Implementing the connected e-bike: challenges and requirements of an IoT application for urban transportation

Kristina Flüchter
ETH Zurich
Weinbergstrasse 56/58
CH - 8092 Zurich
kfluechter@ethz.ch

Felix Wortmann
University of St. Gallen
Dufourstrasse 40a
CH - 9000 St. Gallen
felix.wortmann@unisg.ch

ABSTRACT

As local transportation systems are facing enormous challenges in consequence of extensive urban growth, technological advancements are creating unprecedented opportunities as the Internet is extending into the real world, connecting physical items to the virtual world and creating an Internet of Things (IoT). While many activities are exploring corresponding applications, e.g. connecting bicycles to the Internet, widespread economic success of a truly connected device is still outstanding. Focusing on electric bicycles (e-bikes), this study investigates challenges and requirements of an IoT implementation based on GPS trackers from a technological as well as consumer perspective. The results of a four-month field study suggest a high interest of users in data from a connected e-bike but also indicate that technological restrictions still exist e.g. concerning the completeness of collected data. Also, such limitations appear to become further accentuated in view of high user expectations towards the accuracy and visualization of data, pointing to trade-offs, which may have to be made in the design of IoT implementations between the completeness and convenience of data collection as well as the energy consumption of a sensor and the attractiveness of use cases to consumers.

Categories and Subject Descriptors

H.4 [Information Systems Applications]: Miscellaneous.

Keywords

e-bike, field study, GPS sensor, Internet of Things

1. INTRODUCTION

As the world is currently experiencing an unprecedented wave of urban growth, with almost five billion people worldwide expected to be living in urban areas by 2030 [18], [22], significant challenges arise for local transportation systems, not only relating to travel times and congestion, but also to carbon dioxide emissions and quality of life for people living and working in the cities. Consequently, considerable effort is undertaken and investments are being made to enhance transportation infrastructure as well as to actively manage the demand for specific travel modes. One means of transportation, which is being promoted in this context and which has recently been enjoying substantial market success [24 is the electric bicycle (e-bike). Due to their advantages over traditional bicycles in terms of e.g. reach, effort and independence from local topography, e-bikes may be able to qualify as important element of future transportation systems, eventually replacing automobiles not only on leisure trips but also for commuting to work. At the same time, the concept of the Internet of Things (IoT) is putting forward a vision where the Internet is extending into the real world, connecting physical items to the virtual world and making computing truly ubiquitous. “Smart” objects, featuring embedded information and communication technology, are considered an important building block of this vision. Where they are viewed to have the capacity of revolutionizing the utility of these objects, the IoT idea in general is expected to be opening up huge opportunities for individuals as well as the entire economy [6], [16]. Building upon the unique availability of electrical power on e-bikes, numerous initiatives have started exploring the implementation of sensing devices also on e-bikes, e.g. [19], and we have found evidence that the data collected by such devices may in the form of social normative feedback ultimately be useful in influencing people’s travel mode choice [7].

However, while connecting any device to the Internet may appear trivial in view of today’s technological achievements and many activities are ongoing, attempting to develop not only connected e-bikes, but also e.g. intelligent fridges, spoons or kettles [3], widespread economic success of a truly connected device is still outstanding [2]. Only a limited number of products is commercially available and such products are often offered by small start-up companies rather than established corporations [2], [3]. Hence, it appears as though for the development of “smart” objects, the devil was in the detail. In this paper, we are therefore investigating the challenges and requirements of the development of a connected e-bike from technological as well as consumer perspective. We seek to generate insights particularly concerning the last mile development of such an IoT solution for urban transportation, i.e. the development of the sensor itself as well as a potential user interface and use cases scenarios, by specifically addressing the following research questions:

1. Which technological challenges affect the development of an e-bike sensor and the quality of data from such a sensor?
2. Which requirements do users have towards an e-bike sensor and a “connected e-bike”?

