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Influencing Travel Behavior via an Open-Source Platform Phase 3: Transforming Multimodal Travel Behavior Data to Support Traffic Congestion Reduction Strategies

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16. Abstract

This research proposes an innovative approach that applies crowdsourced data from mobile applications and GPS technology to enhance the information used in transportation planning modeling activities. The study focused on gathering accurate, real-time travel data through the OneBusAway (OBA) app, a widely used open-source transit user application, and the newly developed Travel Transit Tracker (TTT) app. The goal was to address urban congestion and promote more efficient and sustainable management of transportation systems. The study was conducted by researchers from the University of Puerto Rico at Mayagüez in collaboration with the University of South Florida. The goal was to incorporate user travel patterns into transportation models. While OBA was first used for data collection, its shortcomings in terms of accuracy and functionality prompted the creation of TTT. This companion software improved multimodal tracking and data validation capabilities. The suggested platforms are positioned as fundamental instruments for gathering travel behavior data to empower policymakers and transportation planners to make data-driven decisions. Detailed trip data collected through TTT has the potential to help shape future transportation system optimization plans. Technical issues addressed in the study include data cleaning, GPS accuracy, and software optimization for iOS and Android. Integrating GPS-based mobile applications into transportation planning provides precise data to improve traffic management and reduce congestion. This study can serve as a base for similar applications in other urban areas and highlights the potential of mobile technology to improve urban mobility. The project findings contribute to the ongoing development of data-driven, user-centered transportation planning solutions and suggest that using crowdsourced travel data for planning modeling and analysis can significantly enhance cities' ability to manage traffic congestion.

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Abbreviations and Acronyms

AI	Artificial intelligence
ACS	American Community Survey
API	Application Programming Interface
CBD	Central Business District
CE	Civil Engineering
CSE	Computer Software Engineering
DRPU	Daily rate per unit
DRT	Demand Responsive Transport
FHWA	Federal Highway Administration
GIS	Geographical Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GTFS	General Transit Feed Specification
HMM	Hidden Markov Models
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation Systems
LSTM	Long Short-Term Memory
MaaS	Mobility as a Service
MFA	Mayagüez Functional Area
ML	Machine Learning
MoM	Municipality of Mayagüez
NICR	National Institute for Congestion Reduction
OBA	OneBusAway
O-D	Origin-Destination
OS	Operating system
OTSF	Open Transit Software Foundation
PRHTA	Puerto Rico Highways and Transportation Authority
PRPB	Puerto Rico Planning Board
PSTA	Pinellas Suncoast Transit Authority
RTPI	Real-Time Passenger Information
SSL	Secure Socket Layer
TDM	Transportation Demand Management
TOD	Transit-Oriented Development
TNC	Transportation Network Company
TIM	T*ransporte Integrado de Mayagüez* (Mayagüez Integrated Transportation System)
TTT	Travel Transit Tracker
UPRM	University of Puerto Rico at Mayagüez
US	United States
USCB	United States Census Bureau
USF	University of South Florida
VGI	Volunteered Geographic Information

Executive Summary

Transportation is a fundamental aspect of daily life, enabling individuals to access essential goods and services, and facilitating economic activity. However, the collective travel patterns of users within transportation networks can lead to congestion, particularly in urban environments. Effective transportation planning is critical to reducing congestion and improving the efficiency of urban mobility systems. To achieve this, accurate data collection on how and where people travel is essential.

This research, conducted by the University of Puerto Rico at Mayagüez (UPRM), in collaboration with the University of South Florida (USF), initiated two years ago with the implementation of the OneBusAway (OBA) application, an open-source platform used in multiple U.S. cities. This year, the aim was to use the GPS- based mobile app OBA to collect multimodal travel data to enhance transportation planning modeling. However, considering the particular location of the bus routes in montainous terrain with low GPS coverage and dense vegetation, the study encountered accuracy and precision limitations in OBA's multimodal data collection capabilities that led to the development of a complementary application, Travel Transit Tracker (TTT).

The development of TTT was possible because after the second year of the OBA implementation process, the state of the servers became adequate for a Representational State Transfer (REST) app for third party software. Previously the OBA servers were hosted inside a Docker container. The developed REST API served as a cover for OBA and other supplementary services. With this addition, unused data could be filtered from the recorded data sent to users. The external mobile application TTT was developed taking advantage of this API, as a solution for specific user multimodal data acquisition. In addition, TTT includes the functionalities to record data under a username. This feature allows researchers to study the user behavior before and after traveling by bus or any other transportation mode.

Tests were conducted with system users to ensure adequate mobile application capabilities and to verify data acquisition. The test consisted of traveling through the transit system routes, recording user trajectories, feedback and trip information. OBA includes information which can be supplemented to the TTT trajectories, which can verify GPS accuracy with the mobile applications' own cellular data accuracy. As the mountainous region in Mayagüez presented a complex challenge for having an adequate GPS accuracy and location consistency, this method can offer a way to validate correct data and filter out errors. The mobile application TTT was deployed on both Android and iOS operating systems. For testing purposes, Test Flight was used for rapid development and app updates.

Technical issues addressed in the study include data cleaning, GPS accuracy, and software optimization for iOS and Android. The research demonstrated that integrating GPS-based mobile applications into transportation planning can provide precise data to improve traffic management and reduce congestion. This study can serve as a base for similar applications in other urban areas highlighting the potential of mobile technology to improve urban mobility. The findings of this project contribute to the ongoing development of data-driven, user-centered transportation planning solutions. The results also suggest that using crowdsourced travel data for planning modeling and analysis can significantly enhance the ability of cities to manage traffic congestion.

Chapter 1. Introduction

For people everywhere, transportation is essential for life, as it provides access to necessary goods and services. Individuals undertake their trips in the most comfortable and efficient way, adjusting to their needs and possibilities. However, the collective decisions of all the transportation network users have been demonstrated to generate travel patterns that have led to congestion in cities worldwide. Therefore, good planning processes that consider the general characteristics of the population and individual transportation decisions can positively influence the reduction of congestion, as it can affect how individuals move within the network.

It is necessary to understand data on how and where people are traveling to develop good transportation planning models in a city. Observing and determining the data related to several variables that can influence these behaviors is critical. Hence, there is a need to collect precise information to generate models representing the population's transportation in a region. Data collection related to these variables should consider socioeconomic factors that influence transportation and information on the origin and destination of trips, their purpose, preferred routes, and mode of transportation, among other aspects. This information can be collected in various ways, whether through surveys, theoretical studies considering buildings or zones, and the type of activities conducted there, or using GPS tracking individual trips. However, to carry out this data collection process, it may be necessary to complement it with other tools that help identify, more specifically, the users' transportation habits.

The collection of information through GPS and mobile devices is increasingly common and useful for transportation planning activities. This data is more reliable and can be generated and processed quickly. Additionally, user-provided data can supplement this information to obtain precise details about transportation modes and related activities. To address the need for supplemental data, this project was conducted using mobile devices and GPS to gather information about trips in the Municipality of Mayagüez (MoM) in Puerto Rico. This study was carried out by the research team of the University of Puerto Rico at Mayagüez (UPRM), with the support of the University of South Florida (USF) team.

The project has two main objectives. The first objective is to enhance the quality of data collected from the OneBusAway open-source app. Unlike data from commercial sources, OneBusAway provides researchers with direct access to raw activity transition data at the individual level. However, due to the nature of the raw data, it requires further post-processing before it can be used by practitioners and city planners. The second objective is to use the post-processed information to gain a better understanding of the travel behavior of OneBusAway users in Mayaguez, Puerto Rico. Additionally, the aim is to utilize the generated database and additional transportation system information to conduct demand analysis, identify demand patterns, and assess their impact on traffic congestion.

The methodology for this project was developed within the context of creating a transportation planning model using a mobile application to collect data on users' trips in the MoM. This methodology consists of several phases, described in detail in the corresponding chapter.

First, a preliminary investigation was conducted to establish the foundations for using an application as a data collection tool for tracking users' trips. Based on this investigation, the application OneBusAway was selected as the primary tool for project execution. Next, the data generated by OBA was validated to assess its feasibility as a multimodal tracking data collection tool. At the time of this project, additional cleaning algorithms were needed on the OBA platform to obtain OBA data that matched the ground truth data. One way to overcome the impasse was to use the OBA implementation that was already in place as a backbone to develop a new application.

During the third phase of the OBA implementation in Mayagüez, an application called Travel Transit Tracker (TTT) was created. It utilizes the OBA processed data as a starting point to provide automatic tracking data. This merging of software allows the new app to be tailored to the needs of citizens and the Mayagüez Transit System, called *Transporte Integrado de Mayagüez* (in Spanish), or the TIM. The app is an extension of the previously developed OneBusAway services. TTT was released on Android and iOS app stores for users to test. The development of this new application incorporates server optimizations developed in the second year of the OBA NICR research project. These optimizations enabled the server to maintain both the OneBusAway client and TTT service simultaneously.

TTT is an open-source application that automatically tracks users through an algorithm and allows them to provide information that identifies modes of transportation. The UPRM research team developed and used this application, including the following stages: implementation in the municipality, collection of test data, analysis and validation of data, and presentation of the application as a tool for collecting transportation planning data in the municipality to generate strategies that have the potential to reduce traffic congestion.

Simultaneously with the mobile application process, the Mayagüez transportation planning model was developed. This process included defining census zones to facilitate data processing. Based on the trips within each zone, an origin-destination (O-D) matrix was created to indicate the volume of trips between zones. Once the matrices were established, the transportation network was defined. The network also depicted the bus routes to complete the transportation planning model.

