bottleneck; trajectory analysis.

Zusammenfassung: Ein umfassendes Verständnis des menschlichen Interaktionsverhaltens im Straßenverkehr ist Voraussetzung für die Entwicklung kooperativer autonomer Fahrzeuge. In diesem Beitrag wurde anhand von Trajektoriendaten das Interaktionsverhalten von Fahrern an einer beidseitigen Fahrbahnverengung, insbesondere hinsichtlich der Ankunftsreihenfolge, untersucht. Die explorative Analyse hat gezeigt, dass sich an diesem speziellen Ort eine informelle Verkehrsregel entwickelt hat: Nicht die Ankunftsreihenfolge, sondern die Fahrtrichtung bestimmte primär, wer die Straßenverengung zuerst passierte. Dieses Ergebnis zeigt, dass informelle Regeln das Interaktionsverhalten von Fahrern beeinflussen können und dementsprechend bei der Entwicklung von autonomen Fahrzeugen berücksichtigt werden sollten, um sichere und effiziente Begegnungen mit menschlichen Verkehrsteilnehmern zu gewährleisten.

Schlagwörter: Kooperation; informelle Verkehrsregeln; Fahrbahnverengung; Straßenengpass; Trajektorienanalyse.

1 Introduction

Highly automated and autonomous vehicles (SAE level 3 and higher; [1]) are expected to increase traffic safety and efficiency [2]. But the successful introduction of these vehicles will strongly depend on how well they adapt to social characteristics of our traffic system [3, 4]. Accordingly, the topic of cooperative automation has gained in importance in recent years. This research field considers both the technical possibilities regarding cooperation (e.g. via vehicle to vehicle or vehicle to infrastructure communication) and the cooperation between humans and technology (e.g., [5, 6]). In the context of human-machine cooperation, the focus is on both the cooperation between driver and automation, for example regarding shared control between driver and automation, and the cooperation between automation and human road users outside the vehicle, for example communication via external human-machine interfaces (e.g., [6, 7]). A social agent in our traffic system needs the ability to communicate, negotiate and cooperate as well as to follow social norms and informal rules, which might differ depending on the context, e.g., the geographical region or the specific

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traffic scenario [8–10]. Studying and understanding human interactions in today's transportation system is therefore a prerequisite for developing well-accepted cooperatively interacting autonomous vehicles. Accordingly, several studies have conducted traffic observations to gain insights into human interaction behavior (e.g., [11–13]). Björklund and Åberg, for example, found that at intersections not only the formal rule of priority but also the road width influenced drivers' yielding behavior [11]. To give another example, Lee et al. found that in driver-pedestrian-interactions road users rarely communicate with explicit signals (e.g., hand gestures or flashing headlights) but mainly rely on implicit signals (e.g., speed changes) [12].

A scenario, which has gained only limited attention so far, is a two-sided road narrowing that drivers approach from opposite directions. Such a scenario might be the result of narrow streets, an infrastructural measure for speed reduction, or simply caused by parking vehicles on both sides of the road. Because drivers have to negotiate who will pass first and therefore have to cooperate (if the narrowing is not regulated by traffic signs), a two-sided road narrowing will pose a great challenge for autonomous vehicles [14]. Previous traffic observations of this scenario were conducted in the field or using video recordings which were annotated by a human observer [15–17]. This work now complements these studies via trajectory data analysis, which allows a precise estimation of drivers' temporal and spatial relation. While past studies have mainly studied the implicit and explicit communication signals of drivers in this scenario (e.g., [18, 19]), only two studies have explicitly

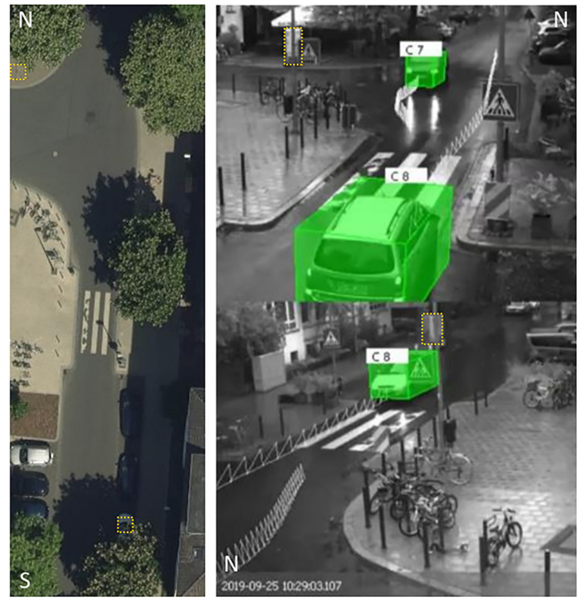

Figure 1: Trajectory data were recorded at a two-sided narrow passage in Braunschweig, Germany. The location was recorded from two perspectives (orange boxes); objects were automatically classified (right).