For this purpose, we have equipped 32 e-bikes with sensors including GPS units and GSM connectivity and conducted a field study with 32 users, who were provided with these “connected e-

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bikes" for the duration of approximately four months. We evaluate e-bike sensor data and provide insights from semi-structured interviews, which we conducted with the participants of our field study.

2. RELATED WORK

We draw from literature in the domains of sports science, wildlife tracking and bicycle research in order to gain an understanding of current technological developments and the performance of GPS trackers in other field studies.

Sports science research represents an important field with respect to the application of innovative technological solutions, offering interesting insights into the performance of GPS trackers [10]. A review of the respective literature by Cummins et al. [4] finds that studies have to date predominantly investigated the use of GPS technology on adult male athletes participating in football codes, such as American football, rugby and soccer. The authors point to acceptable levels of reliability and validity for movement patterns over increased distances and lower speeds but suggest that caution has to be taken in the interpretation of high-speed, short-duration movements and movements involving rapid changes in direction and velocity [4]. Further concern regarding the accuracy of GPS devices is raised by Randers et al. [20], who compared four match analysis systems during a football match, including two commercially available GPS systems and detected rather large differences between the GPS systems with regard to the absolute distances covered. Similarly, Intille et al. [10] point out, that improvements of GPS devices have been made with regard to miniaturization and battery life, but it can still take up to 15 minutes until they lock onto satellite signals. They suggest that not only battery life will further improve over the next years, but also emerging location systems combine multiple radio signals with databases of WiFi node locations and cell towers to infer location, in addition to GPS [10]. Such an approach is also utilized in smartphones, which derive position information not only from GPS signals but also Cell-ID and WLAN positioning [23] and today's ubiquity of such smartphones has consequently been recognized as a major opportunity in physical activity measurement [10].

In wildlife tracking research, GPS trackers represent one of various technologies, which have been utilized to gather data on a range of species [13]. A main concern in studies, which have included GPS trackers and used satellite uploads to transmit data to a base station, was a tradeoff between energy consumption and data quality. As the devices were typically operating off non-recharged battery supply and satellite uploads were found to be power-intensive, the data collection capacity of the devices was constrained [11], [13]. In addition, such GPS loggers have been found to be unsuitable for densely vegetated habitats as they require clear view of the sky and may have surprisingly large location errors [13].

Experiences with GPS devices have also been reported specifically for bicycle-focused studies. For instance, Hood et al. [8] monitored routes taken by bicyclists using GPS data and compared routes taken by cyclists to shortest routes. While the authors were able to identify key factors that influence cyclists' choices of routes, they also report that a large number of the collected GPS traces had to be discarded, with one of the primary reasons being the poor signal quality. Similarly, Dill [5] collected data on cycling behavior by means of a specially programmed personal digital assistant with GPS. The author found evidence for an impact of infrastructure on cycling, but only about half (53%) of participants of this study indicated that all of their trips had been recorded, while for the remaining 47% at least one trip was missing. In an investigation into the feasibility of using either GPS units in smartphones or high-quality external GPS receivers to track the positioning of bicycles in specific lanes, Lindsey et al. [15] report limitations for tracking with both types of GPS devices as the built urban environment was found to interfere with GPS signals and affected data quality.

While numerous studies have investigated the performance of GPS trackers from a technological perspective as described above, insights into the perception of data collected by such devices is very scarce [9] and mostly restricted to comparative studies, which examine the design and functionality of smartphone applications which utilize GPS tracking [9], [12].

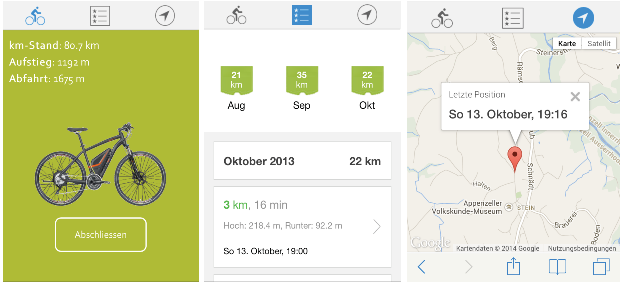
Summing up, GPS trackers have thus been explored for capturing and transmitting information about objects such as animals, athletes or bicycles. While from a technological perspective, important challenges appear to lie particularly in the tradeoff between energy consumption and data quality, in the completeness of data collection as well as the accuracy of the collected data, little is known about the perception of or requirements towards the collected data by users.

