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Wi-Fi and Bluetooth based sensors for pedestrian detection in urban areas

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Abstract

An improvement of pedestrian infrastructure, as well as a higher amount of people walking in inner city areas are desirable. Pedestrian volumes can encourage urban planners and policymakers to argue for an enhancement of walkability. The growing number of mobile devices, equipped with Bluetooth and Wi-Fi interfaces, creates new possibilities in pedestrian data collection in indoor and outdoor situations. An automatic, cost effective pedestrian counting device, operating with Wi-Fi and Bluetooth data to acquire pedestrian information, is highly welcomed. Preliminary tests indicated that Bluetooth and Wi-Fi signals could indeed be utilized for the detection of pedestrians in urban areas. This paper describes the development and testing of a sensor, used for detecting pedestrians via Bluetooth and Wi-Fi signals in urban areas. Implemented controlled and open field tests indicated the practical usability of such a device for the collection of pedestrian data.

Keywords: Active Mobility; ICT Technology Applications; Sensors / Data Acquisition and Management

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1. Introduction

Pedestrian volumes are one of the key performances to evaluate the impact of pedestrian infrastructure improvements. Automatic counting techniques belong to the most promising strategies for enhancing the amount and the quality of pedestrian volume data.

Nowadays, most automatic counting approaches are designed for the motorized transport (Abedi, et al., 2015). The increasing amount of mobile devices, such as smartphones or mobile computers, in recent motivated transport researchers to evaluate the usage of that technique within the field of traffic engineering. Especially, the detection of Bluetooth (BT) and Wi-Fi Media Access Control (MAC) addresses was established as a new approach in automated traffic counting and for travel time estimations. Several authors used and tested the systems for the motorized transport, both on urban roads (Abbott-Jard, et al., 2013) and on highways (Araghi , et al., 2012).

As in motorized transport, methods for automatic traffic counting for non-motorized modes of travel have more and more been investigated in transport research throughout the last years. Some techniques for automatic pedestrian counting, such as infra-red beams, laser scanners and piezo-electric pads, were examined and compared to each other by Greene-Roesel, et al., (2008). Most of these approaches are basically designed for indoor areas and are widely used to count people entering or leaving shops. Main drawbacks were figured out for the usage in outdoor environment, such as disturbances due to weather phenomena. In addition, video based camera systems were examined throughout the last years and their usage for counting pedestrians was tested. Advanced video surveillance has a good capture rate, but its automatic data acquisition is highly sensitive to weather conditions, viewing angels and illumination changes (Liebig, et al., 2012). Also the relative high costs of video based approaches should be mentioned as a certain drawback.

The generation of accurate and reliable pedestrian volumes for urban areas is highly welcomed by urban planners and policy makers to argue towards a better walkability in today's growing cities. A reliable automatic pedestrian counting approach using Bluetooth and Wi-Fi MAC addresses could deliver continuous pedestrian volumes for urban areas and points of interests. The increasing amount of mobile devices equipped with Bluetooth or Wi-Fi carried by pedestrians and cyclists indicates the high potential capability of that system. Previous research investigations were done for Bluetooth (Malinovskiy, et al., 2012) and Wi-Fi (Abedi, et al., 2015) sensors to evaluate their usage for gathering information about pedestrians. Ryeng et al. proofed in 2016 the usability of BT and Wi-Fi signals for the estimation of travel times of cyclists on varying gradients. Using the same sensor equipment as Ryeng et al. in a subsequent study pointed out several disadvantages of the equipment in the field of pedestrian detection. These results motivated us to set up an own, for pedestrian detection optimized sensor unit.

The paper gives an overview about some basic technical issues, regarding the development of the sensor unit and the used detection technique. The developed data processing methodology is presented and a set-up process for testing the sensors in open field tests is developed. The generated results are presented and discussed with respect to the boundary conditions of the system. Subsequently, the usage of the generated data sets for pedestrian volume estimations is examined. The study concludes by giving further recommendations for the usage of the system and its application for pedestrian data collection.

2. Bluetooth and Wi-Fi MAC address tracking for pedestrian detection

Some major technical aspects need to be considered, to understand how Bluetooth and Wi-Fi technologies can be used for automatic pedestrian counting. This study will introduce how MAC addresses in general could be used to track movements of people in urban areas. We will also analyze which technical characteristics of the used sensors are affecting the accuracy of the collected data.

