Inequity by inequity: Community driven investigation of wheelchair user discomfort by infrastructure failures

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ABSTRACT

Wheelchair users face a variety of disability-related inequities in the built environment. The primary challenge is that current legislation for relieving disability inequities focuses on design guidelines and less so in monitoring their discomfort. While there is literature about monitoring wheelchair users, there is little available data regarding wheelchair user discomfort across the built environment. Therefore, we create a transformative approach to measure a wheelchair user's personal comfort (*WheelCom*) using open-source solutions, allowing more citizens to engage in the inequity challenge. To demonstrate, we lectured our approach to local high school students to develop *WheelCom*. Subsequently, actual wheelchair users measured their personal environment by installing the developed *WheelCom* on their wheelchairs. The measurement was conducted around a university campus. Our results show a clear pattern of unhealthy air quality (PM2.5) right after a sharp acceleration change (bump on seat). In addition, the spots flagged for discomfort by wheelchair users line up with more intense levels of acceleration. Further, this indicates that wheelchair users suffered from not only their uncomfortable seating conditions but also unhealthy air quality because of infrastructure failures.

CCS CONCEPTS

• **Applied computing**; • **Human-centered computing**;

KEYWORDS

Citizen Science, Disability Studies, Wheelchair User Comfort, Human-centric Infrastructure

ACM Reference Format:
Steven McCullough, Jessica Eisma,, June Young Park and Mikila Salazar, Sarah F. Rose. 2022. Inequity by inequity: Community driven investigation of wheelchair user discomfort by infrastructure failures. In *The 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation (BuildSys '22), November 9–10, 2022, Boston, MA, USA.* ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3563357.3564081

BuildSys '22, November 9–10, 2022, Boston, MA, USA

ACM ISBN 978-1-4503-9890-9/22/11.
https://doi.org/10.1145/3563357.3564081

1 INTRODUCTION

Modern urban infrastructure strives to be more accessible for its non-ambulatory citizens. Adoption of the Americans with Disabilities Act (ADA) in 1990 shifted our standard for disability access, however the built environment is still not friendly for wheelchair users [6]. Approximately 2.7 million in the US are wheelchair users, making them one of the largest minority groups in transportation disability. The ADA gives very strict guidelines to allow wheelchair users uninterrupted access to the urban infrastructure they wish to use. These guidelines are the minimum at which structures are accessible. However, are they comfortable and healthy for these users? Beyond the design guideline, we should further investigate their perception in the built environment to identify any potential inequity which may result in discomfort.

According to [2], wheelchair users expend more energy and generate more heat than their walking counter-parts. They also have a different breathing zone by height difference as well as physical barriers. The typical breathing zone of a wheelchair user is closer to the ground and smaller than that of an ambulatory person. Physical barriers can include poorly maintained pathways, design flaws, and more that may cause the wheelchair to become stuck. These barriers can be identified fairly easily by visual inspection of an on-site auditor. Nonetheless, these inspections are time inefficient and error prone. Furthermore, this conventional approach still fails at understanding the actual perception of wheelchair users (e.g., thermal comfort, air quality) by such infrastructure failures.

With the recent development of information and communication technology, researchers developed data-driven approaches to mitigate the aforementioned challenge. Mobasheri et al. used crowd sourcing to develop databases for wheelchair accessibility inside built environments [4]. However, this type of crowd sourcing focuses more on compliance (e.g. access ramps or ADA parking spots) rather than the actual experiences of wheelchair users. In fact, wheelchair users typically experience discomfort from poor transportation infrastructure conditions, which ultimately can affect their health conditions [3]. These specific types of discomfort here can cause chronic pain and body sores for the users.

Therefore, the focus of this paper is to 1) develop a DIY based data acquisition tool to collect wheelchair users' data easily and efficiently, 2) analyze their personal environment data to identify any discomfort, and 3) create a community driven framework to identify the inequity of wheelchair users in the built environment. We describe our data acquisition tool (*WheelCom*) and teach high school students to assemble. Then, actual wheelchair users implement the devices on their wheelchair to measure their personal environmental conditions. Finally, we discuss our findings of wheelchair users' critical inequality of seat discomfort and air quality.

