A Multisensory Toolbox for Active Citizen Participation in Cycling Planning on Shared Real and Virtual Roads: A Case Study in Herrenberg, Germany

Peter Zeile[1], Thomas Obst[2], Céline Schmidt-Hamburger[1], Nina Haug[1]

[1]Karlsruhe Institute of Technology KIT, Professorship of Urban Neighbourhood Planning STQP · peter.zeile@kit.edu
[2]High-Performance Computing Center Stuttgart HLRS · obst@hlrs.de

Abstract: This article presents an excerpt from the Cape Reviso Toolbox, which, using digital methods, is designed to better recognize and understand conflicts between cyclists and other road users users. A user survey, distance measurements, emotion sensing and AI camera system modules presented here were carried out as a synchronous test run with 16 test persons and almost 300 data sets in Herrenberg. The positive result motivated subsequent projects to scale up the approach with a longer duration, independent implementation of the measurements by the test persons, and integration into municipal planning processes. The results were discussed with citizens and decision-makers and confirmed local knowledge about uncertainties through sensor measurements.

Keywords: Cycling planning, emotion sensing, mobility design, active mobility, citizens' science

1 Introduction

The article presents three modules from the Cape Reviso toolbox containing sensor technologies for citizens and city administrations, which were designed for active use in participation and planning processes. Embedded in the Cape Reviso project (HLRS 2024), which is funded by the Federal Ministry of Digital and Transport (BMDV 2020) as part of the National Cycling Plan 3.0, we present the use of biostatistical sensors, distance meters and camera systems. The context given is the question of where, when and why cyclists experience stress, what potential conflicts arise between road users and how these findings can be integrated into citizen-oriented planning processes. The focus is on the components of near-body sensor technology, distance measurement and imaging sensor technology, which help to create a more objective view of the subjective issue of personal safety perception / experienced risk.

Following the start of the project in the spring of 2020, combined cycling and pedestrian studies should be carried out in Herrenberg. Because of the COVID pandemic, the collaboration with Herrenberg did not start until July 2022 as a cycling-only trial; the pedestrian trial was carried out alternatively in Stuttgart in 2021 and is not part of this article.

The methodological approach is designed to be open, encouraging replication and implementation by planners in municipalities. All results were incorporated into the municipal planning process – prepared with the participants in a subsequent workshop and in the city's so-called "Cycling Round Table".

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2 State of Research

The most important examples of subjective perceptions of safety in the context of cycling are listed below, and the methods and technologies that have already been tested are explained. More in-depth information on this can be found, for example, in HAUG (HAUG et al. 2023).

2.1 Subjective Emotional Experience and Cycling Planning

International studies show that it is the lack of a sense of safety that deters many people from switching to cycling, and this trend is even increasing in cities with a low cycling mode share (WANG et al. 2014). Cycling experts such as GRAF (GRAF 2016) therefore consider the "reduction of stress" in cycling as a key factor in increasing cycling mode share. The integration of "stress measurements" during cycling has been described and used in several research projects in an international context (GÖTSCHI et al. 2018). Other studies focus more on the mobile participation approach (LIßNER & FRANCKE 2017). The UK Near Miss Project provides with its understanding of "near accidents" or "non-injury accidents" a missing link between perceived safety and objective safety, which could explain the discourage of people not to cycle. Similarly, by compiling route diaries including information on incidents with motorists (e. g. overtaking too closely) as well as infrastructure and traffic behaviour, this approach provides valuable information on attributes that could potentially prevent cycling (ALDRED 2016).

2.2 Personal Characteristics and Mobility Behaviour

So-called endogenous influence factors, targeting individual demographic, socio-economic, and socio-cultural characteristics, as well as the social environment of individuals, play a crucial role in influencing individual responses to stressors from the built environment (WERMUTH 2005). Particularly, age – where children and older individuals perceive their surroundings differently due to varying developmental stages or age-related changes – takes a prominent role. Mobility profiles, especially in individuals with mobility or visual impairments, as well as the purpose of travel and individual habits such as a preference for pedestrian mobility, influence susceptibility to stress reactions (AUSSERER et al. 2013; SCHOON 2010). Gender also plays a role, with women tending to react to stressors more quickly (KYRIAKOU & RESCH 2019). Psychological influence factors, such as personality traits, locus of control, and risk propensity, are considered crucial factors that can amplify or mitigate individual stress responses (SCHANDRY 2016). The inclusion of psychological characteristics in social science studies is deemed important for better describing and predicting processes and phenomena (Personality: RAMMSTEDT et al. 2012, Locus of Control: KOVALEVA et al. 2012, Risk Propensity: BEIERLEIN et al. 2014). Personality is traditionally determined using the so-called Big Five, encompassing the traits of extraversion, neuroticism, openness, conscientiousness, and agreeableness. Locus of control describes a person's belief in having control over various situations and perceiving them as a result of their actions (internal) or attributing them to fate, chance, or powerful others (external). A person's generalized locus of control can be equated to a character trait, as it has been shown to explain and predict behaviour (KOVALEVA et al. 2012). The degree of locus of control is a relevant factor in coping with stress reactions (BROSSCHOT et al. 1994). Risk propensity indicates the extent to which a person is willing to choose risky courses of action. Risk behaviour is empirically associated with driving behaviour and is therefore of significance.