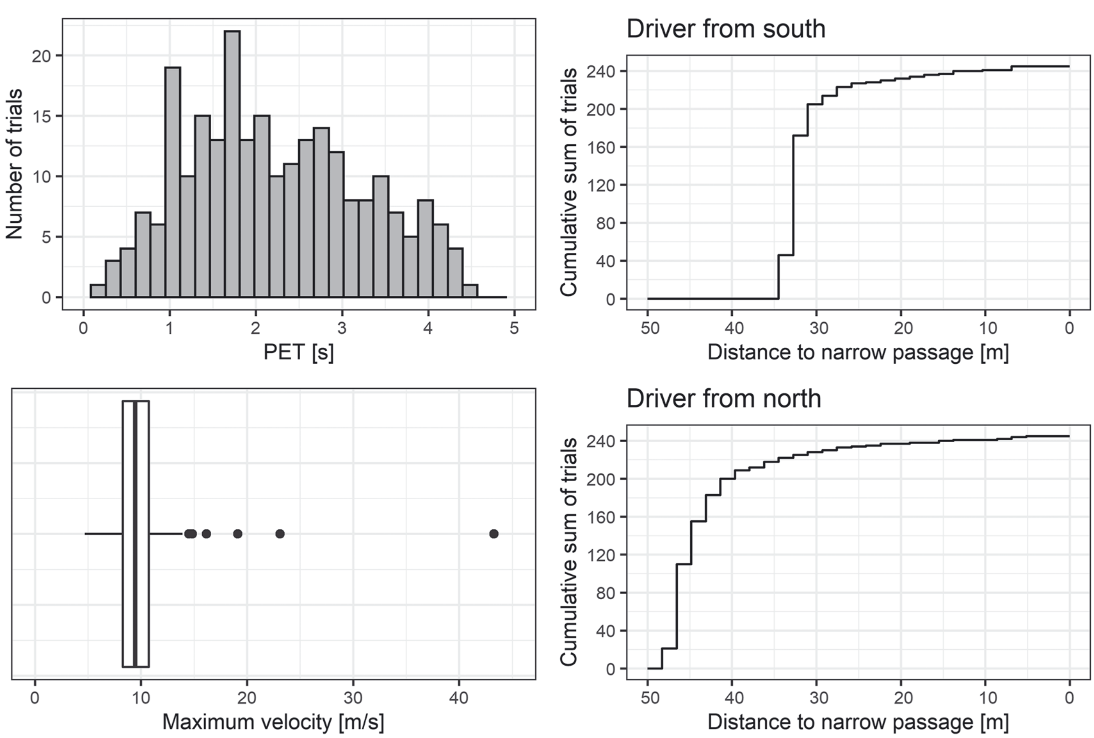

Figure 2: Histogram of PET values (top left), boxplot of drivers' maximum velocity (bottom left), and the availability of data at a given distance to the narrow passage represented as the cumulative sum of trials for the drivers from the south (top right) and north (bottom right) for the extracted encounters ($n = 245$).

looked at the arrival order of the two drivers [16, 20]. In a video-based online experiment, Miller et al. varied the time to arrival (TTA) of the oncoming vehicle, and found that with increasing TTA the probability to pass first increased [20]. Rettenmaier et al. observed 50 encounters, in which two drivers arrived almost simultaneously [16]. They found that the driver passing the narrow passage first, was also the driver arriving first. Both studies indicate that drivers at narrow passages follow the informal rule of "first come, first pass". In comparison to [16], who determined drivers' arrival order as the order of arrival at a specific distance to the narrow passage, this work uses the benefits of trajectory data and classifies arrival order based on two continuous measures of the two drivers' temporal and spatial relation. The exploratory trajectory data analysis is particularly devoted to the arrival order of the two drivers in order to study the presence of informal rules, e.g., who arrives first, passes first.

2 Methods

Focus of this work is the description of drivers' behavior and arrival order when encountering a narrow passage, based on an exploratory analysis of real-world trajectory data. The following sections describe the recorded narrow passage, the data collection, the data pre-processing as well as the data analysis including the calculated metrics.