2 METHODOLOGY

Environmental conditions are monitored when analyzing a wheelchair users' discomfort. These conditions focus on the user's personal environment, e.g., thermal comfort, air quality, and local vibrations. Localized sensors are placed on the rear of each user's chair and record these conditions. The collected data is timestamped, geotagged, and grouped together. Data from the sensors are analyzed through exploratory data analysis to find patterns and anomalies. Patterns are analyzed to see if similar sources of discomfort can be detected with telemetry alone as opposed to visual identification.

2.1 WheelCom

WheelCom is an environmental sensing toolkit used for understanding wheelchair users (dis)comfort (Figure 1 (top)). It is based on the Arduino platform. Peripherals used are an ADXL-345' accelerometer (1), an Adafruit micro SD card reader (2), DHT-20 temperature and humidity sensor (3) and a PM25 PMS 5003 Particle Sensor (4). Locations and local time are observed with a GT-U7 GPS unit (5). These modules are connected via a central breadboard and jumper wires to a single Arduino Uno (6). All values are recorded via an SD card reader module. Power for the unit is provided through a single 9V battery. The unit takes a recording of the wheelchair user's personal conditions and location roughly every second and writes it to a csv file on the SD card. These hardware components were chosen based on being readily available and cost effective. The conceptual design focuses on both easy assembly and access to promote citizen science and DIY assistive technology [1]. These designs were tested in a high-school curriculum with students able to assemble the hardware quickly and correctly with simple instructions.

The sequence of operations for data logging follows pulling data objects, parsing info from them, and storing only the needed portions of data, the rest is then discarded. This happens from sensor to sensor to maintain free memory. Some sensors (e.g., ADXL, DHT) use the I2C protocol, others used asynchronous serial communication, like the GPS transmitter and PM2.5 sensor. The data is written in small blocks to the SD card to prevent stack overflow. To be able to read from two different serial devices in operation, software serial switching was used. To keep the serial devices synchronized for logging input data, loops were used to wait until a proper data packet entered. Once all required data is collected then it is written to file in a csv format. Various open-source libraries were used to interface with the sensors including Adafruit libraries as well as TinyGPS++. The sampling rate is limited to 1 cycle/second due to hardware limitations within sensor sample rates.

The unit is encased in a custom 3D printed case with a method to be affixed to the rear brace bar that was found on each chair to keep placement consistent (Figure 1 (bottom)). The case was designed in Google Sketch-up, the overall design criteria was the easy assembly and interchange of components for different applications. ABS plastic was the material for the case due to its low cost. The case uses a "C-Clamp" style mount to attach to the wheelchairs. Small rubber pads were used to prevent slipping and rotating of the device.

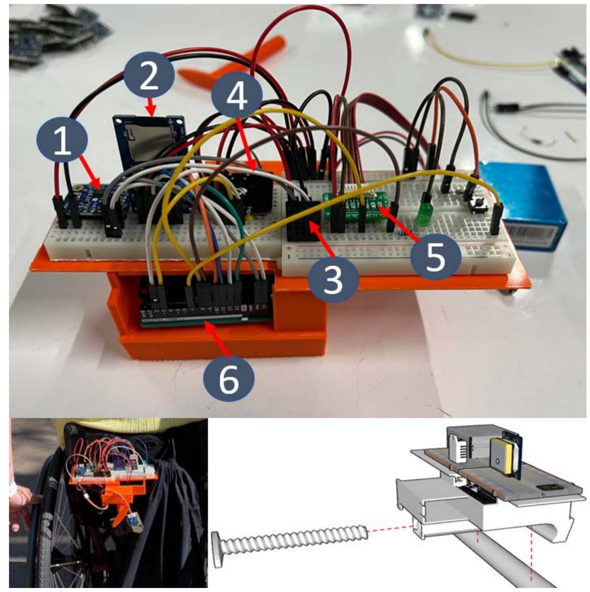

Figure 1: *WheelCom* (Top: circuit and sensors, bottom: installed on a wheelchair by the customized 3d printed case)

The Arduino itself slips onto 4 standoffs, one with a threaded hole and the remaining 3 to have alignment pegs. The top shield of the case was designed to slip on and off easily to access the Arduino if needed, a breadboard is mounted to the top with bonding tape. The Arduino jumper connections are left exposed for easy access, if quick adjustments are needed.

