BRIDGES OF THE BELTLINE

FINAL REPORT

April 2022

Salimah LaForce
Scott Gilliland
Jeff Evans

Georgia Tech

Center for the Development and Application of Internet of Things Technologies (CDAIT)

Table of Contents

Abstract

Urban pedestrian flow, in general, has been under-funded and understudied but is nonetheless critical to city infrastructure monitoring and improvement projects. Conversely, human mobility patterns for emergency management purposes have been explored in a growing body of literature. Studies suggest that the Internet of Things technologies can play a significant role. This project focuses on the development of inexpensive, low power consumption sensors capable of detecting human presence while preserving privacy as a potential method of real-time data collection of pedestrian mobility along the Atlanta BeltLine, a pedestrian-centric transportation corridor.

Acknowledgments

This research was made possible by a grant from Georgia Tech's Executive Vice President of Research, Small Bets Seed Grants program, with supplemental funding from the Center for the Development and Application of Internet of Things Technologies (CDAIT).

Principal Investigators:

Salimah LaForce, Center for Advanced Communications Policy
Scott Gilliland, Interactive Media Technology Center
Jeff Evans, Georgia Tech Research Institute

Technical Advisor: Kore Wireless provided expert knowledge on the current developments and tradeoffs in low-power IoT sensors, specifically data backhaul and sensing technologies. Their help and support were key in several important implementation decisions.

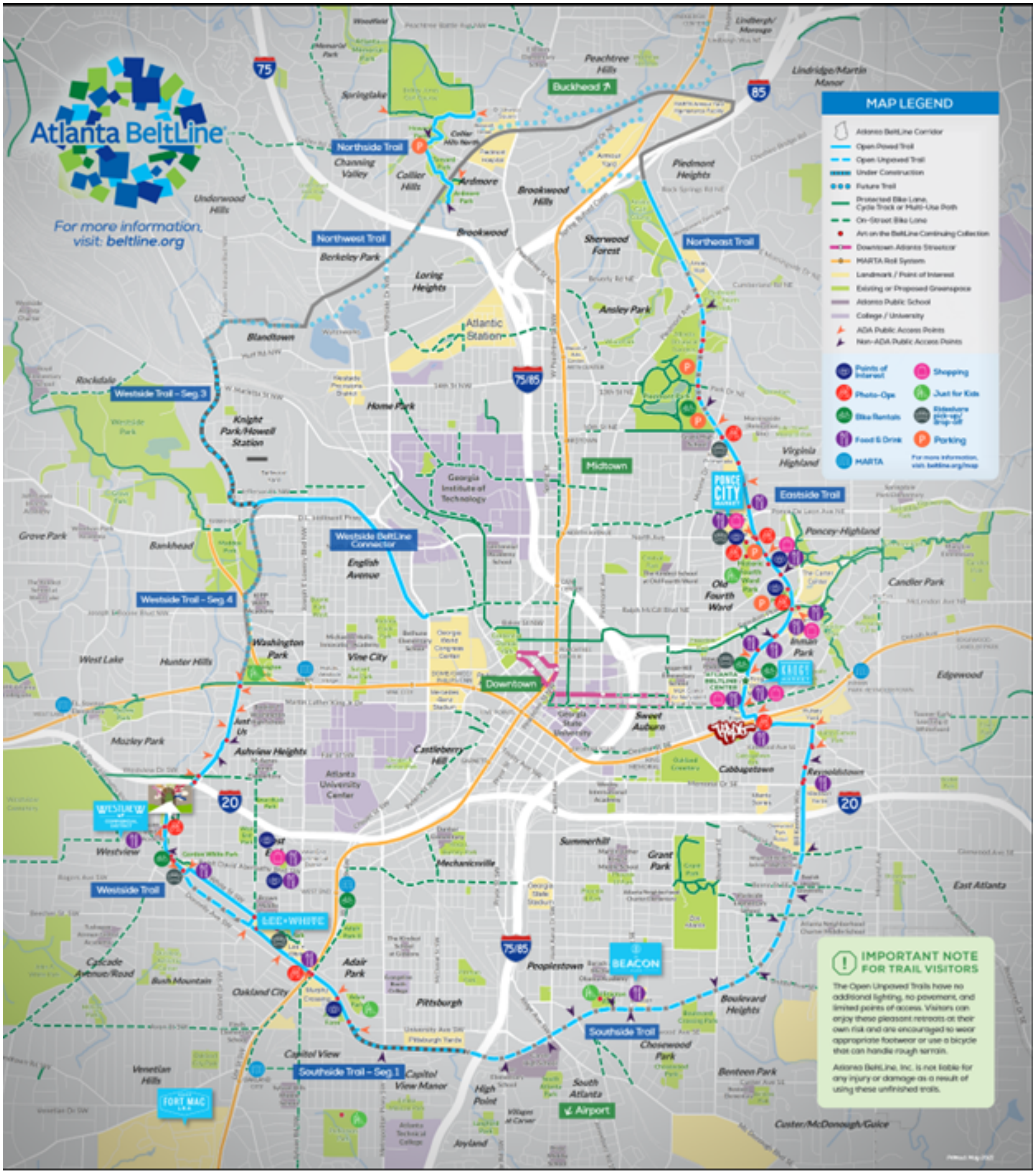
Introduction

The Atlanta BeltLine (BeltLine), currently in phased development, at completion, will be a 22-mile multiuse trail connecting intown neighborhoods of Atlanta, Georgia. It is a redevelopment project, converting unused railway tracks into an urban pedestrian trail with a vision that "All legacy residents, new residents, and business owners – regardless of age, gender, gender identity or expression, sexual orientation, race and ethnicity, ability, income, or political ideology – benefit and prosper from the economic growth and activity associated with the Atlanta BeltLine" (Atlanta BeltLine Partnership, 2021). The BeltLine promises to be a center for arts and culture and achieve sustainable development through environmental cleanup, improved walkability, and the addition of acres of green space (Davidson, 2011). One-third of the BeltLine has been realized, including open paved and unpaved portions located on the Northside, Northeast side, Eastside, and Westside Atlanta neighborhoods. The Southside Trail is currently under construction. (Figure 1)

As currently realized, the BeltLine weaves under, over, and through a multitude of overpasses, footbridges, and tunnels. As in any city, this significant feature is simultaneously an asset and a potential hazard. These types of structures are "vulnerable critical facilities" that should be included in emergency risk assessments and mitigation planning (FEMA, 2013). As such, the Bridges of the BeltLine project was proposed as a mixed-methods study to understand how people's movement along the BeltLine can inform emergency management mitigation, planning, and response. According to Marchiori (2018), understanding pedestrian flow in cities has been under-funded and understudied but is nonetheless critical to city infrastructure monitoring and improvement projects. Much like this study, Marchiori focused on developing inexpensive, low power consumption sensors capable of detecting human presence while preserving privacy.

After conferring with the Atlanta BeltLine, Inc. (ABI) leadership, it became apparent that ABI's primary interest is in understanding which communities are being served by the BeltLine and whether it has changed commuting and travel behaviors or created new demand. As a result, the project's original focus on emergency management has expanded to explore which communities are being served and for what kind of use. As such, the project's revised objective is two-fold: to facilitate understanding of (a) whether the BeltLine is serving the adjacent communities and purpose of use and (b) to inform emergency mitigation, planning, and response.

Figure 1: Atlanta BeltLine Map – The solid turquoise lines indicate an open paved trail, dashed is open unpaved, turquoise and grey hashed lines indicate sections under construction, and dotted lines indicate future trails. Source: https://BeltLine.org/map/.



Background

Multiuse trail development has been an aspirational and realized method to promote urban and suburban communities' public, economic, and environmental health (Chen. Lindsey, & Wang, 2019). These pathways provide nonmotorized access to neighborhoods and businesses, aspiring to be a commuting alternative, a recreational oasis, and an economic boon for local economies. Repurposing of unused railways and canals to create greenspace is supported by federal dollars via MAP-21, the Moving Ahead for Progress in the 21st Century Act (P.L. 112-141), and by regional and local investments and private funders. Along with these investments comes a requirement to report on return on investment. Typically, efficacy is measured by assessment along such dimensions as 1) Intended impacts of trails, 2) Degree and extent that communities are being served by the trail, 3) impact of these trails on recreation and tourism, public health, crime, transportation, land development, real estate, the environment, among other primary objectives found in the literature on multiuse trails (Scherrer et al., 2020). While public safety issues are addressed in the literature, they center on designing safe spaces (e.g., lighting, directional signage, emergency vehicle access) and ensuring that residents' and visitors' perceptions of safety are positive (Luymes & Tamminga, 1995). These are important factors, but absent from the multiuse trail literature is the topic of emergency planning and mitigation.

However, understanding human mobility patterns for emergency management purposes has been explored in a growing body of literature, and Internet of Things (IoT) technologies play a significant role. Sensors that continually monitor people flow can include an algorithm that detects anomalous crowd behavior. Information derived from IoT technologies can also inform the crowd about optimal evacuation routes to safe spaces (Dugdale, Moghaddam, & Muccini, 2021). Most people choose to evacuate using familiar routes and pathways by which they enter a space (Pelechano & Badler, 2006), but this may not be the optimal route, especially when most visitors/occupants enter via a similar route. This behavior can result in congestion at the egress point, delayed evacuation, and injury.

Recognizing that humans often behave in ways that counter effective emergency egress, Al-nabhan (2019) developed an IoT- based evacuation approach "to balance the load of the evacuees among the different available paths of the evacuation area." While this project concerns *building* evacuation, its findings can inform emergency egress planning from an outdoor area such as the BeltLine. For example, the Al-nabhan system includes basic sensor nodes (pathways), master nodes (confined areas), and exit nodes. Each node type has its own algorithm to detect congestion and the presence of evacuees. Evacuees are directed to less congested routes and exits based on what the sensor detects. A similar sensor network can be implemented in an outdoor space like the BeltLine. It can be considered, in a sense, a "closed campus" environment with clear ingress/egress points along a continuous pathway. How a BeltLine evacuation differs is, unlike a building evacuation, real-time messages to evacuees must also consider what is happening on the adjacent and intersecting roadways. Also, there is typically a person(s) responsible for emergency planning and designating safe zones in a building evacuation. That person is typically already on-site to aid the evacuation effort. However, on the BeltLine, emergency responders would be dispatched to the affected trail subsequent to the evacuation order. As such, it becomes necessary to be able to also send first responders to the area on the most expedient route.

To visualize the sensor data (e.g., heat maps, travel routes, location and the number of critical facilities impacted, safe gathering locations), a dashboard approach is an obvious choice to achieve the common operational picture needed to evacuate people out of an area while sending in first responders. The People Mobility Analytics (PmA) solution is a dashboard designed for crowd monitoring and density, trajectory tracking, and people counting (Uras, Cossu, Ferrara, Liotta, & Atzori, 2020). It has been evaluated in controlled environments and in the wild (e.g., music festivals) and utilizes wifi sniffers that allow for monitor and interpretation of network traffic to "know" where people are and are going. Lwin, Sekimoto, Takeuchi, & Zettsu (2019) developed a City Geospatial Dashboard that utilized mobile call detail records and GIS to visualize human movement within a city space and across a specific time period. Their analysis allowed for the "shortest-path" to be determined and suggested that it would be useful for "disaster response teams to estimate the travel time to the disaster area" (p. 3). However, their mobility data is for motorized traffic. Nevertheless, a similar use is envisioned for this project, but we utilize different data sources (sensors) and are primarily concerned with pedestrian flow.

Methods

A mixed-methods approach is taken that incorporates surveys (BeltLine use survey and manual counting of BeltLine traffic type), extant data provided by Atlanta BeltLine, Inc. (ABI), and the application of IoT technology (wireless sensors) to collect people flow data at places along the pathway that have been identified as critical. The automated system was expected to be an optical or radar approach. To determine which approach would be employed, several sensing options were evaluated for (a) ability to differentiate travel modality, (b) power consumption, and (c) solar source power options for long-running data collection. People-counting technologies considered include visible-light or IR cameras, thermal cameras, depth cameras and sensors, break-beam sensors, Bluetooth loggers, and radar systems. These each have advantages and disadvantages in data quality, cost, power, and mounting angle requirements.

Many trail use monitoring systems are available, but each has its strengths and weaknesses. For example, passive infrared monitors are an option, but when used alone, cannot separate modality type and require integrating another sensing technology, such as inductive loops (Lindsey et al., 2019.) An initial consideration in determining which type of sensor to use was the exact counting of people in groups, as undercounts due to occlusion are a common limiting factor to system accuracy (Lindsey, Gobster, Sachdeva, 2019). Furthermore, this study aimed to employ a sensor that could differentiate user modality types (e.g., walkers, cyclists, scooters). Several higher power, more complex systems were investigated and eventually dismissed. Steerable radar arrays require complex integration and higher power, as well as mounting options.

Embedded camera-based facial detection algorithms can capture separate people in groups, but their use invokes privacy concerns, and they require substantial on-device data processing. Optical break-beam sensors have acceptable accuracy levels but would not be able to differentiate travel modality types without multiple sensors a few feet apart, complicating installation.

The sensor technology evaluation, coupled with discussions with ABI leadership, resulted in designing a small, unobtrusive prototype sensor to make unattended multi-day deployment more acceptable. Development goals for the prototype included (a) being able to differentiate pedestrians from cyclists and scooters, (b) operating at low-power consumption and able to be supplied from a battery for the duration of data collection, and (c) could also be powered via a solar source for long-running data collection. As such, this study compares people flow/counting methods to explore and validate the prototype's capabilities. These methods include hand counts (i.e., ground truth), existing EcoCounter data provided by ABI, and prototype data. Additionally, survey data on the travel modes variable may also be proportional to the other methods. These data are meant to inform answers to the following questions.

