"Urban Cycling and Automated Vehicles"

Lutz Eichholz
Technical University Kaiserslautern,
Chair of Urban Planning
lutz.eichholz@ru.uni-kl.de

Nicolas Mellinger
Technical University Kaiserslautern,
Institute for Mobility and Transport
nicolas.mellinger@bauing.uni-kl.de

Wilko Manz
Technical University Kaiserslautern,
Institute for Mobility and Transport
wilko.manz@bauing.uni-kl.de

Abstract

This Paper aims to account chances and risks in future urban traffic systems with automated vehicles (AVs) and bicyclists. AVs have the potential to become a catalyst for urban transformation and influence how bicyclists are integrated in traffic systems. This article focuses on the possible impact of AVs on cyclist’s safety feelings, the influences of the number of traffic and how the use of public space can be changed if AVs are introduced.

The findings show that the intuitive driving style of bicyclists will be a great challenge for AVs. If many cyclists with different driving styles are on the road at the same time, the drivability of AVs is severely limited. In contrast, wider roads dominated by motor vehicles and hardly used by other road users are much more suitable for AVs. Slowing down traffic speed or building separate bicycle infrastructure are possible solutions for a better drivability in a traffic with AVs and bicyclists. The space for these changes can partly be generated by reducing parking areas. This is only possible if future traffic is organized in a way that shared vehicles, public transport and bicyclists are preferred.

To motivate more people to cycle it is important that cyclists feel safe and comfortable. To find out how cyclist’s safety feelings are in today’s traffic and how they will change in a traffic with AVs an online survey was conducted. The findings show that bicyclists feel safer if they have to interact less with motorized vehicle traffic. The lowest stress and highest safety feelings were stated by the participants for a scenario with purely AV traffic. In a mixed traffic with manually controlled vehicles and AVs, stress and uncertainty feelings seem to rise.

Keywords: automated driving, cycling safety, urban mobility, subjective safety, future mobility
Introduction

Automated vehicles (AVs) are going to transform the peaceful coexistence of means of transport in urban areas. This development has multiple effects on participants of the urban transport and the city itself. Overall, four trends can be observed: an increasing automated traffic in cities, a growing bicycle traffic due to adapted planning and social development, a technical upgrade of the vehicle fleet and a revival of the living city. These trends necessitate new concepts of planning and technic.

This is where the research project comes in. The project “Concepts for integration of bicycle traffic in future urban traffic with automated vehicles” is funded by the German Federal Ministry of Transport and Digital Infrastructure of funds to implement the National Cycling Plan.

The goal of the project is to investigate and develop solutions for the coming challenges of bicycle traffic in cities in interaction with AVs. In doing so, concerns of transport, urbanistic and technic are considered. The following lead questions are guiding our research:

- What impact do AVs have on efficient transportation and land use?
- What influences do different road types and different bicycle infrastructures have on AVs and bicyclist drivability?
- What are the cyclist’s expectations on the driving behavior of AVs?
- How does the cyclist’s subjective safety feeling change if AVs are introduced?

Essential components to answer these questions are transport-related methods as surveys and test drives to recognize and avoid conflicts between bicycles and AVs, urbanistic concepts to design cycle paths in urban areas with AVs, technical systems in AVs based machine learning to detect and predict movements of bicycles and algorithm development to track and predict trajectories of bicycles in urban infrastructure.

At the current state, different scenarios for interactions of bicycles with AVs were developed and discussed in a project related advisory board. Based on the conclusions, an online survey was designed and evaluated. Also different scenarios for urban design of bicycle paths are investigated. The outcomes of the survey evaluation and the scenarios for urban planning are presented in this paper.

Background

The state of the art in assisted and automated driving has progressed rapidly in recent years. The degree of automation is divided into five levels. At the current state, assistant systems in vehicle fleets manage to operate in level two. This means that the systems can independently perform certain driving tasks such as lane keeping or acceleration simultaneously. However, the driver has constantly to monitor the vehicle.

