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Design, Implementation and Testing of a New Mobile Multi-Function Sensing Device for Identifying High-Risk Areas for Bicyclists in Highly Congested Urban Streets

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Abstract

The number of bicycle riders in New York City has been increasing steadily in the past few years. These numbers include private and shared bicycles. NYC bicycle network has been expanded to accommodate this new volume. Although this new infrastructure has reduced the number of cyclists killed or seriously injured (KSI) in some areas, in other areas similar improvements were not observed. This inconsistency of how the number of bicycle crashes varies from one region to another in the city is the primary motivation of this paper. A highly portable and inexpensive sensing device for measuring the distance between a bicycle and lateral objects is designed from scratch and developed. The developed mobile sensing device can also map bicycle trajectories to highlight critical segments where the safe distance from passing vehicles is not respected. This device which is powered by a portable power source is comprised of two ultrasonic sensors namely, a Global Positioning System (GPS) receiver, and a real-time clock (RTC). The sensor is secured inside a custom design 3D printed case. The case can be easily attached to any bicycle including shared Citi Bike bicycles for testing. The final prototype is entirely functional and used to collect sample data to demonstrate its effectiveness to address safety-related problems mentioned above. Finally, a dashboard is created to display collected key information. This key information can be used by researches and agencies for a better understanding of the factors contributing to the safety of bicycle routes.

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1. Introduction

Many cities throughout the world have been investing in bicycle infrastructure to improve the safety of bicycle routes due to the increasing importance and potential of biking as an alternative mode of urban transportation. In New York City (NYC), daily bicycle ridership has increased by 70% between the years 2011 and 2016. The average annual growth rate of daily cycling for the same period was 11.2% [1]. Biking has become an important part of commuting as bicycle routes and shared bicycle stations have been dramatically expanded in the city. Currently, NYC has more than 1,100 miles of bicycle lanes [2]. Although there have been significant improvements in the city regarding bicycle facilities, clearly, they do not cover the whole city. For example, the neighborhoods that are further from Manhattan have minimal to no bicycle infrastructure.

The areas with the highest number of bicyclists killed or seriously injured (KSI) in 2016 were in Brooklyn and Queens. Both boroughs have fewer protected and conventional lanes than Manhattan. Seven districts in Brooklyn and three in Queens are considered priority bicycle districts by the NYC Department of Transportation (NYCDOT) [2]. Each of these districts has a high KSI with either medium or low coverage of bicycle facilities. NYCDOT [2] has also identified the categories of crashes responsible for the highest number of cyclist fatalities: cyclist traveling adjacent to a motor vehicle (29%), a cyclist traveling at a right angle to a motor vehicle (27%), and collisions with turning motor vehicles (21%). These fatalities happened mostly at intersections (65%). Based on the types of crashes, one might assume that districts with higher bicycle network coverage would have a lower KSI, and vice versa. However, this is not always the case. They might not always present positive or negative correlations [3, 4]. There are districts that have even fewer bicycle facilities than these priority bicycle districts, but they have a lower KSI [2]. These circumstances raise questions about how these facilities and human behavior influence the overall safety of cyclists in the city.

Many factors can influence why some regions are safer than others. Some studies relate it to the number of cyclists on the road (Jacobsen [5] and Bhatia and Wier [6]). Other studies relate cyclist safety to the street infrastructure (Allen-Munley et al. [7]) or to the distance between the bicycle and moving/parked vehicles (Shackel and Parkin [8] and Walker [9]). Many states have laws that require motor vehicles overtaking bicycles to maintain a safe distance of 3 ft. In New York City there are no specific legal restrictions for vehicles overtaking bicycles [10], but there is a recommendation for cyclists to maintain a safe distance of 3 ft from parked vehicles [11]. Although these studies show relevant to bicycle safety, they can be improved with more data for validation.

With the help of disruptive technologies in transportation, newer and more intelligent sensing systems are being deployed in motorized vehicles. While the advancements in mobile wireless communication and Internet of Things (IoT) technologies have made connectivity between various elements of the transportation system possible, non-motorized modes have not received as much attention. Most of the technologies designed for intelligent vehicles can actually be modified for use with non-motorized transportation modes. However, there are not many studies in the literature providing insights into bicycle and bicyclist dynamics utilizing intelligent sensors. Part of the reason for this is due to the unavailability of on-board power, which can be solved with the use of portable power chargers. The introduction of e-bikes might also solve this issue, as their motor can be used to power the mobile sensing device.

Thus, there is an increasing need for the development of new unobtrusive and low-cost technologies to help improve data collection for research that focuses on promoting the safety of bicycle users. With the proliferation of IoT devices, sensors, and open-source information, it is now possible to develop devices that address different challenges of the data collection process. In addition, data visualization tools have improved with the advance of technology. Using dynamic dashboards to consolidate the key information from data sets in one screen allows users to more easily analyze the data and draw conclusions from it.