MAC addresses are unique identifiers, which are used for various types of communication networks. Each Bluetooth and Wi-Fi device has its personal MAC address and can so doubtless be identified. Hence, these devices can be traced by sensors, which motivates researchers for different applications in the field of transport planning. As previous research by Abedi et al. in 2015 was pointing out, was MAC address data so far mainly used for routing and travel time estimation approaches, while this paper is about to set its focus on studying the application of MAC address data on detection methods for pedestrians in urban areas.

One of the main challenges of this technique is the discrepancy between the collected sample size and the actual amount of road users. Pedestrians may tend to carry several devices with them and might so be detected more than once. On the other hand, people who are not using any Bluetooth or Wi-Fi devices or who have turned off these functions, will not be detected by the sensors. Special user groups like children or elderly people might thus be underrepresented in the sample.

Sensor Equipment

The technical characteristics of the sensors and the design of their antennas are important factors in terms of efficient data collection. The probability of detecting a BT or Wi-Fi device is essentially dependent on the characteristics of the antenna equipment such as signal strength and the size of the antenna's detection zone. As previous studies showed, should the characteristics of the antenna equipment be tailored to the mode of transport, which is about to be analyzed (Böhm, Haugen, & Ryeng , 2016). The probability of detecting a BT or Wi-Fi device is crucially dependent on the time, the enabled device spends in the antennas detection zone.

A car traveling with a speed of 50km/h will only remain for 3.6s in an exemplary 50m circular detection zone. Pedestrians, walking with a speed of around 5km/h and cyclists cycling with 15 km/h will remain in the zone for 36.2 and 12.0 seconds. Previous research showed that Bluetooth devices are detected within a maximum of 10 seconds. However, the usual detection time is around 4 seconds (Chakraborty , Naik, Chakraborty, Shiratori, & Wei, 2008). Considering Wi-Fi devices, the detection time is shorter and around 1.4 seconds for a device (Abedi, Bhaskar, Chung, & Miska, 2015). Regarding the motorized transport, a bigger antenna range should be considered due to the short residence time of only 3.6s in the exemplary 50m detection zone. The time pedestrians and cyclists are within this detection zone can be considered as enough for being reliably detected by the sensors.

Operating with more powerful antenna equipment with larger detection zones for the detection of non-motorized transport can have certain drawbacks. A wide antenna range in urban areas increases the complexity and the processing time of the data analysis (Böhm, Haugen, & Ryeng , 2016). This is caused mainly due to the fact that antennas with higher sending power will collect more samples as they cover a wider area. If the antenna is mounted in crowded inner city areas, a lot of so called background noise may thus be detected. Background noise includes Bluetooth and Wi-Fi signals, sent by non-travelling devices, such as fixed units, mounted in buildings within the antenna's coverage zone, like Wi-Fi routers, smart TVs or stationary computers in offices or apartments. Hence, sensors which are about to be developed for the detection of non-motorized modes of transport should operate with smaller antenna ranges to avoid the detection of too many background signals from fixed devices. A previously performed field test with stronger antennas proofed these concerns. Especially the overlapping of large antennas detection zones in narrow urban surroundings limited the quality of the generated data significantly, since a device was detected by two sensors at the same time.

The during this study developed sensor is tailor-made for the detection of non-motorized travelers in urban areas and consists out of a micro computer chipset and a Wi-Fi and a Bluetooth antenna. The Wi-Fi and Bluetooth antennas are dongles, which are operating in monitoring mode. One of the intentions throughout the development of the senor was, to create an easy to handle and low-cost device, which could be places in many different urban surroundings. Figure 1 shows the sensor unit together with a battery pack in waterproofed box. The sensors can be supplied with a 12V power source. The device is so able to detected BT and Wi-Fi MAC addresses for around 24 hours, before the battery runs empty. Ongoing tests showed the potential to extend this period to up to 3 days by supplying the device with electrical power from a car battery. The sensor can also be connected to a stationary power supply, which makes the frequent battery changes dispensable. The battery solution on the other hand makes the sensor extremely portable and flexible in its usage in different interesting areas. The collected data is stored on an internal SD card but could also be provided to a remote interface if the device would be connected to a mobile network during the recording.

Figure 1 BT / Wi-Fi sensor device

Table 1 gives an overview about the used antennas and their main technical characteristics. The antennas sending power is measured in decibel isotropic (dBi) units.