For the research project only, the levels three and higher are relevant. Only in this levels the driver is not responsible for the car in all situations (SAE International, 2018). This means that our research deals with technics which today are only available in test operations in certain areas.
A major challenge for AVs is to predict movements of other road users (NaWik, 2020, pp. 34–35). This is especially true for micromobility vehicles (bicycles, micro electric vehicles), whose traffic behavior is difficult to predict and individually characterized (Fairley, 2017).

Because of this, many studies predict that the higher levels of automation are first introduced in simpler areas such as highways. Areas with many different road users who have different levels of adherence to traffic rules or many ways to behave in traffic will be a major challenge (Mitteregger et al., 2020, pp. 81–84; Soteropoulos et al., 2021).

Especially the driving behavior of AVs differ fundamentally from that of bicycles. Cyclists drive intimately, sometimes like cars and sometimes like pedestrians with different rules and rule acceptance. AVs will drive defensively and strictly follow the traffic rules.

The German draft law on autonomous driving takes different suitability of AVs in different street spaces into consideration. It allows automated system to operate only in certain areas and only under the condition, that the automated system fully obeys the traffic law (Bundesregierung, 2021).

To achieve more sustainable transportation, livable cities and healthier people, it is desirable that the proportion of cyclists increases. A low subjective safety feeling is a key barrier to motivating people to cycle (Hull and O’Holleran, 2014). That cyclists feel safer if they have to interact less with

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**Figure 1: Levels of driving automation (SAE International, 2018)**

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motorized vehicle traffic is confirmed by many studies (ADFC, 2018; FixMyCity, 2020; ADAC, 2021; Nazemi et al., 2021).

According to that, there are many examples of how separate infrastructure has significantly increased the share of cyclists (Pucher and Buehler, 2016; ADFC, 2019). In particular, during the Covid pandemic, cities that expanded their network of separated bike lanes were able to achieve rapid increases in bicycle traffic (Buehler and Pucher, 2021). For AVs, a major advantage of separated bicycle infrastructure is that their drivability is much easier in these streets (Heinrichs, 2015; Taub, 2019; Eichholz and Kurth, 2021).

Impact on the numbers of traffic through AVs

The extent to which public space and road space can be redesigned after the introduction of AVs depends on whether increased or decreased motorized individual traffic is expected in the future. Many studies dealing with this topic currently assume that individual traffic will increase with increasing automation (Heinrichs, 2015; Botello et al., 2019; Lee et al., 2019; Weert and Ruhrort, 2019; Mitteregger et al., 2020, p. 37). Reasons for this include a higher demand from newly acquired user groups (e.g., people with driving impairments), increased attractiveness of individual transportation, and empty runs of AVs in future scenarios (Heinrichs, 2015, 2017; Botello et al., 2019).

With traffic purely consisting of AVs, urban traffic areas would theoretically have higher capacities than with manually controlled vehicles. The reasons are faster reaction times when starting up and driving in a convoy or dense driving with little distance between vehicles (Beckmann and Sammer, 2016; Rothfuchs and Engler, 2018).

One drawback is that AVs can only apply these advantages if they do not have to interact with manually controlled vehicles and other road users. This would require the creation of new infrastructure over a large area. An alternative would be to exclude other road users in certain areas, which would mean a return to the principles of the car-oriented city planning.

Some studies estimate savings of up to 90 % of stationary traffic when AVs are used by several users at the same time (Rothfuchs and Engler, 2018; Ritz, 2018; Lemmer, 2019; Mitteregger et al., 2020, p. 74). Other researchers expect significantly less savings (Alessandrini et al., 2015; Skinner and Bidwell, 2016). It should be noted that significant reductions in stationary traffic are not predicted in the various studies until there are high percentages of level four and five vehicles with high occupancy rates. Even if level four systems would be introduced this year, it will take decades until a majority of cars are equipped with these systems (ISI, 2019; UDV, 2020, p. 4).

