Exposé für das Promotionsvorhaben: Dynamic Interactions between Multiple Pedestrians and Automated Vehicles in Shared Spaces

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Abstract: This doctoral thesis primarily aims to solve the problem of automated vehicles interacting with multiple pedestrians in an unsignalized traffic situation. At the end of this research, driving strategy and communication concepts will be developed for automated vehicles to promote the safety and efficiency of interactions in shared spaces involving multiple pedestrians. Several methods will be applied in this research: 1) Traffic observation, 2) Virtual reality study, and 3) Driving simulator study.

Keywords: Automated driving, Vulnerable road users, Multi-agent interaction, Shared Space

1. Topic

Shared space is an urban design approach that minimizes the segregation between modes of road users. By removing features such as road surface markings and traffic lights indicating clear right-of-way, drivers must be more cautious while driving, thus reducing their speed and paying more attention to other Vulnerable Road Users (VRUs) to improve traffic safety and efficiency (“Shared space” 2023). However, the presence of multiple pedestrians may lead to reciprocal affection and thus lead to pedestrians’ misbehavior (Faria et al. 2010; Jiang et al. 2018). This could potentially turn a driver-dominated multi-agent scenario into a pedestrian-dominated Shared Space.

According to Fratini et al. (2023), the decision-making process of road users is closely related to the complexity of the traffic environment. In multi-agent Shared Spaces, because of the unclear road priority, the decision-making process of drivers heavily relies on dynamic social interactions with multiple road users, especially pedestrians, such as eye contact and gestures for the negotiation about the right-of-way (Song et al. 2018).

Shortly, when Automated Vehicles (AV) gradually play a more critical role in the traffic environment, drivers will take fewer driving tasks such as observing the surrounding traffic situation, communicating with other road users, and making maneuver decisions. Therefore, in this context, a significant challenge encountered in the widespread adoption of AVs is maintaining safe and efficient interaction between AVs and other road users.

Many researchers and automobile manufacturers are making continuous attempts to solve this difficulty. Firstly, the development of V2V technology ensures instant communication between vehicles. Secondly, improving sensor technology around the AV promotes an accurate detection and prediction of VRUs and their intentions for path and maneuver planning. Furthermore, AVs' external Human Machine Interfaces (eHMIs) and dynamic Human Machine Interfaces (dHMIs) have shown potential in replacing the informal communication of human drivers (Hensch et al. 2020; Merat et al. 2018).

However, in scenarios involving multiple agents, eHMI concepts may lead to worse performance while communicating with VRUs, potentially causing confusion and danger (Dey et al. 2021; Hübner et al. 2022). Few studies have investigated interactions and communications between AV and multiple pedestrians. In multi-agent scenarios, especially in areas with a higher VRU density, such as Shared Spaces, AV might have difficulty determining the correct interaction partner or interaction partners. Therefore, this research aims to design AVs' driving strategy and communication concepts, promoting safety and efficiency in Shared Spaces involving multiple VRUs.

2. Theoretic Background

According to Markkula et al. (2020), an interaction in traffic is a situation where the behavior of at least two road users can be interpreted as being influenced by the possibility that they both intend to occupy the same region of space at the same time in the near future. Therefore, to classify this research's full scope, several aspects must be considered. The first aspect is the scenario in which interactions occur, in this research, a Shared Space involving multiple pedestrians. The second aspect is the design and studies of driving strategies and communication concepts by other researchers in order to ensure safe and efficient interactions between pedestrians and AVs.

2.1 Shared Space Involving Multiple Agents

The concept of Shared Space promotes the motion of sharing a single space by pedestrians, cyclists, and vehicles while promoting the freedom of movement for pedestrians and ensuring the connectivity of vehicular and cycle movement (Carmona et al. 2003; Gehl 2013; Jayakody et al. 2018; Kaparias et al. 2013). In Germany, according to the German Traffic Regulations (StVo), the most common types of Shared Spaces are Verkehrsberuhiger Bereich (Living Street) and Fußgänger Zone (Pedestrian Zone). These traffic areas are pedestrian-dominated, with drivers responsible for ensuring pedestrians' right of way.

***Figure 1**: Traffic Signals in Germany: 1) Verkehrsberuhiger Bereich (Living Street); 2) Fußgänger Zone; 3) Tempo-30-Zone; 4) Tempo-20-Zone*

However, in other traffic areas where drivers have the right of way, such as Tempo-30-Zone and Tempo-20-Zone, the presence of multiple pedestrians may lead to reciprocal affection and thus lead to pedestrians' misbehavior (Faria et al. 2010; Jiang et al. 2018). This could potentially turn such a scenario into a pedestrian-dominated Shared Space. Therefore, the majority of studies investigating the interaction between multiple pedestrians and AVs were not confined solely to Shared Spaces defined by traffic regulations but explored the interaction in unsignalized crossing situations (Dey et al. 2021; Fridman et al. 2017; Lee et al. 2022; Kalantari et al. 2023; Mahadevan et al. 2019).