Table 1 Technical Sensor Characteristics

Interface	Type	Power	Range
WiFi	omni-directional	5dBi	~ 25m
Bluetooth	omni-directional	3dBi	~ 25m

The dongles are plugged via USB to the sensor and can easily be removed by other dongles with stronger antennas and thus larger detection zones. The sending power of the used antenna equipment was chosen due to experiences from previous tests of equipment with stronger antennas for pedestrian detection. These tests proofed the previously mentioned concerns of detecting a high amount of non-relevant fixed devices in a larger antenna detection zone.

3. Method

Field test

In order to investigate the reliability of the collected data, a two-stop test approach was performed to investigate the rate of detected devices and to compare the numbers of detections with actual pedestrian volumes. Therefore one controlled and several open field tests were conducted.

The controlled field test provided us with information about how many of a known number of theoretical possible detections of different BT or Wi-Fi devices were actually made by the sensors. A controlled test run was performed during nighttime with a known amount of BT and Wi-Fi devices such as mobile phones or cameras, passing the sensor unit. The produced datasets were afterwards analyzed to investigate to share of actual detections. The absence of further devices, except the ones used during the test at night gave us a precise overview of the detection performance of our sensor.

In order to investigate the reliability of the system, a comparison to the real number of pedestrians passing the sensor was needed and investigated in two open field tests. These tests took place during the morning peak hours of two different weekdays between 07:00 and 10:00. The field tests were perfomed at Gangbrua, a bridge across the Nidelva River in Trondheim. The sensor equipment was mounted at each end of the bridge. The bridge connects the city center of Trondheim with the residential area of Øya and is accessible for pedestrians and cyclists only. The bridge has a total length of 175m and is 3.8 m wide.

Counting pedestrians in inner city areas can be rather challenging due to the crowd-based movement characteristics of walking people. Pedestrians change for instance their direction more often than cars and tend to dwell in certain areas. The chosen test location was a bridge, due to the relatively low complexity of pedestrians' movement behavior in this place.

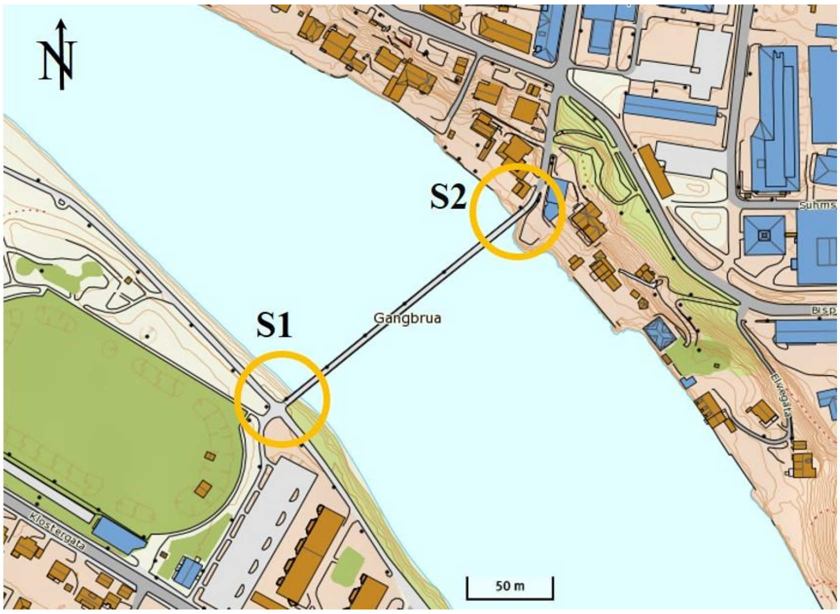

Figure 2: Overview field test area and sensor location on Gangbrua in Trondheim / Norway

Figure 2 shows an overview of the study area at Gangbrua and the location of the sensors, as well as a sketch of their approximate detection area. The antenna detection zone of the sensors on the eastern side of the river is slightly covering a residential area around the bridge. Besides private houses, also an office building is located within the detection zone of this antenna. The relative low environmental complexity and the previously performed tests in this area seemed to indicate the area as appropriate for a first test of the developed sensors for pedestrian detection. During the study, only devices, which were detected by both of the sensors were taken into account for further data processing, which means that only pedestrians who were actually crossing the bridge were registered. The parallel performed manual pedestrian counting was done in the middle of the bridge and pedestrians were counted while they were passing an imaginary line in the middle between the two sensors on the bridge.