The space that AVs could save in cities relates primarily to parking areas. How much space can be made available for other uses through the conversion of parking space is difficult to predict. There are a few studies that show that about 15 % of traffic areas are used for stationary traffic (Agentur für clevere Städte, 2014; Copenhagenize.com, 2017).

The space for parked vehicles could be saved in the case that AVs are used as ride-sharing systems and are almost constantly on the move. However, it is not likely that this scenario will occur in the
near future. For this reason, it is purposeful to assume that the increasing introduction of AVs will initially change little in terms of the need for spaces for stationary and moving traffic.

An inner-city traffic concept geared to avoiding parked vehicles can already develop street profiles with a higher livability and a distribution of space that gives more room to micromobility, especially bicyclists, and recreational areas.

In addition to more space in streets, bicyclists need to be more protected from injuries and critical situations. As described in the chapter above, the subjective safety feeling has a crucial impact on a person’s decision to ride a bicycle. For this reason, the research project started an online survey to gain more knowledge about cyclist’s safety feelings.

Online Survey to Bicyclist’s subjective Stress and Uncertainty

To gain knowledge about the cyclist’s subjective stress and safety feelings while riding on different infrastructures, an online survey was developed. There was no restriction for participation, every person could take part in the survey. 337 persons in total answered all questions completely. Because of an imbalance of the sample group, a weighting over their gender, age and educational achievement was implemented to depict Germany’s population structure.

In the weighted sample group, 18 % were 30 years or younger, 44 % were between 31 and 60 years and 29 % were older than 60 years. The remaining participants did not specify their age. Overall, 55 % ware male, about 35 % female and the rest divers or did not state the gender. Nearly 50 % of all participants rode nearly every day by bicycle and 45 % once a week or more often. According to that, a rather bicycle-addicted sample group was reached by this online survey. This is underlined by the evaluation of the question about the participant’s assessments, where more than 50 % answered to feel safe in mixed traffic with cars and bicycles and 99 % stated to be a safe rider. To query the participant’s stress and safety feelings while riding on different bicycle infrastructures and in different critical situations in today’s traffic without AVs, ten infrastructures and eleven situations were introduced by a describing text and pictures. The participants stated how often they ride on which infrastructure and how often they come in which kind of critical situation. They also rated their subjective stress and uncertainty for each infrastructure and situation in the following scale:

- very stressed / very unsafe
- stressed / unsafe
- neutral
- little stressed / safe
- not stressed / very safe
- no answer

Figure 2 shows exemplary the detailed evaluation of the stress and uncertainty feeling while riding a bike lane and a protected bike lane (A bike lane is a German bicycle infrastructure that belongs to the roadway but may only be used by cyclists. It is marked with a solid line).
Figure 2 shows strong differences in the subjective stress and uncertainty between the two bicycle infrastructure types. A normal bike lane without protection from motorized vehicles generates a lot more stress and uncertainty for the bicyclists than a bike lane with protection: 36 % of the participants felt stressed or very stressed and 41 % felt unsafe or very unsafe on the conventional bike lane, whereas only 1 % in each case felt the same on the protected one. Only about one third in each case felt at least safe without protection, the value on the protected bike lane is about three time higher.