1. How can sensors be used to automate people counting along a multiuse trail?
2. Which communities are being served by the Atlanta BeltLine, and how?
3. How can the BeltLine be used as an emergency management asset?

This mixed-methods study methodology is consistent with other multiuse trail and/or citywide pedestrian and traffic monitoring efforts, including those conducted in Minnesota (Lindsey, Petesch, Vorvick, Holdhusen, 2017), Chicago (Lindsey, Gobster, Sachdeva, 2019), Cincinnati Metropolitan Region, Ohio (Lindsey, Singer-Berk, Johnston, Adcock, Folkerth, & West, 2019), and the Buffalo Valley Rail Trail in Union County, Pennsylvania (Oswald, Beiler, McGoff, McLaughlin, 2017).

Survey

Survey data was collected using a study-specific, self-report, online questionnaire designed by project personnel and coded into Qualtrics. The survey was designed to collect data that the sensors cannot. These data were intended to describe BeltLine users, querying on demographics, reasons, frequency, duration of use, and mode of travel to and on the BeltLine. The survey instrument was developed and vetted amongst team members and personnel at ABI. It is a 27-item survey and includes "display if" logic on select question options to assess whether commuters are using the BeltLine to connect to public transportation and whether the BeltLine has supplanted other transportation modes, particularly driving.

The survey relies on a convenience sample, recruited through the dissemination of the recruitment materials via social media sites and newsletters, as well as posting the survey flyers along the BeltLine trails, in businesses adjacent to the BeltLine, and around the city. The flyers contain a scannable QR code and a Bitly link to the survey.

Limitations of the survey data derive primarily from the convenience sample and the recruitment methods. Regarding the former, the original intention was to conduct what is termed an "intercept survey" on-site at the BeltLine. However, the city's response to the COVID-19 pandemic prohibited in-person data collection. As such, the methodology was pivoted to an online survey so that the project could move forward. As a result of the technology-mediated recruitment methods, consistent with other surveys, we expected the sample to skew young. While the resulting data is not generalizable to all BeltLine visitors, it provides insight into who uses the BeltLine and for what purposes. The analysis also yielded information about the impact of the BeltLine on commuting/traffic, health/wellbeing, and communities served. We also derived insight into the impact of travel modes to the BeltLine to inform evacuation potential should BeltLine or adjacent neighborhoods require emergency egress.

Hand Counts

Ground-truth for daily and hourly usage was collected by in-person hand-count. These hand counts capture the exact numbers of people traveling, the direction of travel, and the method of transportation. Using an iOS app, 'QTally' for recording enabled recording precise timestamps of when each count was logged.

Transportation modality was recorded as 'walker', 'jogger', 'cyclist (unassisted)', 'e-bike', 'escooter/skater', and 'misc'. Users of the BeltLine do not always fit perfectly into these (or any) category. It is quite difficult to ascertain if a cyclist is using electric assist, so cyclists were considered unassisted if they were observed pedaling. Kick scooters are lumped in with skaters. Children in strollers were not counted, but children walking or biking on their own were.

QTally allowed for recording timestamps, which is useful for comparison against the EcoCounter and prototype radar sensor data. We used a line on the pavement as the boundary where we count individuals. We also use the time between people to later infer information about the size of groups. While not as good as manually noting group size, this was a tradeoff to reduce the logging load on the person performing the hand count in periods of dense traffic. Even with QTally, the sheer volume of traffic (>30/minute) sometimes outpaced the speed of manual logging, but rarely by more than 10 seconds.

Automated people counting sensor

The automated people counting sensor uses non-steerable 24-GHz Doppler radar modules developed to separate people by speed, giving a method for identifying transportation modality while maintaining counting accuracy similar to the current EcoCounter sensors that the BeltLine has installed. Unliked the EcoCounters, however, these are small, inexpensive modules that do not require major infrastructure investments to install.

Automatic Counting Development

Survey of Sensing Modalities

Technology	Example Module	Multiple People	Cost (dev kit)	Electrical Power	Range (in daylight)	
Radar						
Scanned radar	IWR1443 77GHz	Yes	$150.00	3 W	30 meters	Very precise speed
FMCW radar	IFL2411A	Yes	$24.00	225 mW	4 meters	Very precise speed
CW doppler radar	CDM324	No	$5.00	225 mW	4 meters	Very precise speed
Optical Camera						
Camera with face detection	ESP32CAM	Yes	$15.00	390 mW	1.5 meters	Power-intensive processing
Time-of-Flight Depth Camera	LIPSEdge M3	Yes	$229.00	4.5 W	2 meters	
Active IR Stereo Depth	Intel RealSense D455	Yes	$425.00	3.5 W	6 meters	
Passive Stereo Depth	Zed 2	Yes	$449.00	1.9 W	20 meters	Uses ambient lighting
Optical Single-point						
Single-point Time-of-flight	VL53L3CX	Maybe	$4.67	45 mW	1.1 meters	Significant decrease in daylight
Single-point Time-of-flight	Garmin LIDAR-Lite v3	Maybe	$130.00	675 mW	40 meters	
Cross-path optical break-beam	Panasonic CX-400 series	No	$55.00	300 mW	30 meters	
Optical reflective break-beam	Banner DQ12	No		250 mW	3 meters	
Other						
In-ground inductive loop		Maybe		5 mW		High installation cost
Ultrasonic pulsed ranging	HC-SR04		$4.00	30 mW	4 meters	
BT or Wifi fingerprinting						No longer works with modern cell phones

Many sensors have been employed for people counting. Wanting to learn more about the people using the BeltLine, we investigated various sensing technologies, evaluating the use of each when installed along the BeltLine in a stand-alone, battery-powered form factor.

The most powerful technology available today is visible light cameras paired with object or facial recognition. Facial recognition allows for detecting the same individual across multiple cameras at various points along the trail, and across multiple visits. Even without the use of any external databases, such a system would provide very rich data about the way the trail is used.

There are two key downsides to the use of cameras: installation/infrastructure costs, and privacy concerns. First, any system would need hard-wired power and preferably have a hard-wired network connection, due to the power and data requirements of sufficiently high-resolution cameras. Second, there is the negative public perception of any system that does facial recognition or is perceived to be recording video, even in a public place.

There are also a variety of privacy-preserving depth cameras. These each use active IR illumination, power-hungry onboard processing, or both. Daylight conditions are particularly challenging, since the active illumination needs to compete with the sun, even in IR. That results in high power consumption, unsuitable for small-scale battery or solar installation. While the output of these systems may be privacy-preserving, the public perception of a camera may still be an issue.

Single-point optical systems, such as optical break-beam, reflectivity, or time-of-flight systems are much less sophisticated but have much more appropriate power needs for our use case. This is possible, even under outdoor illumination, due to the very small field of view of the optics, typically less than a degree.

A big limitation of such systems is the inability to disambiguate multiple people passing by simultaneously. Assumptions that work well on a narrow bike lane or sidewalk don't necessarily hold true on the 8’-16' wide BeltLine trail, and groups of pedestrians and cyclists passing side by side can be significantly undercounted, as they 'break the beam' only once per group. A Texas Transportation Institute study tested the performance of three systems using these single-point optical systems and found that in >90% of cases, they all missed counting the second of a pair of pedestrians traveling with less than 2 feet of separation (Turner, Middleton, Longmire, Brewer, & Eurek, 2007).

Radar-based systems have exploded in popularity in the last decade, as the IC's for 24 GHz and 77GHz have become inexpensive. At the simplest, these systems put out a radio signal and look for a reflection to come back. While the human body is not a particularly good reflector, it is sufficient at short ranges. CW doppler radar systems can detect objects moving towards or away from the sensor, while FMCW systems can additionally measure the distance to objects. Scanning radar systems use multiple antennas and beam steering to scan a in a 1D plane or 2D volume, similar to scanning Lidar systems. These systems can consume a fair amount of power for beam steering or long-range operation and are primarily limited by the efficiency of the electronics and the drop-off of returned power with the fourth power of distance. For our use, only low-power CW and FMCW modules are within our power budget.

There are also a few miscellaneous sensing mechanisms. Sidewalk-scale inductive loop sensors are similar to what is installed in streets to detect cars at traffic lights, detecting metal (such as bikes) passing over an in-ground loop. There are also load-cell based systems that directly measure the weight of trail users through the pavement. Both require installation into or under the concrete of the trail.

Ultrasonic systems exist that are similar to CW or FMCW radar systems, but operating acoustically, typically at 40 KHz. The electronics for these systems can be simpler, but the transducers need direct exposure to air, and these seem to have fallen out of favor as 24 GHz and 77 GHz radar systems (capable of working through a plastic housing) have become more prevalent.

Finally, there's a type of people counting that depends on a device that most trail users carry with them: cell phones. In the late 2010's, it was possible to track a cell phone via Bluetooth or wifi using the MAC addresses of the radio hardware inside the device. This depended on the phone's radios using a consistent, unique MAC address. Once tracking people in this manner became common, cell phone operating systems (iOS and Android) started to improve user privacy by using randomized MAC addresses when scanning via wifi and Bluetooth. Due to the short replacement cycle of cell phones, most cell phones in use today can no longer be tracked using this method.

It is still possible to use wireless communication protocols to track users, but this requires spoofing wifi access points already known to the cell phones, or acting as a cell tower, both of which are beyond the limits of ethical data collection in a public setting.

Existing BeltLine Sensors

The BeltLine has several commercial EcoCounters installed at points along the completed Eastside and Westside trails. These systems are EcoCounter' Multi' systems, combining the sensors from the 'Zelt' bicycle counters and the 'Pyro' range.

The 'Zelt' portion consists of a magnetic loop sensor installed into concrete cuts crossing the trail. It detects the metal of bike frames and wheels as they pass over the loop. The 'Pyro' portion of the sensor consists of an IR optical reflection-based sensor, mounted approximately a meter off the ground in a wooden post, and aimed across the trail. The system uses changes in reflection brightness to determine when people pass by. It appears to use multiple sensor elements, detecting slightly different directions horizontally, to determine the direction of travel past the system.

The two sensors are used together to disambiguate cyclists from pedestrians. Currently, the tools and interface do not support other traffic types, such as the electric scooters and skateboards commonly seen along the BeltLine. The system is also limited to reporting data in 15-minute increments, presumably due to power-saving measures.

BeltLine Environment for Sensor Implementation

The BeltLine environment is challenging for installation of sensing equipment, especially temporary research equipment. There is no easy and consistent access to hard mounting points or electrical power. The only reliable data connectivity already available is commercial cellular data networks. Finally, any hardware left unattended is exposed to weather and the whims of the passing public. The permanently installed Eco-counter systems have been found with stickers over their optical sensors, dirt dauber nests in the optics, or knocked over at an angle by some unknown collision.

The BeltLine is a work in progress and will be for years to come. Even the first-completed Eastside trail gets occasional additions, changes, and improvements as needs are better understood, and adjacent construction projects are finished. While Atlanta BeltLine, Inc. (ABI) can speak for much of the trail and immediately adjacent land, sidewalks connecting to adjacent businesses and intersecting roadways are not under their control. Where the ABI does have control, they must consider the maintenance and liability concerns of something so close to the trail.

Due to the temporary nature of our work, the costs of any permanent installation were prohibitively expensive. We also discarded the idea of mounting to overhead bridges due to few locations with overpasses over the BeltLine and the difficulty of obtaining permission for mounting. With these constraints, we designed a solar or battery-powered system to be mounted to existing fence posts, lamp posts, railings, or new lightweight stakes. As discussion progressed, we narrowed this to installing on the post of the existing Eco-counters for a few reasons. They were an already-accepted hazard to the traveling public, they were placed consistently near the trail for collecting radar data, and ground-truth data at these points would allow direct comparison to the Eco-counter data.

In the context of radar sensing systems, this placement works out well. The sensors can be aimed at an angle along the trail and will pick up people as they travel towards or away from the system.

Radar Sensing using Low-power Modules

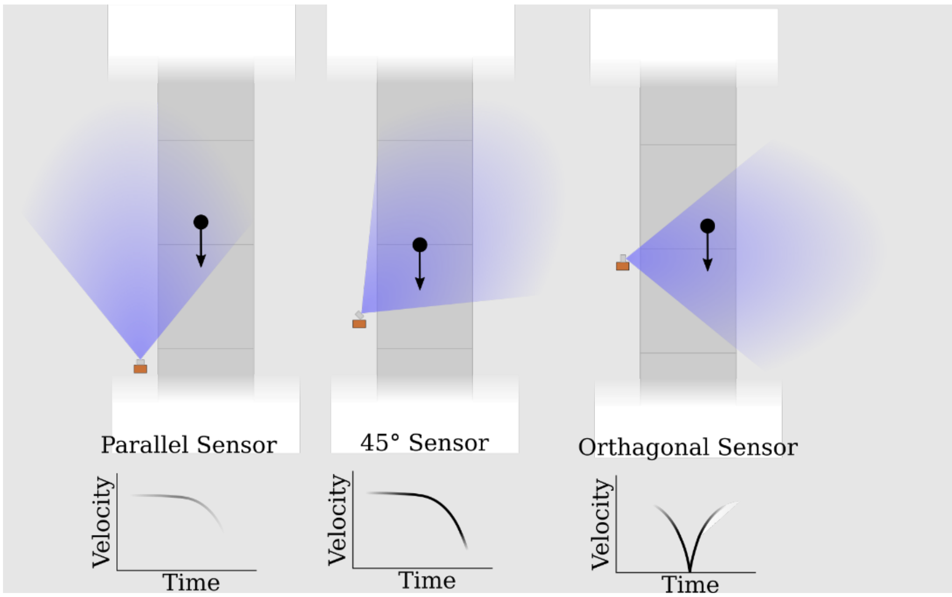
A series of low-power, low-cost non-steerable CW radar modules, the IFL2411A, was selected for further investigation for this project. It is based on the Infineon BGT24LTR11 and is similar to the CDM324 module and the Infineon Sense2GoL dev kit. These modules feature separate I and Q output, allowing for phase measurements, and have a built-in amplifier on the I channel, allowing easier interfacing with a microcontroller. They are also capable of FMCW with additional electronics, although we only use them as CW doppler radar modules. While the I and Q data can be combined to obtain phase data, which can, in turn be used to differentiate travel towards/away from the sensor, we are not using the Q output in our system.