Data Processing

The raw data sets provided by the sensors had to be processed to obtain the required information. If the detection zones of the antennas for a two sensor approach are not overlapping, fixed devices will not appear in the data set due to the fact that only MAC addresses which are detected by both of the sensors are registered.

Table 2 shows a part of the sensors' raw data output, generated by one of the devices during the study. Beside the MAC address, a timestamp, a received signal strength indicator (RSSI) and the interface through the device was detected is registered.

Table 2 Exemplary raw data set from BT / Wi-Fi sensor device

Timestamp	MAC Address	RSSI	Interface
17:28:17	00:0f:60:0a:26:ba	-67dBm	Wi-Fi
17:28:23	00:0f:60:0a:26:ba	-63dBm	Wi-Fi
17:28:37	7c:f9:0e:ed:08:31	-85dBm	BT
17:28:38	b8:27:eb:b0:08:95	-19dBm	Wi-Fi
17:28:41	00:0f:60:0a:26:ba	-35dBm	Wi-Fi

The RSSI value is sent from every detected Bluetooth and Wi-Fi device and indicates the strength of the received signal (Lui, Gallagher, Li, Dempster, & Rizos, 2011). The higher that characteristic value is, the closer is the detected device to the sensor (Sauter, 2011). Devices, which are detected with a low RSSI value, are in further distance to the sensor, than those with high RSSI values. The range of the observed RSSI values is in a range between -100 and 0.

Pedestrians are traveling with a relatively low speed, while they are in the sensor's detection zone. Thus, the probability of several detections of one device is high. In case a MAC address was detected more than once while the device was in the 50m circular antenna detection zone, the MAC address with the highest RSSI value was filtered out and used for further matching purposes. The registered MAC address with the highest RSSI value was thus detected closest to the sensor and can gives us some relative precise information about the location of the detection. Controlled tests showed that RSSI values of around 0 to -30 are equal to distances of 0 to 5m from the sensor. Devices with RSSI values in range between -30 and -60 were approximately 5 to 15m away from the sensor. Information about the approximate distance of the registered devices to the sensor can help to distinguish the different modes of transport from the collected data. Due to the fact that every MAC address is registered in combination with a time stamp the speed of the travelers, passing both of the sensors can be calculated. During this study a cut off value of 7 km/h was used to distinguish between cyclists and pedestrians. All devices traveling slower than 7km/h were considered as pedestrians, while all devices travelling faster than 7 km/h were considered as cyclists. The manual countings showed the presence of a group of runners which could possibly be assigned to both groups since their speed levels are between 6 and 12 km/h. We did not include such a third group within this preliminary study but are about to test this approach in ongoing reserach.

4. Results

The following chapter presents the findings of several tests performed with the developed sensor equipment. Initially, a controlled test run was conducted, to examine the coverage of the antenna equipment, followed by open field tests. Parallel manual countings helped to evaluate the reliability of the equipment's detections during the open field tests.

The controlled field test was arranged in order to investigate how many of the enabled Bluetooth and Wi-Fi devices, passing the sensor are registered. The test was implemented on the early morning of Monday, August 1 2017 between 02:10 and 03:10 at the Gangbrua location. A test person passed the sensor (10 times back and forth) carrying six mobile devices in bags or pockets (mobile phones, cameras, PC mouse, wireless speaker). Three of the devices were equipped with a Bluetooth interface and all six of them with Wi-Fi. The sensors registered 37 out of 60 potential Wi-Fi trips (62%). Considering the Bluetooth sensor equipment, 25 out of 30 possible trips (83%) were detected. The detection rates are in line or even slightly higher than found in previous own tests with different sensors (Böhm, Haugen, & Ryeng , 2016). In addition, other researchers such as Abedi et al. found in 2015 similar shares between BT and Wi-Fi detections while they were using similar sensors in comparable urban geometries. The subsequently preformed open field test should demonstrate how close the data sets from the sensors are in numbers and structure to the parallel done manual counts.

