Measuring Pedestrians' Gap Acceptance when Interacting with Vehicles

A Human Gait Oriented Approach

Nina Theobald[0000-0002-5509-8274], Philip Joisten[0000-0001-8390-7588], and Bettina Abendroth[0000-0003-4431-4661]

Technical University of Darmstadt, Department of Mechanical Engineering, Institute of Ergonomics and Human Factors, Otto-Berndt-Straße 2, 64287 Darmstadt, Germany
{nina.theobald,philip.joisten,bettina.abendroth}@tu-darmstadt.de

Abstract. A significant variable describing the pedestrians' behavior when interacting with vehicles is gap acceptance, which is the pedestrians' choice of temporal and spatial gaps when crossing in front of vehicles. After a review of relevant approaches to measure gap acceptance used in studies, this paper presents a novel approach, which is suitable for the usage in field experiments and allows a natural crossing behavior of subjects. In particular, following a detailed analysis of forces exerted during human gait, an algorithm was developed that is capable of identifying the accurate temporal point at which subjects start crossing as the basis for calculating gap acceptance. Pretest results show the system's stability and reliability as well as the gait algorithm's robustness in determining the correct gap acceptance value. The human gait oriented approach can serve as a basis for designing interaction processes between pedestrians and automated vehicles that are a focus of current research efforts.

Keywords: Gap Acceptance, Pedestrian, Vehicle, Human Gait.

1 Introduction

In the European Union, more than 51,000 pedestrians died between 2011 and 2018, and more than 30,000 pedestrians were seriously injured in 2018 [1]. Due to the frequent interaction between pedestrians and motorized traffic in cities, 70 % of all pedestrian deaths in 2017 occurred on urban roads [1]. Pedestrian behavior in interaction with vehicles has therefore long been a subject of investigation in traffic research [2]. In view of increasing urbanization and the development of automated vehicles, this research area is once again gaining relevance.

In order to study the interaction between vehicles and pedestrians, different measures have been developed and applied [3]. Even though perception and attitude have been shown to be important determinants of people's behavior and are widely investigated in pedestrian behavior studies [4], there is a potential discrepancy between stated perceptions or attitudes and actual behaviors [3, 5]. A significant behavioral variable describing pedestrians' interaction behavior with vehicles and opera-

https://doi.org/10.1007/978-3-031-06394-7_33

tionalizing the construct of safety is gap acceptance [6]. Gap acceptance is the pedestrians' choice of the temporal and spatial gap when crossing in front of an approaching vehicle [7] and is usually defined and measured by the last acceptable start of crossing by pedestrians [6].

In this paper, an approach for measuring pedestrians' gap acceptance is introduced, which builds on considerations based on an analysis of currently used measurement approaches and improves them through an orientation on the human gait pattern.

2 Gap Acceptance Measurement Approaches

To measure pedestrians' gap acceptance, different approaches exist. With regard to the research environment, some measurement approaches are applied in field experiments, while some others are used in laboratory settings with monitor- and virtual reality-based representations of the investigated traffic scenario [5]. On the one hand, measurement approaches used in laboratory settings benefit from the advantages of a high level of control of confounding factors and test conditions as well as the manipulations of variables as crucial requirements for testing hypotheses and answering formulated research questions [6, 8]. Moreover, these studies enable a simple and cheap proof-of-concept validation [5]. On the other hand, with implications for gap acceptance, some studies show significant differences between human judgments, crossing decisions and strategies in real and virtual environments [9]. The different field of view, ambient noise as well as embodied perception in real life seem to influence the subjects' decision [6]. While virtual representations of robots are sufficient and ecologically valid when perceptions and attitudes are of main interest, physically embodied robots are required if affective or behavioral outcomes are of primary concern [10]. Furthermore, since crossing in laboratory studies ensures subjects' safety and therefore does not pose any risks in terms of physical harm, subjects might behave in a more risk-taking manner compared to real life situations reducing the ecological validity of evaluations [9]. Given the literature's postulated need for real-world interactions in behavioral research [5], testing under controllable but more naturalistic conditions with a physically embodied presentation of the vehicle that allows for direct interaction and live observation is needed to validate the gap acceptance results.