2.3 Digital Tools and Sensors for Participation Informational Equality

Without the establishment of an “informational equality of arms”, any form of participation is obsolete (STREICH 2014, 137). After all, a good participation process should be able to be measured by the level of information available to all. According to STREICH (STREICH 2014), genuine participation requires not just data availability but also technical-organizational measures. Inspired by the PlaceMatters initiative, he advocates for 'open tools,' specifically “open source planning tools,” accessible to all with disclosed source codes (STREICH 2014,137 & 148). So nearly all methodologies and technologies used in this approach are open, as described below. For the detection of near misses, subjective safety and “stress” there is a range of different sensors: Stationary sensors for “dynamic scene understanding” (BUXTON 2003), the automated detection and classification of pedestrians (ROMEROCANO et al. 2016), hand mobile sensors such as GPS receivers or microphones to detect sounds (MAUSONNEUVE et al. 2008), light intensity and colour (GURIERREZ-MARTINEZ et al. 2017) pollutant concentrations via USB interface (SCHÄFER et al. 2017) or even biostatistical sensors (KANJO et al. 2015).

3 Cape Reviso – Toolbox

Cape Reviso uses different methods that are independent of each other. Distance meters, real-time human sensors and machine learning provide planners – both in the city administration and in civil society – with technologies to collect and analyse data about cyclists and bicycle traffic.

3.1 Network Analysis with the OpenBikeSensor

The so-called OpenBikeSensor (OBS) was designed as an open-sensor platform (GITHUB 2021). Ultrasonic sensors continuously measure the physical distance to other road users and store it georeferenced. By aggregating all data sets, it is possible to identify areas where overtaking occurs more frequently at a distance of less than 150 cm. In combination with data from traffic monitoring, etc., initial suspicion points for potential hotspots of near misses and other conflict areas emerge.

3.2 Sensorbased Stress Measurements and Standardized Questionnaires

To conduct the “stress measurements” in this project sensor wristbands (Empatica e4) are used to measure the vital data (skin conductivity and skin temperature) of the test person during bicycle use or walking. The vital data is synchronized with the corresponding GPS data using a smartphone. A stress reaction is identified in the evaluation when the skin conductivity increases and the skin temperature decreases (KYRIAKOU & RESCH 2019). By combining this with a mixed-methods survey of the participants, more specific attention can be paid to the identified stress points. This subjective stress evaluation, in turn, can be further specified by adding information about the mobility profile, sociodemographic as well as sociopsychological assumptions. These data will be elicited using standardized questionnaires before sensor measurements and included in the evaluation. Through this methodology, the presented approach aims to identify particularly vulnerable groups in terms of stress.

3.3 Machine Learning / Training Data Generation / Camera System

The system deployed at (near-) accident hotspots utilizes stationary camera systems for long-term video data recording to investigate conflicts, dangerous situations, and accidents. Featuring a camera attached to an embedded computing board with a powerful GPU (NVidia Jetson AGX Xavier, 32 TOPS), the system enables edge computing for on-site processing of image data using machine learning algorithms. This approach ensures that image data remains within the system's volatile memory, transforming it into anonymized traffic metadata for data protection compliance. The modular software design, comprising detection, tracking, and trajectory analysis, incorporates clearly defined interfaces for swift integration of newly developed third-party algorithms.

For image recognition, the system employs the Convolutional Neural Network YOLO (REDMON & FARHADI 2016) with the deep neural network library tkDNN (VERUCCHI et al. 2020) operating at around 40 fps for FullHD video, with detections saved locally or streamed in JSON format. It was trained using the COCO detection dataset (LIN et al. 2015) and the ImageNet classification database. Adaptations for the European/German micromobility mix involve a web portal (https://capereviso-portal.hlrs.de/) using the Image Labeling Tool (KIM 2019) for crowdsourcing additional classification data. The portal facilitated volunteer interactions, resulting in training data for the classification of various road users, including bicycles, pedestrians, scooters, wheelchairs, and persons with prams.