Our main objective is to use emerging mobile sensing and other technologies to improve the safety of bicyclists in urban environments. We hope to achieve this overarching objective via three distinct and challenging goals. The first goal is to use the developed mobile sensing device to identify hotspots where vehicles operate dangerously close to the bicycle. This information is expected to help identify high-risk street segments for bicycles. The second goal is to build a comprehensive dataset for existing and future studies. The final goal is to create a device that will alerts bicyclists when they might be in a dangerous situation.

This paper mainly focuses on our first goal of developing an integrated, inexpensive and highly portable mobile sensing device as well as an accompanying customized software platform for collecting and processing bicycle safety
data. This portable and multi-functional sensing device which can collect bicycle trajectory data and lateral distances between the bicycle and objects around it is built using ultrasonic sensors connected to a Raspberry Pi (R Pi) to measure the distance between the bicycle and lateral obstacles, especially moving vehicles. R Pi is a single board computer using a Linux based operating system, and it is widely used in research projects in the literature (Miha [12], Dozza et al. [13], Ambrož [12], Kurkcu and Ozbay [14], and Kurkcu, Ozbay [15]). Fig. 1 shows how the bicycle is usually positioned on the road and a representation of ultrasonic sensor measurements.

![Fig. 1 - Bicycle/Motor vehicles clearance detection representation](image_url)

The second outcome of the project is a customized software architecture. The developed architecture has a structure focused on the collection and processing of the ultrasonic sensors and Global Position System (GPS) receiver used in this project. The device can be adapted to attach to different types of bicycles, including e-bikes. This would allow devices to be deployed across a fleet of bicycles, providing large-scale, crowdsourced data. Crowdsourcing can provide a significant volume and variety of data to help improve data reliability and validate safety studies.

The following sections discuss in detail the development of the sensor device. The next section provides the context for the development of the project. The device architecture section describes the components of the device, its operational system, and the steps of the development of the device. The preliminary data results and visualization section describes the results of preliminary data collection efforts and presents a new dashboard design containing the main information provided by the device. The final section presents the conclusions and discusses the main findings of the work and suggests ideas for future work.

### 2. Background

The number of studies concerning bicyclist safety has significantly increased in recent years. They range from identifying the factors that influence the number of incidents involving bicyclists, to new technologies deployed to improve the data collection and overall experience of the bicyclist. Most of these bicycle safety studies have mainly used data available from surveys, police crash reports, and simple video observations. Their efficiency can be improved by making the data collection process more ubiquitous, faster and more reliable and inexpensive. For example, Laureshyn, Goede [16] used video processing to evaluate accidents involving cyclists at intersections in Norway. They compared three different models by how they quantify and identify the frequency of the accidents by type. Their results show that the models have great potential as tools for identifying unsafe interactions. Nonetheless, more data is needed to validate these models. A possible solution for acquiring more reliable data is the use of multiple sensors for continuous data collection. Dozza and Fernandez [17] implemented a device using multiple sensors to collect cycling data. The study presented a methodology similar to that used for naturalistic driving data for motor vehicles. They collected data including video, acceleration, directional vector, angular rate, latitude and longitude, heading, velocity, and pressure on the brake, which was used to understand the behavior of cyclists and bicycle dynamics.
In addition to the increase in ridership of traditional bicycles, the introduction of e-bikes has brought up new considerations in bicycle safety studies. The e-bikes can reach higher speeds and enable longer rides. Therefore, they increase the probability of accidents involving cyclists [17, 18]. To understand the differences between bicyclist behavior and dynamics of traditional bicycles and e-bikes, Wemeke and Dozza [19] and Dozza [18] created two systems called BikeSAFE and e-BikeSAFE to collect naturalistic cycling data from traditional bicycles and e-bikes. They identified that the collection of data from e-bikes is still not as efficient as on traditional bicycles. The development and enhancement of systems like e-BikeSAFE can provide valuable data to address the unique issues of e-bikes.

A significant example of how such sensors could help with e-bike safety is the latest problem faced by Citi Bike. The company announced that it would expand its fleet with 4,000 pedal-assist e-bikes on February 28th, 2019. Shortly after the announcement, they reviewed a small number of reports from riders who experienced hard braking problems on the front wheel [20]. The New York Daily News [20] reported that one user flipped over the handlebars and broke his hip. The newspaper also confirmed at least four other people received medical treatment following incidents involving hard-stopping front brakes. However, it is still not clear whether the reason for such incidents is hard braking [21, 22]. If pedal-assist e-bikes had embedded smart sensors, it would have been possible to identify actual reason for these incidents by analyzing collected data from the bicycles.