Moreover, the measurement approaches require subjects to perform different tasks with movements corresponding to varying degrees to the natural behavior of crossing pedestrians. In some of those approaches, subjects are instructed to indicate gap acceptance by verbal expression, e.g. shouting [11, 12]. Studies show that actual crossing behavior differs from a verbally expressed crossing intention and people appear to distinguish between a vision for perceptual purposes and a vision for action [9, 13, 14]. Therefore, purely verbal judgments might not be appropriate to replace action-based evaluations in street crossing tests [9, 14]. Some other approaches require subjects' upper extremity motion by pressing a defined key or a button on a handheld device [6, 15]. However, this requires subjects to perform an additional atypical upper extremity motion not necessarily performed during real road crossings. With regard to the subjects' stationary position, studies note that merely standing still had negative effects as natural and intuitive body movements are an integral part of the perceptual process [13–15]. This shortcoming is overcome by approaches that rely on lower extremity movements, such as walking forward or backward [8, 9, 11, 12, 16]. Yet, instructing subjects to step back as soon as they no longer feel safe requires subjects to move in a direction opposite to their natural path when crossing [9]. The procedure of instructing subjects to indicate their crossing decision by taking two steps towards the curb suffers from a perceptual bias because subjects judge the traffic situation from a location several steps away from the usual place for crossing [11, 12]. Moreover, user-worn hardware components to capture movements of subjects, such as the head-mounted display or the motion-capture suit in virtual reality studies, could cause discomfort and limit perceived freedom of natural movement, thus affecting user performance [9, 17]. Hence, there is the need for a gap acceptance measurement approach that allows for pedestrians' usual perceptual perspective of the traffic situation and builds on pedestrians' natural motion for crossing initiation not constrained by hardware components.

Furthermore, the comparability of the gap acceptance values captured by the different measurement approaches is hampered by the use of different trigger points for measurement start and by different levels of automatic recording. Even though observation is a data collection method widely used in pedestrian behavior studies and also for measuring the pedestrians' gap acceptance, this approach suffers from an observer bias and a variability in the recording [3]. In order to prevent a possible influence of a third person, subjects are equipped with an input device (e.g. handheld device or keyboard) [6, 15] or sensors are installed that capture a subject's movement execution (e.g. photoelectric barrier, invisible virtual plane, force sensors) [8, 9, 16]. However, because the execution of the different tasks required from subjects by the different measurement approaches takes different amounts of time, the gap acceptance values may differ. In particular, by building on subjects' movement execution, the approaches use different moments in movement execution as algorithmic trigger points of sensors. Since gap acceptance is defined as pedestrians' decision for a gap, an observer-independent, more detailed measurement approach is needed that captures the time point when pedestrians have completed decision making and are physically activated to begin crossing, which is then used for calculating the chosen gap.

3 Human Gait Oriented Measurement Approach

The measurement approach of gap acceptance presented in this paper takes into account the aforementioned design considerations. Thereby, the concept invented by Faas et al. [8, 16] served as a basis, which only requires subjects to perform the natural behavior of a step forward on the road to indicate crossing initiation and uses force sensors installed on the ground at the subjects' start position that allow a detailed analysis of the force exerted by each foot. An accurate measurement in accordance with the targeted behavioral variable of gap acceptance requires an algorithm oriented to the vertical forces of the feet during human gait. The gait cycle based on a double step describing the sequence of walking from the first ground contact of one foot to the renewed ground contact of the same foot is divided into a stance phase and a swing phase [18]. The swing phase is the period during which the foot is not in contact with the ground [18]. The stance phase is the period during which the foot is in contact with the ground [18]. However, in case of pedestrians deciding whether and when to cross in front of approaching vehicles, they usually first observe the traffic situation while standing on both feet and then start crossing by moving one foot forward. With both feet in contact with the ground in the beginning, the so-called double stance phase [19] is enclosed within the time stamps t_1 and t_2 in **Fig. 1**. At the beginning of the double stance phase (t_1) both feet are on the ground corresponding to the situation of a pedestrian observing and evaluating the traffic situation in order to make a crossing decision. Once the decision to cross is made, the pedestrian initiates the crossing by moving forward with one foot (in the following called "moving foot") and shifting body weight from this foot to the other foot, which thereby exerts increasingly more force on the ground (in the following called "power foot"). Thus, the force of the power foot increases while the force of the moving foot decreases. The double stance phase is completed (t_2) when the moving foot swings, i.e., has no contact with the ground at all and therefore exerts a force of zero, while the power foot reaches the maximum force exerted on the ground.