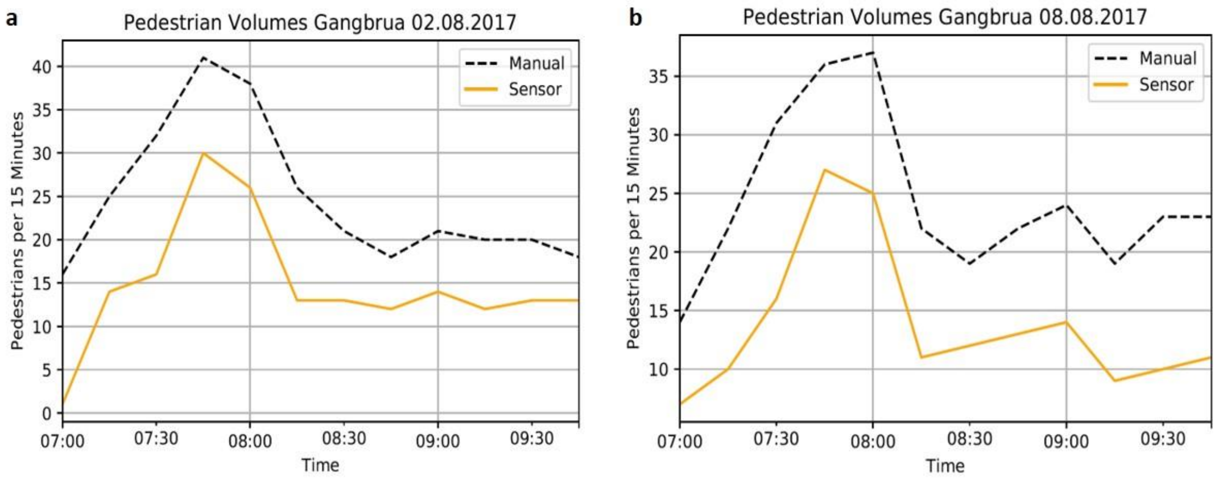

Figure 3 Pedestrian volumes and parallel generated sensor data collected on field tests on 02.08 (a) and 08.08 (b)

The graph in Figure 3 shows the results of two field studies, performed during the morning peak hours (07:00 to 10:00) of Wednesday 2nd and Tuesday 8th of August 2017. Both during the manual counts as well as in the detections made by the sensors, only pedestrians who were crossing the bridge from the western to the eastern side of the river were taken into account. The orange lines in figure 3 are showing the results, including the Wi-Fi and BT data sets. The dashed black lines are showing the pedestrian volumes, generated through the manual counts.

During the manual count on the 2nd of August, in total 296 pedestrians were detected while they were crossing the bridge between 07:00 and 10:00. The number of people passing the bridge increases from 07:00 to 07:45, when it reaches a peak of 41 counts per 15 minutes and decreases afterwards to a plateau of around 20 counts per 15min. The detected Wi-Fi and BT signals follow the structure of the manually counted pedestrian volumes. 87 % [258/296] of the detected devices during the field test on the 2nd of August were Wi-Fi units and 13% [38/296] were Bluetooth devices. During the field test on the 8th of August, in total 292 devices were detected. The data has a similar structure, compared to the previously conducted field test. We see a clear morning peak and a flattering data structure towards a plateau afterwards. The field test showed also a similar share of detections, made via the BT and Wi-Fi interface compared to the controlled test. 234 of the in total 292 detected devices were registered via the Wi-Fi interface (80%) and 58 devices (20%) were registered via Bluetooth. The relative low amount of BT detections is probably caused by the different daily usage of the interfaces. People might tend to leave their Wi-Fi interface turned on during the entire day. However, Bluetooth might be used and turned on only when it is actually needed, for example to connect a phone with a car or wireless speaker. People might leave Bluetooth turned off by default to save battery power.

The similar structure of manually counted and sensor-detected pedestrian volumes motivated further investigations to evaluate the structure of pedestrian volumes over a longer period. Therefore, the sensors were running for 50 hours while in particular the detections on Friday the 4th and Saturday the 5th of august were taken into account for further analytics. The same data processing approach as presented previously was implemented. Figure 4 shows the results of Friday the 4th and Saturday the 5th, where in this case the data is grouped in hourly intervals and again only pedestrians are taken into account. Ongoing tests are about to include data, collected from cyclists as well. Therefore the distinguishing method for data from the different modes of transport is about to be further optimized. The data for the observed days is different in its structure, which was about to be expect since we were running the experiments on one day during the week and on one day during the weekend. The blue graph shows the typical characteristics of a morning and an afternoon peak hour and a realtiv low amount of detections during the night. The detections during Saturday are increasing at around 09:00 and do not have obvious peak hours. The generated numbers are of course not representing the actual amount of pedestrians crossing Gangbrua but do give an overview about the structure and shift of the volumes.