To compare all surveyed bicycle infrastructures and situations, average values of both stress and uncertainty levels were built. The comparison of all infrastructures is shown in Figure 3, Figure 4 shows the comparison of the situations. In both figures, stress is pictured in the orange, uncertainty in the grey line. The frequency of infrastructures and situations (how often the participants experienced them) is shown in the blue line.
Both Figure 3 and Figure 4 show a number of findings. First, a strong correlation between the stress and uncertainty statements appears by comparing their average values as shown in the orange and grey lines. For that reason, the uncertainty feelings will represent both uncertainty and stress feelings in the following text.
Second, the proximity and velocity of motorized vehicles appears as a high indicator for uncertainty feelings of bicyclists. Figure 3 shows, that low subjective uncertainty are given on cycle paths, bicycle streets, protected bike lanes, country lanes and bus lanes, where bicyclists ride in distance to other vehicles. When riding on the same infrastructure as motorized vehicles, as it is without any bicycle infrastructure and on bike lanes without protection, the participant’s uncertainty feelings were quite high. In addition to that, riding without bicycle infrastructure together with vehicles travelling at 50 km/h causes remarkable higher uncertainty feelings than with vehicles travelling at 30 km/h. Figure 4 shows the same results concerning proximity, as cars standing on the bike lane, leaving a parking space or property entrance, cars keeping no or little distance while overtaking, dooring risk and high traffic intensities at all cause the highest uncertainty feelings by bicyclists in that comparison.

A third finding is that some triggers of high uncertainty feelings occur more frequently than others. Riding on roads without bicycle infrastructure or with bike lanes without protection from motorized vehicles, as well as cars overtaking with a small distance or standing on bicycle infrastructure, occur frequently. In contrast, other high uncertainty feelings are fortunately rarely triggered, such as door situations or cars leaving parking lots or property entrances and overlooking bicyclists.

Those types of infrastructure and those situations, that cause high subjective uncertainty and appear often, ought to be the first ones to be designed safer for bicyclists. How bicycle infrastructure can be designed safer is also shown in Figure 3. Infrastructures with the lowest subjective uncertainty feelings and highest frequencies are cycle paths and country lanes. Thus, bicyclists feel the most safely when riding separated from motorized vehicles. But the statistics of bicycle accidents show contrary results. Looking at the number of accidents and the injuries in Germany, the proximity to motorized vehicles is a safety factor for bicyclists because they are better seen by vehicle drivers (Below, 2016; Katja Schleinitz et al., 2015; Marcel Schreiber et al., 2011; Schwaibold, 2013; Schreck, 2016).

Protected bike lanes could be a suitable solution, as they also cause very little uncertainty feelings among cyclists. Moreover, they are just not as highly frequented as the two previously mentioned, as they are not as common in Germany. Bicyclists are protected and in some kind separated from the motorized traffic. Nevertheless, they are still easily visible.

Bicyclists and Automated Driving

In the online survey about subjective stress and uncertainty of bicyclists, the participants were asked about their expectations and recommendations of important characteristics of AVs as well. In each case, more than 90 % indicated that AVs should maintain a safe distance from bicyclists when following and overtaking, in addition to maintaining a reasonable speed when overtaking. Other important recommendations, with more than 90 % consent as well, were that AVs should reliably recognize the bicyclist’s behavior (e.g. braking, turning, hand signs) and should signalize its own driving intention (e.g. braking, flashing, standing). According to the majority of the participants, AVs should not have a special appearance compared to other vehicles like visual or audible signs. A feedback that the AV has recognized the bicyclist is not recommended as well.

In addition to the uncertainty feelings on different bicycle infrastructures and in different critical situations in today’s traffic with only manually controlled vehicles, the participants of the survey were
asked to state their expectation of uncertainty feelings in a traffic with AVs. Therefore, three scenarios were defined: the first scenario solely deals with manually controlled vehicles as described in Figure 3 and Figure 4, the second scenario contains a mixed traffic consisting of both manually controlled and autonomous vehicles and the third scenario deals with a purely autonomous traffic. The participants stated their uncertainty feelings the same way as they did in the first scenario before.

The evaluations showed again a strong correlation between stress and uncertainty. Analogous to the approach described for the first scenario, average values for all ten bicycle infrastructures and eleven situations were calculated. Figure 5 shows the comparison of the uncertainty feelings on the infrastructures for the three scenarios. Figure 6 shows analogously the comparison for the critical situations.

