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CyclAir: A Bike Mounted Prototype for Real-Time Visualization of CO_2 Levels While Cycling

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Abstract. With the increased global focus on the environment, pollution, greenhouse gases, as well as carbon footprint, a multitude of initiatives have emerged in order to reduce air pollution and also increase awareness of air quality. In this paper, we developed CyclAir, a system enabling cyclists to monitor the traffic-related air pollution, measured in carbon dioxide (CO_2) levels, both in real-time as well as retrospectively. Based on a first user study with seven test participants, we found that our participants were often confirmed about their preconceptions of the immediate CO_2 level and air quality, but interestingly they were also sometimes surprised. 6 out of the 7 participants expressed willingness to change route choosing behavior when presented with new evidence about the air quality, even when this increased the route length.

Keywords: Air Quality Measurement · CO_2 sensing · Real-time CO_2 visualization · Participatory Sensing in the Wild · Traffic based air pollution

1 Introduction

Global warming is a significant environmental concern and various initiatives e.g. by the European Union [5] or the United Nations [4] attempt to address and tackle this problem - including reduction of carbon dioxide (CO_2) emissions. One way to reduce CO_2 is to better utilize transportation means with no or limited CO_2 emissions, such as cycling. However, while cycling for transportation is favorable in terms of CO_2 emission, cyclists often expose themselves to air pollution and low air quality as they move around cities. Therefore, HCI research has studied effects on cyclists behavior and attitudes of air quality and pollution by collecting data for a retrospective analysis [2, 11, 14]. However, we have a limited understanding of the implications of real-time air quality feedback on cyclists behavior and awareness.

In this paper we developed CyclAir, which is a bike mounted prototype that visualizes real-time measurements of CO_2 levels when cycling through a simple LED-based, traffic light inspired, interface. The aim of our work is twofold. Firstly, we present a prototype developed in order to explore the possibility to increase awareness about air quality by giving cyclists real-time feedback of the air quality in their immediate surroundings. Thereby rendering something invisible visible, namely the local CO_2 level.

Secondly, we want to identify if there exists a willingness for a behavioral change when it comes to the choosing of the cycling route when presented with previously unknown information about air quality.

2 Related Work

Several studies investigate mobile air quality tracking among others [2, 14, 1, 8, 7, 11, 9]. These studies usually employ a multitude of different sensors in order to collect data about air quality and often for various purposes. The studies have employed different means of transportation and data collection e.g. bikes [7, 8, 11], motorized vehicles [2, 11, 14] or mobile phones [9].

Aoki et al. [2] and Westerdahl et al. [14] both made use of motor vehicles equipped with different sensors in order to capture data about the air quality of San Francisco. Aoki et al. developed a system attached to street sweepers in San Francisco in order to collect three different air quality measurements as well as temperature, humidity, motion, and GPS data. Their primary focus was the development of a research vehicle for data collection for researchers, government agencies as well as public health NGOs. They identified shortcomings when using motorized vehicles which themselves have air pollution emissions, which resulted in the need of additional calibration of the system itself, in order to account for the street sweepers. Carvalho et al. [3] developed a system for measuring air quality, which can be attached to taxis and buses in Lisbon, in order to generate a real-time overlay for google maps on air quality which can be accessed through a web browser. Just like Aoki et al. they made use of emission causing vehicles for the collection of data which can involve some additional challenges. Westerdahl et al. [14] chose a zero-emission electric vehicle (Toyota Rav4 SUV) which did not contribute to emission. Their main contribution was the development of a sophisticated real-time mobile air quality measuring platform that got tested in Los Angeles. Furthermore, they identified strong differences in ultrafine particle density, depending on the road type and truck density at the given time.