2.1 Location

The data was collected at a two-sided narrow passage in Braunschweig (Bültenweg, next to Spielmannstraße; Figure 1), Germany. The narrow passage is caused by an extension of the sidewalk (of approximately one meter on either side of the road) over a length of 8.90 m. The width of the narrow section is 4.20 m, making it difficult for two vehicles to pass simultaneously. North of the narrow passage is a right-before-left T-junction. The speed limit in this area is 30 km/h.

2.2 Data collection

Trajectory data were recorded with a frequency of 25 Hz via DLR's Application Platform for Intelligent Mobility (AIM) Mobile Traffic Acquisition, which enables real-time identification of objects via a mobile sensor system [21]. The camera-based system classifies passenger cars, vans, trucks, cyclists and pedestrians. Data were continuously collected over twelve consecutive days in September 2019 as part of the project @CITY. In order to observe the entire scene, two masts were placed on either side of the narrow passage (the two perspectives are shown in Figure 1), which allowed a fused field of vision of up to approximately 30 m on either side of the narrow passage.

2.3 Data extraction and pre-processing

The recorded data show a large variance with respect to, for example, time gaps between vehicles, direction of travel, and velocity. In order to analyze comparable and potentially cooperative encounters, data selection was based on various steps. In a first step, encounters between car drivers were automatically extracted based on a post encroachment time (PET) of less than 5 s (Figure 2 top left). The PET was defined as the time between the first driver leaving the narrow passage until the second driver entering the narrow passage. In a second step, all encounters were selected that took place between 7 am and 8 pm (daylight), and in which the two drivers were going straight, i.e., not turning into or turning out of any side street. This resulted in $n = 245$ encounters. In a third step, the availability of data at a given distance to the narrow passage was calculated (Figure 2 right). From the 245 encounters, only those were further analyzed which had consistent data over a distance of 25 m before to 5 m after the narrow passage. In a last step, drivers' maximum velocity was calculated to identify encounters in which the speed limit was clearly violated. Encounters in which the maximum velocity was larger than 13.91 m/s (= upper quartile plus 1.5 times the inter-quartile range [22]) were excluded (Figure 2 bottom left). This procedure of data exclusion was chosen to not set an arbitrary value but consider the statistical properties of the data set and therefore the specific circumstances in

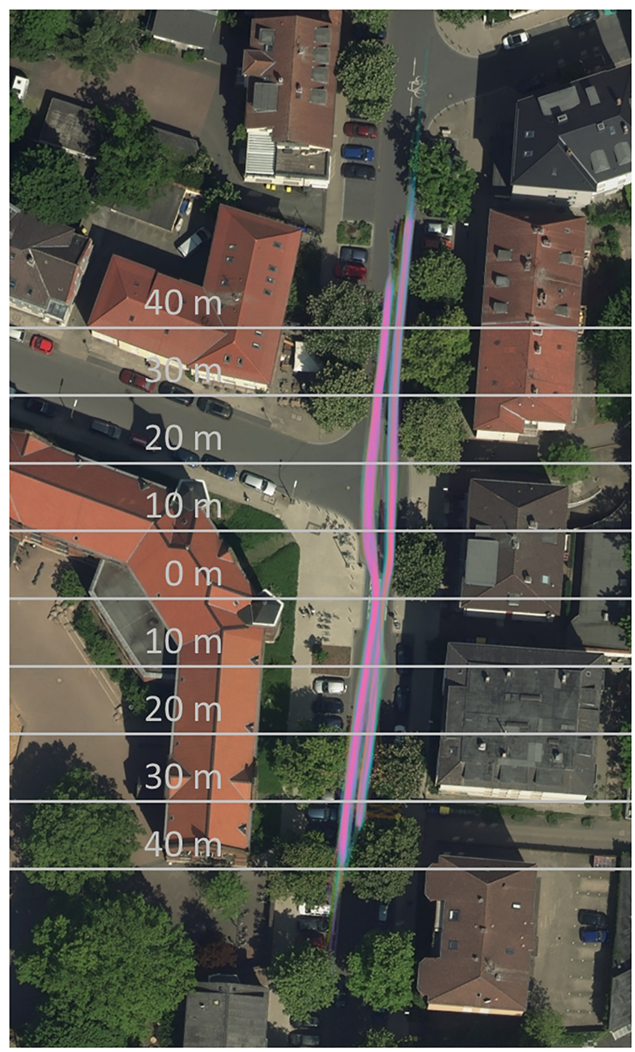

Figure 3: Trajectories of $n = 209$ encounters ($n = 418$ vehicles). Distance to the narrow passage was based on the trajectories' UTM north coordinate (exemplary distances are shown as grey lines).

this specific location. Finally, $n = 209$ encounters, i.e., trajectories of $n = 418$ vehicles, were included in the analysis (Figure 3). Drivers' velocity was smoothed by a rolling mean with a window length of 1 s. The lateral position of the vehicles was calculated as the distance to the west edge of the road. The driver passing the center of the narrow passage first was coded as “V1” and the driver passing second as “V2”.