TTT produced accurate data on multimodal travel behavior patterns that are critical to optimizing travel efficiency and reliability. Based on the field observations and advancements found in the literature concerning using crowdsourcing data in transportation planning modeling, a procedure to integrate crowdsourcing tracking and multimodal data with the planning models is presented at the end of this report. The research team has produced a tool that has the potential to allow transportation agencies to develop new strategies to improve congested multimodal systems.

The report is divided into seven chapters. Chapter 1 covers the project introduction, goals, and the research methodology used in the study. Chapter 2 contains a detailed literature review on mobile applications and GPS-enabled real-time data collection, OneBusAway as an open-source platform, the information technology aspects to consider in developing tracking applications, and several aspects of transportation planning and modeling and their integration. Chapter 3 includes the implementation of the methodology developed by NICR I-Corp to conduct interviews with stakeholders that facilitate the implementation of the results obtained in this project in the real world. Chapter 4 explains the data collection process with OBA, including ground truth data. Chapter 5 details the development of a new application called Travel Transit Tracker (TTT) that complements OBA to obtain detailed user travel behavior data. Chapter 6 includes the activities to develop the Mayaguez transportation planning models and implement the TTT application in the planning process. Finally, Chapter 7 summarizes the study's conclusions, recommendations, and suggestions for further research. A list of references used and the appendices are included at the end of the report.

Chapter 2. Literature Review

The recent widespread adoption of mobile applications (apps) implementing the Global Positioning System (GPS) technology has transformed the transportation planning processes and have introduced new tools and methodologies for data collection, analysis, and decision-making. These innovations offer opportunities to improve transportation systems' efficiency, safety, and sustainability (Dablanc et al., 2020). Strategic planning for technological innovation involves evaluating potential impacts, addressing regulatory challenges, and fostering collaboration between the public and private sectors (Cohen et al., 2017).

Mobile Applications and GPS Enabled Real-Time Data Collection

Mobile apps and GPS enable real-time data collection on travel patterns, route preferences, and transportation choices. By leveraging smartphone sensors and GPS receivers, researchers can collect high-resolution datasets on a large scale with minimal cost and effort (Axhausen et al., 2019). This data provides insights into movements, congestion, and transportation preferences, guiding the development of transportation models and policies (González & Cajka, 2018). Mobile apps equipped with GPS navigation systems provide functionalities for dynamic route planning, assisting users in optimizing their travels in response to real-time traffic conditions (Hörl et al., 2020). Users can avoid congested areas by accessing live traffic data and incident alerts, reducing travel times, and minimizing fuel consumption (Zheng et al., 2014). This dynamic planning improves mobility and efficiency, optimizing the overall performance of transportation networks (Li et al., 2018).

The use of tracking applications not only helps collect data, but also improves the quality of information available for transportation planning. This allows for more effective management tailored to the community's needs (Korpilo et al., 2017). In other words, the tracking data obtained from public transit applications are used to enhance planning and management tasks. This data enables system operators to understand users' travel patterns across the transportation network (Zhu et al., 2018). To obtain this data, servers, GPS integrated into mobile devices, and programs for processing the information are necessary. However, data collection through applications presents certain challenges that need to be addressed to ensure data accuracy and to create an efficient planning model (Karami & Kashef, 2020).

Mobile apps play a crucial role in promoting sustainable transportation modes through Transportation Demand Management (TDM) strategies. By offering trip planning features, ride-sharing options, and incentives for alternative modes such as walking, cycling, and public transit, apps are actively encouraging modal shifts and reducing reliance on single-use vehicles (Dablanc & Muñoz-Raskin, 2018). TDM initiatives facilitated by mobile apps contribute to mitigating congestion, improving air quality, and reducing carbon emissions (Chen et al., 2019).

Mobile apps serve as platforms for user participation and feedback, facilitating direct communication between transportation planners and the public. Through crowdsourcing techniques such as participatory sensing and Volunteered Geographic Information (VGI), apps facilitate data sharing, community input, and collaborative decision-making (Miller et al., 2017). Planners can improve transparency, accountability, and user satisfaction by soliciting user feedback on transportation services, infrastructure projects, and policy initiatives (Silva et al., 2020).

Despite their benefits, using mobile apps and GPS in transportation planning raises concerns about privacy, data security, and ethical implications (Froehlich et al., 2009). Location tracking and the collection of personal data can infringe on individual privacy rights and exacerbate surveillance risks (Hawthorne et al., 2019). Therefore, planners must adopt measures to preserve privacy, data anonymization techniques, and transparent consent mechanisms to mitigate potential harms and uphold ethical standards (Yao et al., 2017).

Mobile apps also can integrate the Internet of Things (IoT). IoT is a tangible object that consists of integrated software or technology. A group of researchers in Indonesia developed a transit-tracking application as an approach to include IoT technologies (Nivaan et al., 2021). A city in Indonesia implemented and ran a transit bus management system by proposing a series of steps, including IoT tech and software. The authors proposed a network of sensors at each vehicle to retrieve bus tracking data. The previously cited research is “tangible” proof that a smart bus providing ridership and location information is related to an intelligent transit system implementing IoT technologies. Implementing this traffic management system app extends from the error-prone practices of manually retrieving bus data. Transit bus tracker software was developed to assess better how to make a more efficient system or notice where the system is failing. This software was successfully made using IoT technologies, rightfully providing user data.

The development of open-source applications for transportation planning has emerged as a powerful tool, offering flexibility, transparency, and opportunities for collaborative development. These applications can leverage advantages such as data access, customization, community collaboration, innovation, and sustainability. However, it is crucial to consider ethical and privacy implications to ensure these technologies' responsible and equitable use in transportation planning.

OneBusAway as an Open-Source Platform

OneBusAway (OBA) is a software designed as a Multi-Region Architecture that distributes bus stop arrival predictions through a series of processes. One of the main goals of the development was to create a strategy to enhance the sustainability and fragmentation of cities using such software and the scalability of the running application. Because such a project was implemented with the expectation that multiple cities could provide transportation data through one application, its structure multi-region architecture was made to facilitate the scalability of having multiple cities providing their transit data and user traffic. As an Open-Source solution to informative traffic planning, OBA offers a collaborative experience and development process so that their software can be implemented in other cities (Barbeau et al., 2014).

The OBA mobile transit app is typically used by around 350,000 travelers in several large U.S. cities (e.g., Seattle, WA, San Diego, CA, Tampa, FL, Washington, D.C.) to get real-time bus, rail, and ferry arrival information. Unlike other transit apps, OBA is an open-source software program implemented by transit agencies that are non-profit Open Transit Software Foundation (OTSF) members in their cities. The OTSF plays a crucial role in the cooperative management of OBA, leveraging its long history of serving as a research platform to understand many aspects of public transportation, such as the effect of real-time information on rider satisfaction, perceived and actual wait times, and transit ridership [Brakewood and Watkins, 2019]. Members of the OTSF also come from several research universities.

Researchers have direct access to the raw activity transition data without any additional preprocessing or aggregation, making OBA a unique source of multimodal data, even though its user population is restricted to participating cities (although any city can deploy the app for free) and is skewed towards public transportation users. Furthermore, researchers can communicate directly with participants via mobile app or email. This allows for gathering extra data through online surveys, which can be individually connected to the activity transition data. In addition, usage behavior within the app is also tracked, offering more information that can improve the dataset's richness and help uncover the reasons behind a user's modal decision.

In another city in Indonesia, a Transit Tracking application was implemented (Nugraha, 2023). In contrast to OBA, this application was designed to return estimated predictions based on low, medium, or high traffic. With specific analyses, the research was able to generate a classification for traffic density over a period of time. By implementing an application specific to the city, the researchers were able to specify the User Interface and features to suit user traffic information needs. This unique app allowed the city to retrieve crucial values from trips, which can help the administrators better understand public transportation behaviors. In contrast to other software, this research implements the direct use of Google Directions API for data unlike OBA.

Information Technology Aspects to consider in Developing Tracking Applications

According to Balbin & Leung (2020), mobile tracking applications encounter various challenges that may compromise their effectiveness. First, GPS errors, transmission issues, and interference can lead to inaccurate location and time data, affecting the precision of the information. Additionally, the substantial volume of real-time data generated poses significant challenges for storage, processing, and analysis, a common issue in the context of big data. Privacy and security are also key concerns, as location tracking can jeopardize the protection of personal data, making strict compliance with data protection regulations essential. Another major challenge is data variability, which can be influenced by external factors such as weather or traffic, complicating the prediction of behavioral patterns. Moreover, integrating data from various sources can lead to inconsistencies in both formats and data quality. Regular maintenance and updates of the applications are also critical, as any system failure can result in data loss or inaccurate collection, undermining the reliability of the tracking system. Finally, the cleaning and validation of the collected data present yet another challenge, requiring specialized tools to ensure data accuracy and reliability.

In their 2018 study, Yang et al. explored different methods for cleaning and validating GPS data in mobile transportation planning applications. The study focused on advanced techniques like map-matching algorithms, which align GPS points with actual road networks to fix errors caused by environmental factors. They also discussed the use of Hidden Markov Models (HMM) in projects like Valhalla or Mapbox to improve GPS data accuracy by analyzing likely routes from noisy data. The study emphasizes the role of big data analytics in efficiently managing large volumes of GPS data in real-time, taking into account variables such as weather and traffic conditions to enhance decision-making. Additionally, the study highlights the importance of predictive analytics and machine learning in addressing the variability in GPS data, leading to more accurate forecasts for transportation systems, especially in the context of smart city projects (Verma et al., 2024).