An alternative to the mentioned motorized vehicles is the use of bicycles. Among others Anowar et al., Elen et al., Eisenman et al., and Hertel et al. [1, 8, 7, 11] conducted research in relation to bicycles and air pollution. Anowar et al. [1] tried to identify the willingness to chose alternative cycling routes to lower air pollution exposure, even if this resulted in longer routes. They investigated this using a survey, and concluded, that participants were willing to drive up to 4 minutes longer, given a reduction of NO_2 by 5ppb. For data collection Elen et al. [8] developed a research bike, the Aeroflex. They used the research bike to generate map representations for hot spot identification, air quality mapping as well as exposure monitoring. Although attached to a bike, the system still requires a certain degree of technical expertise, making the use hard for everyday cyclists. Furthermore, it required the transportation of a Laptop, batteries as well as a lot of other equipment which makes it less everyday friendly. Eisenman et al. [7] developed the BikeNet, which is a system for cyclist experience mapping in terms of fitness and environment tracking. They developed a bike and helmet mounted sensing system for the collection of several factors such as noise, roughness of the terrain or CO_2. Given their Health index definition, they calculated the healthiness of a given route which can be accessed through a web portal. Hertel et al.[11] compared a variety of air pollutants on three different routes, shortest bike route, less trafficked bike route and bus taking route. They performed a study with two groups of 25 people traveling from home to work and vice-versa. They could conclude, that the slower "greener" route reduced the intake of the measured pollutants on average by 10% - 39%, although the increased travel time increased the exposure time to the pollutants.

Froehlich et al.[9] developed the UbiGreen mobile phone system in order to increase awareness about transportation habits. They conducted a field study using semi-automatic tracking while giving feedback to the users via the mobile phone in order to encourage green transportation. They concluded that test participants value the feedback about traveling behavior, which could lead to a lasting behavior change.

In this study, I aim at developing a system for real-time air quality monitoring in the wild, without the need for any technical expertise or complex to setup system. CyclAir has been developed with simplicity in mind, both in terms of compatibility with every bike, as well as in terms of non-intrusive feedback while cycling.

3 CyclAir

CyclAir is a system enabling cyclists to monitor the CO_2 levels both in real-time while cycling as well as retrospectively. CyclAir consists of a water-resistant encasing (IP44) in order to be durable enough for outdoor use on a bicycle. An Arduino Uno, running a custom C++ implementation, was used to control the system. The Adafruit SGP30 Air Quality Sensor Breakout Board (SGP30) was attached in order to measure CO_2-equivalent, which corresponds to the greenhouse gases measured, converted to the equivalent amount of CO_2 concentration. In order to increase air contact with the SGP30, the sensor was mounted on the handlebar of the bike. Air holes on the bottom of the SGP30 encasing increased air exchange within the encasing. Beside the SGP30 sensor, the NeoPixel 16 LED RGB lighting system (LED-ring) was mounted on the handlebar for visual feedback about CO_2 level to the cyclist. The LED-ring mounted on the bike's handlebar can be seen in Figure 1B.

To ensure visibility while maintaining water resistant qualities, both the LED-ring as well as the SGP30 were mounted on the handlebar in a 3d printed enclosure. In order to enable the mapping of air quality measurements to a specific location, the Neo6M-V2 GPS module was used. The GPS module was used to acquire timestamps, date, longitude, as well as latitude. All measurements were collected and written to a micro SD-Card in 1-second intervals which were deemed sufficient. The average cycling speed in Copenhagen is 16.4 km/h which would correspond to a distance of 4.5 m/s using a 1-second interval [13].

The design of CyclAir was developed in a preliminary design workshop. One button is installed in order to turn the system on/off. This starts the data collection in 1Hz intervals. Visual feedback was provided in-situ via the handlebar mounted LED-ring. Through this the cyclist was receiving timely information about the CO_2 content of the air traversed during the last 10 seconds. Both shorter (down to 3 seconds) and longer (up to 30 seconds) intervals were experimented with, but this felt either too distracting when the interval was shorter, or not informative enough, for longer intervals. Each

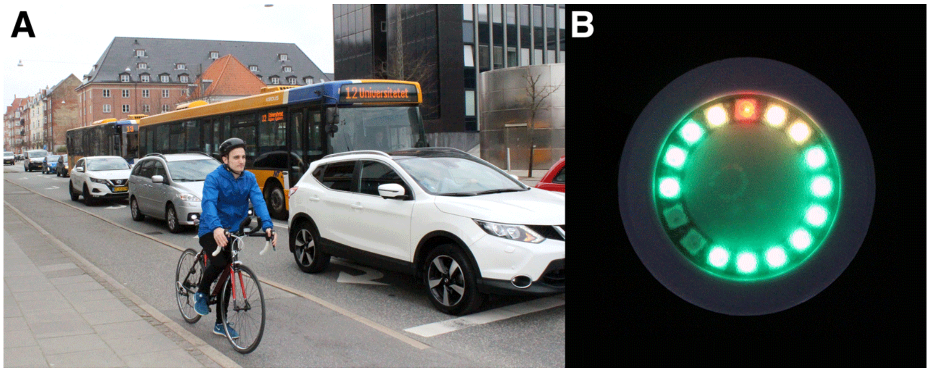

Fig. 1. A: CyclAir system in context - here on a high traffic road in the center of Aalborg waiting at a red light. **B:** Close-up of visual feedback based on the 10 second average CO_2 level.