Strauss, Zangenehpour [23] addressed deceleration braking and its relationship to cyclist safety in their study. They used smartphone GPS data to correlate the deceleration rate of traditional bicycles to the number of injuries observed at intersections and along with segments of the road. They showed that the deceleration rate has the potential to be used as a surrogate safety measure. Although smartphone GPS data was used to get the deceleration rates, it can have lower accuracy in dense urban environments. A combination of multiple sensors can expand the safety of all users on urban transportation networks [24].

Sensors can not only be used to record data for later analysis but also to perform real-time analysis of various data sets [25, 26]. A multiple-sensor system can be used to collect real-time data and process it to warn the bicyclists of possible dangerous situations. For example, it can identify a failure in the brake system or if the bicyclist is hard braking and warn the bicyclist to prevent an accident from happening. Liebner, Klanner [27] used a similar methodology to deploy a warning system for drivers. They use a smartphone GPS to continuously send the location of the bicycle to the warning device on the vehicle. The device uses that information to alert the driver in case of possible dangerous interaction. They use a high precision differential GPS to assess the accuracy of the smartphone GPS data.

Other projects have used ultrasonic sensors to measure the distance of motor vehicles overtaking bicycles. However, the size, weight, and cost of the equipment used in these studies are unsuitable for large-scale data collection. Shackel and Parkin [8] and Walker [9] used ultrasonic technology to measure the distance of a bicycle from passing vehicles. The device developed in this project differs from the previous ones because it adds the GPS module, which contributes to the identification of routes and critical points where dangerous overtaking happens. The use of cheaper and smaller components results in a product that is portable and adequate for mass data collection. The data obtained with the device can be used to help identify the locations where drivers get closer to bicycles and investigate if this behavior is related to the type of bicycle facility. Additionally, the mapping of hotspots of dangerous clearance between motor vehicles and bicycles can be combined with the crash data to evaluate the connection between safe distance and the KSI number.

3. Device Architecture

The mobile sensing device prototyped in this paper is designed to continuously measure the distance between two objects in a spatially-temporally accurate manner. The device is developed to collect lateral distance data with time and space stamps data to help analyze safety related patterns in terms of lateral distances between bicyclists and drivers operating in different types of bicycle facilities in highly congested urban transportation networks. To achieve this goal, a prototype which consists or multiple sensors was built and attached to a shared bicycle in NYC. To make the device portable and easy to mount, a special enclosure was designed using the software Fusion 360 and 3D printed in Polylactic Acid (PLA) with an Ultimaker 3 printer. Fig. 2 shows the finished rendered image of the mobile sensing device’s prototype.
Fig. 2 – a) 3D rendering of the device’s prototype. It includes the case, RPi, the ultrasonic sensors, GPS, and portable charger; b) Device with its components;

The device is built using two ultrasonic sensors, an RTC and a GPS receiver connected to a low-cost small computer board namely Raspberry Pi 2 B v1.2. The ultrasonic sensors used in this study are cost-efficient and can detect a variety of solid objects without being intrusive to pedestrians [28]. The maximum efficiency for this type of sensor is achieved when the pulse emitted is perpendicular to the surface. It can reach a minimum and maximum range of 2cm and 400cm, respectively. The accuracy of the sensors can vary depending on the temperature and humidity of the environment [29].

The sensing device is charged by a portable dual USB power pack, which has a 12,000mAh lithium-ion battery and output of 5VDC. The power pack can charge the device for up to 15 hours. The components chosen for building the device were based on their quality, cost, and dimensions. The final prototype dimensions are 11.2 cm by 16.5 cm, and its total cost is around $200.

A Python code was developed by the authors to read the data from the ultrasonic sensors and from the GPS receiver and then combine this data into a single file. The code defines the left and right sensors according to the GPIO pins they are connected to. The differentiation of left and right sensors is needed to identify if the distance read is from moving or parked vehicles. The data from the sensors and GPS are stored in a database file using the library SQLite3. Another SQL table is created to store log messages to keep track of when the GPS is initialized and there are reading errors.

The code is set to run on the device at the RPi operational system startup, and it keeps running in the background as long as the device is powered. The database file is created in the first run of the code and then, for the next runs, the data is added to the existing file. At the end of the data collection period, collected data is transferred to a desktop computer to be post-processed and further analyzed. Fig. 3 shows the sensing device’s architecture.

Fig. 3 – Architecture of the Developed Mobile Sensing Device
In Fig. 3, the first process represents the collection of the data by individual sensors of the device. The data aggregation process is performed when the data collected is pre-processed and temporarily stored by the device. The final step is to permanently store the data to make it available to the public. The visualization comes after the data analysis process. In the visualization process, the cleaned and processed data is used to create different visualizations for better understanding of various safety performance measures.