![Figure 5 Scenario-comparison of Subjective Uncertainty at Bicycle Infrastructures](image)

*Figure 5 Scenario-comparison of Subjective Uncertainty at Bicycle Infrastructures*
Figure 5 shows that the uncertainty feelings in today’s traffic (shown in the red line) get slightly worse in the second scenario with manually controlled and autonomous cars (yellow line). In conclusion to that, the mix of manually controlled and autonomous vehicles seems to cause a lower safety feeling for bicyclists. In a purely autonomous traffic (green line), the uncertainty feelings decrease for nearly every infrastructure, which is an important result of the survey. Only in bicycle streets and on country lanes, the participants feel safer without any AVs. Another important finding is that autonomous driving can provide the highest improvements for bicyclist safety on infrastructures that cause the highest uncertainty feelings today. Figure 5 shows the largest spread between the red and green line for roads without any bicycle infrastructure.

Figure 6 shows a very similar phenomenon. Critical Situations are nearly stated the same in both the first and the second scenario. The mixed traffic with manually controlled and autonomous vehicles does not ensure bicyclists compared to a traffic with purely manually controlled vehicles. Though, a traffic with purely autonomous vehicles does cause lower uncertainty feelings than both other scenarios. Especially situations, that are made critical by human drivers, as overtaking with little distance, leaving parking spaces or dooring, gain the highest safety effects through autonomous driving.

Conclusion

It will be challenging for AVs to interact with bicyclists, which will change overall drivability depending on road type and bicycle infrastructure. If many cyclists with different driving styles are on the road at the same time, the drivability of AVs is severely limited. In contrast, wider roads dominated by motor vehicles and hardly used by other road users are much more suitable for AVs.
Slowing down traffic speed of motorized vehicles or building separate bicycle infrastructures are possible solutions to increase the drivability of AV in all road spaces.

The space for these changes can partly be generated by reducing parking areas if AVs are used as shared vehicles. This is only possible if future traffic is organized in a way that shared vehicles, public transport and micromobility are preferred. The most important task for city administrations will be to limit the rebound effects of AVs and to design public spaces, including traffic areas, in a way that cyclists, pedestrians and AVs will coexist without conflicts.

Another important goal for urban planners is not to allow unplanned "islands of autonomy", areas or streets where it is possible to drive automated vehicles earlier. The goal should be to use the deployment of AVs as an opportunity to design streetscapes equitably for all road users.

Equally shared streetscapes can only work, if users of micromobility, especially bicyclists, feel safe and comfortable. For this reason, the research project surveyed the impacts for bicyclist’s stress and uncertainty feelings to avoid them in future planning. The evaluation of the survey shows a number of important results due to stress and uncertainty feelings of bicyclists. Ten different bicycle infrastructures and eleven different critical situations were surveyed for three different scenarios with manually controlled and autonomous vehicles. As a conclusion, the participants did not distinguish between stress and uncertainty feelings. Both were equally stated for each infrastructure and situation in every scenario.

Motorized vehicles are found out to be the main stressors for bicyclists. Riding on roads without bicycle infrastructure or on bike lanes without protection to the motorized vehicles, cars overtaking with little distance or standing on the bicycle infrastructure, doorling situations, cars leaving parking spaces or property entrances and overseeing bicyclists caused the highest uncertainty feelings of all investigated infrastructures and situations.

The lowest stress and highest safety feelings were stated by the participants for the scenario with purely AVs. In a mixed traffic with manually controlled and AVs, stress and uncertainty feelings seem to rise.

This project has highlighted important recommendations of bicyclists for automated driving and coexistence in road space. In summary, AVs can be expected to make huge improvements to the subjective safety of cyclists on the road. Tough, the absence of manually controlled vehicles is crucial. Initial approaches for a future urban design that combines these requirements with the technical hurdles of automated driving were also presented. Further research and development should start here and additional develop both the urban design, especially the division of traffic areas, and the technology in an adapted way.
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