LED would light up in green, yellow or red (LowCO_2, MediumCO_2, HighCO_2), as illustrated in Figure 1, dependent on the average CO_2 level in the last 10 second interval. The LED notification system was chosen in order to provide a subtle, non-intrusive notification approach using light [10, 12] in an environment where distractions are not acceptable. The led-ring was chosen in order to give the possibility to identify tendencies while cycling, by providing current real-time information, which is comparable to the previous data points represented through earlier LEDs. After each cycling trip, the data was collected and visualized. This gave the cyclists the possibility to correlate the CO_2 levels on the traversed route, represented on a line graph, with the specific location, plotted using Google Maps, see example in Figure 2.

4 Field Study

We conducted a field study of CyclAir using seven test participants (5 female; age: 25 - 55; mean age: 33.3, sd: 11.4) to evaluate our prototype and to gain a deeper understanding of cyclists experiences, motivation and use of CyclAir. The test participants were unpaid and were recruited through word-of-mouth. All seven test participants ride bikes at least several times each week. Test participant T1 and T6 used the system on multiple days whereas the others used CyclAir once. Each test participant drove between ~3 - 16 kilometers (mean: 6.7km, sd: 4.1km), resulting in a total of ~47 km. The system was in use for a total duration of ~3.5 hours across all seven test participants with an average use time of 28.3 minutes per participant.

All cycle tours were performed in the two Danish cities Aalborg (~116000 citizens) and Haderslev (~22000 citizens), with four test participants in Aalborg and three in Haderslev. Both cities have a very good cycling infrastructure with predominantly dedicated bike lanes next to the road whereas cycling on the road is the exception.

In order to give in-situ air quality feedback to the cyclists, the test participants got visual notifications about the air quality using the LED-ring attached to the handlebar of the bike. This was an averaged value for the CO_2 over the last 10 seconds. Depending on the average, the next LED on the LED-ring would light up in green, yellow or red. In order to give the user insight into which LED was the next to light up, the two LED lights following the current one were turned off, leaving 14 lit LEDs and two turned off, see Figure 1. The two threshold values, for the switch between the colors, were chosen to represent Danish air quality, meaning that even red was not necessarily representational for bad air quality when compared to the global air quality levels. After each bicycle tour, the data was collected and processed. Using a custom python script, the GPS data was plotted using Google Maps, and the CO_2 was smoothed using a 10-second moving average without overlap, and plotted into a line graph. With the map and the line graph as a basis, a semi-structured interview was conducted to gain some insight into the cyclist's experiences and thoughts of the CyclAir system.

5 Results

The cycling trips for the seven participants covered a total of ~47 km. When asked on what basis the test participants chose the cycling route, five of the seven test participants replied that the route choice was based on the expectation of seeing a red LED - meaning they chose roads which they hypothesized had high traffic density and therefore would lead to a reduction in air quality. Test participants T4 and T5 simply used the system for work-related commuting.