2.2 Experimental setup

With a collaboration with Garland ISD, we created 5 *WheelCom* units by high school students' efforts. Then, 5 wheelchair users (from the Movin' Mavs wheelchair basketball teams) were recruited, one device for each wheelchair. The experiment was held over the course of roughly 1 hour, on June 16th of 2022. The experiment was held on the campus of University of Texas at Arlington. Participants were asked to go in groups of either 1 or 2, and follow a single path that is typical of their daily routine. A proctor accompanied each group of students to document any discomfort the students had. When a participant voiced concern about something that has either caused discomfort or can cause discomfort, it is then photographed and tagged by location. Results are then pulled from each machine and consolidated to be analyzed. The whole experiment process was approved by Institutional Review Board (IRB).

3 RESULTS

Figure 2 visualizes five route from wheelchair users with *WheelCom* measurement. Starting from the basketball court of the team, device 1 & 2 went to the West side, device 4 & 5 went to the East side, and device 3 went through the center of the campus. These were again their typical routes during the semester, which is one of only a few options to navigate the campus from wheelchair user's perspective. The left bottom inset figures indicate box plots of acceleration and PM2.5 grouped by each device. Instead of strictly

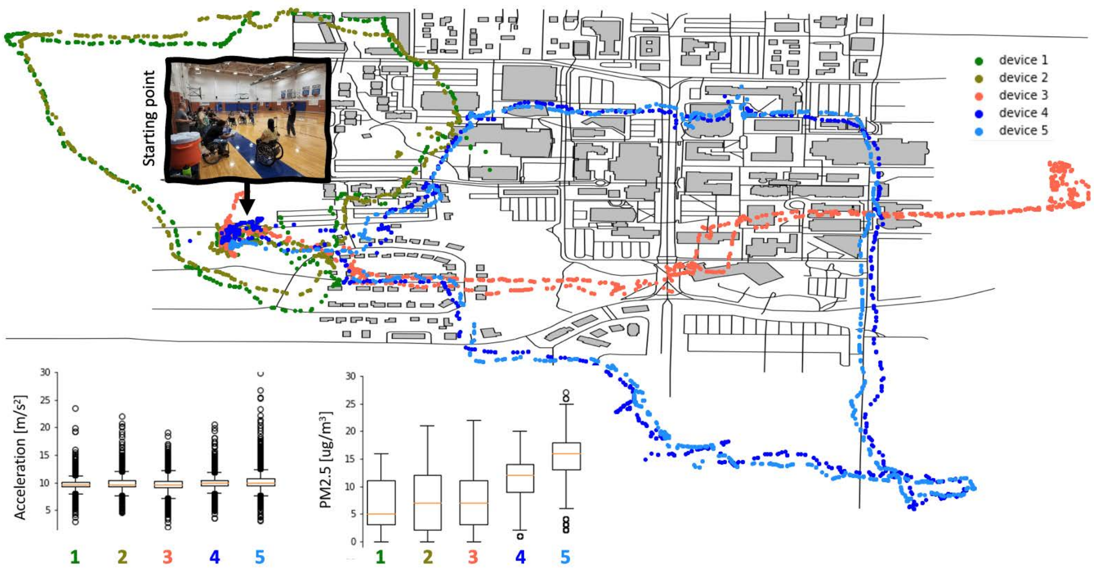

Figure 2: Distribution of PM2.5 concentration and acceleration intensity

using Z-axis values for acceleration, the resultant vectors intensity is calculated. The assumption is that the most intense acceleration is going to be felt in the vertical axis as a bump is crossed, this is also to account for the device possibly slipping or rotating during the test, changing the axes. Obviously, the acceleration values are distributed very narrowly around the Earth gravity (9.8 m/s^2). Based on previous literature [5], the higher acceleration values indicate some seat discomfort for wheelchair users (e.g., pothole, crack, pavement change, leveling issues). Particle count levels are taken directly from the unit as ug/m^3. Typically higher particle count levels are found closer to streets and busier intersections. The Environmental Protection Agency (EPA) recommends to keep PM2.5 levels to $12ug/m^3$ or below to maintain respiratory health while being sure to not be exposed to sudden spikes over $35ug/m^3$. While device 1, 2, & 3 showed fairly low mean values, the routes from device 4 & 5 had relatively higher PM2.5 values.