3. METHOD

Due to the explorative character of the research questions, a qualitative, field study-based research approach was chosen. For the purpose of the field study, 32 participants were provided with e-bikes for the duration of approximately four months. The participants (14 women, 18 men) were employees of a Swiss insurance company (30) and of the local university (2) and at the age of 22 to 64 years (M = 35.3; SD = 11.9). All e-bikes were equipped with prototypes of GPS sensors, which we had received from a large German technology manufacturer. The sensors were connected to the e-bike battery for power supply and transmitted the GPS data by means of a built-in GSM connection. GPS position information was collected every 60 seconds of a trip or after 50 meters of trip distance had been completed.

Data was collected from two main sources. First, GPS log data generated by the e-bike sensors was analyzed. Second, semi-structured interviews were conducted with all participants of the field study. This method offers the advantage that the researcher can keep a more open mind about the topics to be covered in detail during the interview, so that theories and concepts can emerge out of the data [1]. An interview guideline was developed in order to structure the responses [1], which was evaluated in two mock interviews and consequently refined. All interviews were audio recorded with a smartphone and the interview length was M = 20 (SD = 5) minutes.

As part of the interviews, interviewees were given the opportunity to explore a smartphone application, which had been developed as part of the research project and visualized the data collected by the e-bike sensors. As illustrated in figures 1 to 3, the app offered three main functionalities. On a first screen, interviewees could lock their e-bikes by clicking a corresponding button in the app. A second screen provided an overview of the trips the participant had made with his or her e-bike during the field study. By clicking on an individual trip, the interviewee was taken to a more detailed screen which showed the respective track on a map. A third functionality consisted of the visualization of the last known location of the e-bike on a map. In order to investigate a potential impact of the display of individual tracks on the overall assessment of the application, the app was discussed with the interviewees in two scenarios. In one scenario the full application was provided to interviewees and in a second scenario, only a limited version of the app was considered, featuring the locking and last location functionalities and excluding the trip details. In order to avoid a bias of results from the order of discussion, we alternated the sequence in which the two versions were reviewed and evaluated by the interviewees.



Figures 1, 2 and 3: Smartphone application visualizing e-bike data collected by sensors as discussed during interviews

The analysis of the interviews was conducted following inductive category building. This method allows for a systematic and structured analysis of content while avoiding a distortion of results by the researcher as much as possible [17]. In line with this approach, the material was systematically reviewed and analyzed in two main steps. First, answer categories were derived based on an examination of a first part of the interview material by reducing, rephrasing and generalizing answers. A first set of categories was considered complete when no new categories could be formed, after 47% of the material had been reviewed. Subsequently, a formative check of inter-coder reliability was conducted to assess the quality of the constructed categories. Two coders independently reviewed a randomly selected excerpt (19%) of the material [17] and the inter-coder reliability was assessed by means of Krippendorff alpha, a coefficient which assesses the agreement among coders relative to what could be expected by chance [14]. The calculation of the coefficient resulted in α = .744 (95% CI .666 .821), which is a level of reliability at which cautious conclusions may be drawn from the data [14]. In a second step, differences in coding were discussed by the coders and coding categories and guidelines revised accordingly before the remaining 53% of the material were coded. For a final assessment of inter-coder reliability, two further coders independently coded a randomly selected excerpt (19%) of the entire material. The summative inter-coder reliability resulted in a coefficient of α = .803 (95% CI .746, .856), a magnitude, at which variables can be relied on as it establishes confidence in the reliability of the coding system [14].