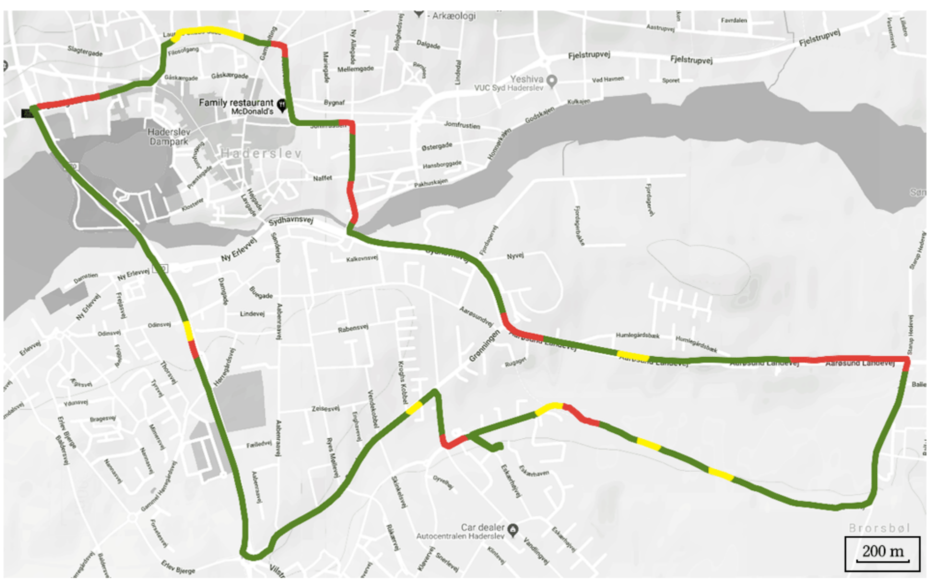

Fig. 2. First route driven by test participant T1, with color coded LowCO_2 (Green), MediumCO_2 (Yellow), and HighCO_2 (Red) peaks.

The CO_2 zone ratio overall tours for all test participants was of 73.7% LowCO_2, 16.3% MediumCO_2, and 10.0% HighCO_2. Test participant T4, who was cycling in Aalborg, was the only test participant who did experience the HighCO_2, and therefore did not see the red LED. The average CO_2 level, based on the 10-second moving window, was 442.1 parts-per-million (ppm) (max: 10163 ppm, sd: 265.7). The CO_2 value was LowCO_2 for 73.7% of the time, meaning below 425 ppm, while it only exceeded 475 ppm, HighCO_2, for 10.0% the measurements.

Based on the interviews and the collected data, we identified four themes on real-time visualization of CO_2-levels. ① **Increased awareness** about the air quality in the cyclist's immediate surroundings, which correlated with their sensual experiences. Cyclists became more aware of the differences in air quality in their immediate surroundings and could often identify, using their senses, why CyclAir would change color. Especially the HighCO_2 indications given by CyclAir matched with the cyclist's senses, which often could be identified using the sense of smell. Furthermore, T7 stated that at one point during the drive his eyes felt slightly irritated which, according to his own judgment, might have been related to low air quality. The second theme was the ② **High curiosity** in terms of linking the real-time information presented by CyclAir to a visible cause. Test participants expressed that when observing a red LED, or identifying bad air quality using their sense of, primarily, smell, they were trying to identify a visible cause. Test participants identified three typical causes for HighCO_2. 1) while crossing larger roads, 2) cycling parallel to high traffic roads with cars passing by, 3) or while standing at red intersection lights near cars, buses or other motorized vehicles, as illustrated in Figure 1A. The first two themes are supported by, quotes made independently by several test participants. T7 for instances stated that:

> *"There was a good connection between the peaks [referring to HighCO_2 areas] and the impression I got through my senses when driving through these areas."* - T7.

This statement was independently supported by test participants T1 and T6. T2 expressed that he became increasingly aware of the local differences in air quality, especially when driving parallel to high-traffic roads, by stating:

> *"The system gave me a better idea about the difference in air quality, I noticed for instance that it can have a huge effect [on the air quality] when a car passes me."* - T2

The third theme identified, ③ **Weather impact**, relates to impact the weather condition has on CO_2 levels. T1 and T3 were curious about the impact of the wind, during their cycling tour, on the level of air pollution. This curiosity arose after observing almost exclusively driving in the LowCO_2 and MediumCO_2 zones while cycling on windy roads with high traffic density. Quite interestingly these situations surprised the test participants since they deliberately chose these roads as part of the cycling route, with expected high traffic density, but still got less red LEDs than expected, an example for one of these roads is the western road (leftmost), in Figure 2. This was for instance expressed by test participant T1 who expressed that:

"I deliberately choose this route in expectation of bad air quality - this was not the case which was very surprising. Maybe related to the wind?" - T1.

T4, who chose the route based on work-related commuting was the only one experiencing a rainy cycling tour. T4 was also the only test participant not experiencing HighCO_2. To identify if there exists a correlation between rain and an effect on the CO_2 levels was not investigated and is left for future work.