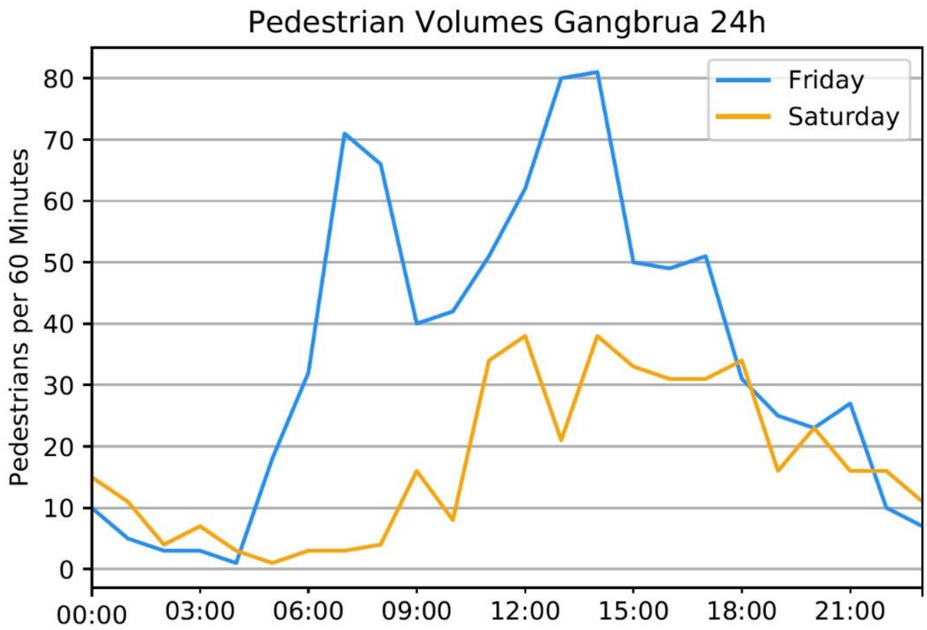

Figure 4 Pedestrian volumes Gangbrua 24h

The results from both tests are fitting into the travel behaviour of pedestrians on Gangbrua. As already mentioned is this bridge connecting the Øya residential area with the inner city of Trondheim. The morning peak during weekdays indicates the importance of the bridge for people to commute to work or school. Pedestrians, returning from work or school back to their homes, cause probably the afternoon peak hour. Pedestrians are using the bridge also during the weekend, to access the city centre of Trondheim.

5. Conclusion

The implemented field studies and the following data processing approaches confirmed the suitability of the developed sensor units for detecting pedestrians in urban areas. The controlled test runs showed the specific probabilities of detecting passing enabled Bluetooth and Wi-Fi devices. Additional tests could strengthen the justification of the presented method. The developed data processing approach helped to match the MAC address data from both sensors. Furthermore helped the generated RSSI values to filter out the detections, made closest to the sensor. The RSSI values are hereby used as a quality indicator for the local accuracy of the data and controlled test runs categorized RSSI values to ranges of physical distance. Thereby the preciseness of categorizing detected devices into speed levels was increased, which helped to distinguish between different modes of transport. Nevertheless should the discrimination between different modes of transport be part of ongoing research approaches. This study was using a hard cut off value of 7 km/h to distinguish between cyclists and pedestrians. Both the recorded data as well as the observations during the manual countings indicated the need of having a closer look into runners or slow cyclists, who may now be categorized wrongly, since they are not moving with the predetermined speed levels.

Previous studies introduced calibrating factors, to scale the generated data from BT and Wi-Fi MAC address detection sensors to pedestrian volumes in real scenarios. These factors need to be calculated for each observed area and require a certain amount of parallel manual countings, both in peak and non-peak hours. The generated pedestrian volumes can help to proof the importance of existing infrastructure for pedestrians. Reliable pedestrian volume data helps urban planners and policy makers to argue for an enhancement of walkable infrastructures. Pedestrian volumes and their variation over time could thus also point out the necessity of an improvement of pedestrian infrastructure due to the high or increasing amount of people walking in an observed area.

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