Sensor Angle Relative to the BeltLine

There are some considerations for placing these doppler modules beside the trail. First, the system isn't looking at passing people head-on. Since the radar doppler shift is proportional to the velocity towards/away from the sensor, this introduces some artifacts into the received signal.

If the system is aimed perfectly parallel to the trail, the system's field of view will mostly 'see' people in the distance (Figure 2). While the detected speed will be consistent and close to the actual speed, the radar return will be significantly lower, as the radar return drops off with the fourth power of distance. Additionally, multiple people are more likely to be seen by the sensor at once, making it more difficult to distinguish groups.

Figure 2: Expected radar return differences from various radar sensor angles.



It is worth noting that higher power radar systems will be able to overcome this range limitation. In our case, we're limited by our module's 50 mW transmit power, and the radar's electrical power consumption is already a concern while operating on battery power.

If the system is aimed perpendicular to the trail, the radar return will be stronger due to the short distance, but the speed of approach/departure to/from the sensor will vary greatly as people pass the sensor, making direct speed measurements widely inaccurate.

Best results can be achieved between these two extremes. With the sensor at an acute angle relative to the trail, it can pick up people at the far edge of the trail, while still having the detected approach speed towards the sensor largely represent the travel speed of the trail user. The doppler shift at the point of strongest radar return can still be corrected to the travel speed along the trail using geometry.

There are still some effects from the placement that need to be considered. People passing by the near side of the trail still show a much stronger radar return. People traveling along the trail at a diagonal (such as to go around someone else) may cause a significant error in the detected speed. Finally, multiple people passing through the field-of-view of the sensor at the same time are still difficult to distinguish.

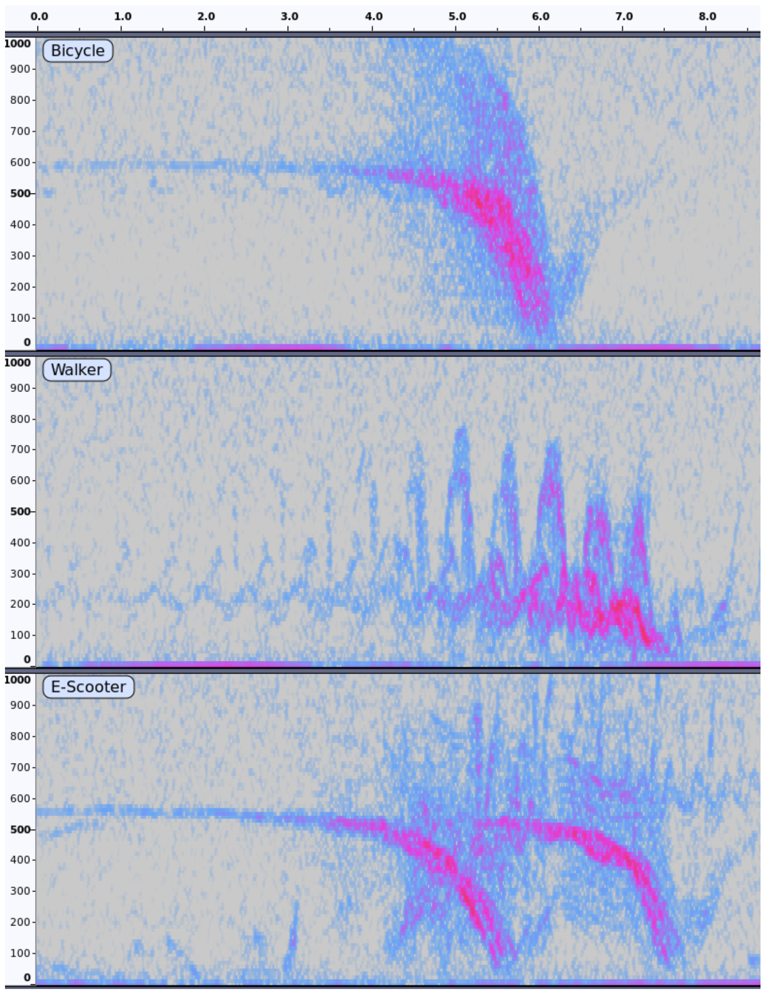
Results

Raw Sensor Data Analysis

Observations from 24 GHz Radar Module Raw Data

To judge what is possible with our low-cost, low-power radar modules, we performed raw data collection directly from the hardware on a busy section of the BeltLine.

Figure 3: Spectrograms of typical raw radar data from different types of tail users.



This raw data is sampled at 192 kHz and 24-bit depth, a higher sample rate and depth than used in our deployed IoT system. This was done to determine what would be possible with the radar hardware under ideal sampling conditions. Due to the 24 GHz frequency used by our modules and the speed of light, our recorded doppler radar signal can be converted using the factor 71 Hz / MPH.

In Figure 3, short recordings of three different transportation modalities are shown. These are a bicycle, a walker, and a pair of e-scooters. The 0-1000 Hz vertical scale on the images represents 0-14 MPH of approach speed. The horizontal axis is in seconds, and all three examples are of people approaching a radar module aimed at a 45-degree angle across the trail.

Transportation Modality Detection via Radar

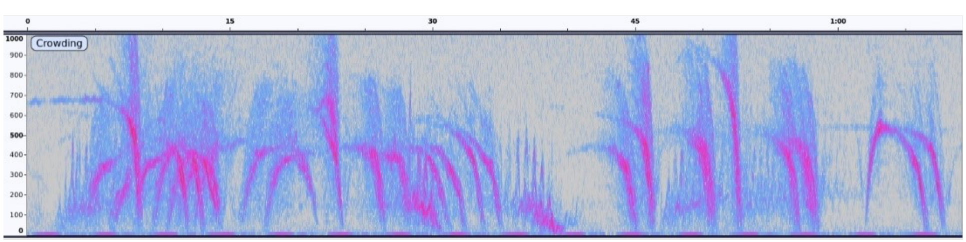
There are some obvious differences between different modes of transportation. First is travel speed, a reason we chose radar sensing. There are additionally some unique characteristics of the spectrograms of each type. The scooters in Figure 3 are traveling ~7.8 MPH, right near the 8 MPH speed limit imposed on dockless scooters using geofencing on the BeltLine. The shown bicycle pass is faster, at 8.2 MPH, although cyclist speed varies widely, especially during times of congestion. Bicycles also exhibit a distinctive 'frequency smearing' up to double their travel speed. This is due to the radar return from the wheels of the bicycle, the tops of which are traveling double the speed of the rest of the bicycle. While not always this visible, it's been a useful way to visually differentiate scooters from bicyclists. Finally, walkers and joggers are the slowest, with the above person traveling 2.8 MPH, probably at a walking speed. Interestingly, the leg and arm movements are visible, indicating that this person had a stride of about 556 ms or around 69 cm. This falls right in the expected range for a walking adult.

Onboard analysis of these signals is limited by power requirements and only uses velocity, but the spectral data contains rich information about how people move. Existing research has investigated gait analysis of pedestrians from this kind of radar data (Tahmoush, & Silvious, 2009), and further work may be able to more accurately differentiate transportation modalities using these low-cost, low-power radar sensors.

Limitations in Crowded Locations

Since a non-steered radar system will combine the radar return of all objects in front of it (weighted by the directionality of the antenna system), there is no easy way to separate objects, particularly if they are traveling at the same speed. This limits its use as a precise people-counter since it will only be able to detect groups, not individuals within the group, and means that in very dense conditions, groups will blur together. However, this limitation reveals that the system is quite capable of detecting congestion.

Figure 4: Raw doppler radar data during congestion.



The above sample appears to contain over 35 people, coming about one every two seconds, but the pedestrians are particularly difficult to pick out behind the cyclists and scooter riders, as they are slower and are more likely to travel side-by-side. An in-person hand count of the same 70-second period recorded 40 people – 9 of which were walkers.

To be clear, this situation is not representative of the norm along the BeltLine – this was recorded at the busiest counter location, during an hour that saw almost half maximum hourly traffic recorded in 2021. There are many locations and times that have much lower traffic.

Stand-alone Radar-based Counting

To continuously capture data from the radar sensors in the field and over longer durations, we developed an embedded system providing power, processing, and data connectivity. As discussed, the sensor type was in part determined by the need to inconspicuously mount to the existing infrastructure next to the trail, without the need for external power or data connections.

One constraint was immediately clear: raw radar data processing must be done on-device. The raw data is, at a minimum, 750 Kbps. Storing multiple GB of data per day is not feasible, nor is it possible to send that amount of data over a radio link without significant power cost. As a result, the raw data was processed onboard, down to individual detection events with the resulting data aggregated and uplinked in 5-minute intervals.

Data Uplink

A few options for data uplink were considered. Near-real-time data connectivity was targeted to eventually enable long-term deployment and monitoring of these devices. Thus, regularly downloading stored data in person was not an option. While wifi is available in a few places along the Eastside trail, it is not readily available in most of the counter locations targeted.

LoRaWAN, a 900-MHz protocol already in use on the Georgia Tech campus, was initially considered. It can be incredibly low-power, making it ideal for battery-powered sensing applications. It also has a much longer range than wifi, conceivably allowing the coverage of much of the BeltLine using only a few gateways. LoRaWAN has already been successfully used by a team member on another project in coastal Georgia, the Smart Sea level Sensors project.

The main drawbacks with LoRaWAN are the need to deploy the gateways, and the relatively low data rate, typically well under 10 Kbps. There is increasing commercial LoRaWAN coverage, but at the time of our development, this wasn't a viable option for the entire BeltLine.

While it is reasonable to work within LoRaWAN's bandwidth limitations for a finalized system, the low data rate imposes some limitations for development. Debug and diagnostic data would surpass LoRaWAN's limits, and specialized protocols and data formats would be used instead of more common ones, such as IP, MQTT, or JSON. While there is a well-developed ecosystem for working with the data coming from gateways, it does introduce friction.

Instead, we explored the possibility of using newer, low-power cellular protocols, LTE-M, and NB-IoT. Kore Wireless, a company partnering with the Center for the Development and Application of Internet of Things Technologies (CDAIT), provided technical guidance that cellular data uplink could be workable from a power and cost perspective. These protocols allow devices to turn off their radio hardware for long durations while remaining associated with a cell tower. This allows for short, intermittent communication bursts, with very low power consumption in between. LTE-M has seen wide roll-out with existing 4G cellular carriers in the U.S. since 2016, and the modules and software tools that support this have come to market in the last couple of years. The wide coverage and potential for high data throughput caused us to choose this technology.

The Nordic Semiconductor nRF9160 radio module was chosen, which is compatible with both LTE-M and NB-IoT on many common cell bands. It is a combined host processor and radio, enabling its use for our data processing as well. Around the BeltLine, consistent connectivity through AT&T on LTE band 12 (700 MHz) has been observed, with connection settings that allow average radio power consumption in the 30 µA range.

This work uses JSON-formatted commands and data, sent back and stored on an MQTT-based server over an HTTPS connection. There are more efficient protocols, such as CoAP/CBOR over DTLS, that could be interesting in the future, but the use of familiar and well-supported protocols aided in this initial development.

Power

As currently developed, the system's primary power consumption is the radar module itself, consuming around 150 mW. In the future, this could be substantially lowered by disabling the radar module for short durations or when people are not expected to pass by. As deployed, the system uses an 8000 mAh 3.7V lithium-ion battery, providing 29 wH of energy. This battery can run the system for over a week, allowing a realistic initial test deployment without external power.

Onboard Processing

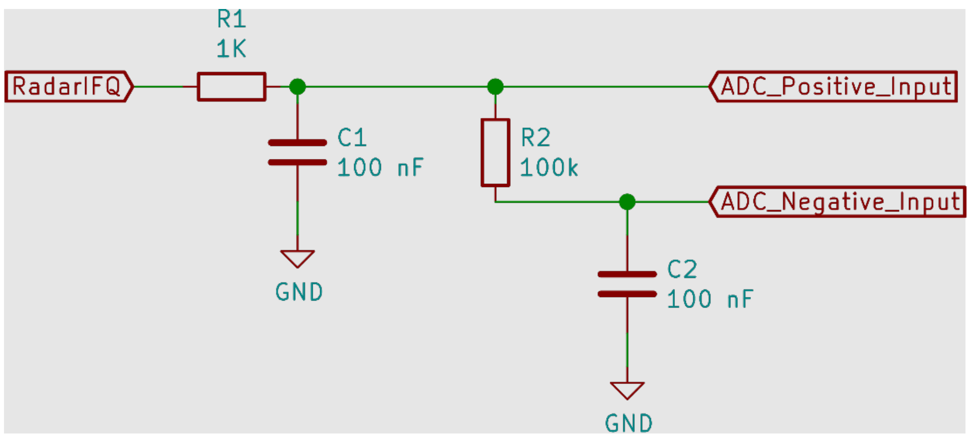
The data capture pipeline starts with the radar module, which sends a 24 GHz CW signal out and receives the reflected signal off any objects in front of it. The module mixes the received signal internally with the output signal, resulting in a down-shifted version of the reflected signals (generally referred to as CW radar) This baseband signal is carried as simple analog voltage I and Q outputs, with low-frequency sine-waves representing objects moving towards or away from the radar sensor. In the case of this 24 GHz radar signal:

> [Output frequency] = 2 * [speed of light] / 24 GHz
> This works out to a conversion ratio of 71.575 Hz / MPH.