Numerous strategies have been developed to enhance data accuracy. For instance, Nurmalasari et al. (2020) utilized machine learning techniques like autoencoders and Long Short-Term Memory (LSTM). Autoencoders compress information to detect anomalies by comparing the original inputs with the reconstructed outputs, while LSTM networks specialize in handling sequential data and identifying changes in the behavior of time series. Model evaluation is based on the Mean Absolute Error (MAE), which measures the average difference between predictions and actual values, with a lower MAE indicating higher precision. The data is divided into training and validation sets to ensure the model generalizes well and avoids overfitting. Additionally, hyperparameters such as the learning rate and network structure are optimized using the Adam optimizer to improve training efficiency. The model is adjusted iteratively, monitoring the loss throughout the process, and data labeling is automated, facilitating the identification of anomalous or normal patterns without manual intervention.

Big data storage and management have seen significant advancements in recent years. For example, Venkatesh et al. (2019). outlines a predictive analytics process based on relational data that involves several key stages. This process begins with collecting data from various sources, ensuring their relevance and quality, and then storing it efficiently in relational database systems. Prior to analysis, the data undergoes cleaning and normalization during preprocessing to ensure accurate analysis. An exploratory study is then conducted to identify relevant patterns. In the predictive modeling phase, algorithms such as regression or neural networks are used to forecast future outcomes. The model is subsequently validated with a test dataset and adjusted as necessary to improve performance. Finally, the model is deployed in production with continuous monitoring to maintain its effectiveness in a real-world environment.

Transportation Planning

Transportation planning plays an essential role in shaping the socio-economic fabric of societies, impacting urban development, environmental sustainability, and public welfare. Through rigorous analysis and strategic foresight, transportation planning seeks to optimize the movement of people and goods while mitigating adverse effects such as congestion, pollution, and disparities in access. This discipline encompasses many considerations, from land use management and infrastructure design to modal integration and technological innovation. Effective transportation planning drives economic growth by enhancing connectivity and accessibility, promoting trade, job opportunities, and regional competitiveness (Banister, 2011; Cervero & Murakami, 2010). Additionally, it focuses on promoting social equity, ensuring equitable access to mobility options for all segments of society, including those in disadvantaged situations and marginalized communities (Gutiérrez, 2018; Ishaque et al., 2020). In summary, transportation planning constitutes a fundamental pillar of contemporary urban governance and plays a crucial role in shaping cities' and regions' quality of life, resilience, and progress.

The following steps can be defined to develop a transportation planning process to propose efficient strategies:

- Strategic Planning: Strategic planning involves setting long-term goals and objectives for transportation systems, considering projected future needs and trends. It includes activities such as vision exercises, scenario planning, and the development of comprehensive transportation plans (Cairney, 2012). This type of planning helps ensure that transportation investments are aligned with broader social goals, such as economic development, environmental preservation, and promotion of social equity (Litman, 2020).
- Policy Formulation: Policy formulation in transportation planning involves establishing rules, regulations, and guidelines to guide decision-making and implementation. This process involves the participation of various stakeholders, data analysis, and consideration of political, economic, social, and environmental factors (Rodrigue et al., 2017). Policy formulation helps shape the regulatory framework governing transportation systems and influences investment priorities in infrastructure (Givoni & Banister, 2013).

- Technological Innovation: Technological advances, such as Intelligent Transportation Systems (ITS), vehicle automation, and real-time data analysis, are transforming transportation planning processes. These innovations provide opportunities to improve transportation systems' efficiency, safety, and sustainability (Dablanc et al., 2020). Planning for technologicalinnovation involves evaluating potential impacts, addressing regulatory challenges, and fostering collaboration between the public and private sectors (Cohen et al., 2017).
- Performance Evaluation: To carry out effective transportation planning, continuous monitoring and evaluation of system performance are necessary, providing information for decision- making and policy adjustments. Performance evaluation involves measuring key performance indicators, such as travel time, reliability, safety, and environmental impacts (Litman, 2018). By analyzing these performance data, planners can identify areas for improvement and optimize resource allocation (Wang et al., 2019).

Chapter 3. NICR I-Corps Workshop: From Research to Implementation

The I-Corps program is an entrepreneurial training program geared to immerse the participants in delivering innovative, impactful solutions to stakeholder problems, providing ways to deliver research that meets the needs of its stakeholders and is ready to be implemented. The NICR-USF and NICR-UPRM teams participated in a three-week course on understanding stakeholder problems and needs utilizing the Business Model Canvas. The goal was that the NICR teams could provide meaningful and innovative solutions. This chapter presents the results of the activities performed as part of the NICR workshop in the context of the research project documented in this report.

Business Model Canvas

The I-Corps workshop is centered around developing a business model canvas to validate business ideas, particularly in the context of innovative NICR projects. The I-Corps business model canvas is founded on the nine building blocks summarized below, designed to help systematically understand, design, and differentiate an impactful business model.

1. Value Propositions: Describes the bundle of products and services that create value for a specific stakeholder segment. This block focuses on what makes the product or service unique and why stakeholders would choose it over alternatives. This block aims to answer the following questions:
    a. Who are our most important stakeholders?
    b. What are their archetypes?
    c. What job do they want to get done for them?

2. Customer Segments: Defines the different groups of people or organizations and the research aims to reach and serve. In this block the research team should answer the following questions:
    a. Which of our stakeholder's problems are we helping to solve?
    b. Which stakeholder needs are we satisfying?
    c. What are the key features of our product that match stakeholder problems/needs?

3. Channels: Outlines how the research team communicates with and reaches its stakeholder segments to deliver a value proposition. This block could affect sales channels, distribution, and marketing strategies. It answers the following question:
    a. Though which channels do our stakeholders want to be reached?

4. Customer Relationships: Details the types of relationships the research team could establish with specific stakeholders. These relationships can range from personal assistance to automated services, answering the following question:
    a. How will we get, keep, and grow stakeholders?

5. Revenue Streams: Represents the cash a company generates from each stakeholder segment. This block includes understanding the different ways to monetize the product or service.
    a. How do we make money?
    b. What is the revenue model?
    c. What are the pricing tactics?

6. Key Partnerships: Defines the network of suppliers and partners that make the business model work. This block can include strategic alliances, joint ventures, or partnerships with academia and industry.
    a. Who are our key partners?
    b. Who are our key suppliers?
    c. What are we getting from them?
    d. What are we giving them?

7. Key Activities: Describes the most important things needed for a business model work. These are the critical actions necessary to deliver the value proposition, reach markets, maintain stakeholder relationships, and earn revenues. Questions here include:
    a. What key activities do we require?
    b. What Software is needed?
    c. What is the supply chain?

8. Key Resources: Lists the most important assets required to make a business model work. These resources could be physical, intellectual, human, or financial.
    a. What key resources do we require?
    b. What are the financial and physical key resources?
    c. Who are the key investment partners?
    d. Who are the key human resources?

9. Cost Structure: Describes all costs incurred to operate a business model. This block includes fixed and variable costs, economies of scale, and cost advantages.
    a. What are the most important costs inherent in our business model?
    b. Which costs are fixed?
    c. Which costs are variable?

Figure 1 is a visual chart with elements describing a company's value proposition, infrastructure, stakeholders, and finances. The nine business model components can be grouped into three categories: (1) Desirability, which comprises building blocks 1–4; (2) Feasibility, comprising blocks 6–8; and (3) Viability, which includes blocks 5 and 9.

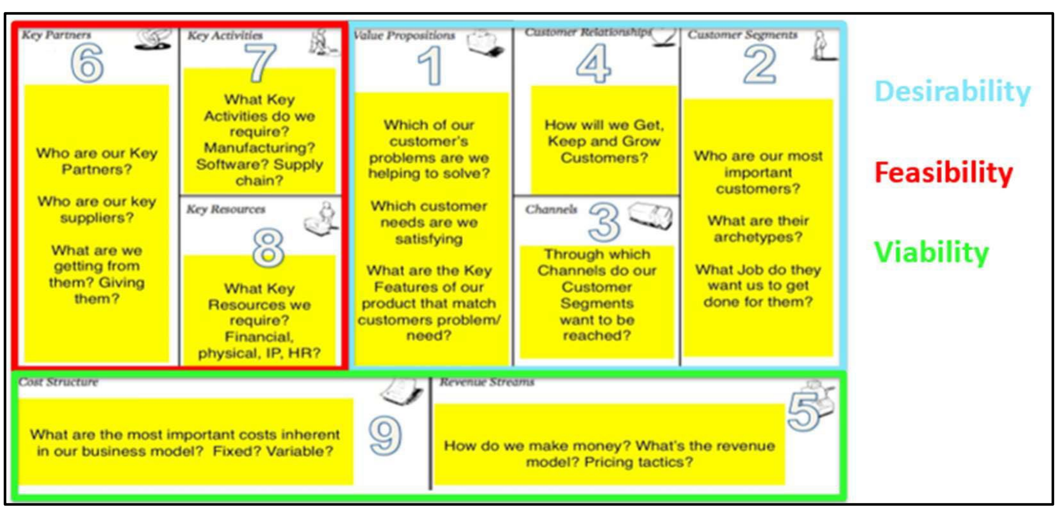

Figure 1. Business Model Canvas Categories and Block Components. (Umihanic, 2014)

In the NICR research, both teams used the Business Model Canvas to test whether implementing the proposed ideas was desirable, feasible, and viable. After that, the teams engaged directly with potential stakeholders to test their hypotheses and gather feedback. This process helped us refine and improve the business model iteratively.

Value Proposition Canvas

The I-Corps Value Proposition Canvas was used to ensure that the product or service the research team could provide was aligned with stakeholder needs and desires. As an extension of the Business Model Canvas, the focus is on the value proposition and the stakeholder segments. The Value Proposition Canvas consists of two main parts: the Stakeholder Profile and the Value Map.