Three tracking algorithms were tested and partially implemented during the project. The Poisson Multi Bernoulli Mixture (BOHNSACK 2019) was extended for live tracking, and a multi-camera system with sensor fusion was explored (VALDER 2021). SORT (BEWLEY et al. 2016) exhibited promising results in single-camera systems, and efforts are underway to extend DeepSORT (WOJKE et al. 2017) to multi-camera systems. Trajectory analysis spans from basic traffic participant counting to in-depth examinations of complex interactions. Criticality metrics (WESTHOFEN et al. 2023) adapted for vulnerable road users provide insights into conflict mechanisms, distinguishing single extreme events from recurring ones. Beyond speed and acceleration metrics, trajectory analysis will include TTCE (time to closest encounter) and DCE (distance of closest encounter), with potential expansions to identify infrastructure promoting critical encounters.

4 Results of Case Study Herrenberg

The partner municipality of Herrenberg serves as an example to illustrate the usage of Cape Reviso's toolbox. Herrenberg is located in the southwest of Germany, 40 km southwest of Stuttgart. With 33,000 inhabitants it can be considered as a medium-sized city. In 2016, the modal split confirmed a cycling share of 11% and a walking share of 19% (MEIGL et al., 2019). As part of Cape Reviso, various surveys were carried out in autumn 2022. These include stress and distance measurements over two weeks with 16 participants and the use of the camera system. Although we are aware that 16 participants are not yet representative of the population in Herrenberg, this test run is of particular importance, as this was the first time that the synchronous use of all technologies in conjunction with the individualized questionnaires was used and scalability from pure individual evaluation (as in the Urban Emotion Cycling experiments ZEILE et al. 2016) to unsupervised daily use was tested.

4.1 Standardized Questionnaires

The standardized questionnaires reveal key insights into participants' cycling behaviours, personality traits, and attitudes offering insights into the factors that may influence their preferences and behaviours related to cycling (cf. Table 1).

Table 1: Description of the sample, own calculations

Variable	**$N_{participants}$=16 (in %)**
Age (>40)	69
Gender (female)	56
Education, high	81
Cycling types (GELLER 2009)	
No chance, no matter what	0
Interested cyclists	44
Everyday cyclist	56
Fearless cyclist	0
Type of drive of the bike	
Conventional	81
Electric	19
Bike type (most commonly used)	
Trekking bike	50
City bike	31
Evaluation of the situation in Herrenberg (average school grades)	
Cycling	4.1
Walking	3.4
Big Five personality traits	
Extraversion (above average)	57
Neuroticism (above average)	71
Openness (above average)	64
Conscientiousness (below average)	79
Agreeableness (below average)	33
Locus of control	
Internal (below average)	73
External (below average)	80
Risikaffinity (high)	73

The majority (69%) of participants are over 40, with slightly more females (59%) than males. A significant portion (81%) have a high level of education. Participants are categorized into cycling types (GELLER 2009), with the majority being “everyday cyclists” (56%) and “interested cyclists” (44%). Therefore, no extreme positions concerning cycling behaviour are represented in the study. Most participants (81%) cycle using muscular power, while 19% use E-Bikes. Common bike types include trekking bikes (50%) and city bikes (31%). Herrenberg is rated average for walking (grade 3.4) and poorly for cycling (grade 4.1), as per the Fahrradklimatest by ADFC (grade= 3.9, N= 154). “Conflicts with pedestrians” (grade: 4.1) is a notable concern amongst Herrenbergs cyclists, rated 0.5-grade points lower than the town-size class average (ADFC 2022).

The participants exhibit distinctive personality traits (RAMMSTEDT et al. 2012), with higher extraversion, neuroticism, and openness compared to the German average. They are less conscientious and socially agreeable. Locus of control shows a preference for internal control in Herrenberg. Participants also display a high average risk affinity (73%) (BEIERLEIN et al. 2015).

4.2 Sensorbased Stress Measurements

When measuring the biophysical characteristics for stress detection, 16 test subjects with 283 data sets were collected. The pure driving time of the test persons amounted to 58.46 hours, corresponding to 210467 measurement points. In the process, 5422 moments of stress MOS were detected. Figure 1 shows the entire measurement campaign across the urban area of Herrenberg as well as a focus area around Reinhold-Schickplatz and the adjacent ring road. A high number of MOS was detected here, which goes hand in hand with the “urban knowledge” of the high level of traffic problems at this location.

Fig. 1: All Measurement Points and MOS Detection in the City of Herrenberg (left) and with a focus spot on Reinhold-Schickplatz (right)

With participant questionnaires and anonymized data, initial assessments based on personality traits were conducted. Key inquiries include gender differences in perception, stress levels among cyclists involved in accidents, and variations based on bicycle types (Fig. 2).