3.1. Data Analytics and Pre-processing

The stored data is transferred to a computer for further analysis using a secure file transfer protocol. When sensors have a network connection, this data transfer process can also be executed on-line. This feature will allow researchers to remotely analyze and evaluate historical and real-time data.

Currently, the data file is manually imported to a GIS software for data querying, analysis, and visualization. It is post-processed to clean the failed GPS readings, data points that are not part of a route actually flowed by the bicycle, or ultrasonic sensor measurements that are out of range or too large due to erroneous readings. The last step is to filter the above-mentioned data points and display the remaining relevant GPS pings on a map.

3.2. Data Storage, Management and Analysis

The final stage is for permanently storing the data and preparing it for final use and presentation. For this project, the final cleaned and queried data is stored in the cloud. The file containing the 3D design of the case was stored in the Autodesk cloud service. The project is open source, and its data and enclosure design will be made accessible in the GitHub repository after the completion of this project. The defined routes were associated with the characteristics of the available bicycle network and the time of day, such as if a determined trajectory was covered during the rush hour, at nighttime, and over a conventional bicycle lane or not. Finally, initial data visualization is enhanced by formatting and adding features such as legends and scale to the images. The graphs and images containing the main information of the data set are combined in a dynamic dashboard. The dashboard allows the user to see the different data combinations using filters.

4. Preliminary results and visualization

The device was tested in the real-world setting by a young and experienced male rider. The performance of the device was satisfactory for each of the processes namely, data collection, data aggregation, data analysis, and data storage. The data was collected for about 20 min and about 0.9 miles. The data set had some null values for the coordinates readings, which can be justified by the initialization time to get the minimum number of satellites needed by the GPS. The readings from the device did not present records out of range, but it had readings off for more than 2000 cm. These readings are assumed to be empty parking spaces, as they represent objects that were not in the range of the ultrasonic sensor.

The final cleaned and processed data is consolidated in a dashboard to summarize the key aspects related to the bicyclists’ safety. The dashboard contains the trajectory of the bicycle, the distribution of the right-side ultrasonic sensor readings in centimeters, climb in meters per second, altitude in meters, and speed in meters per second. Fig. 4 shows the dashboard with the map representing the GPS points and their spatial distributions. The dashboard is available online through the link https://tabsoft.co/2vlNcKF. The dark green points on the map represent the spots where there is no vehicle by the side of the bicycle, whereas the red ones represent where there is a vehicle at a distance shorter than the safe distance namely, 3 ft. From the dashboard, it is possible to see that the ride had a considerably higher amount of records closer than the recommended safe distance.

More specifically, there are 74 records with distance readings smaller than the safe distance. One of these records is registered at an intersection, which can indicate that a moving car approached on the right side of the bicycle and might represent a dangerous situation. The average speed throughout the ride was 6.76 fps (4.61 mph). For the records with a distance shorter than 3 ft, the average speed was 9.02 fps (6.15 mph). The records within the safe distance had an average speed of 6.69 fps (4.56 mph).
5. Conclusion

A new prototype for collecting ultrasonic and GPS data was developed. The device was stable during the data collection process and was able to provide the expected data set necessary for the proposed analysis. The processed data obtained from the mobile sensing device was used to demonstrate how this type of data can be useful for conducting different and detailed safety analysis. The analysis of the sample data showed the points in which the bicycle was within an unsafe distance from parked vehicles. In addition, it was possible to identify one potential interaction between bicycle and vehicle at one of the intersections. Finally, the dashboard was successfully applied as the main visualization tool, and it facilitated the data analysis process.

5.1. Future work

As the developed mobile sensing device provided good initial results, 5 more units will be built in the near future to be road-tested on bicycles traveling along with different types of routes. Some improvements will be implemented in future units. First, it is necessary to design an improved enclosure to be able to mount the developed mobile device to various bicycle models and to better fit the device on a generic bicycle. Second, a new communication feature will be added to send the data directly from the RPi to a cloud server using a wireless connection. The remote and real-time access to the data will make it possible to create a real-time tracking system to monitor the functioning of the units, observe the behavior of each cyclist and monitor dangerous distances. With the increased sample size, it will be possible to conduct a more in-depth analysis of the factors influencing bicycle safety and to develop new studies after enhancing the device with new types of sensors such as LiDAR and cameras. A more powerful portable charger could be used to attend the power consumption increase due to the cloud connectivity and addition of new sensors. Tests using the e-bike’s on-board power supply to charge the device could be performed as well. Lastly, a warning system can be implemented to help the cyclists to keep a safe distance from other vehicles. In this proposed version, the sensor device would detect when a motor vehicle violates the safe distance and then send a warning to a screen mounted on the bicycle. The warning would be based on criteria developed to classify safe, unsafe, and dangerous situations.

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