The Stakeholder Profile was used to define and understand the stakeholders clearly. It includes three components: customer jobs, stakeholder pains, and stakeholder gains.

- Customer Jobs: These are the tasks the stakeholders are trying to perform, the problems they are trying to solve, or the needs they are trying to satisfy. Stakeholder jobs can be functional (specific tasks or problems), social (how stakeholders want to be perceived), or emotional (feelings or emotional states stakeholders want to achieve).
- Stakeholder Pains: These are the negative experiences, emotions, or risks the stakeholders encounter before, during, or after trying to get a job done. Pains can include undesired costs, situations, or characteristics preventing stakeholders from achieving their goals.
- Stakeholder Gains: These are the benefits or positive outcomes that the stakeholders want to achieve. Gains can include functional utility, social gains, positive emotions, or cost savings.

The Value Map helps to describe how the product or service creates value for the stakeholder. It includes product services, pain relievers, and gain creators.

- Products and Services: The Value Map encompasses diverse products and services, including physical products, intangible services, and digital offerings, all designed to assist stakeholders in their tasks.
- Pain Relievers: These are how the products or services alleviate specific pains for the stakeholders. A pain reliever is described as how the offering reduces or eliminates the negative experiences or risks that the stakeholders face.
- Gain Creators: These are the ways the products or services create gains for the stakeholders. Gain creators describe how the offering produces positive outcomes or benefits that stakeholders expect, desire, or would be surprised by.

Aligning the Two Parts

The key objective of the Value Proposition Canvas is to unite fit between the Stakeholder Profile and the Value Map. The goal is to achieve unison between the products and services and their pain relievers and gain creators for the stakeholders.

Practical Application in I-Corps

In the context of NICR, the Value Proposition Canvas is used extensively during the stakeholder discovery process. It involves engaging with potential stakeholders to validate assumptions about their jobs, pains, and gains, and then iteratively adjusting their value propositions based on the feedback. This iterative process ensures that the final product is closely aligned with stakeholder needs, making every effort count.

By systematically analyzing the stakeholder segment and the value proposition, the I-Corps Value Proposition Canvas helps the research team build products and services that genuinely impact stakeholder needs.

Stakeholders

The first step was determining the adequate stakeholders on which NICR projects could have a meaningful impact. This task was divided among the stakeholders of the USF team (Tampa, Florida) and the UPRM team (Mayagüez, Puerto Rico). The following stakeholders were identified for the OBA implementation project:

- A Social Scientist - The Lab @ D.C., Office of the City Administrator, Executive Office of the Mayor.
- A Senior Data Analyst - San Diego Metropolitan Transit System.
- A Transit System Supervisor - Sonnell Transit (Public Transit System Operator).
- The Director of the Office of Economic Development and Planning of Mayagüez.

These stakeholders were identified due to the potential impact of transforming multimodal travel behavior data from an open-source platform to support traffic congestion reduction strategies. This project could significantly assist in the functions of the stakeholders, underlining their importance in the project.

Interviews

In preparation for a meeting with the identified stakeholders, the research team prepared a hypothesis and experiment parameters.

- The hypothesis was as follows: Government agencies in charge of transit and congestion policies require data related to travelers' behavior focused on origin and destination, specifically in areas of interest to the agencies.
- The experiment was as follows: The research team interviewed individuals from government agencies instrumental in shaping congestion and transportation policies. The questions were crafted to delve into the complexities of congestion and the strategies for collecting data to combat it.

The interviews were conducted in two rounds. During the first round, Roxanne Oroxom and Neomi E. Woods were asked the following questions:

- How would you describe the congestion problem in Florida/ Puerto Rico?
- What are the biggest hurdles in trying to mitigate the problem?
- How has the pandemic affected congestion? Early pandemic vs now?
- What strategies have been/ are being implemented to solve congestion?
- What happened / what is expected to happen to? Public transportation?
- What data sources are implemented, if any? What data is collected? How reliable is the data? What metrics are available?

The feedback received from the stakeholders was as follows:

Social Scientist - The Lab @ D.C., Office of the City Administrator, Executive Office of the Mayor.

- *Utilize card scanning to collect rider data in the Washington D.C. area.*
- *Mainly focused on implementing policies that increase ridership.*
- *Interested in data to measure the transit system usage and evaluate the effectiveness of implemented policies.*

Senior Data Analyst - San Diego Metropolitan Transit System.

- *Mainly interested in origin and destination data. Access to the intermediate stops is a plus.*
- *Have access to bus occupancy numbers.*
- *They collect data through surveys (every few years) to comply with FHWA regulations but have not implemented any other data collection methods.*
- *Origin and destination data can be used to optimize stop locations and routes.*

The first interview round was based on the initial hypothesis that government agencies in charge of transit and congestion policies require data related to traveler behavior. For the follow-up interview, additional questions were asked about the data types and format appropriate for the agencies to review. Therefore, the following questions were included for round 2 of the interviews:

- How can knowing traveler behavior help develop strategies to reduce congestion?
- What kind of information specifically would be useful?
- What is the most appropriate data format for your agency.
- Can you provide the metrics (and or methods to calculate them) that interest your organization?

During round 2 of the interviews, the feedback received from the stakeholders was as follows:

Transit System Supervisor - Sonnell Transit (Public Transit System Operator).

- *Interested in passenger count data.*
- *Data about traveler mobility, including origin and destination data.*

Director of the Office of Economic Development and Planning of Mayagüez.

- *Interested in the Peak Demand Times, Passenger Count, Origin and Destination, and Wait Times data.*
- *Data format is expected to be in charts and tables for easy use.*
- *Better availability of information on transit systems.*

Results and Discussion

The feedback from the stakeholders was compressed in developing a Business Model Canvas and a Value Proposition Canvas. Figure 2 depicts the final Business Model Canvas developed during the I-Corps workshop.

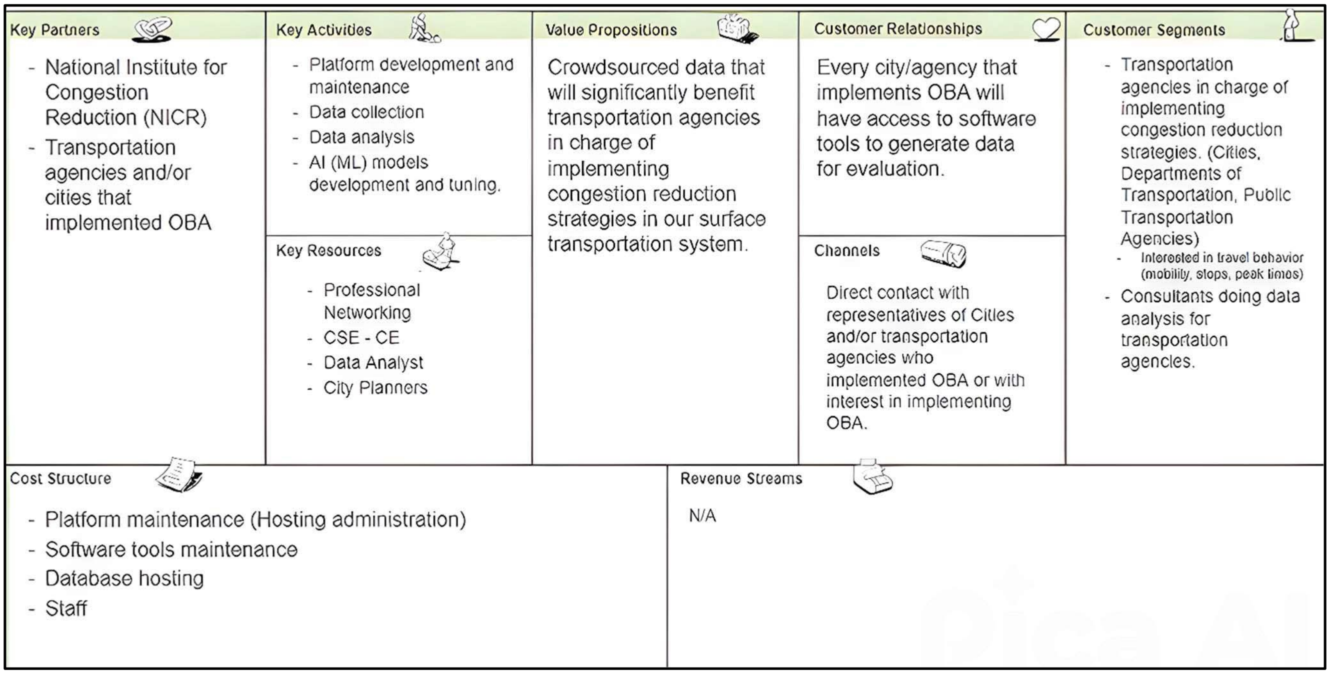

Figure 2. Final Business Model Canvas Developed During the I-Corps Workshop. (Umihanic, 2014)

1. Value Propositions: Crowdsourced data will significantly benefit transportation agencies implementing congestion reduction strategies in our surface transportation system.
2. Customer Segments: Transportation agencies in charge of implementing congestion reduction strategies. (Cities, Departments of Transportation, Public Transportation Agencies)
    a. Interested in travel behavior (mobility, stops, peak times)
    b. Consultants doing data analysis for transportation agencies
3. Channels: Direct contact with representatives of Cities and/or transportation agencies who implemented OBA or with interest in implementing OBA.
4. Customer Relationships: Every city/agency that implements OBA will have access to software tools to generate data for evaluation.
5. Revenue Streams: The research project would not generate revenue but has the potential to decrease costs by helping the stakeholders optimize operations.
6. Key Partnerships: National Institute for Congestion Reduction (NICR), Transportation agencies and/or cities that implemented OBA.
7. Key Activities:
    a. Platform development and maintenance
    b. Data collection
    c. Data analysis
    d. AI (ML) models development and tuning
8. Key Resources:
    a. Professional Networking
    b. CSE - CE
    c. Data Analyst
    d. City Planners

9. Cost Structure:
    a. Platform maintenance (Hosting administration)
    b. Software tools maintenance
    c. Database hosting
    d. Staff

The targeted stakeholders identified were transportation agencies and consultants involved in data analysis. Focusing on these stakeholders would ensure a clear and focused approach. The core value the OBA implementation project can provide for the stakeholders would be actionable, crowdsourced data that can help transportation agencies optimize congestion reduction strategies. Collaborations with NICR and relevant transportation agencies would be crucial for credibility and resource support. Ensuring alignment between key activities (like data analysis and AI model development) and critical resources (professional networking and skilled personnel) could be essential for future project success. Effective data management could be critical to ensure the project's sustainability. Figure 3. Depicts the final Value Proposal Canvas developed during the I-Corps workshop. The Value Proposition Canvas further expands on the value proposition and customer segment.