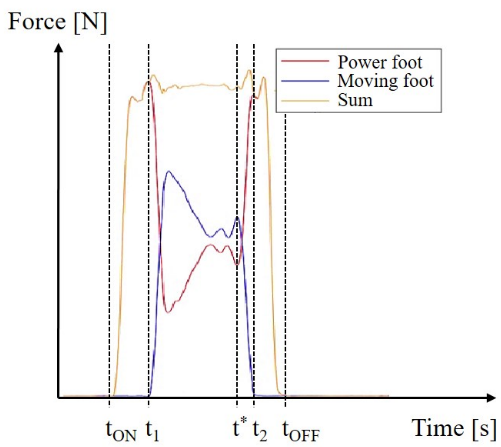

Fig. 1. Vertical forces of moving and power foot in the process of stepping on (t_{ON}) and off (t_{OFF}) the force sensors, i.e., start position. Start and end of the double stance phase are marked with the time stamps t_1 and t_2. The calculated time point of crossing initiation is marked with t^*.

Therefore, the time point when subjects start to step forward, i.e., to leave the force sensors, corresponds to the last local maximum before the recorded force of the moving foot decreases respectively the last local minimum before the recorded force of the power foot increases and is used in the approach followed here (t^*). In contrast, the algorithm by Faas et al. [8, 16] uses the time point when one foot was removed completely from respectively a zero force of either foot was registered by the force sensors to measure gap acceptance (t_2). Corresponding to the end of the double stance phase, this implies some delay with respect to the time point of crossing initiation. To also avoid the error of this measurement system reporting a crossing even though a subject only lifted one foot and put it down again while remaining in the same place, the algorithm developed here does not start identifying the last force peak respectively valley until the sum of the recorded forces by both feet is zero (t_{OFF}).

To calculate the gap acceptance variable as the remaining time or distance between the pedestrian and the approaching vehicle, for the absolute time point of crossing initiation as determined by the algorithm, the associated distance of the vehicle must be identified. With the respective vehicle speed, the distance accepted by the pedestrian can then also be specified in time units. So far, the measurement approach of Faas et al. [8, 16] has only been designed for video-based studies. In order to capture the gap acceptance variable by subjects interacting with a physically embodied representation of the vehicle in field experiments, the distance between the subject and the approaching vehicle as a function of time can be measured by using a LIDAR sensor, for example.

4 Pretest Study and Results

A pretest was conducted in a field experiment to check the measurement system's stability and reliability as well as to verify the robustness of the gait algorithm to determine the gap acceptance value. After hardware and software were implemented, the system's performance was tested with movements that deviate from the actual instructed behavior, but could well be exhibited by subjects. In the present scope of investigation, subjects are instructed to cross the street in front of an approaching vehicle at the last time when they still feel safe by taking a step forward. However, in the decision-making process, they may hesitate which could be expressed, for example, in a shift of weight causing them to lift one heel without ultimately taking a step. Thus, extreme tests simulating four different possible behaviors of the subjects were used: 1) one foot up and down - the other foot does not move; 2) one foot forward and back - the other foot does not move (see **Fig. 2**); 3) lift one heel - the other foot does not move; 4) lift and lower both heels. With continuous data plots of the force sensors with smooth curves and no jumps mapping the predefined leg movements, the pretest results indicate good stability and reliability of the force sensors' data recording. Most importantly, the implemented algorithm proves to not misclassify a deviant behavior of the subjects as a crossing initiation, but to start determining the time point of crossing initiation backwards only when the sum of the recorded forces of both feet is zero, i.e., the crossing initiation is successfully completed.

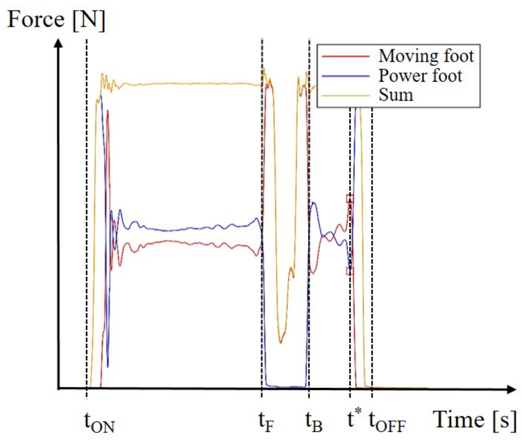

Fig. 2. Force curves of the pretest scenario "one foot forward (t_F) and back (t_B) - the other foot does not move". The algorithm does not start calculating the time point of crossing initiation before the subject has stepped fully forward and the sum of the recorded forces by both feet is zero (t_{OFF}). The calculated time point of crossing initiation is marked with red squares (t^*).