The embedded processor samples the I signal with a 12-bit Analog-to-Digital Converter (ADC) in differential mode. The positive input of the ADC is fed with the module's output after an RC

Nyquist filter. The negative input is fed with the same signal but passed through a longer low-pass RC filter to eliminate DC offsets.

Figure 5: Input Filter for Analog Radar Signal



Once at the ADC, the samples are taken using the timer and DMA hardware of the nRF9160. The CMSIS DSP library, which takes advantage of the DSP extensions in the nRF9160's Cortex M33 core, is heavily used to speed up the processing pipeline from this point on. Batches of 512 samples are taken and passed through a 512-point FFT, and the complex magnitude is calculated to yield a single scalar for each bin.

Once the FFT output is produced at a rate of ~13 Hz, the higher frequency bins are discarded, leaving the lowest 64 bins (corresponding to approximately 0-20 MPH). Next, each bin is run through a pair of single-pole IIR filters. The first, using α=.998, is used to get a long-running baseline to allow for ignoring continuous noise sources. The second, with α=0.83, is used to average out sampling noise. Each processing cycle, for each bin, the difference of these two filters is calculated, yielding the amount of short-term difference in the frequency content in each speed bin.

Next, a spectral centroid is calculated to detect the frequency of the strongest radar response. This is then used to sum together adjacent frequency bins (after clipping extreme values), using a kernel of [1,2,4,6,4,2,1]. The response of the bins near the centroid is compared to the mean value of the bins to determine the 'peakiness' of the signal. A threshold is applied to this value to determine if there appears to be a single moving object (a person), and the center of energy is divided by the 71.575 Hz/MPH conversion to get the speed of that object.

The triplets of [timestamp, peak radar return, velocity] are queued up, and are reported in batches when the cellular modem is next powered up to send data.

Limitation of the Single Target Algorithm

While the above algorithm works well for detecting individuals traveling alone, it cannot distinguish between an individual passing nearby vs. a group of two or more passing farther away. The radar return differences due to distance are much greater than the difference due to group size. Different people will have stronger radar returns, either due to physical size or radar-reflective properties of the objects with them (like bikes, scooters, or even cell phones). Thus, this algorithm can't reliably count multiple people in its field of view, only the number of times the field of view contains people.

The differentiation of individuals within a group depends on the radar module detecting each group member separately. Due to the angle of the sensor to the BeltLine, the drop-off of radar return with distance, and the typical separation distances, the algorithm has some success separating scooters and cyclists who keep more distance when travelling together. On the other hand, the algorithm often failed to distinguish individual pedestrians, as they stay much closer together.

Additionally, the algorithm as implemented uses baseline subtraction. This fails in densely crowded environments where there are periods with near-continuous radar response.

An alternative algorithm was partially implemented that only used a long-running summation of radar return in each frequency bin to estimate the number of people traveling past in each speed range. This method would still work in densely crowded environments but would require large amounts of ground truth data to calibrate. It would also still overestimate people passing nearby and people with a great radar reflection. As a result, it would always have significant error unless averaged over a long enough period.

Cellular Radio Interference

The test system does experience significant interference in the radar module's output when the nRF9160's cellular radio is active. This is due, in part, to the small form factor, placing the cellular antenna within 40mm of the radar antenna and even closer to the nRF9160 itself. This interference is mitigated by entirely disabling radar processing when the nRF9160's radio is active via the LTE_LC_EVT_RRC_UPDATE events exposed via Nordic's API. It leaves the system 'blind' while the radio is active, but due to LTE-M's discontinuous reception modes, that state can be restricted to short, predictable bursts of only a few seconds. Objects detected via radar (and other events) are logged in RAM and sent in batches to reduce the total duration where the radar samples must be discarded.

People Counting Results

The relative accuracy of the people counting methods available were compared: in-person hand counts, the commercial EcoCounter system already installed along the BeltLine, and the prototype radar-based system. Overall, in a low-density environment along the westside trail (mean of 116 people per hour), the EcoCounter system matched the hand-counts quite well, undercounting in each time period by an average of 9.4% (std dev 7.5%), while the prototype radar-based system undercounted by an average of 32.1% (std dev 10.8%).

The prototype people counter's single target algorithm was able to detect many, but not all, of the people passing it on the BeltLine. The primary limitations were in detecting people that passed at the far edge of the BeltLine, especially those passing through quickly (cyclists and e-bikes). As expected, it also had great difficulty detecting pedestrians traveling together in tight groups.

Survey Results

The survey yielded a total of 256 respondents, with 232 valid responses. These data reveal insights into which variables can be used to validate the sensor data and which variables are informative of the research questions noted above.

Demographics

A descriptive analysis was conducted using Excel to produce frequencies for the variables. The sample was majority female, White/Caucasian, young, educated homeowners with annual household incomes of more than $75K (Table 2). The considerable age skew is depicted in Figure 7. The remainder of respondents were Black/African American/West Indian (11%), bi/multi-racial (7%), Latinx (4%), Asian or Indian (2%), and Middle Eastern or North African (1%), and less than 1% were Alaskan/Native American. Three percent preferred not to answer. Only 5% of respondents identified as having a disability: cognitive, lower body physical limitation, low vision or vision-related disability, hard of hearing, psychiatric, co-occurring cognitive and psychiatric, co-occurring psychiatric and chronic migraine, co-occurring deafness and speech communication limitation were selected, and in the other category chronic fatigue, autoimmune, and herniated disc were indicated.

Table 1: Summary Demographics

Variable	Sample Characteristics
Gender % Female	53%
Age [Range, Mode, Mean (SD)]	18-75, 28, 35.74 (10.59)
Race % White/Caucasian	60%
Household Income % <$75k	79%
Home Ownership % Own	58%
Education % ≥ Bachelor's Degree	86%

Figure 6: Age Histogram

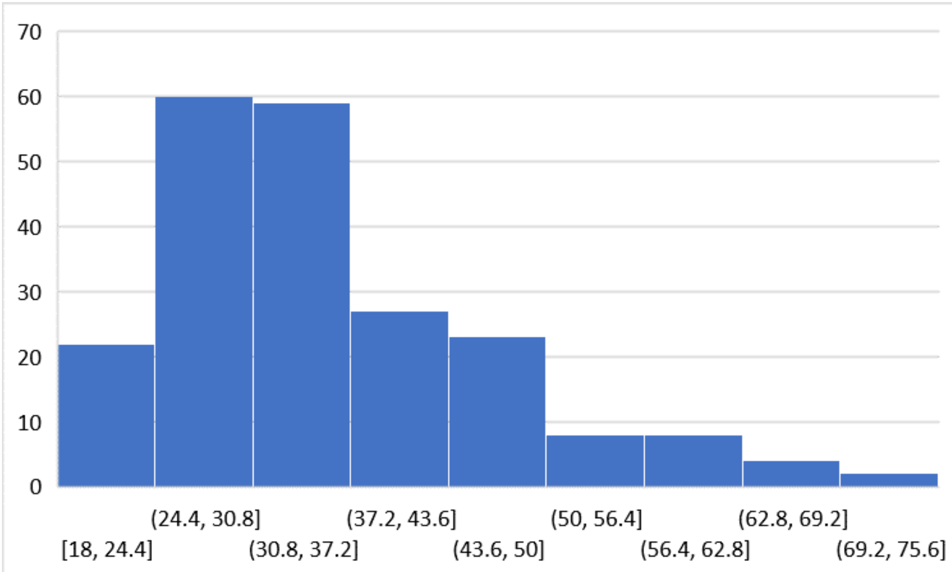


Figure 7: Respondents Annual Household Income

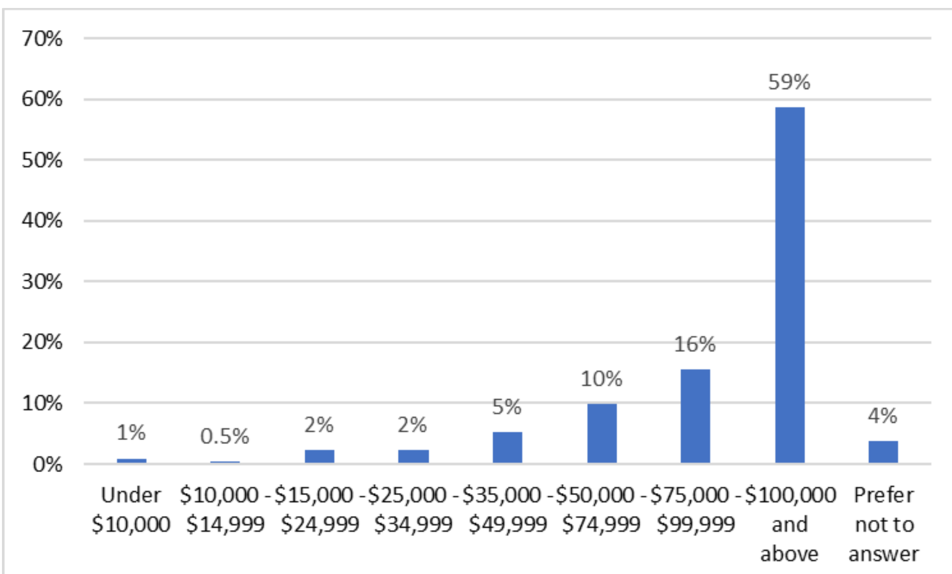
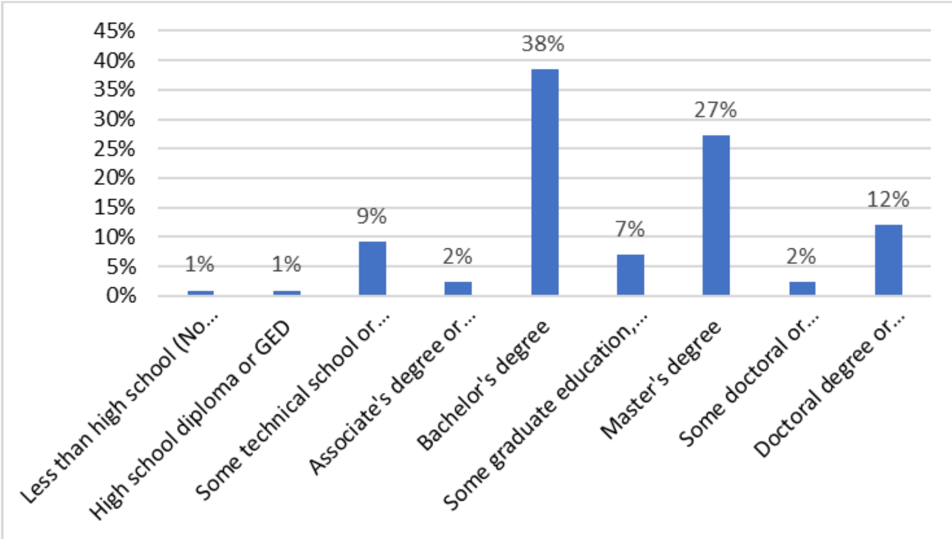


Figure 8: Highest Level of Education Completed



Purpose

Consistent with other survey research on trail use (Chen, Lindsey, & Wang, 2019), the top three reasons why respondents visited the BeltLine were for exercise (54%), local leisure (53%), and general recreation (41%). Local leisure was described as dining and shopping, while general recreation was described as non-commerce-related activities such as the skatepark. These designations were selected to facilitate understanding of the impact the BeltLine has on the local economy, and the number one reason these respondents visited the BeltLine included spending. In contrast, only 4% of respondents indicated that their time spent on the BeltLine was earning money: 3% to work remotely, and 1% were employed at a BeltLine business. Another area for growth includes promoting the Atlanta BeltLine as a tourist attraction, as only 5% of respondents selected tourism.

Importantly, the data indicates that the existence of the BeltLine can supplant the need for vehicular transportation for certain types of trips. Taken together, 31% of respondents use the BeltLine for mobility, either to walk to another neighborhood (16%) or for commuting to work/school/errands (15%). Trip displacement is illustrated in Figures 11-12. Most respondents (71% and 117% ([item was select all that apply]) indicated that if the BeltLine did not exist, they would have driven or been driven to their destination.

Finally, 17% of respondents indicated using the BeltLine to connect to MARTA[1] bus or rail. Of those, in a typical week, 77.7% use it as a connector 1-2 times per week, 11% 3-5 times per week, and 8.3% daily. The low percentage of people who regularly use the BeltLine to connect

[1] MARTA is Atlanta's public transit system.

to public transportation may be influenced by the proximity of bus stops and rail stations to BeltLine access points.

Some respondent comments to an open-ended question related to the utility of the BeltLine for transportation:

- I use the BeltLine to commute (i.e., to work in the morning, home in the afternoon).
- I don't own a car. I use the BeltLine to connect to grocery stores and to get to MARTA.
- I wish the BeltLine connected to Westside neighborhoods as I work downtown and wish to take it on my commute. I support the connect the comet effort.
- Love the BeltLine and have lived within proximity to it for 8 years. At one point I got rid of my car and used it for my main method of transportation.
- I really enjoy having it as a method of transport/community center.
- I love using it to eliminate car trips.
- More connections to transit would be great.
- I would visit it and the businesses a lot more if there was reliable transit to the BeltLine.