Fig. 2: Different stress hotspots of the cyclist types “interested cyclist” (left) and “everyday cyclist” (right)

4.3 Network Analysis with the OpenBikeSensor

Until November 2022, over 210,000 points were surveyed in the study area. Among 402 recorded overtakes, 179 were close overtakes under 150 cm. Hotspots include Reinhold-Schickplatz, Horber Straße, and Hindenburgstraße (Fig. 3). Breakdown of close overtakes: 25 in the 0-50 cm range, 53 in 50-100 cm, and 101 in 100-150 cm. Additional points (64 in 150-200 cm and 41 >200 cm) fall outside legal minimum distances but are still perceived as "close manoeuvres". Particularly on roads exceeding 50 km/h, cyclists experience strong lateral forces, potentially impacting their subjective feeling of safety (GROMKE & RUCK 2021).

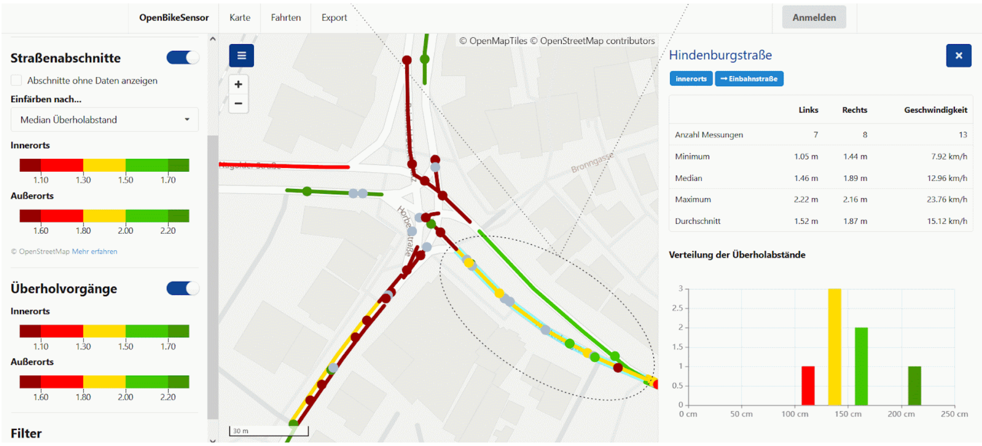

Fig. 3: Information generated from the OBS Portal, tailored to Herrenberg (https://openbikesensor.hlrs.de/map#17.66/48.59486925734776/8.867378921008): Focus spot with statistical information to a road segment

4.4 Machine Learning / Training Data Generation / Camera System

Between 2022 and 2023, Herrenberg's traffic detection systems recorded for over 1600 days across four systems and five locations. Due to limitations in the tracking algorithm, pure detections on single frames were stored and later analyzed with adapted algorithms. Areas of interest were selected based on mobile sensor data and municipal experience. In this context, spatial density analysis provides insights into traffic patterns, revealing the main routes for different types of traffic participants. Figure 4 illustrates the results of the camera detection system at Herrenberg's Community College.

Also, single trajectories of interest can be displayed along with the other traffic participants present at a specific time can be displayed. An empirically verifiable correlation between the movements of several road users (in particular approach, taking into account visibility, speed and the time remaining until a possible collision), the time course of the reaction (sudden change of direction or abrupt braking) and the potential of this situation to cause stress is still a work in progress.

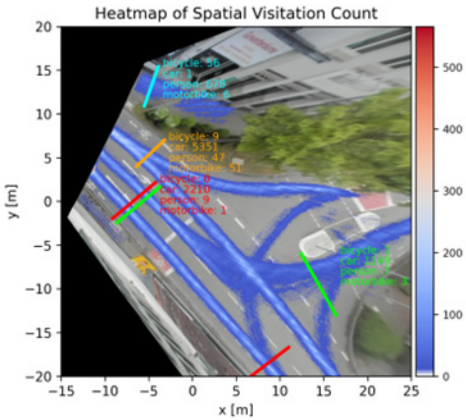

Fig. 4:
Camera recordings at Community College Herrenberg. Spatial Distribution of traffic participants reference point visitation count on a grid with 0.1m resolution together with counts of single (cyan and orange) and multiple line intersections (red and green). Accumulated data of May 1st, 2023.