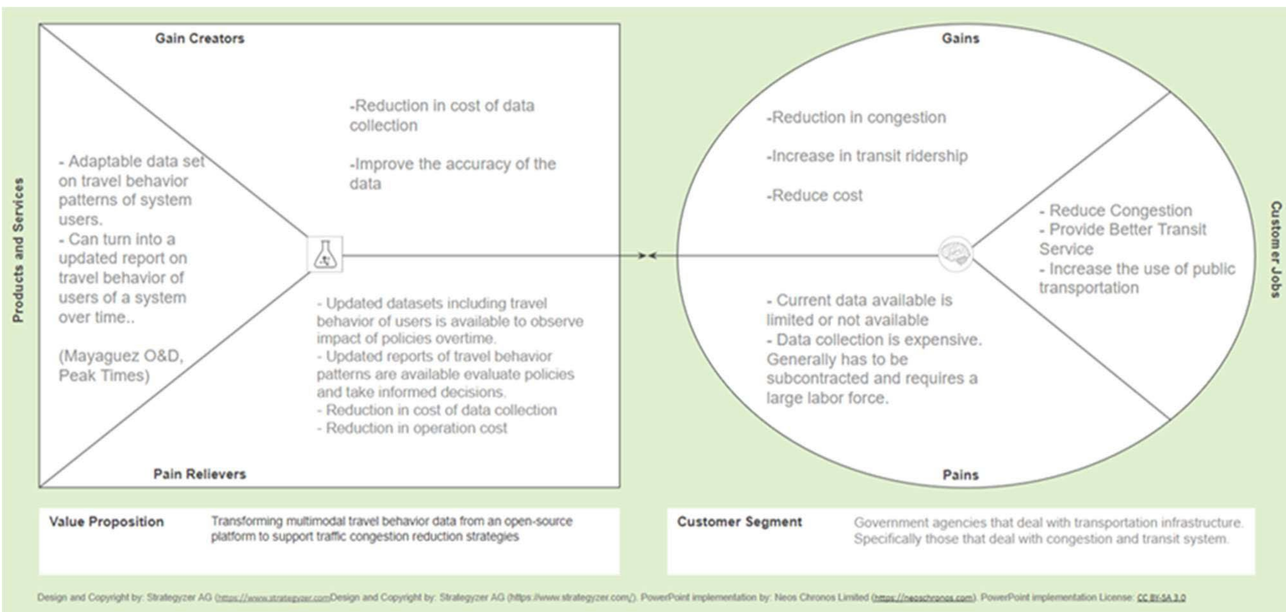

Figure 3. Final Value Proposal Canvas developed during the I-Corps workshop.

The Stakeholder Profile was used to define and understand the stakeholders clearly. The following was understood:

Customer Jobs:

- *Reduce congestión.*
- *Provide better transit service.*
- *Increase the use of public transportation.*

Stakeholder Pains:

- *Current data available is limited or not available.*

- *Data collection is expensive. Generally, must be subcontracted and requires a large labor force.*

Stakeholder Gains:

- *Reduction in congestión.*
- *Increase in transit ridership.*
- *Reduction in cost.*

Products and Services:

- *Adaptable data set on travel behavior patterns of system users.*
- *It can turn into an updated report on the travel behavior of users of a system over time.*

Pain Relievers:

- *Updated datasets, including users' travel behavior, are available to observe the impact of policies over time.*
- *Updated reports of travel behavior patterns are available to evaluate policies and make informed decisions.*
- *Reduction in the cost of data collection.*
- *Reduction in operation cost.*

Gain Creators:

- *Reduction in the cost of data collection.*
- *Improve the accuracy of the data.*

The stakeholders' critical jobs are reducing congestion, providing better transit service, and increasing public transportation usage. One of the major pains faced by the stakeholders is the limited availability of data and the high cost of data collection. Therefore, stakeholders would like to reduce congestion and increase transit ridership while lowering costs. The research team's value proposition is clear and unwavering: we are committed to providing accurate, cost-effective, and regularly updated data to help stakeholders achieve their goals of reducing congestion, improving transit services, and increasing public transit usage. Understanding the needs of potential stakeholders allows the research team to tailor the end product to be readily applicable in real-world use cases.

Chapter 4. Data Collection with OBA and Ground Truth Data

Data Collection with OneBusAway (OBA)

After the implementation of OBA in Mayagüez, the UPRM research team gained access to the system's user tracking information through the USF research team. The information recorded on the OBA server, to which USF has access, was sent to UPRM for processing. Table 1 displays a portion of the data generated by OBA. This data reflects the details gathered from monitoring trips taken by users of the app in Mayagüez. The values may be obtained from GPS or other network servers, each with varying levels of precision. The objective of examining and contrasting this data with field data is to evaluate the accuracy of the generated data.

Table 1. Data Generated by OneBusAway

User ID	Device Trip ID	Trip ID	Region ID	Google Activity	Destination Location Provider (*best)	Tour ID	Tour Index	Origin gps Date and Time (UTC)	Origin gps latitude
82VcA4ry1zbMBd4iqIP6VUjOfio2	0	0	0	WALKING	network	0	1	9/8/2022 8:11	1.82167E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	1	1	13	STILL	fused	0	2	9/8/2022 8:11	1.82167E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	2	2	13	WALKING	fused	1	1	9/8/2022 8:11	182164297
82VcA4ry1zbMBd4iqIP6VUjOfio2	3	3	13	STILL	fused	1	2	9/8/2022 8:41	1.82147E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	4	4	13	WALKING	fused	1	3	9/8/2022 8:45	1.82149E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	5	5	13	STILL	network	1	4	9/8/2022 9:23	182151187
82VcA4ry1zbMBd4iqIP6VUjOfio2	6	6	13	WALKING	fused	1	5	9/8/2022 9:23	1.82152E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	7	7	13	STILL	fused	1	6	9/8/2022 9:33	1.82146E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	8	8	13	WALKING	gps	1	7	9/8/2022 10:24	1.82113E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	9	9	13	STILL	fused	1	8	9/8/2022 11:04	1.82153E+16

The variables compiled in Table 1 are outlined along with brief descriptions:

- User ID: Identifier generated by the mobile device and registered by OneBusAway, assigning a unique ID to each user to differentiate devices.
- Device Trip ID: Identifier related to trips recorded by the mobile device.
- Trip ID: Trip identifier generated by the OneBusAway algorithm.
- Region ID: Region identifier determined by the programming of OneBusAway for its operation.
- Google Activity: Detection of the user’s mode of transportation performed by the program, classifying the data into categories such as walking, in-vehicle, or "still" (stopped) if the user remains stationary for more than 10 minutes or has completed a trip.
- Destination Location Provider: Source of the device’s location provider, which can use network, GPS, or fused, depending on which is more accurate at the time.
- Tour ID: Identifier of tours generated by the mobile device and recorded by OneBusAway.
- Tour Index: Identifier of the trips within each tour, generated by the mobile device and recorded by OneBusAway.
- Origin GPS Date and Time UTC: Date and time when the device detects the start of the user’s trip.
- Origin GPS Latitude: Latitude at which the program records the start of the user’s movement.

The guidelines provided by USF were followed to collect the data generated by OBA. The OBA application was used to conduct multiple test trips. The user captures the position at points where the user's location and mode changed. Gathering a few data points per trip avoids tracking the user throughout the day and optimizes cell phone battery usage. Sending tracking information throughout the day would generate excessive data, potentially draining the battery quickly and discouraging users from providing their travel information.

The team conducted several test trips to become familiar with the data collection process and reduce errors. These test trips were carefully planned with a specific starting point, destination, and route. A template provided by USF was used, which played a crucial role in the data collection. The template had preset fields to be filled in, allowing us to generate accurate information for each trip, known as *ground truth data*. The fields in the template included information about the user, the coordinates of each point, the time, the type of trip, and the mode of transportation used.

Additionally, it is essential to note that, according to the program's implementation, a "tour" is defined as a set of trips that ends at the point of origin. Table 2 presents an example of the ground truth data table that was completed manually and then transcribed to an Excel file.