Figure 9: What was the purpose of your most recent visit to the Atlanta BeltLine?

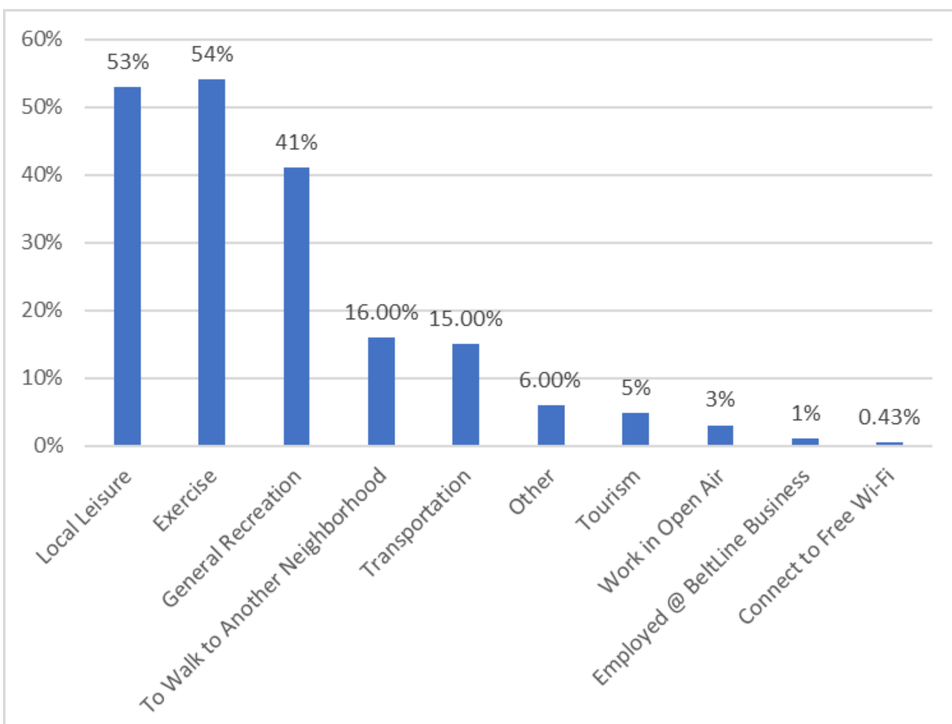
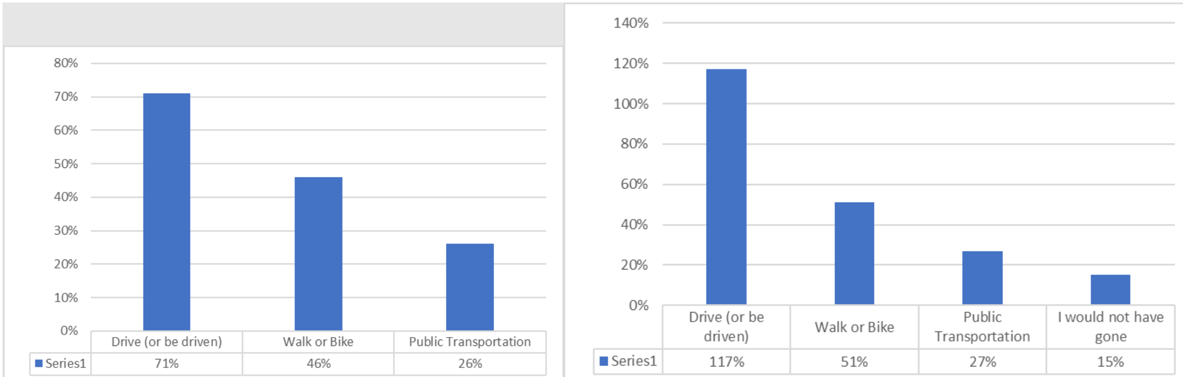


Figure 10 - 12: If the BeltLine didn't exist, how would you have commuted (Fig. 12)? How would you have traveled to other neighborhoods (Fig. 5)?

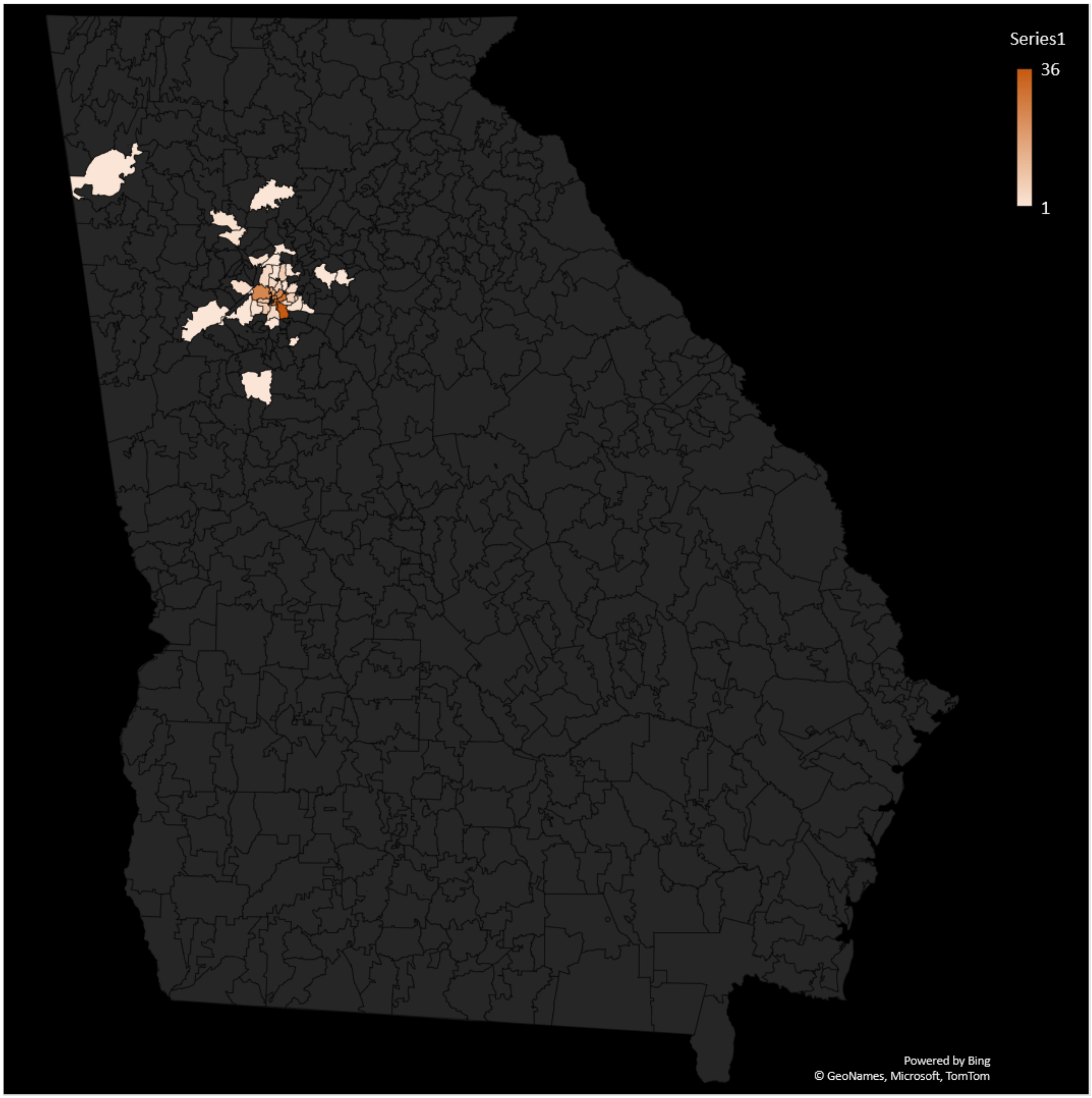


Proximity and Distance Travelled to the BeltLine

The most used mode of transportation to the BeltLine is nonmotorized, with 63% of respondents indicating that they walked, rode a bike, scooter, or skated (Figure 13). This result is unsurprising considering that 58% of respondents indicated that they lived within walking distance to the BeltLine. Figure 12 is a map of BeltLine visitors by zip code. By and large, the BeltLine is serving its adjacent communities. However, visitors have traveled quite a distance, up to 60 miles, to spend time on the BeltLine.

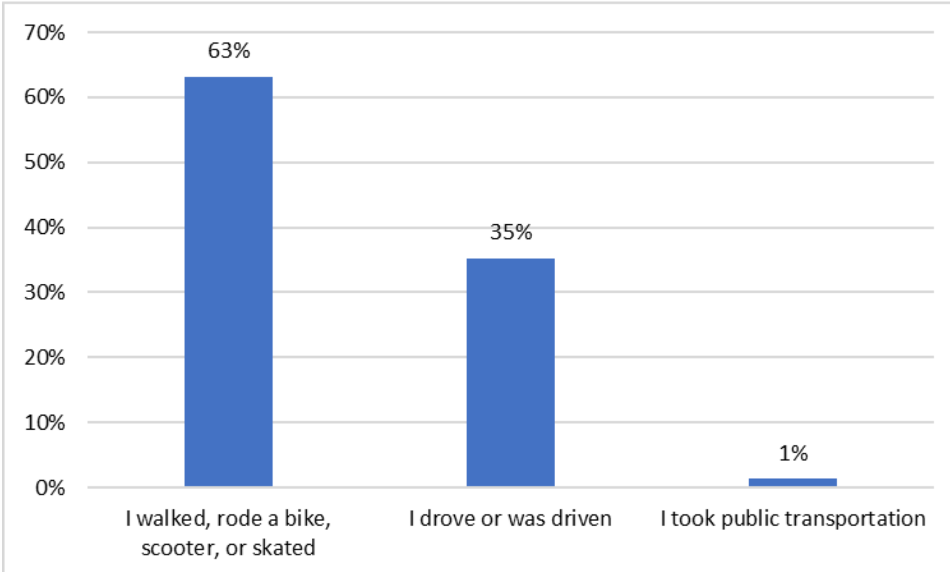
Thirty-five percent of BeltLine visitors drive to the BeltLine, of those, 41% are traveling with a group, and 41% are meeting friends/family. Though this survey did not collect data on the travel modes of friends or family that were met on the BeltLine, it is reasonable to assume that a portion of them also drove. Therefore, visitors that drive to the BeltLine likely represent a larger number of cars and people when taking into account the people they bring and/or meet. To illustrate, for those that use nonmotorized transportation to the BeltLine, 55% come alone, 30% are in a group, and 15% meet friends/family.

Figure 11: BeltLine Visitors by Zip Code (Map)



Range	0-60
Mode	0.5
Average	4.2 miles
STDEV	7.7

Figure 12: Travel Mode to the BeltLine



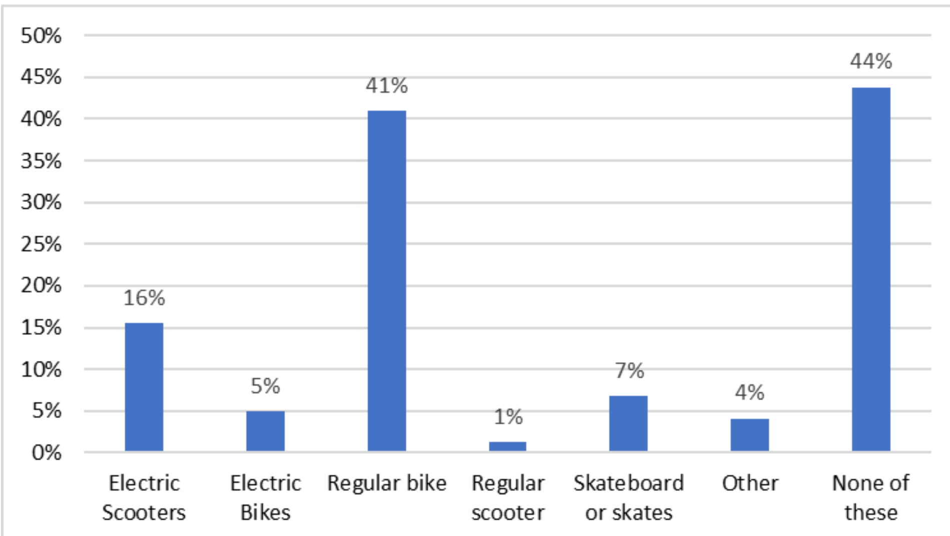
Transportation Mode on the BeltLine

At 44% and 41%, respectively, walking (i.e., none of these) and cycling (unassisted) are the most oft forms of travel on the BeltLine. Trailing 25 percentage points behind, the third most frequently selected mode of travel was electric scooter at 16%. (Figure 7) As a multiuse trail, during a busy time, one would observe an intermingling flow of foot traffic (walkers and joggers) and cyclists and scooters zipping past (or meandering). According to written comments made by survey participants in response to the open-ended question: **Do you have any comments about your experience(s) on the Atlanta BeltLine?** This wheels-walkers sharing of the trail is perceived as risky and disordered. Of the respondents that chose to write comments, 28% focused on their dislike of scooters or the impact of multimodal travel on their enjoyment of the trail. Some comments included:

- Hate those electric scooters. Hate them.
- Too many different speeds. I wish the BeltLine rail plans would be eliminated and the BeltLine doubled - one for pedestrians, one for bikes, scooters, etc.
- I do not like the electric bikes and scooters on it. That is something I wish would change because it's definitely getting a bit dangerous with them, especially on busy weekend days.
- NO MORE SCOOTERS. PEOPLE DONT KNOW HOW TO USE THEM. ITS SO UNSAFE. IVE SEEN TOO MANY ACCIDENTS.
- I love it, but bikes, skateboards, and scooters can be obnoxious during peak hours.
- It's crowded and unsafe. We need separate lanes for wheels.
- I don't like fast vehicle travel. I think speeding bikes, scooters are dangerous and should be controlled much more and possibly banned
- Crowded; can get tricky walking with so many bikes, scooters, etc.
- There should be bike/pedestrian separation

Further analysis that compared BeltLine walkers and cyclists in terms of their mode *to* the BeltLine, however, revealed that cyclists are more likely to be local and less likely to drive to the BeltLine. The range of distance that cyclists travel to the BeltLine is 0-12 miles, the average distance is 1.35 miles (STDEV 2 miles). Whereas those walking on the BeltLine range of distance that they travelled to the BeltLine was 0-60 miles, the average distance was 5.5 miles (STDEV 9 miles). Hence, accommodating cyclists with wheels lanes would show strategic support of the BeltLine adjacent cycling community, and would appease the walkers.