4. EVALUATION

4.1 Technological perspective

Over the course of our field study, we collected a total of 21’567 log entries including the sensor ID, time and GPS coordinates, i.e. latitude and longitude from 30 e-bike sensors. As some difficulty arose at the beginning of the field study with regard to the GSM connection of the sensors, an update of the embedded software was conducted after the first five weeks. 35% (7’509) of total log entries were collected before the software update, and 65% (14’058) entries refer to the remaining 12 weeks until the end of the field study. Figure 4 provides an overview of the latter data.

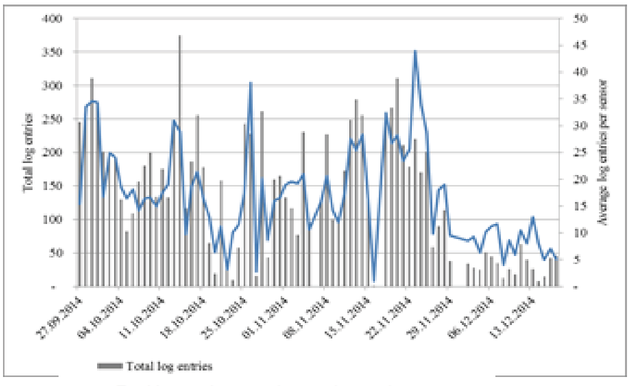
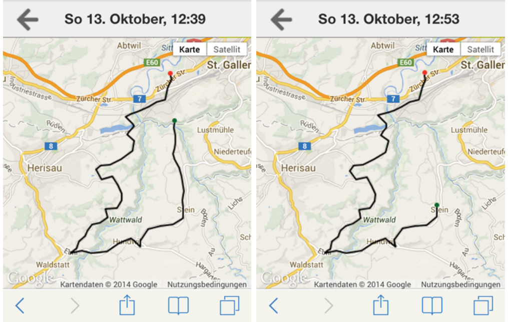


Figure 4: Log entries collected during field study

An examination of the accuracy of log entries reveals sporadic inaccuracies of GPS information at the beginning of our field study with log entries displaying unrealistic values e.g. in France and China as opposed to Eastern Switzerland, the location of the field study. No such issues were detected after the sensor software update as all GPS coordinates correspond to positions within the vicinity of the field study.

The completeness of the collected data appears more problematic in two dimensions. First, for one third of sensors no data was reported on the day of the return of the e-bikes at the end of the field study, i.e. in a situation for which movement of the e-bikes is confirmed, indicating that some sensors incurred issues leading to their complete failure at some point during the study. Given the explorative character of the field study and the development stage of the sensor, this was not unexpected and may be attributed to malfunctions in either the sensor, backend or network. Second, incompleteness of data was yet also found concerning the tracking of individual trips. Figures 5 and 6 visualize the joint trip of two field study participants. The illustrations show that one sensor started recording the trip at 12:39pm, while according to the second sensor, the trip only started at 12:53pm from a different location. A discussion of the trip with the field study participants revealed, that in fact both sensors are providing the wrong starting point and that the interviewees actually started at the same location at which both trips end.



Figures 5 and 6: Log entries for joint trip of two participants

Further evidence for the incompleteness of the data was encountered in the form of various comments by further field study participants, indicating that the displayed trips and distances did not reflect their actual usage behavior, as well as in a comparison of trips as collected by the sensors to a self-reporting of 17 field study participants over the duration of five weeks. As illustrated in figure 7, in on average 73% of cases, the self-reported information matched the data collected by the sensors, i.e. either a participant reported not to have used the e-bike and no data was reported by the sensor for that day or the participant reported e-bike usage and log entries were found. In on average 11% of cases, the participants indicated e-bike usage but no sensor data was logged on that day by the corresponding sensor. And in an average of 16% of cases, log entries were available for a specific sensor and day while the respective field study participant reported not to have used the e-bike. Naturally, the comparison of sensor data with self-reported information introduces two general sources of error, i.e. the sensor technology and the person who is self-reporting his or her usage behavior, and we cannot rule out that some of the field study participants may e.g. simple have forgotten to report a trip or confused usage dates as self-reporting occurred on a weekly basis rather than daily. Nonetheless, the analysis constitutes a further indication for the probable incompleteness of data collected by the sensors.