2.2 Interaction in urban traffic

During the process of pedestrians crossing the street, the decision-making processes of pedestrians and drivers are dynamic and influenced by multiple factors (Rasouli & Tsotsos, 2019). Before deciding to initiate a cross, pedestrians would observe the current traffic conditions and estimate the speed and distance of the approaching vehicle and the gap between vehicles to determine whether to cross or wait. In this process, the perception, interpretation, and decision-making of pedestrians are not only influenced by individual characteristics such as age, gender, and distraction but are also significantly impacted by the surrounding physical environment. Moreover, the presence of several pedestrians has a strong influence on pedestrian crossing behavior (Kalb & Bengler 2021; Mahadevan et al. 2019; Rasouli & Tsotsos 2019). When crossing the street in a group, pedestrians tend to exhibit more risky behaviors, cross at a lower speed, and be willing to accept a smaller gap between vehicles (Rasouli & Tsotsos 2019; Sarmady et al. 2009). Additionally, individuals not belonging to a pedestrian group can influence each other, leading to a homogenization of their behaviors, for example, when crossing against a red light (Faria et al. 2010).

When interacting with pedestrians, drivers' decision-making is constrained by traffic regulations and influenced by their driving style, primarily defensive or aggressive. This differentiation can be observed in the acceptance of cooperation and speed profiles in aspects of driving behavior, such as speed and acceleration (Szumska & Jurecki 2020; Velazquez & Mouloua 2021).

2.3 Approaches

In the following part, the discussion revolves around various research methods and focuses on the interaction between multiple pedestrians and human drivers or AVs. Research on pedestrians primarily involves traffic observations and laboratory simulation studies. Compared to a simulation study, pedestrians may be less aware of their environment in a traffic observation, making it more conducive to understanding their behavior in a natural setting (Ortiz et al. 2017). Many researchers, through traffic observations, attempt to identify behavioral trends and communication methods among multiple pedestrians crossing the street (Dam et al. 2023; Kalb & Bengler 2021). The observed sites typically include city centers or university campuses, where the scenarios are either regulated Shared Spaces or temporary Shared Spaces created by the crossing behavior of multiple pedestrians. Another common method employed to study the behavior of multiple pedestrians is laboratory simulation studies, especially virtual reality (VR) studies. It creates virtual environments for interactions between multiple pedestrians and AVs by either utilizing multiple participants as pedestrians (Feng et al. 2023; Jiang et al. 2018; O'Neal et al. 2019) or introducing pre-programmed Non-Player Characters (NPCs) with specific behaviors as additional pedestrians (Dey et al. 2021; Joisten et al. 2021; Rad et al. 2020; Wilbrink et al. 2021). The objectives of these studies consist of primarily two aspects: 1) evaluate the usability of eHMI and dHMI concepts mounted on an AV (Dey et al. 2021; Feng et al. 2023; Joisten et al. 2021; Rad et al. 2020; Wilbrink et al. 2021), 2) or quantitatively analyze the mutual influence among multiple pedestrians in a relatively safe and controlled environment (Jiang et al. 2018; Koilias et al. 2020; Mahadevan 2019; O'Neal et al. 2019).

However, in the studies mentioned above, there has been limited in-depth analysis of driver behavior when interacting with multiple pedestrians. According to Fuest et al. (2018), driver behavior is a form of implicit communication that conveys intentions to pedestrians. Currently, analyses of driver behavior patterns heavily rely on recorded real traffic data and machine learning technology. Subsequently, these data are used to train decision models for AVs. However, these models often lack a focus on modeling driving strategies in the micro scenarios of drivers interacting with multiple pedestrians, and there is a deficiency in an in-depth analysis of the driver decision-making process and the underlying logic behind driving strategies.

Therefore, to ensure the safe and efficient interaction between AV and multiple pedestrians in urban traffic situations, it is imperative to employ the methods mentioned above, including qualitative traffic observations, simulation studies, and data-based modeling. Such an integrated approach leads to a more comprehensive consideration of complex traffic situations involving multiple pedestrians, facilitating the design of AV driving strategies and communication concepts that align more closely with current human driver driving styles.

3. Approach and Research Questions

The primary goal of the research is to develop recommendations and requirements on AVs to promote safety and efficiency in multi-agent Shared Spaces.

The following research questions are set based on this goal:

- RQ1. What are the decisive factors for a multi-agent scenario to transit into a Shared Space?
- RQ2. How should AVs' driving strategy be designed in multi-agent Shared Spaces?
- RQ3. How should communication concepts be designed in multi-agent Shared Spaces?

In order to determine relevant scenarios, the first step of the research is to conduct a traffic observation, aiming to find: 1) regulated Shared Spaces, which involve multiple pedestrians and consist of dynamic social interactions between road users; 2) temporary Shared Spaces, which are created because of the existence of multiple pedestrians and the social interactions between them.

The second step of the research is to conduct a VR study based on the scenarios determined after the traffic observation, involving multiple pedestrians and AVs, aiming to compare the pedestrian behaviors within these two kinds of Shared Spaces, as well as solve the RQ1 – determine the decisive factors to transit a multi-agent scenario into a temporary Shared Space.

After gathering the behavior data of multiple pedestrians in these scenarios, the following is a driving simulator study. By simulating the two kinds of Shared Spaces in a driving simulator environment, the driving strategy of human drivers could be derived through their driving behaviors in the study.

Since the driving strategy of human drivers might differ from individual driving styles, different driving strategies will be developed for the AV and evaluated in another VR study by pedestrians in order to solve RQ2.

Finally, suitable communication concepts will be designed and evaluated for specific scenarios where additional communication, in addition to driving behavior, is necessary for pedestrians in order to solve RQ3.

4. Literature

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