From the observation of both acceleration and PM2.5 data, we investigated the correlation between the two. In fact, there was no shape-wise similarity between the two time series patterns since both are noisy and contain other compound factors. Figure 3 indicates a snapshot of device 5. It clearly shows first sharp acceleration increase before 550 second and delayed response of PM2.5 increase after 550 second. These sharp acceleration increases are not usually associated with poor design but rather infrastructure failures such as potholes, cracking sidewalks, or expansion joint separation. This physically explains that those failures of infrastructure management may generate seat discomfort (high acceleration) first and the rotation of two wheels moves dust toward wheelchair users upper level (e.g., chest, head, nose). To confirm our anecdotal evidence, we systematically evaluate the observed relationship across the five devices. Figure 4 indicates the 95% confidence interval of PM2.5 values of 30 seconds after it detects the significant acceleration increase ($> 15m/s^2$). Although their patterns are all different, it is clear that all five devices show the increasing trends of PM2.5 values after their shape acceleration increase. They are all above $12ug/m^3$, which is the guideline from EPA, and the route from device 5 was the worst experience for the wheelchair user.

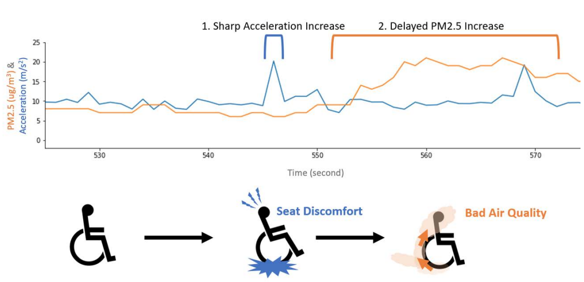

Figure 3: Visualization of acceleration impact with PM2.5

4 DISCUSSION

Wheelchair users have physical obstacles; however, the results from this experiment show that potentially other factors can affect a wheelchair user. If a user has discomfort from an uncomfortable pathway that causes their chair to shake as they move, they might also have an issue with dust potentially. Our results also point to sharper impacts bringing about more intense changes in PM2.5 levels. The weather during the test was clear, with minimal cloud coverage and no fire weather warnings, PM2.5 levels were shown to be at or below 12 for that day. Car traffic was typical around busy streets, the higher PM2.5 levels shown around street intersections can be explained by car traffic disturbing dust and debris on the street as well as vehicle exhaust in proximity. The campus had minimal traffic as the test was performed during a summer semester,