Table 2. Example Template of the Ground Truth Data

GT_Collector	GT_TourID	GT_TripID	GT_Mode	GT_Mode_Original	GT_Date	GT_TimeOrig	GT_LatOrig	GT_LonOrig	GT_TimeDest	GT_LatDest	GT_LonDest
Giraldo	GIR_1	1	WALKING	WALKING	[redacted]						
Giraldo	GIR_1	2	STILL	WALKING							
Giraldo	GIR_1	3	STILL	WALKING							

The names and brief description of each column in the ground truth data table follows:

- GT_Collector: User ID of the data collector
- GT_Mode: Activity mode (‘WALKING’, ‘IN_VEHICLE’, ‘STILL’, ‘ON_BICYCLE’, ‘BUS’, ‘ON_SCOOTER’)
- GT_Date: Date of the recorded activity
- GT_TimeZone: Time zone of the location for the recorded activity
- GT_TimeOrig: Time recorded at the origin of the trip
- GT_TimeOrigMinuteRounded: One (1) if the
- GT_TimeOrig value was rounded to the closest minute while recording the activity, zero (0) otherwise.
- GT_TimeDest: Time recorded at the destination of the recorded activity
- GT_TimeDestMinuteRounded: One (1) if the GT_TimeDest value was rounded to the closest minute while recording the activity, zero (0) otherwise.
- GT_LatOrig: Latitude of the GT trip origin
- GT_LonOrig: Longitude of the GT trip origin
- GT_LatDest: Latitude of the GT trip destination
- GT_LongDest: Longitude of the GT trip destination

After completing the planned trips and filling in the table, the data generated by OBA was requested from USF. A matching process was carried out using the ground truth (reference) data to verify the accuracy of the obtained data. This process will be detailed in the next section of this chapter.

During the initial implementation of OBA, it became apparent that the data tracking for user location was prone to errors due to factors such as climate, altitude, presence of trees and dense vegetation, and other inconsistencies. It is crucial to clean these faulty locations from the dataset to ensure the accuracy of our analysis of users' trajectories.

Using the application in some regions of Mayagüez generated an error range for GPS coordinates. Some trips for one day not only had disconnections from the OBA trajectory but, in some cases, never continued the trip after disconnection. Even when the device reconnected, it generated coordinates that did not correspond to the actual data. Figure 4 represents the transit system routes (orange) and the tracking data lines (purple). The purple lines in Figure 4 demonstrate how the GPS coordinate jumps from one route to another, creating faulty data. The randomized trajectories of the purple lines reflect how coordinate locations shift in various regions of Mayagüez.

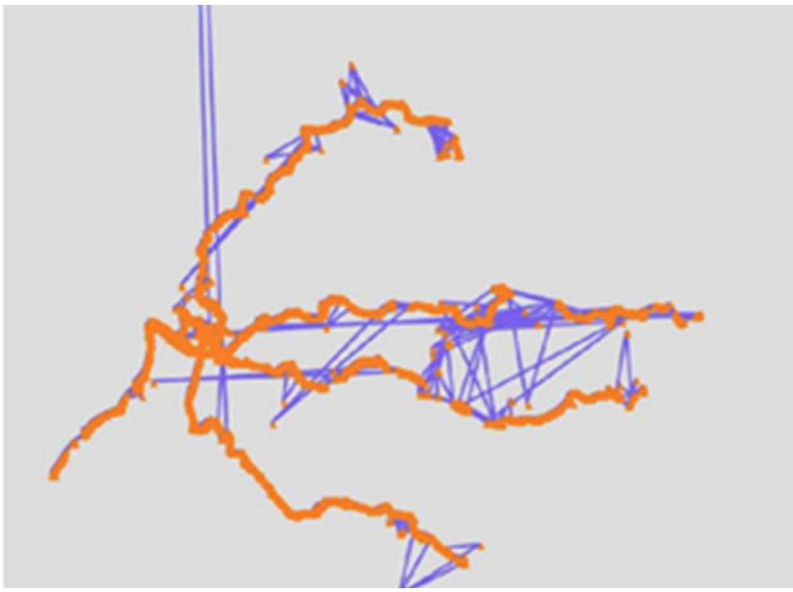

Figure 4. **Map of Trip Trajectories During OBA Implementation in Year 1**

As the GTFS files for the transit system in OneBusAway in Mayagüez were developed, we encountered a similar problem. This underscores the need for a secondary source of GPS data to validate the coordinates collected during user trips. The introduction of a supplementary application for comparison and validation would greatly enhance the validation process for both OneBusAway data and the ground truth data for the Mayagüez transit system.

The errors related to the natural environment or poor signal conditions mentioned above highlighted the necessity of creating a new application. This requirement was further confirmed after the validation process. Two sources of trip trajectories enabled the removal of inaccurate data from a tracked trip, which will facilitate future analysis. Nevertheless, the ground truth data and the OBA data from USF were utilized to validate the information, as detailed in the following section.

Validation of Data Collection from OneBusAway Using Ground Truth Data

The validation involved comparing the data collected by the OneBusAway (OBA) app with the ground truth data obtained by the user. Test trips were conducted using a mobile phone with an Android operating system because the app was not optimized for Apple's iOS in Mayagüez at the time. The OneBusAway app was installed on the device, enabling the user to track the proposed bus routes and collect the necessary data.

Considering that the application's results may vary depending on the characteristics of the device and the network, it was necessary to consider these factors when making the trips. For the first trips made by the data collector, a Motorola cellular device, model GTPower, with an Android 9 operating system, Qualcomm Snapdragon 632 octa-core chipset launched in February 2019, and Claro as mobile network operator, was used.

After selecting the equipment, the data collection process was carried out. Initially, the origin and destination points were established along with their respective geographic coordinates in decimal format, as specified in the template. These points represent the start and end points of each trip. However, it is essential to consider the tour concept as outlined by OBA. Based on the origin and destination points shown in Figure 5, a trip is defined as a journey from the Barcelona Transport Terminal to the Civil Engineering Building, and it is necessary to return to the Barcelona Terminal to complete the tour. It is worth noting that there may be additional destinations, but to be considered a tour, the journey must end at its point of origin. Once the origin and destination points are identified, the routes are determined.

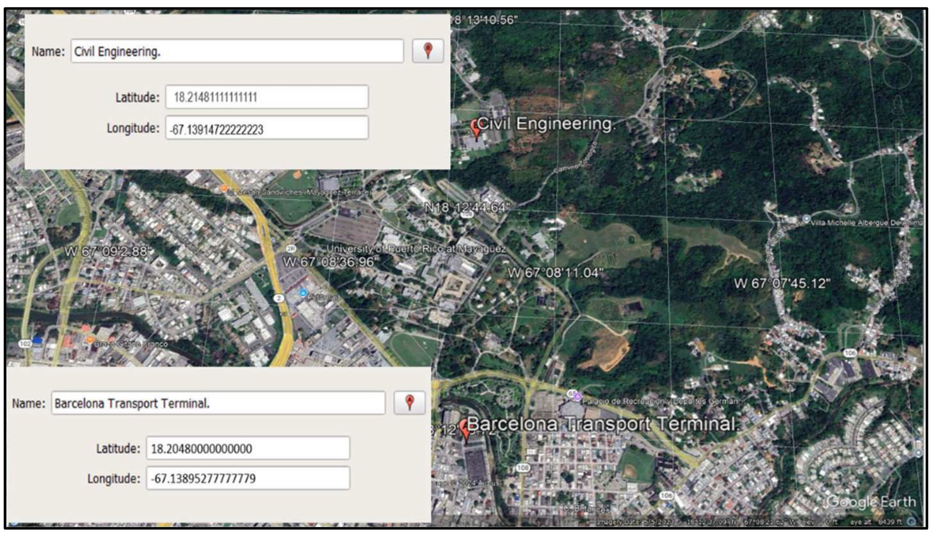

Figure 5. Location of the Origin and Destination Points for the Validation Trips.

After identifying the starting and ending points, the next step is to find the typical route options. For example, the routes from the Barcelona Transit Terminal to the UPRM Civil Engineering Department are shown in Figure 6 and Figure 7 for car travel and walking, respectively. It's worth noting that during data collection, walking and car travel modes were considered, which made the analysis of OBA's provided data simpler.

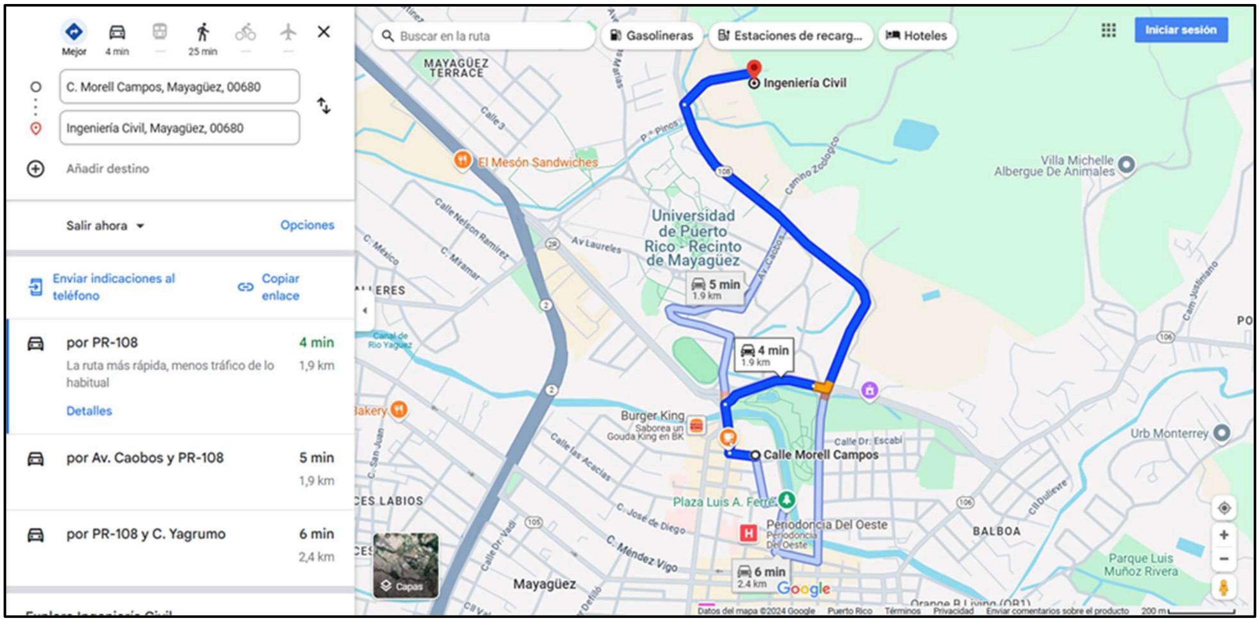

Figure 6. Vehicle Route Options.