5 Discussion and Conclusion

In this paper a gap acceptance measurement approach was presented that identifies the accurate temporal or spatial point at which pedestrians initiate crossing in front of an approaching vehicle through an algorithm analyzing the human gait pattern. Once the subject has stepped completely forward and the sum of forces of both feet detected by sensors installed on the ground at the subject's start position is zero, the algorithm calculates backwards the time point when the recorded force of the moving respectively power foot starts to decrease respectively increase. This time point is then used for calculating the remaining gap between pedestrian and vehicle. Other approaches, such as taking a recorded force of zero of one foot as a basis for calculating the gap acceptance value, lead to a heuristic approximation because lifting of one foot is an insufficient indication of crossing initiation and it takes on average 0.537 s [20] for a foot to fully leave the force sensors. At a driving speed of 20 km/h this time interval results in an error of approximately 2.983 m. Thus, the algorithm proposed here provides gap acceptance values that are more accurate. Moreover, since the measurement approach is built on pedestrians' natural crossing behavior and can be used not only in laboratory but also in natural yet controllable research settings, the results derived from this measurement setting can be seen as highly representative for the actual crossing behavior of pedestrians. Thus, these accurate and representative gap acceptance values can serve as input for further research, such as deriving driving strategy algorithms (e.g. communication initiation) for automated vehicles.

However, despite an accurate operation on the software side, unavoidable frequency and accuracy errors in the hardware structure should be mentioned. Further, by asking subjects to step forward at the last moment when they still feel safe, crossing is initiated from a standing position after having observed the traffic [21]. In contrast, crossing decisions are made daily while walking and without prolonged observation of approaching vehicles. In addition, the measurement approach presented here only captures a single choice in form of the smallest gap that pedestrians just accept.

With the qualitative comparison of existing gap acceptance measurement solutions and an exemplary demonstration of quantitative deviations, this paper draws attention to differences of the measurement approaches and resulting gap acceptance measures. In order to drive standardization efforts for measuring the behavioral variable gap acceptance, based on a systematic literature review, available methods should be systematically and quantitatively compared. Since automated vehicles enter our daily and working lives not only for passenger transportation but also as working machines, the detailed analysis of variables measuring the behavior of humans interacting with vehicles, such as the gap acceptance measure considered here, becomes increasingly important for the development of human-centered algorithms for automated vehicles.

Acknowledgments. This research was funded by research project "Campus FreeCity – real lab for the research of a networked fleet of modular robot vehicles", carried out at the request of the Federal Ministry for Digital and Transport (BMVI), under research project No. 45KI15I091. The authors are solely responsible for the content and thank Xu Liang, Zhiyuan Xiao, Peng Yan, Jiangdong Zhao for their assistance in developing and implementing the gap acceptance measurement approach.

References

1. Adminaité-Fodor, D., Jost, G.: How safe is walking and cycling in Europe? European Transport Safety Council, PIN Flash Report 38, https://etsc.eu/how-safe-is-walking-and-cycling-in-europe-pin-flash-38/ (2020).
2. Petzoldt, T.: On the relationship between pedestrian gap acceptance and time to arrival estimates. Accident Analysis and Prevention 72, 127–133 (2014). https://doi.org/10.1016/j.aap.2014.06.019
3. Rasouli, A., Tsotsos, J.K.: Autonomous Vehicles That Interact With Pedestrians: A Survey of Theory and Practice. IEEE Transactions on Intelligent Transportation Systems 21(3), 900–918 (2020). https://doi.org/10.1109/TITS.2019.2901817
4. Hafeez, F., Ullah Sheikh, U., Mas'ud, A.A., Al-Shammari, S., Hamid, M., Azhar, A.: Application of the Theory of Planned Behavior in Autonomous Vehicle-Pedestrian Interaction. Applied Sciences 12(5), 2574, 1–21 (2022). https://doi.org/10.3390/app12052574
5. Frison, A.-K., Forster, Y., Wintersberger, P., Geisel, V., Riener, A.: Where We Come from and Where We Are Going: A Systematic Review of Human Factors Research in Driving Automation. Applied Sciences 10(24), 8914, 1–36 (2020). https://doi.org/10.3390/app10248914
6. Beggiato, M., Witzlack, C., Springer, S., Krems, J.: The Right Moment for Braking as Informal Communication Signal Between Automated Vehicles and Pedestrians in Crossing Situations. In: Stanton, N.A. (ed.) Advances in Human Aspects of Transportation: Proceedings of the AHFE 2017 International Conference on Human Factors in Transportation, vol. 597, pp. 1072–1081. Springer International Publishing, Cham (2018). https://doi.org/10.1007/978-3-319-60441-1_101