Figure 13: Modes of Transportation While on the BeltLine

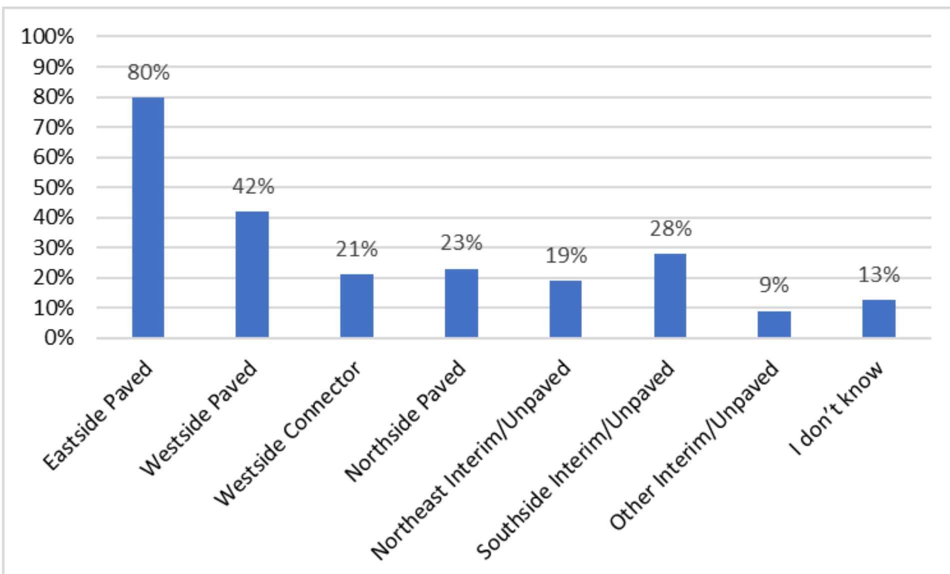


Trail Use location, Frequency, Time, & COVID Impact

Most of the respondents (80%) have visited the Eastside trail. This result was expected given that it is the most developed portion of the trail and has a multitude of businesses to visit. The Eastside trail also connects to Piedmont Park and Midtown Highschool at the intersection of Monroe Drive and 10th Street, providing walkable access to nearby neighborhoods and amenities (e.g., Trader Joe's, Midtown Cinema). There are also many access points along the Eastside trail, including via Ponce City Market. Furthermore, on the other end, it connects to Krog Street, the popular graffiti wall walk on Wiley Street, with walkable access to Krog Street Market and other local amenities in East Atlanta. The second and third most selected trail portions visited are the Westside paved trail (42%) and the Southside Interim/Unpaved trail (28%). The Westside Connector and the Northside Paved sections are only a few percentage points behind, at 21% and 23%, respectively (Figure 15). The precipitous drop in the use of trail portions other than the Eastside is likely related to the fact that they are not fully developed (e.g., retail and access points), include unpaved sections, and have sections that are completely closed due to construction, impacting the experience of fluid connectivity. Another inhibitor of using these sections of the BeltLine may be related to a lack of access points and walkability to the trail. Some comments included:

- I wish I had sidewalks to get to the access point near my house. (30314)
- I live near the unpaved southside BeltLine. I will likely use it more once it is paved.
- I wish there were more entrances and exits on the south side.
- I wish the BeltLine connected to Westside neighborhoods as I work downtown and wish to take it on my commute.
- Focus on finishing the 22-mile path and increasing connectivity!
- Would highly utilize the south side trail if paved.
- The actual parts I have visited are really not within walking distance of restaurants or businesses (30331)
- Challenge to get to the belt line in a pedestrian or bike safe way

Figure 14: Which portion of the BeltLine have you visited?

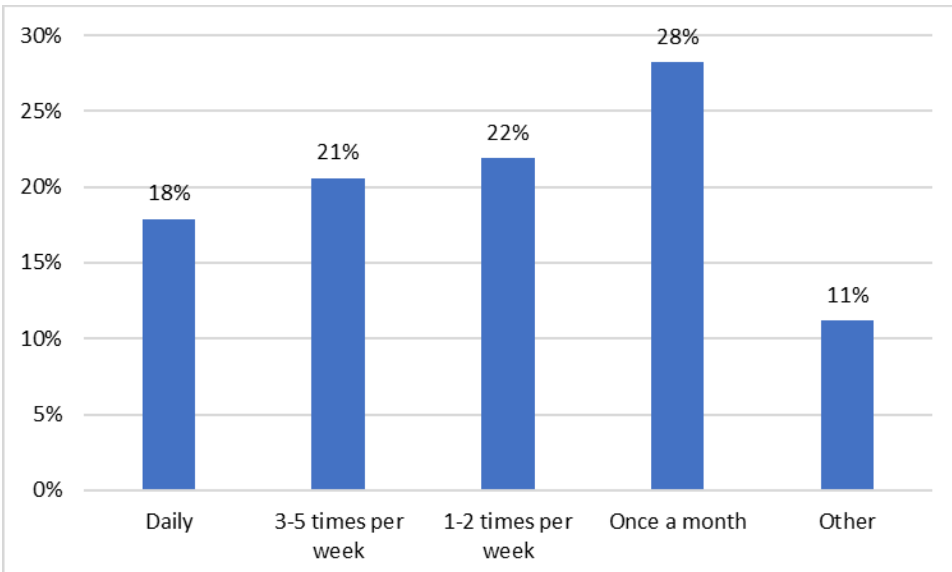


The frequency of use ranged from 18% (daily) to 28% (Once a month) (Figure 16). The "Other" selection, which accounts for 11% of the sample, described their use as once, first time, or last year. However, if the frequency variable is simplified into a binary of weekly and monthly, 61% of respondents visit the BeltLine at least once per week, while 28% visit it once per month. These data indicate repeat and potentially habitual use of the BeltLine, which speaks to its utility and the occupants of the adjacent communities embracing its presence. Many respondents praised the BeltLine in their comments:

- We love it! Great public amenity!
- I have really enjoyed living near and walking on the BeltLine.
- LOVE IT! Every time I get a chance to bring a new friend or family member to town, I love showing it off. My favorite part is the active graffiti wall near the rhino statue
- ATL's best asset!!
- I love it so much. It's the main reason I was excited to move to atl. It's the reason the city is even remotely walkable.

- My favorite part of Atlanta life.
- I love the BeltLine for leisure and foraging! It's been a lifesaver during covid.
- Love the use of artwork the emergence of various businesses and entertainment experiences.
- We greatly enjoy the convenience and connectivity.
- I love the BeltLine…for walking, looking at the different art pieces all along the BeltLine.
- I'm excited about all the public art works and hope to have some of my art out there too.
- I love it! It's very nice and peaceful. Thank you

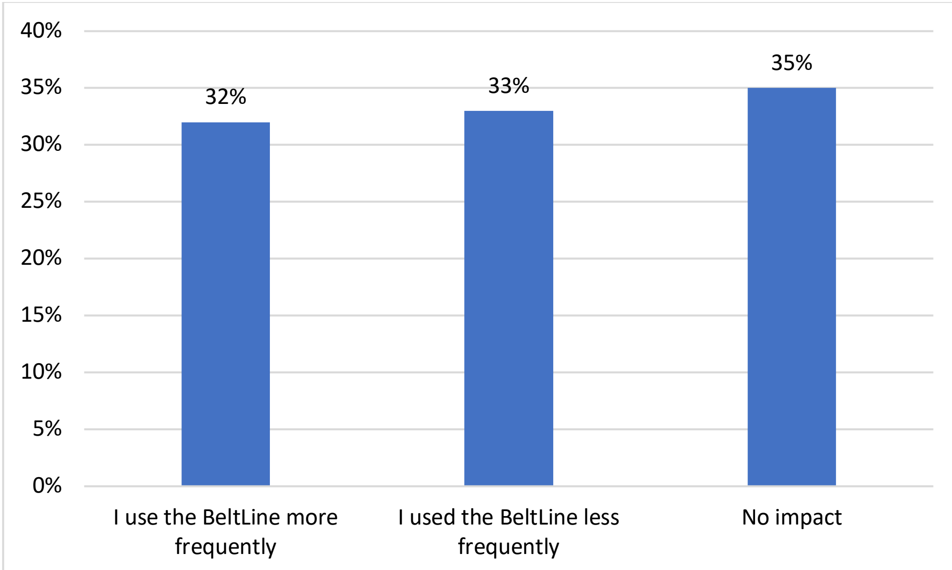
Figure 15: Frequency of Visits



Because this survey was deployed during the COVID-19 pandemic, these authors were concerned about how COVID-19 restrictions may impact the collected data. For example, pre-COVID, people may have used the BeltLine to commute more frequently. Whereas during the pandemic response, a large segment of the workforce became remote employees. As such, we asked, **How has the COVID-19 pandemic impacted your use of the BeltLine?** The result was a an almost equal spread, with 35% using the BeltLine more frequently, and 39%, indicating no impact. Twenty-six percent of respondents indicated using the BeltLine less frequently (Figure 17).

The "why" behind the selections was not queried, but one could postulate that some chose to use the BeltLine more frequently as substitute activity for the daily life events that were suddenly missing (e.g., commutes, lunch breaks, socializing). Those that used it less frequently may have deemed the BeltLine as a risky undertaking. It would be an interesting research pursuit to understand how attitudes about and perceived risk of COVID-19 interact with the use of outdoor spaces and sense of wellbeing during the height of the pandemic response period.

Figure 16: Impact of COVID-19 on Frequency of Use



To understand how people converge on the BeltLine, we asked about group size, duration of visit, and time of day most often visited. We found that most respondents travel along the BeltLine as a group. Taken together, 59% of respondents either come with a group or meet friends/family on the BeltLine, thereby forming a group, and 40% come alone (Figure 18). Group size was reported as large as 25 people, but the average group size was 2.6 (STDEV 3.51).

The average time spent on the BeltLine for the majority of respondents (58%) was 1-2 hours (Figure 19). The afternoon at 31% is a more popular time to visit than the morning (15%) or evening (14%), with the exception of respondents that indicated it varied for them (40%). These data may also have been impacted by the COVID-19 pandemic, with fewer people using the BeltLine to commute during the mornings and evenings, fewer people patronizing bars and restaurants along the BeltLine in the evening, and more people using the BeltLine in the afternoon as a substitution activity.

Figure 17: Which best describes your visits to the BeltLine?

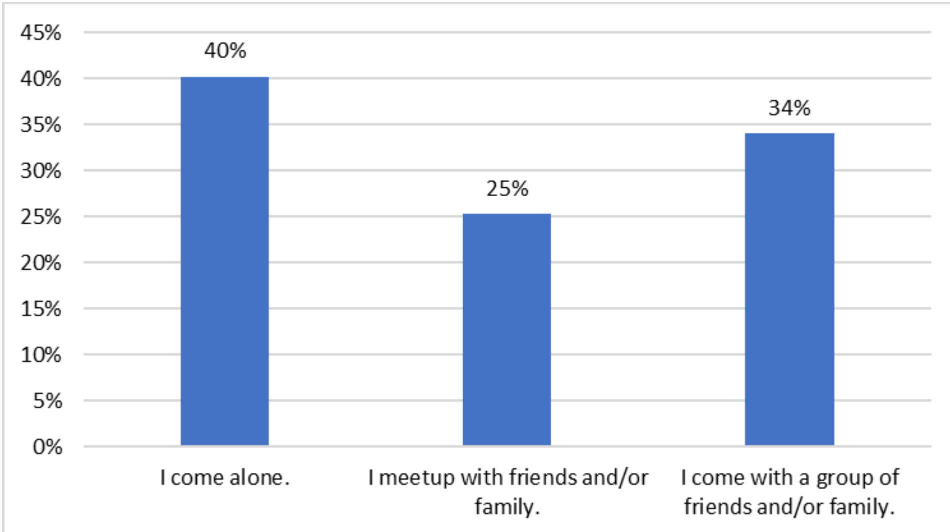


Figure 18: Average Time Spent on the BeltLine

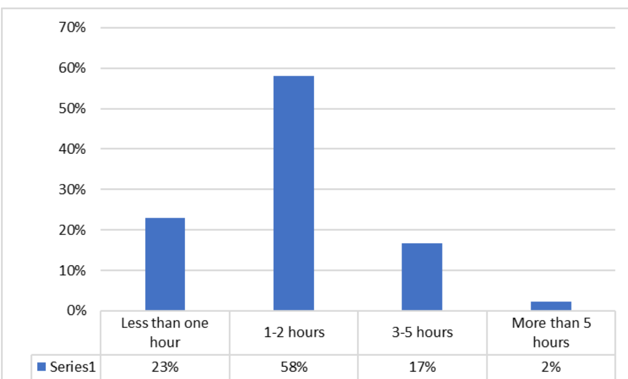
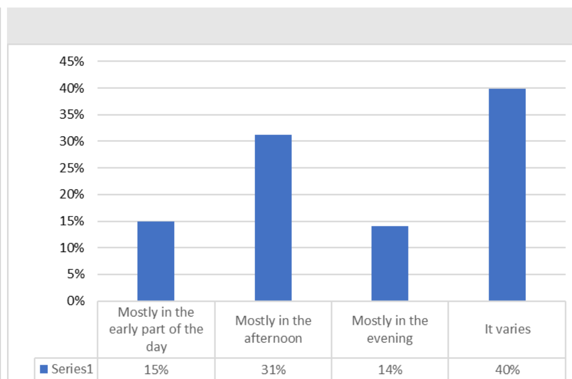


Figure 19: Time of Day



Discussion

How can sensors be used to automate people counting along a multiuse trail?