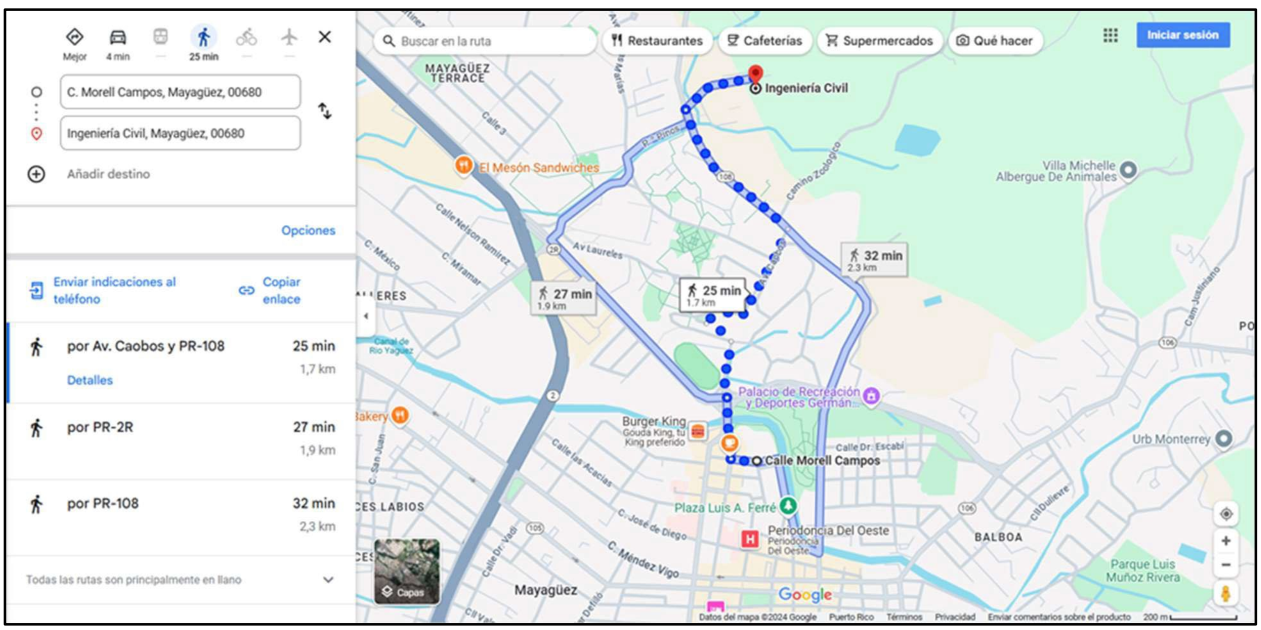

Figure 7. Walking Route Options.

The information gathered from these trips was manually recorded in a spreadsheet using the format shown in Table 2. The data automatically generated by OBA was retrieved from the OBA server for validation. The details of the manual data collection are included in Appendix A, and a portion of the manual records can be found in Table 3.

Table 3 contains manually collected information, including the collector's name, a code identifying the tour, a number specific to the trip within that tour, and the mode of transportation used (on foot or by vehicle).

If applicable, it also includes the duration at a single point over a period of time. Additionally, the start and end times of each trip were recorded, along with their corresponding geographical coordinates.

Table 3. Example of the Information Manually Recorded "Ground Truth Data"

GT_Collector	GT_TourID	GT_TripID	GT_Mode	GT_Mode_Original	GT_Date	GT_TimeOrig	GT_LatOrig	GT_LonOrig	GT_TimeDest	GT_LatDest	GT_LonDest
Giraldo	GIR_1	1	WALKING	WALKING	6/9/2022	9:57:00 AM	18.216369	-67.148244	10:15:00 AM	18.214297	-67.141231
Giraldo	GIR_1	2	STILL	WALKING	6/9/2022	10:15:00 AM	18.214297	-67.141231	10:21:00 AM	18.215122	-67.139288
Giraldo	GIR_1	3	STILL	WALKING	6/9/2022	10:21:00 AM	18.215122	-67.139288	10:43:00 AM	18.214297	-67.141231
Giraldo	GIR_1	4	WALKING	STILL	6/9/2022	10:43:00 AM	18.215122	-67.1392288	11:05:00 AM	18.215136	-67.139379
Giraldo	GIR_1	5	IN_VEHICLE	IN_VEHICLE	6/9/2022	11:05:00 AM	18.214297	-67.139379	11:51:00 AM	18.214585	-67.141197
Giraldo	GIR_1	6	WALKING	WALKING	6/9/2022	11:51:00 AM	18.214585	-67.141197	1:15:00 PM	18.216369	-67.148244
Giraldo	GIR_2	1	WALKING	WALKING	8/9/2022	9:38:00 AM	18.214297	-67.141231	9:47:00 AM	18.215122	-67.139288
Giraldo	GIR_2	2	STILL	WALKING	8/9/2022	9:47:00 AM	18.215122	-67.139288	10:36:00 AM	18.215136	-67.139379
Giraldo	GIR_2	3	IN_VEHICLE	IN_VEHICLE	8/9/2022	10:36:00 AM	18.215136	-67.139379	11:22:00 AM	18.214585	-67.141197
Giraldo	GIR_2	4	WALKING	WALKING	8/9/2022	11:22:00 AM	18.214585	-67.141197	11:32:00 AM	18.214297	-67.141231

After completing the table that corresponds to the manual data collection of the "ground truth data," the research team proceeded to request the data generated by OneBusAway from the server. Once the data was provided, a data fusion process was conducted in Excel. This process allowed for merging the data from the manually generated tables with the data obtained through the OBA application.

The data generated by the OBA application are presented in Table 4. The validation task aims to evaluate the effectiveness and precision of the OBA data. This data represents the values obtained through the application's tracking of user trips. These values are derived from information provided by various GPS servers, each with different levels of precision. Precision affects GPS data gathering because a user might have low GPS tracking capabilities, causing the mobile tracking application to have an imprecise user location. The GPS data precision can further negatively be affected by tall structures in the area, dense vegetation, or lack of reception.

Table 4. Example of the Data Generated by OneBusAway

User ID	Device Trip ID	Trip ID	Region ID	Google Activity	Destination Location Provider (*best)	Tour ID	Tour Index	Origin gps Date and Time (UTC)	Origin gps latitude
82VcA4ry1zbMBd4iqIP6VUjOfio2	0	0	0	WALKING	network	0	1	9/8/2022 8:11	1.82167E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	1	1	13	STILL	fused	0	2	9/8/2022 8:11	1.82167E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	2	2	13	WALKING	fused	1	1	9/8/2022 8:11	182164297
82VcA4ry1zbMBd4iqIP6VUjOfio2	3	3	13	STILL	fused	1	2	9/8/2022 8:41	1.82147E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	4	4	13	WALKING	fused	1	3	9/8/2022 8:45	1.82149E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	5	5	13	STILL	network	1	4	9/8/2022 9:23	182151187
82VcA4ry1zbMBd4iqIP6VUjOfio2	6	6	13	WALKING	fused	1	5	9/8/2022 9:23	1.82152E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	7	7	13	STILL	fused	1	6	9/8/2022 9:33	1.82146E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	8	8	13	WALKING	gps	1	7	9/8/2022 10:24	1.82113E+16
82VcA4ry1zbMBd4iqIP6VUjOfio2	9	9	13	STILL	fused	1	8	9/8/2022 11:04	1.82153E+16

Table 5 shows the combined data from OneBusAway and the manual ground truth data collection. It displays location and time data that align with each other. It is crucial to note that only the data showing a 1-to-1 match between the information provided by the OBA server and what has been observed is accurate and reliable.