2.4 Data analysis

Analysis of trajectory data was performed in RStudio (Version 2021.09.2). Drivers' behavior was assessed based on velocity and lateral position, and encounters were analyzed in terms of the direction of travel as well as arrival and passing order. The following metrics were calculated:

- Drivers' distance to the narrow passage was based on the trajectories' UTM north coordinate, because the street went almost perfectly straight from south to north (Figure 3). The distance is positive before a driver reaches the center of the narrow passage and negative after the driver has passed the center of the narrow passage.
- Based on both drivers' distances to the narrow passage, the difference in distances (DiD; [23]) was calculated, which is the difference of the distances to the narrow passage of the driver passing first and the driver passing second. DiD is positive when the driver passing first is closer to the narrow passage than the driver passing second, and negative when the driver passing second is closer to the narrow passage than the driver passing first.
- Based on both drivers' time to arrival (TTA; distance to the narrow passage divided by velocity), the difference in TTAs (DiTTA) was calculated. Similar to DiD, DiTTA is positive when the driver passing first is supposed to arrive before the other driver and negative when the driver passing second is supposed to arrive before the driver passing first.
- The approaching phase of a driver was defined as the distance between 25 and 0 m to the narrow passage.
- A classification of arrival order was based on both the minimum DiD and the minimum DiTTA. For both DiD and DiTTA, the minimum was calculated while the driver passing first was in the approaching phase. If the minimum was negative, the driver passing second was said to arrive first; when the minimum was positive, the driver passing first was said to arrive first.