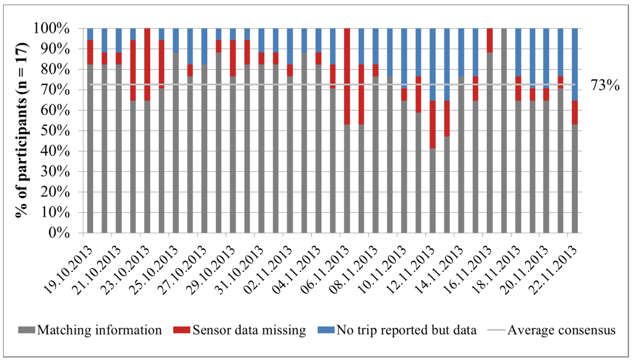


Figure 7: Comparison of sensor data with self-reporting

With regard to the power supply of the sensor, the e-bike as the object which we connected to the internet, offered the specific advantage of already being equipped with a rather large battery, which is in addition commonly recharged by the e-bike user. The e-bike battery is primarily intended to supply the power train with electricity, but was also utilized to provide energy for the sensor in our field study. Although the sensor could thereby be supplied with sufficient energy, we discovered negative implications of this design on the performance of the e-bike itself. At the end of our field study, 34% of interviewees reported issues with the performance of the e-bike battery, e.g. that the battery ran down very quickly or was found empty in the morning when it had still been half full the previous evening. We are confident that these problems can largely be addressed by improvements in the power management and sleep mode functionality of the sensor. Yet, such potential secondary effects on the operations of the object to be connected should in any case be taken into consideration in IoT settings.

All in all, our field study thus confirms the technological challenges of GPS sensors with regard to completeness of data collection as well as energy consumption, which can be found in the literature, while accuracy of data was not a main concern in our case. We further showed that, with regard to energy consumption, sufficient energy for a GPS sensor might be procurable by tapping into existing, product-specific energy sources, such as on an e-bike, but that undesired negative effects on the performance of this product itself need to be considered. Finally, we identified GSM coverage and service provider roaming as further potential sources of malfunction, which may become relevant particularly in an IoT context.

4.2 Consumer perspective

Our discussion of the e-bike sensor and corresponding smartphone application with the participants of the field study generated interesting insights particularly with regard to the interviewees' interest in e-bike sensor data and the information privacy of such data.

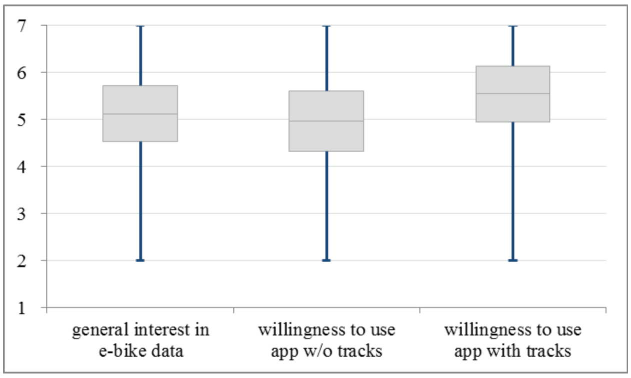


Figure 8: Interviewee interest in e-bike sensor data and willingness to use smartphone application