At this location, northbound cyclists arriving from the east have to decide whether to mix with motorized traffic entering Herrenberg from a rural road or to use the pedestrian path which is not in full conformity with the law. This also leads to potential conflicts with pedestrians. Whether this path can be legally opened up to cyclists is an ongoing discussion. The assumptions about the current use of space and distribution of use between cyclists and pedestrians on pedestrian paths can be confirmed by using the system.

4.5 Interconnection of Tools

As a vision, the interconnection of all approaches holds great potential: the entire road network is scanned for stressful situations of users when cycling, and small overtaking distances are logged and aggregated for possible widening of the cycle lane widths by proving that cyclists are at risk. Focus analyses were carried out with the camera system at the hotspots identified in the network and, ideally, the results of the questionnaires will also tell us which locations are particularly avoided by "transfer users" because they generate stress.

In this experiment, the camera locations were set up at the identified hotspots.

Especially at one hotspot, the community college, we could identify contextual advantages to the camera recordings. By analyzing traffic flows and the actual routes taken we observed that cyclists prefer the sidewalk to the road. The actual cycling infrastructure was avoided and there were fewer MOS than expected and no accidents in the accident statistics. The toolbox can be used to distinguish functional from dysfunctional traffic situations, for example, and can provide information for urban planning to prioritize measures.

Another result was, that there is no clear correlation between a short overtaking distance and the individual stress triggers: In some places, this is true, in other places with very small distances no stress triggers were registered (see Fig. 5). This phenomenon is also consistent with the findings of HAUENSTEIN (HAUENSTEIN et al. 2023): An increased stress correlation at lower overtaking distances below 1.6 m is statistically detectable with Pearson's Chi-square test, but not "visible" for every stress trigger. The superimposition of both measurements thus systemically supports the legal requirement for an overtaking distance of 1.5 m in urban areas, but as a combined application in the planning context of bicycle traffic, both series of measurements together do not provide the required indications. In this context, however, it would also be interesting to see whether there is a correlation between stress triggers, distance and the above-mentioned personality traits.

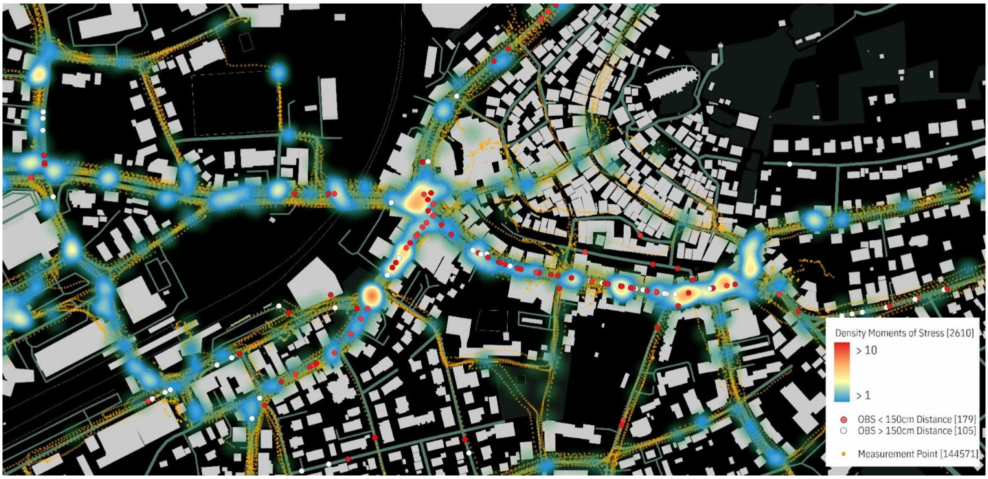

Fig. 5: Correlations between overtaking distance and stress, Overlay OBS measurements with Stress Triggers on the focus point Schickplatz

5 Conclusion

Within the Cape Reviso project, a toolbox that incorporates biostatistical sensors, distance meters, and a camera system for citizen and administration involvement in planning processes has been developed. Having started with the intention of being able to measure conflicts between pedestrians and cyclists, the results presented here in combination with the studies on pedestrian traffic on Stuttgart's Marienplatz (SCHMIDT-HAMBURGER et al. 2023) are an important component to understanding stress and conflicts between cyclists and pedestrians.

All circumstances considered the example of Herrenberg demonstrates how citizen-centric planning could contribute to a safer urban environment. The methodological approach is designed to be open, encouraging replication and implementation by planners in municipalities.

While the multisensory toolbox demonstrates a holistic analysis approach with strengths like cost-effectiveness and adaptability, limitations include a small and biased participant sample, challenges in drawing precise conclusions from camera recordings, and current constraints in digital twin measurements. Despite these limitations, the toolbox shows promise for further development and use in urban planning, particularly with its focus on citizen involvement and multisensory data integration.

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