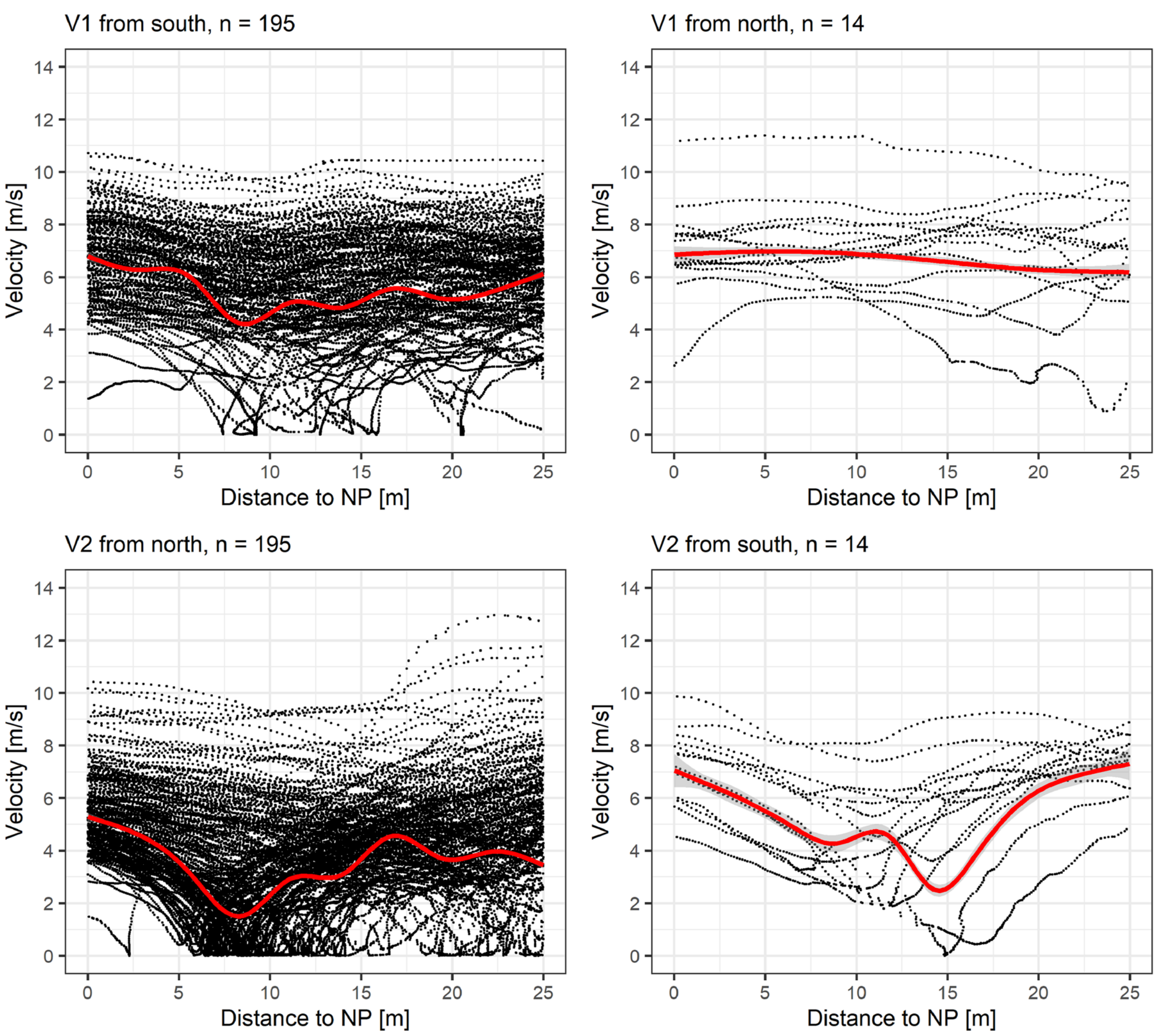

Figure 4: Velocity over distance to the narrow passage (NP) of the driver passing first (V1, top) and second (V2, bottom) divided by the direction of travel. The red lines represent the smoothed data (smoothing was based on local polynomial regression fitting).

3 Results

In a first step, the $n = 209$ encounters were analyzed in terms of direction of travel and approaching behavior, considering the drivers' passing order. With respect to the direction of travel it was found that the driver who passed the narrow passage first came from the south in 195 cases and from the north in only 14 cases. The approaching behavior of the driver passing second was characterized by deceleration and a lateral movement to the edge of the road; the driver passing first showed smaller deceleration or maintained speed (Figures 4 and 5).

In a second step, drivers' arrival order was analyzed to investigate the presence of informal rules. The interaction plots in Figure 6 show that the driver passing first was not always closer to the narrow passage than the driver passing second (data points above the red diagonal). For the n = 195 encounters, in which the driver passing first came from the south, the drivers' arrival order was classified based on DiD and DiTTA (see Methods). Figure 7 shows that regardless of minimum DiD and minimum DiTTA, in approximately one-third of the encounters, the driver passing first is classified as arriving second (corresponding to a negative minimum). It was further calculated at which distance to the narrow passage the driver passing first was always ahead of the driver passing second (both in terms of distance and TTA; Figure 8). This distance was called "zerocrossing", because DiD and DiTTA are always positive after the driver passing first has reached this distance. Figure 8 shows that in some encounters, the driver passing second was ahead of the driver passing first until close to the narrow passage.