The prototype radar system did not perform as well as hoped at direct counting of people, primarily due to the inability to consistently detect all people passing by it, and the inability to separate individuals out of groups traveling together or in dense environments. The sensing hardware itself can clearly detect dense crowds, and with a slightly higher power budget or better detection algorithms, it seems quite possible to count people accurately with similar low-cost radar modules.

We were able to implement a system that required very little infrastructure – just a post to attach it to and batteries providing multi-day runtime. The simplicity of the deployment allowed for much more flexibility within the complicated environment of the BeltLine. Simply stated: if we had required wired power or network, we could not have coordinated everything needed to deploy a realistic system during a short initial exploration.

Radar-based People Counting Discussion

Based on the raw sensing data collected initially and the works of others (Tahmoush, & Silvious, 2009), it is clear that the onboard single target algorithm was not able to fully utilize the rich information available for people counting. Transportation differentiation modality was achieved via approach speed. Further refinement of the onboard processing and more processing power (at the tradeoff of electrical power consumption) could lead to much better results.

The radar modules used are at their limits when detecting people passing at the far edge of the 14-foot-wide trail. They would be more suitable for a 6-foot width sidewalk, and a more powerful radar system would be needed to improve the performance across the entire width of the BeltLine, again at the expense of electrical power consumption.

The raw data collection in dense environments also shows the issues of overlapping radar returns in the highest of densities. Wide multi-modal pathways like the BeltLine, can simply become too dense for accurate counting from non-steered radar systems. Individuals stay within the FoV of a trail-side sensor for 2 or more seconds, so densities over 25/minute will very commonly cause overlapping signals. While these simple modules are still useful for detecting crowded congestion, they do not provide rich enough information to pick apart the signals from each individual.

More advanced radar systems exist and will be better suited for counting in these dense environments. FMCW techniques could be applied to these simple modules, but that may not be enough for such dense path usage. 1D and 2D steered radar systems should be able to perform much better, such as those from TI and others (https://www.ti.com/sensors/mmwave-radar/overview.html), but bring increased system cost, electrical power consumption, and a need for more on-system data processing. Unfortunately, due to these tradeoffs, these solutions are not currently well suited to compact battery-powered or solar-powered installations.

Camera-based People Counting

In contrast to radar-based systems, various camera systems can be used for people tracking. If the upfront installation costs for placement, power, and data are not an issue, object and facial recognition can provide a plethora of information about how the trail is used, more so than radar-based systems. The big tradeoff is privacy, which can be a contentious issue in public spaces.

Along the BeltLine, there are already some cameras installed. To the best of our knowledge, these cameras are being installed for the purposes of public safety by the Atlanta Police, with no access for data collection efforts. There are negative public perceptions associated with video recording in public, especially when facial recognition is employed. The BeltLine officials are particularly sensitive to public perception. For these reasons, in addition to the infrastructure requirements, we chose not to focus on camera-based people tracking along the BeltLine, even going as far as to avoid recording video along the trail.

Power

The possibility of using small solar panels for recharging the system during sunny days was kept in mind while the sensing method and wireless communication technology were chosen. While a small solar panel (130 x 150 mm) mounted flush with the case would be enough to power the processor and the cellular communications 24/7, the power required to operate the radar sensing module continuously would necessitate a larger panel, and thus a larger and more obtrusive installation than was used. That said, a reasonably sized post-top solar panel would be adequate.

It is worth mentioning that rails-to-trails projects, including the BeltLine, often have relatively unobstructed views of the sky compared to many places in the densely wooded southeastern US, as the wide railbed means less tree cover in the first years after the trails are converted. Still, between existing adjacent trees, newly planted trees, and BeltLine-adjacent buildings, an anecdotal observation recorded less than 5 hours of direct sunlight at the two people counter locations worked most closely with.

Sensing using some other methodology (such as an optical sensor or in-pavement sensor) could allow even lower power requirements. Lengthening the duration that data is queued before sending it over cellular would also help. The existing EcoCounter systems are good examples of this.

Communications

The choice of using the newly-released nRF9160 LTE-M and NB-IoT-based module worked better than expected. This kind of low-power cell module did not exist just a few years ago, and it enables all sorts of low-power applications that were impossible before. Coverage was great along the BeltLine, the high data throughput was helpful during early development, and the power consumption was a non-issue compared to the continuous power draw of the radar module. That said, LoRaWAN seems to have advantages for ultra-low-power application, or when there is no existing LTE-M or NB-IoT infrastructure.

Counter Location near Pinch-Points

Our data collection locations were at existing Eco-counter installations, which are often placed near 'pinch points' along the BeltLine, near on-level roadway intersections, or where the BeltLine crosses over roads. This placement is useful because the traffic is easier to count in a constrained width, but the narrowing trail does affect people's behavior.

Figure 20: An EcoCounter and prototype radar counter before a pinch-point at Ponce De Leon Ave.

The above location is the bridge crossing Ponce De Leon Avenue, with the Eco-counter post (and our raw data collection system) located next to the trail. The trail goes from over 11 feet wide to under 8 feet. On busy days and on this popular section of trail, the narrowing results in cyclists and scooters slowing as they pass through the pinch point. This makes speed-based detection of transportation modality more difficult. It makes it harder to tell groups apart and makes it nearly impossible to tell if cyclists are travelling together as a group, even when observed in person.

Another effect is bunching due to the cycle of traffic lights and crosswalks. At busy intersections such as Dekalb Avenue or Memorial Avenue, people cross the intersection together right after the crosswalk signage allows and do not have enough time to space out before reaching counters.

Further, wheeled users slow down before and speed up after those intersections, so their speed within a few hundred feet of an intersection is not a great indicator of their average travel speed along the rest of the BeltLine. Therefore, the optimal placement for trail usage sensors would be farther from intersections, where people's pace of travel is uninfluenced by the above-mentioned factors.

Is the BeltLine serving the adjacent communities, and how?

The results of the survey show that the BeltLine is serving both adjacent communities and the greater Metro Atlanta area. The majority of respondents (58%) reported living within walking distance to the BeltLine, but a significant proportion (42%) reported that they did not. This result is a mixed blessing. On the one hand, the BeltLine's ability to draw visitors from farther counties is a testament to its appeal. On the other hand, these non-adjacent visitors are driving to the BeltLine which can pose problems related to parking, roadway congestion near the BeltLine, and congestion on the BeltLine, especially during the weekends. Adding parking to accommodate the people who drive to the BeltLine will lessen the need for visitors parking on residential streets, and a minor parking cost can help sustain the BeltLine. However, adding more parking may also encourage more drivers which is counter to the environmental sustainability goals of multiuse trails.

Many respondents noted overcrowding and wheeled traffic (e.g., electric scooters, cyclists) diminishing their BeltLine experience. To remedy congestion on the BeltLine, respondents plead for its completion. "Focus on finishing the 22-mile path and increasing connectivity!" and "Complete it! It is extremely congested on the east side," are exemplars of this sentiment. To improve use and enjoyment of the BeltLine, sensor data could be visualized on a mini, community-facing dashboard to help visitors plan their trips, biking routes, and sense of safety based on personal preference for either a lively, crowded experience or a leisurely stroll. The dashboard could display how congested the trails are and the speed of travel.

Opening more paved sections of the BeltLine may relieve the congestion issues noted on the Eastside Trail, and likely reduce the proportion of visitors that drive there if there was BeltLine access within walking distance of their homes or places of work. Other recommendations include widening the BeltLine and adding wheels-only lanes to reduce negative perceptions of cyclists and scooters as a nuisance (at best) and dangerous (at worst) to walkers. With the majority of the 22-mile BeltLine corridor in the planning and design phases, there is an opportunity to implement access and experience improvements before paving begins. For example, edge strips have been added to widen portions of the Eastside trail as a post-development improvement. This type of retrofitting can be avoided when data on BeltLine use experiences inform the design of planned sections.

When defining communities as a demographic unit, as opposed to being defined by physical proximity, the BeltLine is not serving a demographic that is reflective of the diversity of the BeltLine adjacent communities and the City of Atlanta. For example, the Westside trails traverse majority African American neighborhoods (upwards of 97% Black/African American), and taken together, 63% of respondent have visited the Westside Paved and Westside Connector trails, yet only 11% of those respondents identified as Black/African American. Also, the household income of respondents skews higher than Atlanta's median household income. Of course, the study's recruitment methods may have skewed the sample. Nevertheless, understanding why Atlanta's African American community is not represented more in the data is worth further inquiry. Likewise, considering that the BeltLine is a free activity, more study is needed to understand how to encourage use by working-class and working-poor populations in the city. This brings us to the purpose of BeltLine visits.

A majority of respondents visited the BeltLine for exercise (54%) and leisure (53%); and a minority used the BeltLine for mobility purposes (15%), or to connect to public transit (17%). Though, there is great potential in this seed of data. Improving BeltLine usage for utilitarian purposes such as commuting may increase the representation of socioeconomic *and* race/ethnicity diversity. For example, 66.9% of Atlanta's public transit riders are Black/African American, and 68.6% earn less than $75,000 annually (Atlanta Regional Commission, 2019). If BeltLine development plans included improving connectivity to MARTA, more people of color would likely take advantage of the BeltLine. Connectivity can be improved by placing bus stops closer to BeltLine access points, providing pathways and ramp connections from rail stations to the BeltLine, and integrating the same into MARTA's "Plan a Trip" feature that outputs step-by-step walking and riding directions. Increasing connectivity to bus and rail to encourage users of public transport to use the BeltLine and to encourage BeltLine users who drive to the BeltLine to use public transportation is supported in both our quantitative and qualitative data. Survey respondents agree. "It would be incredible if it had MARTA rail access," shared one respondent, and "More connections to transit would be great," shared another.

Community amenities along the BeltLine would encourage a more diverse demographic. Using the Eastside Trail as an example of how BeltLine use is tied to visitors contributing to the local economy, i.e., 53% of respondents indicated that their purpose was to shop or dine, and the Eastside Trail has many retail and restaurant destinations, it is a reasonable assumption that the BeltLine trails on the south and west should have equally developed business spaces. The Westside Trails need better connectivity to adjacent amenities. In Southwest Atlanta, there are examples where BeltLine access was not a priority for the design of the commercial offering, i.e., there is no direct access to enter the establishment from the BeltLine. Development plans for the south and westside sections should include discussions with existing businesses on options for providing direct access, as well as develop first floor retail/storefront space and kiosks for new businesses to grow the local economy in these areas. As proven on the Eastside, people need and want a reason to use the trail beyond exercise and dog walking.

Design can anticipate behavior when data reveals how people move on the BeltLine in terms of speed and mode of travel, meandering, versus purposefully moving, and how the built environment influences the same. For seamless integration of business, people, and their purposes for visiting, and travel modes, we recommend conceptually considering the BeltLine a "linear park." Doing so would allow for the development of strategically placed plazas where congregation is anticipated or encouraged, designating out-of-the-way eScooter/eBike parking, and deliberate separation of the BeltLine's wheeled users from walkers. Sensor and hand-count data supports this recommendation, given the prevalence of cyclists in the data. Encouraging slowing and congregation through the design of outdoor seating (benches and picnic or café tables) near adjacent businesses affords the opportunity for pit-stops for refreshment, business patronizing, gathering spots for meeting friends/family, and general enjoyment of the outdoors, all the while letting the cyclists and other wheeled traffic continue unimpeded. With the BeltLine's recent acquisition of land parcels and significant funding made available via the creation of the Atlanta BeltLine Special Service District (SSD), implementing these data-informed design recommendations is practicable.

How can the BeltLine be used as an emergency management asset?

Survey data describing how people travel to and move along the BeltLine has revealed its potential for use as a pedestrian evacuation route. The sensor data results show their potential for crowd detection. More than 1/3 of BeltLine visitors drive to the BeltLine, of those, 41% are traveling with a group, and 41% are meeting friends/family. Therefore, visitors that drive to the BeltLine likely represent a larger number of cars and people when taking into account the people they bring and/or meet. Knowing this informs scenarios for which to plan in an evacuation such as parent-child reunification and where to deploy or preposition personnel to direct traffic. The sensor data may also inform determining the pathway to the emergency site on the BeltLine and decision-making around whether it is advisable for emergency vehicles to drive down the BeltLine.