As illustrated in figure 8, the interest of field study participants in the data generated by the e-bike sensor was generally high. On a 7-point Likert scale, ranging from 1, i.e. very low to 7, i.e. very high, interviewees responded with an average of 5.13 (95% CI 4.53, 5.72) when asked about their interest in the data generated by the e-bike sensor. Responses regarding the interviewees' willingness to use the smartphone application, which was introduced to them during the interviews, were similarly positive (M = 4.97; 95% CI 4.33, 5.61 for app version without tracks; M = 5.55; 95% CI 4.95, 6.14 for app version with tracks). On average, participants expressed a higher willingness to use the more elaborate version of the application including a locking functionality, the last known position of the e-bike as well as details of individual trips (M = 5.55, SE = .29) than the version which did not display detailed tracks (M = 4.97, SE = .31), $t(31) = -2.16$, $p < .05$, $r = .36$. While on average, interest in e-bike data and willingness to use the discussed smartphone application appear to enjoy similar resonance, a closer examination of responses indicates a more differentiated picture. For six respondents, interest in e-bike data and willingness to use the app in either version were equally high. Further 14 respondents displayed a higher willingness to use the app than they had previously stated an interest in the e-bike data, implying that the visualization of the data within the app may have had a positive effect in these cases. However, twelve interviewees showed a lower willingness to use at least one version of the app compared with the degree of interest in the e-bike data they had stated before. Comments by these participants suggest that this may be attributed to a relatively high level of expectations, which these interviewees have and which have been raised by the usage of alternative smartphone applications particularly in the sports and fitness area: "It looks ok, but I've seen much more sophisticated apps, which offer more possibilities.", "It would be nice if the trip information could be enhanced with further information."

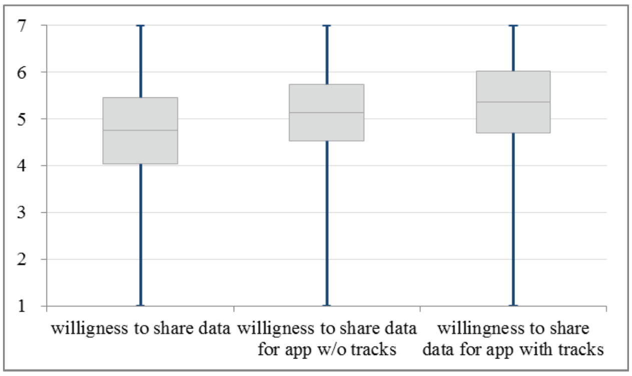


Figure 9: Interviewee willingness to share e-bike sensor data with e-bike manufacturer

With respect to the information privacy of the e-bike sensor data, interviewees displayed a relatively high willingness to share their e-bike sensor data with the manufacturer of the e-bikes on a 7-point Likert scale, ranging from 1, i.e. very low to 7, i.e. very high (M = 4.75, 95% CI 4.05, 5.45 for willingness to share without presence of app; M = 5.14, 95% CI 4.54, 5.75 for willingness to share if access to app without tracks; M = 5.36, 95% CI 4.69, 6.02 for willingness to share if access to app with tracks) as illustrated in figure 9. No significant differences could be detected between the three scenarios, i.e. on average, participants were not found to be more willing to share information if they were offered access to a smartphone application in return. Nonetheless, a more detailed look at the interview results suggests that three types of respondents might in fact be identified in this context. First, a group of 13 participants, showed a higher willingness to share their data when offered access to a smartphone application. Comments by these interviewees suggest, that this may be attributable to the notion that they receive something in return for their data and are thus more willing to share it: “My interest in my performance would probably outweigh my reservations regarding the disclosure of the data.” Second, ten respondents indicated a lower willingness to share their data after they had seen the app. Two potential explanations for this behavior might be offered based on interviewee comments. Either, participants may not have fully grasped which type and extent of data the e-bike sensor collected until they were shown the app and consequently revised their assessment of the corresponding data sensitivity: “I would share it only under the condition that it’s anonymous and used only internally.”, “I just do not want to be located.” Or, the introduction of the smartphone app may have created a sense of expectation, which the specific app, which was shown to the interviewees, could not fulfil: “I feel like I’m not getting something in return.”, “I would rather use other apps which offer more information.” Finally, for a group of eight interviewees, the willingness to share the e-bike sensor data was neither increased nor decreased by the introduction of the smartphone application.

Summing up, we find a relatively high interest of field study participants in the data collected by the e-bike sensor and a similarly high willingness to use a smartphone application displaying such data. The willingness to use the smartphone application is significantly higher if the app includes a broader set of features rather than a limited offering. At the same time, existing smartphone applications in the sports and fitness domain appear to represent a benchmark in the evaluation of such offerings and induce high quality standards. With regard to information privacy, the willingness of field study participants to share their e-bike sensor data with the e-bike manufacturer is relatively high on average. However, three patterns appear to materialize among participants where for one group of respondents the willingness to share data can even be increased through the offering of a corresponding smartphone application while other interviewees displayed an opposing behavior and willingness to share their e-bike sensor data was effectively reduced after being shown the smartphone application, and a third group of participants did not change their opinion in dependence of the availability of a smartphone application.