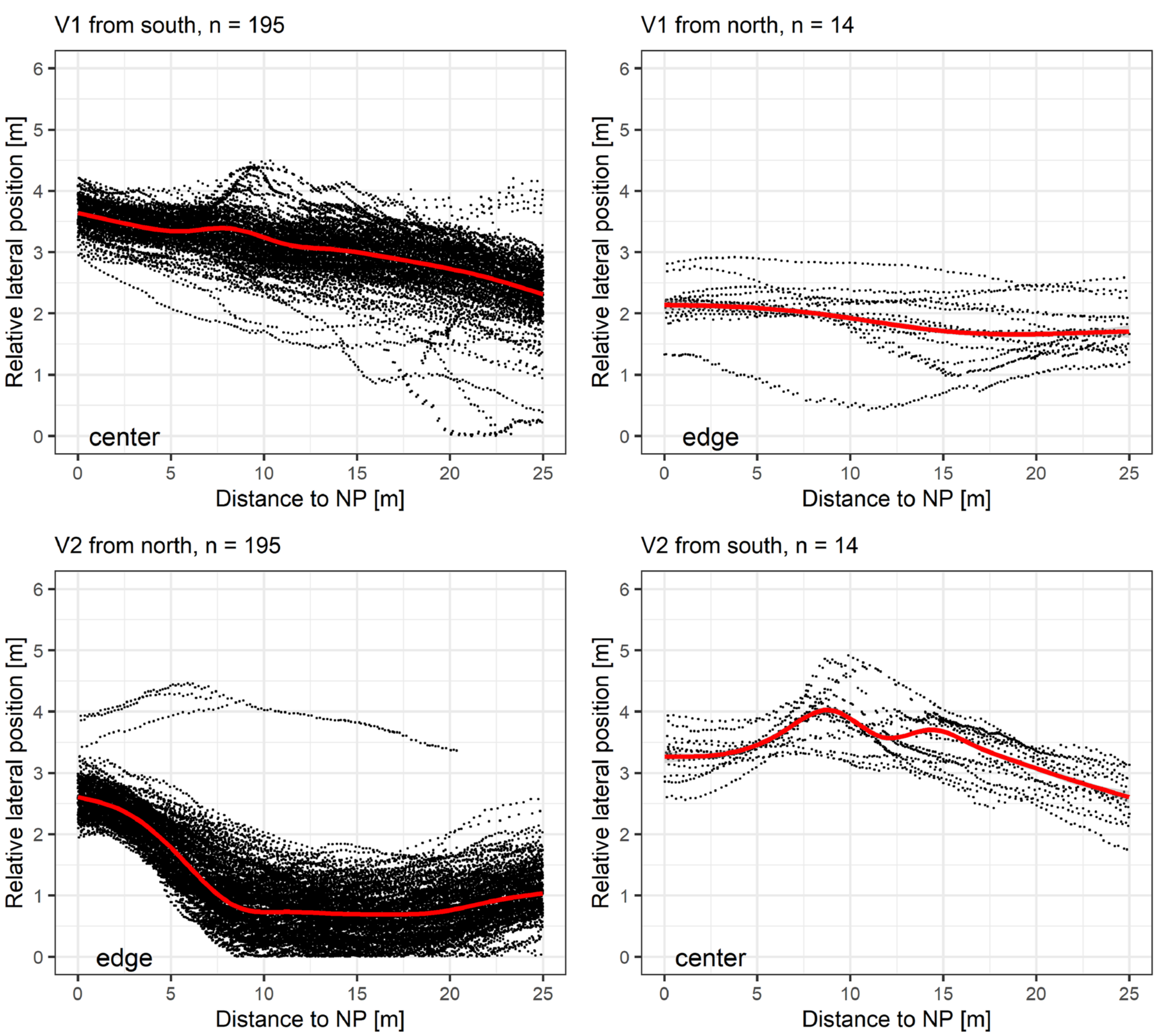

Figure 5: Lateral position over distance to the narrow passage (NP) of the driver passing first (V1, top) and second (V2, bottom) divided by the direction of travel. The red lines represent the smoothed data (smoothing was based on local polynomial regression fitting). Center, center of the street, i.e., left to the direction of travel; edge, edge of the street, i.e., right to the direction of travel.