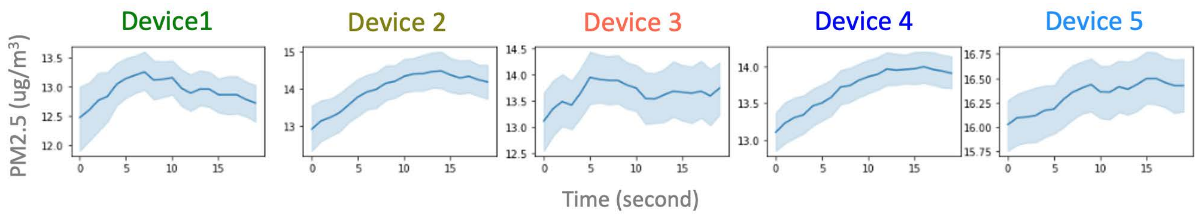

Figure 4: Plot of intense acceleration with PM 2.5 concentration

the wheelchair users and proctors were the only people using the pathways on campus. It is possible that with more foot traffic (e.g. during a fall semester), higher levels of PM2.5 concentrations could occur on all walkways and in turn have higher spikes around walkway failure. With a lower breathing zone it is likely that this would impact wheelchair users even more than those that are ambulatory.

In Civil Engineering, minor design changes can have major effects on the comfort of wheelchair users around urban infrastructure. For instance, in the results discomfort was had by all users that rode over pebble paths on and around campus. However, there is little that they can do to avoid these paths. Photos taken where discomfort was either recorded or anticipated to happen are shown in Figure 5. Figure 5 (A) shows both architectural design issues like the brick trim used to separate spaces on pathways as well as civil infrastructure issues like the water service access. In Figure 5 (B), separation of the expansion joint in concrete walkways cause wheels to become stuck or potentially cause users to fall. More extreme forms of this can be seen as entirely missing portions of walkway that would not normally be an issue for ambulatory people, like shown in Figure 5 (C & D). An example of wheels being caught on these walkway issues can be seen in Figure 5 (E), where the caster wheels of a user's chair are stuck in an expansion joint that connects two different types of walkways. Some severe walkway issues are inherent to the design like bollard holes as shown in Figure 5 (F). The holes left where walkway bollards mount cause severe issues with wheelchair users. These holes do not have plugs and are full of debris and dust.

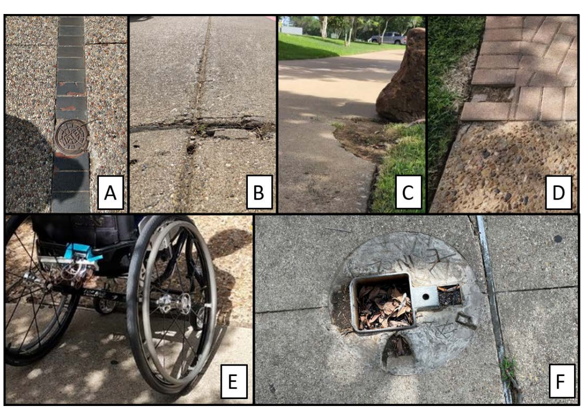

Figure 5: Areas of discomfort and concern marked by wheelchair users

The primary limitation of this study is the current method of obstacle marking, as it uses a proctor that has to be involved to mark a spot or obstacle. A future version could utilize voice commands, or leverage virtual or augmented reality to mark spots, preventing interruption. Another issue is the currently selected hardware, the resolution of the data recorded can be acceptable but can be potentially masking important information. The last limitation of this study is the scale, only 5 devices were implemented which is too small to cover the whole campus. *WheelCom*'s application in this study was focused on wheelchair users, however the methods and tools used here can be used in a variety of applications e.g. monitoring conditions for children in schools. In addition to this, the primary focus of the units used here were to monitor air quality and the kinematics of the wheelchairs themselves and seeing how they affect users. Another form of discomfort that can be monitored by these devices could be thermal comfort and more of the biological aspects of the users, like monitoring metabolic levels and surrounding humidity and temperature. *WheelCom* was successful in its primary task, more research must be done to see what is possible to uncover with this methodology. To discover any potential inequity challenge (i.e., air quality issue in this paper) of wheelchair users, it is necessary to first collect more data from our own community, and this paper started its small contribution toward the environmental equity for wheelchair users.

ACKNOWLEDGMENTS

This work was supported by a grant from the Center for Transportation Equity, Decisions and Dollars funded by U.S. Department of Transportation Research and Innovative Technology Administration (OST-R) and housed at The University of Texas at Arlington.

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