These use cases are not entirely hypothetical. Figure 21 shows two occurrences in Atlanta's recent history that impacted traffic congestion and, by extension, linkage to local amenities. In 2020, there was a sinkhole on the BeltLine that caused the closure of a portion of the Eastside Trail (Keenan, 2020), car accidents have caused damage to the BeltLine and endangered pedestrians (Johnson, 2022), medical emergencies occur requiring a paramedic response (Atlanta Police Department, 2016), and during the COVID-19 pandemic response, officials considered closing the BeltLine (Deere & Brasch, 2020). Should the BeltLine ever require closure for safety, the people flow sensors can remotely monitor whether people are complying with the mandate, and if not, enforcement can be deployed to clear the areas.

Figure 21: 2014 Snow Jam Atlanta and the Interstate 85 Bridge Collapse (2017)

Crowd Detection

Both existing optical counters and this project's novel radar-based system have issues distinguishing people that are close together. As some other work has shown, this gets worse with higher density and where people can travel side-by-side. This limits their use as precise people-counters since in more congested conditions it will detect groups, not individuals within the group, and means that in very dense, potentially overcrowded conditions, groups will blur together. However, this limitation reveals that the system is quite capable of detecting congestion. The prototype also effectively and accurately collects speed data and can display how fast a group is moving. Taken together, crowd detection and speed data have emergency management implications. For example, stampede detection. With the sensors on an average day detecting speed of travel and learning what is typical, an algorithm could be implemented to discern anomalous crowd behavior, such as a large group suddenly moving quickly in the same direction. The algorithm, as implemented, uses baseline subtraction, which as stated earlier, fails in densely crowded environments where there are periods with near-continuous radar response. A threshold, however, can be set for these periods of near-continuous radar response, to alert emergency managers of overcrowding.

Evacuation

The Eastside trail is the busiest portion of the BeltLine. Should an emergency event (e.g., fire, gas leak) occur in a neighborhood adjacent to the Eastside trail, directing BeltLine visitors, based on their location, to either travel west or east to get out of harm's way while not congesting the roadways and slowing first responders' travel to and out of the impacted area. Considering that 35% of respondents indicated that they drove or were driven to the BeltLine, a mass exodus of those drivers during an emergency event could cause delays. Alternatively, they could be directed to walk to a safe harbor, such as the Midtown Highschool stadium or Piedmont Park. However, without real-time data via sensing, connectivity, and a dashboard to visualize people's mobility behavior in the impacted area, the potential of the BeltLine as an emergency management asset cannot be optimally realized. The people flow sensors, if connected to a city dashboard that has other critical inputs such as roadway traffic information, the people flow data, speed of travel, and congestion, can serve emergency managers in deploying targeted emergency messages to avoid the area and redirecting traffic (foot and motorized). Additionally, the sensor's speed detection capability can be used to estimate the time it will take for people to evacuate the impacted area of the BeltLine considering cycling, scooter, and walking speeds.

Observations for Trail Development Planning

The major finding from the exploration of using speed detection to discern transportation mode on the BeltLine was that the optimal placement of sensors needs to take into account the influence of the built environment on human mobility patterns. As discussed above, the existing EcoCounters are installed at points that impact mobility by causing bunching and slowing of foot and wheeled traffic. This exacerbates the occlusion problem with radar-based sensing for people counting and makes speed-based detection of transportation modality less accurate. As such, the recommended placement of radar-based, speed detection sensors is on inner portions of the trails where wheeled traffic will be moving at average speeds, and the pedestrians are not being funneled together because of narrowing trail, such that happens when crossing bridges. Placement of battery-powered radar-based sensors on lower density sections will also allow for more accurate individual counts of pedestrians, cyclists, and eScooters, the top three modes of transportation along the BeltLine according to both the sensor and survey data.

Another major finding was the need to address congestion on the BeltLine. Survey respondents expressed concern about the safety of the BeltLine due to the multi-modal travel. Cyclists and scooters sharing the same space as the much slower foot traffic resulted in a diminished experience for many of the respondents. Likewise, large groups walking together and people that are not "situationally aware" were equally vexing. There is still a significant portion of the BeltLine that is unpaved. As these sections are designed, planners should account for the need to have a wider trail and separate wheeled traffic from foot traffic. Likewise, for the already paved sections, retrofitting them to allow for wheels lanes is recommended. These recommendations are not only supported by the respondents' comments, but quantitatively, the cyclists are more local to the BeltLine-adjacent neighborhoods than the respondents on foot and therefore accommodating cyclists would be supporting the community.

Given the reality that BeltLine visitors will vary in their purpose for visiting the BeltLine and their mode and speed of travel, again, conceptualizing the BeltLine as a "linear park" is applicable. Directing people to areas of congregation through the design of the built environment, may also address congestion on the trail. Encouraging slowing and congregation at designated spaces, out of the way of the main trail can be accomplished through the design of outdoor seating near adjacent businesses. This would afford the opportunity for business patronizing, meeting spots, and general outdoor enjoyment. It also would allow the cyclists and other wheeled traffic to continue around these plazas with less constraints. These congregation areas would also be good places to deploy battery-powered radar-based sensors for crowd detection.

Notably, the data indicated that the existence of the BeltLine has, for some respondents, supplanted the need for vehicular transportation for certain types of trips, including walking to other neighborhoods, running errands, and commuting. These respondents indicated if the BeltLine did not exist, they would have used motorized transportation for the trip. So, the BeltLine is connecting communities and having a positive impact on the environment. Implementing the above-detailed trail improvements would likely encourage greater use of the BeltLine for commuting and connecting.

To that end, it is also important that the BeltLine capitalize on existing city infrastructure. Namely, public transit. Seventeen percent of respondents indicated using the BeltLine to connect to public transportation, and mostly only 1-2 times per week. The low percentage of people who *regularly* use the BeltLine to connect to public transportation is likely influenced by the proximity of bus stops and rail stations to BeltLine access points. Increasing connectivity to bus and rail to encourage users of public transport to use the BeltLine and to encourage BeltLine users who drive to the BeltLine to use public transportation is supported in both our quantitative and qualitative data. Concomitantly, it would likely increase representation of the Black/African American community on the BeltLine, as the majority of public transit riders in Atlanta are people of color.

In meetings with BeltLine officials, it became abundantly clear that they wanted the public to have equal benefit from the existence of the BeltLine, not diminished experiences based on socioeconomics, race/ethnicity, and identity. This means that small business opportunities and efforts to boost local economies in BeltLine-adjacent neighborhoods should be as pronounced on the Southside and Westside Trails as they are on the Northside and Eastside Trails. The Eastside Trail is an exemplar for how multiuse trails can increase the circulation of money in a community. The BeltLine Trails on the south and west sides of Atlanta should have equally developed business spaces. The Westside Trails, and by extension the westside neighborhoods, would benefit from better connectivity to adjacent amenities by providing direct access to enter establishments from the BeltLine. Development plans for the south and westside sections should include first floor retail/storefront space and kiosks to grow the local economy in these areas.

Conclusion and Future Directions

This study found differences in where battery-powered radar-based sensors should be installed along the BeltLine. The prototype sensors did not perform as well as the existing EcoCounters in terms of individual person counts. But they are viable for people counting in low-density trail usage areas and for crowd detection in high-density trail usage areas. The prototype sensor can also accurately distinguish travel mode based on speed. The crowd-detection and travel speed capabilities show promise for emergency management use. But to realize their potential, continuous data collection is needed so that over time, and with the deployment of multiple sensors, the system may be programmed to learn anomalous mobility activity on the BeltLine. This is a future direction of this study, to gather long durations of ground truth data to calibrate the sensors to reduce the error in dense crowds so that the sensors could accurately count individuals and detect crowds regardless of placement on the trail.

While higher-power radar systems are promising for people counting in dense environments while remaining privacy-preserving, the goal of this study was to develop low-power, affordable, and easily deployable sensors that could be powered by solar panels. Likewise, facial-recognition camera systems are promising for people counting in dense environments, but they invoke privacy concerns. Hence, continuing development of low-powered, privacy-preserving, radar-based approach is warranted. Beyond, further calibration of the prototype sensor, visualizing the data via dashboard development is another area of future work. Smart emergency management of the Atlanta BeltLine and other parks and recreation assets in Atlanta will require integration of data from vehicular traffic. And other critical inputs. First responder dispatch access to the dashboard could be supportive of next-generation 911 efforts, as well.

Trail usage and *equality in public benefit* are especially important metrics to understanding the impact of multiuse trails. This study showed that the Atlanta BeltLine is having a positive impact on the surrounding communities where the BeltLine is open. Its continued development necessitates additional study of its use so that data-driven decisions inform BeltLine improvement projects and the continued development of the unpaved sections in a manner that promotes public, economic, and environmental health.

References

Al-nabhan, N. (2019, December). An IoT-Based Congestion-Aware Emergency Evacuation Approach. In *International Conference on Big Data and Security* (pp. 468-478). Springer, Singapore.

Atlanta BeltLine Partnership. (2021). A transformational project. Available at https://BeltLine.org/the-project/project-goals/equity-and-inclusion/

Atlanta Police Department. (2016). Atlanta Police Path Force and Atlanta Fire Rescue Mobile Medics Partner to Patrol the Atlanta BeltLine. Available at Atlanta Police Path Force and Atlanta Fire Rescue Mobile Medics Partner to Patrol the Atlanta BeltLine | Press Releases | Atlanta, GA (atlantaga.gov)

Atlanta Regional Commission. (2020). Regional On-Board Transit Survey, 2019 Final Report. Available at https://cdn.atlantaregional.org/wp-content/uploads/final-report-arc-2019-regional-transit-on-board-survey.pdf

Chen, N., Lindsey, G., & Wang, C. H. (2019). Patterns and correlates of urban trail use: Evidence from the Cincinnati metropolitan area. *Transportation research part D: transport and environment*, *67*, 303-315.

Congress, U. S. (2012). Moving ahead for progress in the 21st-century act. *Washington, DC*.

Davidson, E. (2011). The Atlanta BeltLine: A Green Future. U.S. Department of Transportation. Available at The Atlanta BeltLine: A Green Future | FHWA (dot.gov)

Dugdale, J., Moghaddam, M. T., & Muccini, H. (2021). IoT4Emergency: Internet of Things for Emergency Management. *ACM SIGSOFT Software Engineering Notes*, *46*(1), 33-36.

FEMA. (2013). Mitigation ideas: A resource for reducing risk to natural disasters. Available at www.fema.gov › fema_mitigation_ideas_final_01252013

Johnson, M. (2022). Road safety is a big concern after multiple interstate offramp crashes. WSB-TV. Available at Road safety is a big concern after multiple interstate offramp crashes – WSB-TV Channel 2 - Atlanta (wsbtv.com)

Keenan, S. R. (2020). Sinkhole on BeltLine's Eastside Trail shuts down high-traffic section of path. *Curbed Atlanta*. Available at Sinkhole on Atlanta BeltLine's Eastside Trail shuts down high-traffic section of path - Curbed Atlanta

Lindsey, G., Qi, Y., Gobster, P. H., & Sachdeva, S. (2019). The 606 at three: Trends in use of Chicago's elevated rail-trail. In *Proceedings of the Fábos Conference on Landscape and Greenway Planning* (Vol. 6, No. 1, p. 37).

Lindsey, G., Petesch, M., Vorvick, T., Austin, L., & Holdhusen, B. (2017). The Minnesota Bicycle and Pedestrian Counting Initiative: Institutionalizing Bicycle and Pedestrian Monitoring.

Lindsey, G., Singer-Berk, L., Johnston, W., Adcock, K., Folkerth, M., & West, E. (2019). Monitoring Trail Traffic in the Cincinnati Metropolitan Region, Ohio. *Journal of Park & Recreation Administration*, *37*(3), 123–133. https://doi.org/10.18666/JPRA-2019-9179

Lwin, K. K., Sekimoto, Y., Takeuchi, W., & Zettsu, K. (2019, December). City geospatial dashboard: iot and big data analytics for geospatial solutions provider in disaster management. In *2019 International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)* (pp. 1-4). IEEE.

Luymes, D. T., & Tamminga, K. (1995). Integrating public safety and use into planning urban greenways. *Landscape and urban planning*, *33*(1-3), 391-400.

Marchiori, M. (2018, October). People flow reconstruction in cities. In *2018 International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS)* (Vol. 3, pp. 292-299). IEEE.

Oswald Beiler, M., McGoff, R., & McLaughlin, S. (2017). Trail network accessibility: analyzing collector pathways to support pedestrian and cycling mobility. *Journal of urban planning and development*, *143*(1), 04016024.

Pelechano, N. & Badler, N. I. (2006). Modeling Crowd and Trained Leader Behavior during Building Evacuation. *IEEE Computer Graphics and Applications*, *26*(6), doi: 10.1109/MCG.2006.133.

Scherrer, P., Dimmock, K., Lamont, M., & Ripoll González, L. (2020). Rail trails literature: Current status and future research. *Journal of Leisure Research*, 1-23.

Tahmoush, D., & Silvious, J. (2009, September). Radar micro-Doppler for long range front-view gait recognition. In *2009 IEEE 3rd International Conference on Biometrics: Theory, Applications, and Systems* (pp. 1-6). IEEE.

Turner, S., Middleton, D. R., Longmire, R., Brewer, M., & Eurek, R. (2007). *Testing and evaluation of pedestrian sensors* (No. SWUTC/07/167762-1). Southwest Region University Transportation Center (US).

Uras, M., Cossu, R., Ferrara, E., Liotta, A., & Atzori, L. (2020). PmA: A real-world system for people mobility monitoring and analysis based on wifi probes. *Journal of Cleaner Production*, *270*, 122084.