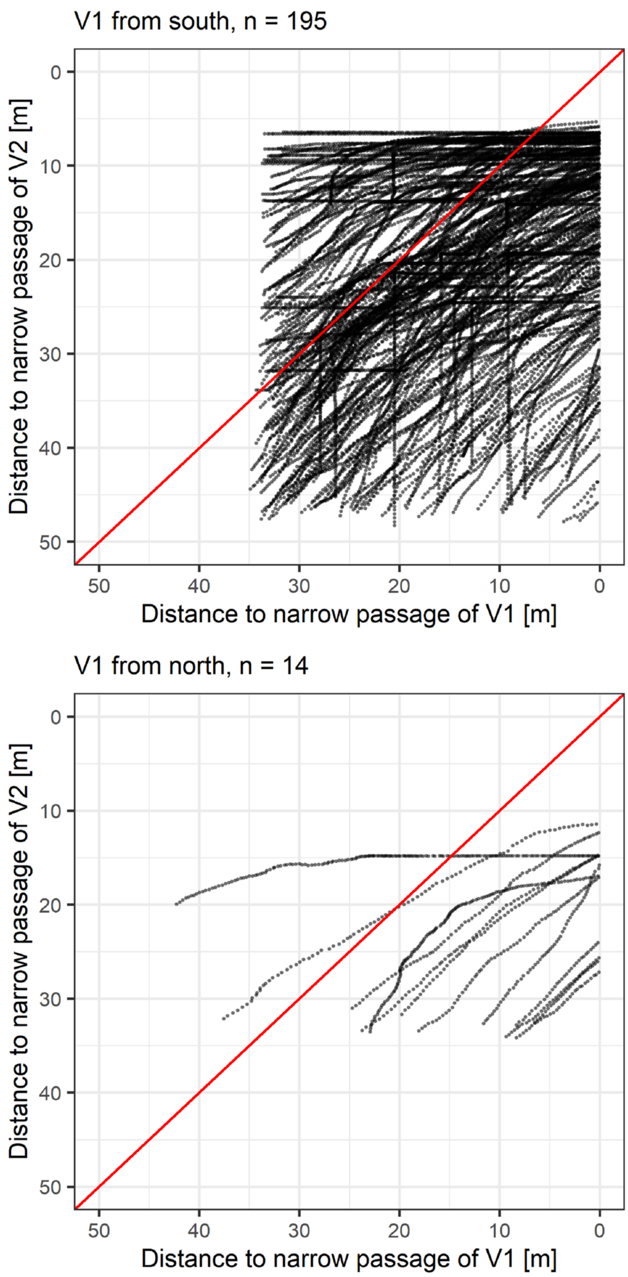

Figure 6: Interaction plots of encounters in which the driver passing first (V1) came from the south (top) and north (bottom). The red line symbolizes an encounter in which both drivers are always at the same distance to the narrow passage.

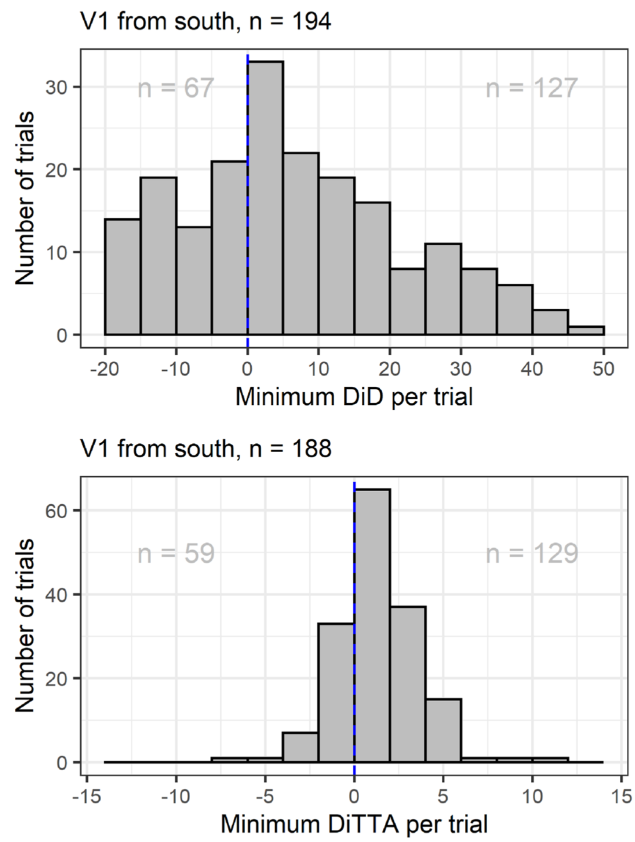

Figure 7: Histogram of minimum DiD (top) and minimum DiTTA. Both metrics were used to estimate drivers' arrival order. The driver passing first is said to arrive first if minimum DiD/DiTTA is positive (grey numbers on the right), and to arrive second if negative (grey numbers on the left).

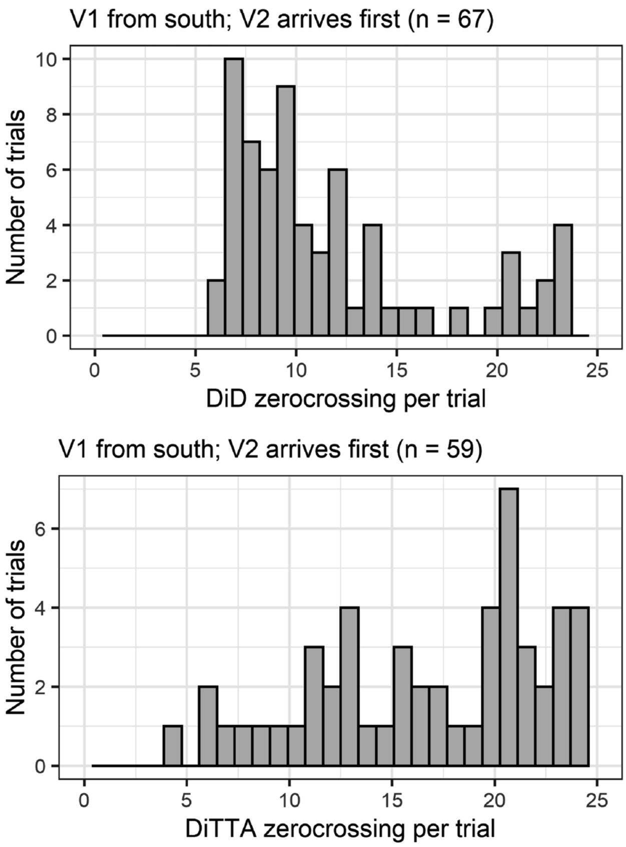

Figure 8: Histogram of every encounters' smallest distance to the narrow passage of V1 before V1 is always closer to the narrow passage than V2 (for trials in which V2 was classified to arrive first), based on DiD (top) and DiTTA (bottom).