5. DISCUSSION AND CONCLUSIONS

In this paper, we investigated the challenges and requirements of the implementation of a connected e-bike, from technological as well as consumer perspective. Our findings are derived from a field study with 32 users, who were provided with e-bikes, which had been equipped with sensors featuring GPS units and GSM connectivity, for the duration of four months. With regard to our first research question, which technological challenges affect the development of an e-bike sensor and the quality of data from such a sensor, we find evidence confirming the technological challenges of GPS sensors especially with regard to completeness of data collection, which can be found in the literature. We identify GSM coverage and service provider roaming as further potential sources of malfunction with particular relevance in IoT settings and finally encounter undesired negative effects of supplying energy to the sensor from the e-bike battery on the performance of the e-bike itself. Concerning our second research question, which requirements users have towards an e-bike sensor and a “connected e-bike”, we see a relatively high interest of users in the e-bike data, which is however accompanied with high expectations regarding data quality and visualization that appear to be driven by existing smartphone applications, which are setting standards in the sports and fitness environment. The willingness of users to share their e-bike sensor data with the e-bike manufacturer appears generally high. The offering of a smartphone application which visualizes the data can increase some users’ willingness to share their data, while it has the contrary effect on others and no impact at all on the assessment of a third group, resulting in no significant impact on average.

While our findings are derived from a field study involving a relatively small sample, we suggest a number of insights might be gained for theory and practice. Our research indicates that user interest in data from a connected e-bike may be high, while information privacy issues appear not to represent a major concern, which is an encouraging finding for the development of intelligent future transportation systems. Yet, our findings suggest that technological restrictions still exist with regard to the completeness of data collected by GPS sensors and the energy consumed to collect such data, while in the meantime user expectations towards accuracy and visualization of data have reached high standards. It appears as though trade-offs exist between the completeness of data and the energy consumption of a sensor as well as the attractiveness of use cases to consumers and the convenience of data collection. Hence, practitioners as well as researchers may want to consider either a focus on use cases, which are feasible on the basis of a less complete set of data or alternatively the leveraging of user smartphones for collecting and transmitting data in addition to embedded sensors. We suggest that such challenges should be reflected upon also in the software development process. While requirements engineering suggests that user requirements are the starting point for development [21], the possibilities and limitations of technologies might in fact be a crucial building block to begin with, in domains where technology enforces major restrictions.

Some limitations need to be considered in the assessment of our contribution. First, as the focus of our contribution is on a holistic view of the implementation of an IoT application, we do not address the solution of individual technological problems. Next, our results are explorative in nature and based on a small sample of 32 participants in our field study, which of course limits the generalizability of our findings. Next, the field study was geographically confined to Eastern Switzerland and conducted during the months of August to December, a period which is not ideally suited for a warm weather endeavor such as bike riding, which might further restrict the generalizability of our findings. Next, participants took part in our field study voluntarily, so that we cannot entirely rule out the possibility that they might be particularly interested in cycling and thus create a bias in our results. Finally, we utilized the prototype of a bike sensor for the purpose of our field study, which means that while we are able to provide insights into the challenges incurred in the development of such a device, it does not mean these issues might not in the future be addressable through further development.

Future research into the performance and user evaluation of GPS trackers based on a broader data basis and particularly larger samples should therefore be insightful. In addition, further investigations into potential improvements in energy consumption as well as completeness of data collection by GPS sensors would be highly valuable. Finally, it would be interesting to examine whether some consumers' willingness to share data may indeed be negatively affected by the visualization of such data in a smartphone application as indicated in our interviews, and how this issue might be mitigated.

6. ACKNOWLEDGMENTS

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