The last theme, ④ **Confirmation of beliefs**, relates to the possibility the test subject had during the use of CyclAir, in order to confirm previously unconfirmed assumptions or beliefs about air quality. T6, who already chose an alternative route, compared to the fastest, for work-related commuting, stated that, after cycling the comparison, CyclAir confirmed her assumption that the air quality on the chosen route was better in comparison the fastest route. T1 partially made the same observation, on some roads where she expected low air quality, the use of CyclAir could confirm this.

Although the information CyclAir revealed did not feel entirely new to all test participants, it increased the awareness to local air quality changes and made test participants think about differences in air quality in their local environment. When asked about route choosing behavior, T6 stated that she already now chooses a route, for work-related commuting, that she expected to have less traffic-related air pollution compared to the alternative, sometimes more direct, routes. This expectation was confirmed during her cycling tours with CyclAir. T1, T5, T6, and T7 explicitly stated that they without a doubt would take alternative routes even when slightly longer, if they could reduce exposure to traffic-related air pollution. Test participants T2 and T3 stated that they might consider choosing a different route, and only T4 would not be willing to consider an alternative, longer, route to decrease air pollution exposure. Thereby we could confirm the willingness to drive detours to lower CO_2 exposure, even at the cost of increased distance, which confirms the findings in [1].

T1 asked if it would be possible to get route recommendations based on air quality, instead of the typical time or distance minimization's when planning a route pre-trip. This feature could be relevant both for a web interface, for the planning of the cycling trip, as well as in-situ based on current data. In relation to the, originating in the preliminary design workshop, CyclAir design all test participants agreed on the intuitiveness of the output given by the system. The traffic light inspired output was easy to understand and, with only one change every ten seconds, not too distracting. Several test participants indicated that the 140-second history, that was accessible at all times given the 14 simultaneously active LEDs each representing 10 seconds, was longer than necessary while cycling. The main focus was on the current and the last measurement which made it possible to identify if the air quality is improving or worsening.

All test participants agreed on, that by giving them real-time information about the local air quality, that the system either increased their awareness about air quality, which was the case for five of the seven test participants, or confirmed previously held, yet unconfirmed, assumptions the test participant had.

6 Discussion and Conclusion

In this paper we described the development and the field study, using 7 test participants, of the bike mounted prototype CyclAir. We ventured out to identify a possibility to give cyclists an increased awareness of air quality in their immediate surroundings. This was done by providing the 10 second average for the CO_2 value, using a traffic light inspired green, yellow and red system, representing LowCO_2, MediumCO_2 and HighCO_2, on the bike's handlebar, and thereby giving real-time in-situ information about something invisible made visible, namely the traffic-related air pollution in the current area. We extend on the current HCI research with findings based on real-time experiences while cycling, which were expressed during post cycling tour interviews. All test participants stated that they, after the use of CyclAir, had an **increased awareness** of the air quality differences, or at least a **confirmation** of previously unconfirmed assumptions about their local environment. An additional interesting finding is the impact of different **weather conditions** such as rain and wind on air pollution. Both seem to have an impact on air pollution, although confirmation of this is left for future work. The impact of the weather on air quality supports tendencies observed by Devarakonda et al. [6]. The impact of the weather, as well as the easy to understand visualization of traffic-related air pollution incited the test subjects **curiosity**. We confirmed that the CyclAir was able to increase air quality awareness, additionally, we could confirm [1]s identification of the cyclist's willingness to consider longer routes - if a reduced exposure to traffic-related air pollutants can be achieved.

This work opens up for several different areas of research for future work. One possibility would be how to optimize route planning, pre-cycling tour, based on information supplied by CyclAir. This could be supported with the development of a web-based platform, making the air quality data accessible for all cyclists. A different direction would be the exploration of in-situ directional information based on the current data for air quality in the given location. This can be followed by supplying deeper insights into the bike trip data for post-session analysis and tracking. The usefulness of user input, for instance when experiences particularly bad air, could be explored in a future study.

During this study a single pollutant, CO_2, was chosen to give the test participants a simplified representation of real-time air quality in their immediate surroundings. A topic for future work would be the system optimization with increased complexity by adding additional metrics such as Particulate Matter ($PM_{2.5/10}$), Ozone (O_3) or Carbon Monoxide (CO).

Given a large enough user base, the generation of heat maps based on air pollution is another area for future research. This can have several different application areas like for instance route planning for cyclists or air quality information for urban planners. Here a heat map could be useful in order to identify areas with, particularly high air pollution. This would gain additional potential with an extended set of sensors as described earlier.

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