4 Discussion

Based on trajectory data, drivers' behavior when encountering a two-sided narrow passage from opposite directions was studied by focusing on the drivers' arrival and passing order. With respect to who will pass first, an effect of direction was found: Drivers coming from the south passed first in over 90% of the analyzed encounters ($n = 209$). For these encounters, the driver passing first was not always the driver arriving first both in terms of distance and time to arrival. Accordingly, the informal rule of "first come, first pass" [16] does not seem to apply at this particular location, but rather the informal rule of "priority for the driver from the south" seems to have evolved at this narrow passage [11]. The reason for the development of this rule could be the right-before-left intersection next to the narrow passage, which influences the behavior of the drivers coming from the north in particular. It could be hypothesized, for example, that drivers from the north have to decelerate because of the right-before-left intersection, and that drivers from the south interpret this deceleration as a signal for them to pass first. Another possible explanation could be that drivers from the north choose to pass the narrow passage second because they have more room to swerve. The exact factors, e.g., speed differences, availability of road space or intrinsic motives, that led to the development and consolidation of this informal rule need to be addressed in further research. It is also necessary to investigate whether other road narrowings are characterized by different informal rules and how representative the observed road narrowing is.

The approaching behavior of the driver passing second was found to be more defensive (lower velocities and a lateral movement to the edge of the road) than the behavior of the driver passing first. This is consistent with the findings of other traffic observations [15–17]. However, the trajectory data cannot be used to explain why a particular behavior was exhibited. The driver passing second could, for example, have braked (a) to give right of way to a vehicle possibly coming from the right, (b) in reaction to offensive behavior of an oncoming (e.g., faster, larger) vehicle, or (c) to cooperate, i.e., to proactively offer the oncoming driver to pass the narrow passage first. In order to explain the observed behavior, information about the driver's intentions is required. Collecting this information in the context of a traffic observation can be very complex and time-consuming. Instead, (experimental) driving simulator studies or studies on a test field would be suitable.

The classification of arrival order based on DiD and DiTTA offers the advantage of not only considering one specific distance to the narrow passage [16] but a broader area to classify who arrived first. However, this area has to be defined, and further research is needed to find the area at which the oncoming driver is considered relevant. In addition, it has to be investigated whether human drivers base their arrival order estimation only on distance or also take the oncoming driver's velocity into account.

With regard to the method used, i.e. trajectory-based traffic observation, it can be emphasized that the behavior of road users can be described in more detail with respect to the spatial and temporal occurrence of specific behaviors (e.g., deceleration) and to the temporal-spatial relationship of road users compared to on-site or video-based traffic observations. However, explicit communication signals (e.g., flashing lights and turn signals) can only be captured by the latter methods. In addition, real-world data are often characterized by a great variance in observed behavior, which requires a pre-selection of encounters and bears the risk of over- or under-interpreting certain factors. The present work also shows that some localities are characterized by informal traffic rules. Accordingly, these are best identified in advance to ensure that the observational data can actually be used to answer the research questions of interest. The finding of an informal traffic rule further underlines the importance of observations of real traffic to reveal the peculiarities in our current traffic system. In any case, it can be emphasized that the data obtained by means of trajectory-based traffic observation enable the exploratory analysis of a research object and the extraction of further research questions and hypotheses.

5 Conclusions

The exploratory analysis presented highlights the importance of traffic observations in developing an understanding of human driving behavior. Traffic observations, as shown here, can reveal open research questions and hypotheses and stimulate further research accordingly. Specifically, the present work shows that for the specific narrow passage studied the informal rule of “first come, first pass” does not seem to apply, but priority for a specific direction of travel has become the dominating informal rule. The reasons for the development and consolidation of this informal rule must be investigated in further studies. However, from the presented analysis it can be concluded that different informal rules might influence human drivers’ interaction behavior. The development of well-accepted autonomous vehicles should therefore consider informal traffic rules to ensure safe and efficient encounters between human drivers and autonomous vehicles.

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Bionotes

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