7. Brewer, M.A., Fitzpatrick, K., Whitacre, J.A., Lord, D.: Exploration of Pedestrian Gap-Acceptance Behavior at Selected Locations. Transportation Research Record 1982(1), 132–140 (2006). https://doi.org/10.1177/0361198106198200117
8. Faas, S.M., Mattes, S., Kao, A.C., Baumann, M.: Efficient Paradigm to Measure Street-Crossing Onset Time of Pedestrians in Video-Based Interactions with Vehicles. Information 11(7), 360, 1–21 (2020). https://doi.org/10.3390/info11070360
9. Feldstein, I.T., Dyszak, G.N.: Road crossing decisions in real and virtual environments: A comparative study on simulator validity. Accident Analysis and Prevention 137, 105356, 1–12 (2020). https://doi.org/10.1016/j.aap.2019.105356
10. Roesler, E., Manzey, D., Onnasch, L.: A meta-analysis on the effectiveness of anthropomorphism in human-robot interaction. Science Robotics 6(58), 1–31 (2021). https://doi.org/10.1126/scirobotics.abj5425
11. Schwebel, D.C., Gaines, J., Severson, J.: Validation of virtual reality as a tool to understand and prevent child pedestrian injury. Accident Analysis and Prevention 40(4), 1394–1400 (2008). https://doi.org/10.1016/j.aap.2008.03.005
12. Demetre, J.D., Lee, D.N., Pitcairn, T.K., Grieve, R., Thomson, J.A., Ampofo-Boateng, K.: Errors in young children's decisions about traffic gaps: Experiments with road-side simulations. British Journal of Psychology 83(2), 189–202 (1992). https://doi.org/10.1111/j.2044-8295.1992.tb02434.x
13. Goodale, M.A., Milner, A.D.: Separate visual pathways for perception and action. Trends in Neurosciences 15(1), 20–25 (1992). https://doi.org/10.1016/0166-2236(92)90344-8
14. Te Velde, A.F., van der Kamp, J., Barela, J.A., Savelsbergh, G.J.P.: Visual timing and adaptive behavior in a road-crossing simulation study. Accident Analysis and Prevention 37(3), 399–406 (2005). https://doi.org/10.1016/j.aap.2004.12.002
15. De Clercq, K., Dietrich, A., Núñez Velasco, J.P., De Winter, J., Happee, R.: External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions. Human Factors 61(8), 1353–1370 (2019). https://doi.org/10.1177/0018720819836343
16. Faas, S.M., Kraus, J., Schoenhals, A., Baumann, M.: Calibrating Pedestrians' Trust in Automated Vehicles. In: Kitamura, Y., Quigley, A., Isbister, K., Igarashi, T., Bjørn, P., Drucker, S. (eds.) CHI '21: CHI Conference on Human Factors in Computing Systems, pp. 1–17. ACM, New York, USA (2021). https://doi.org/10.1145/3411764.3445738
17. Willemsen, P., Colton, M.B., Creem-Regehr, S.H., Thompson, W.B.: The effects of head-mounted display mechanics on distance judgments in virtual environments. In: APGV '04: Proceedings of the 1st Symposium on Applied perception in graphics and visualization, pp. 35–38. ACM, New York, USA (2004). https://doi.org/10.1145/1012551.1012558
18. Whittle, M.W.: Gait analysis. In: McLatchie, G.R., Lennox, C.M.E. (eds.) The Soft Tissues - Trauma and Sports Injuries, pp. 187–199. Butterworth-Heinemann (1993). https://doi.org/10.1016/B978-0-7506-0170-2.50017-0
19. Claeys, R.: The analysis of ground reaction forces in pathological gait secondary to disorders of the foot. International Orthopaedics 7(2), 113–119 (1983). https://doi.org/10.1007/BF00266460
20. Brunt, D., Lafferty, M.J., Mckeon, A., Goode, B., Mulhausen, C., Polk, P.: Invariant characteristics of gait initiation. American Journal of Physical Medicine & Rehabilitation 70(4), 206–212 (1991). https://doi.org/10.1097/00002060-199108000-00009
21. Dey, D., Martens, M., Eggen, B., Terken, J.: Pedestrian road-crossing willingness as a function of vehicle automation, external appearance, and driving behaviour. Transportation Research Part F: Traffic Psychology and Behaviour 65, 191–205 (2019). https://doi.org/10.1016/j.trf.2019.07.027