Table 5. Match "OneBusAway-Ground Truth Data"

GT_Collector	GT_Date	GT_TimeOrig	GT_LatOrig	GT_LonOrig	GT_LatOrig	GT_LonOrig	GT_TimeDest	GT_LatDest	GT_LonDest	GT_TourID	GT_TripID	Google Activity	GT_Mode_Origi	Automatic Assignment
Giraldo	9/6/2022 0:00	1/0/1900 9:57	18.216369	-67.148244	18.216369	-67.148244	1/0/1900 10:15	18.214297	-67.141231	GIR_1	1		WALKING	Match-3
Giraldo	9/6/2022 0:00	1/0/1900 10:43	18.215122	-67.1392288	18.215122	-67.1392288	1/0/1900 11:05	18.215136	-67.139379	GIR_1	4		STILL	Match-3
Giraldo	9/6/2022 0:00	1/0/1900 11:05	18.214297	-67.139379	18.214297	-67.139379	1/0/1900 11:51	18.214585	-67.141197	GIR_1	5		IN_VEHICLE	Match-3
Giraldo	9/6/2022 0:00	1/0/1900 11:51	18.214585	-67.141197	18.214585	-67.141197	1/0/1900 13:15	18.216369	-67.148244	GIR_1	6		WALKING	Match-3
Giraldo	9/8/2022 0:00	1/0/1900 9:38	18.214297	-67.141231	18.214297	-67.141231	1/0/1900 9:47	18.215122	-67.139288	GIR_2	1	WALKING	WALKING	Match-1
Giraldo	9/8/2022 0:00	1/0/1900 10:36	18.215136	-67.139379	18.215136	-67.139379	1/0/1900 11:22	18.214585	-67.141197	GIR_2	3		IN_VEHICLE	Match-3
Giraldo	9/8/2022 0:00	1/0/1900 11:22	18.214585	-67.141197	18.214585	-67.141197	1/0/1900 11:32	18.214297	-67.141231	GIR_2	4	WALKING	WALKING	Match-1
Giraldo	9/12/2022 0:00	1/0/1900 8:29	18.214297	-67.141231	18.214297	-67.141231	1/0/1900 8:32	18.215122	-67.139288	GIR_3	1		WALKING	Match-3
Giraldo	9/12/2022 0:00	1/0/1900 9:12	18.215136	-67.139379	18.215136	-67.139379	1/0/1900 10:01	18.214641	-67.141018	GIR_3	4		IN_VEHICLE	Match-3
Giraldo	9/12/2022 0:00	1/0/1900 10:01	18.214641	-67.141018	18.214641	-67.141018	1/0/1900 10:29	18.214641	-67.141018	GIR_3	5	WALKING	IN_VEHICLE	Match-1

In a typical instance of a single trip, OBA generated a total of 25 data points. After validation with ground truth data, ten of these points matched the actual data collected. The points that did not match had coordinates indicating locations outside the study area. Despite this process, some data remained difficult to relate. The non-matching data accounted for 60% of the total, emphasizing the need for thorough data cleaning and validation. This situation posed an unresolved problem at the time of the study.

Another issue was the retrieval process for OBA data, which required waiting for the server operators to send the data for validation. This operation could take at least one day as the server scripts collected data once per day during off-peak hours. Sometimes, the research team had to wait longer than a day to receive the information. As a result, the research team considered exploring alternative approaches to enhance data collection efforts. One potential solution involved developing a new application to enable local registration of data without having to wait for the OBA server to deliver the information.

The validation process revealed that the information automatically collected from OBA did not match all the data points recorded in each trip, including some entire trips that were not registered in the OBA dataset. It was evident that a new supplementary application was needed. Travel Transit Tracker (TTT) application was created to validate the data collected by OBA. TTT would validate the data from OBA by comparing it with manually input data from users, particularly in the 'Google Activity' and 'GT_Mode_Origin' columns. TTT, which is designed to be used in conjunction with OBA, aims to improve data collection by allowing users to provide manual input for changes during their trips. The app will support various modes of transportation such as e-scooters, cars, buses, and walking, and users can manually select their trip mode to generate their trajectory before and after using the bus. This additional information will provide insights into user behavior while using the OBA service. The next chapter explains the development and main features of the TTT application developed as part of this research project.

Chapter 5. Development of the New Application Travel Transit Tracker (TTT)

To start developing a new application, the research team began by taking some initial steps to lay the groundwork for integrating with OBA. Last year, the OBA service was updated by adding different support software, including OBA, to server containers. This server configuration marked the first step in the development process, enabling the servers to handle more requests. The development cycles were carried out for the servers in Digital Ocean, a server provider that grants developers full accessibility and customization options for the server. There are various methods for deploying and implementing a series of open-source software. Therefore, careful planning was conducted to develop the TTT application.

Planification of Travel Transit Tracker

Before development began, the features and functionalities needed had to be planned. The proposed application is a supplementary tool for OneBusAway. For this reason, the features included in the application seek to validate the OBA data with manual input. Before developing new software, an evaluation of which APIs and resources could be used was made. This evaluation concluded by using Expo as an open-source platform to program mobile applications. The Expo library allows the developer to program one version of the User Interface and export this code to both iOS and Android devices. This flexibility would facilitate the development and future testing of TTT. As an external resource of the mobile app, the REST API services from OneBusAway and Traccar will be used as supplementary data for the mobile app.

Development of Travel Transit Tracker

The mobile app was developed using the programming language JavaScript. We planned the User Interface using Figma before starting the programming. Figma allowed us to create accurate interpretations of the application before development. In some areas of the mobile application, the Interface differs between different devices. These different layouts were tested using Figma and Android and iOS Emulators.

Key features of Travel Transit Tracker

The first step in viewing the user activity was to access the Expo device capabilities. The Expo library allows the developer to use the device location and sensors. The device coordinates, orientation, and movement activity can be accessed from the information provided by device sensors. With the OBA documentation, the data generated by the hosted OBA server was accessed through TTT. With access to device information, they completed the capacity to validate incoming OBA data. The application will allow the user to track and plan the bus trip taken manually, allowing a second form of data recollection to be made.

Figure 8 below demonstrates an early visual of how the online buses from the OBA API and route time arrival are shown in TTT. Figure 9 demonstrates how the user can select a traveling method to start the trip. The user is expected to visit the bus arrival time per stop for a route before creating a trip. This screen can be seen in Figure 10.

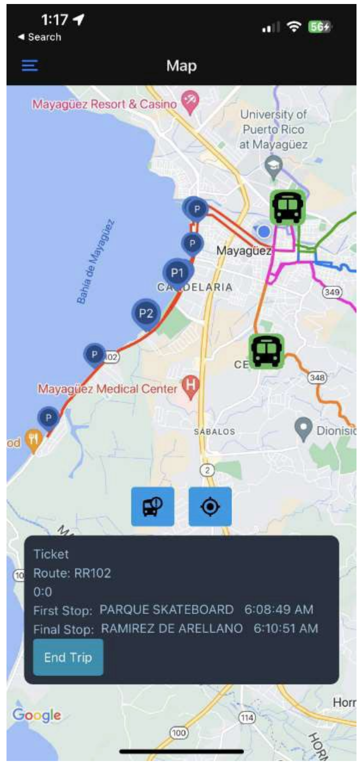

Figure 8. Travel Transit Tracker (TTT) Implementation Between OBA API and Device Trip Tracking.

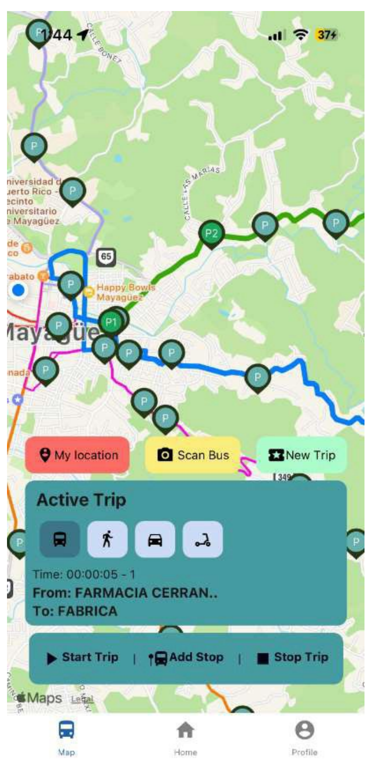

Figure 9. Travel Transit Tracker (TTT) Travel Method Selection.

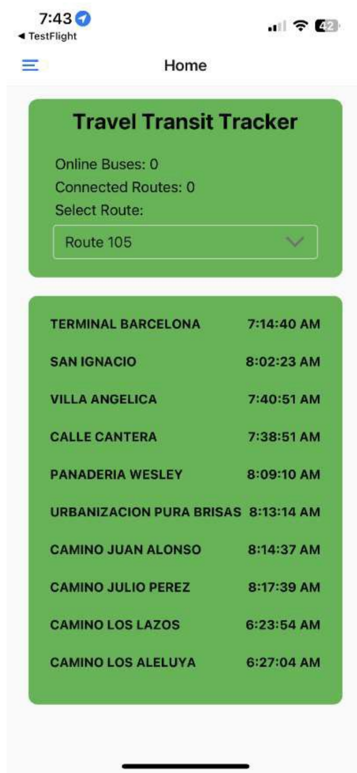

Figure 10. Travel Transit Tracker (TTT) Selection Screen for Route Arrival Time.

Testing and Deployment

The mobile application was tested on various iOS devices using TestFlight. For Android, the Play Store allows beta versions of applications before an official release. Figure 11 below demonstrates the release of the iOS version on the app store. This release shows the complete process of deploying a supplementary tool for OneBusAway.

The diagram in Figure 12 depicts the architecture designed and implemented for a mobile app that utilizes active services as data. The upper section of the diagram illustrates the components implemented using Expo, while the middle section shows the software services hosted on servers. It is essential to implement Apache as a comprehensive security method in this area, ensuring that HTTPS requests are handled over a secure connection. This approach to security instills confidence in the app's safety. Additionally, to publish a mobile application in the app store, a set of security-related inquiries need to be addressed and specified.

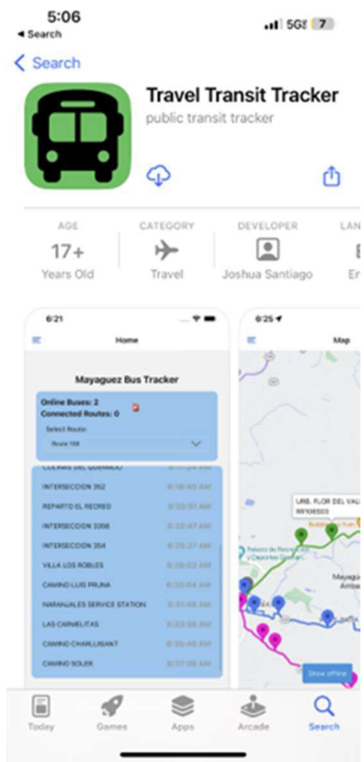

Figure 11. Travel Transit Tracker (TTT) App Store Release.

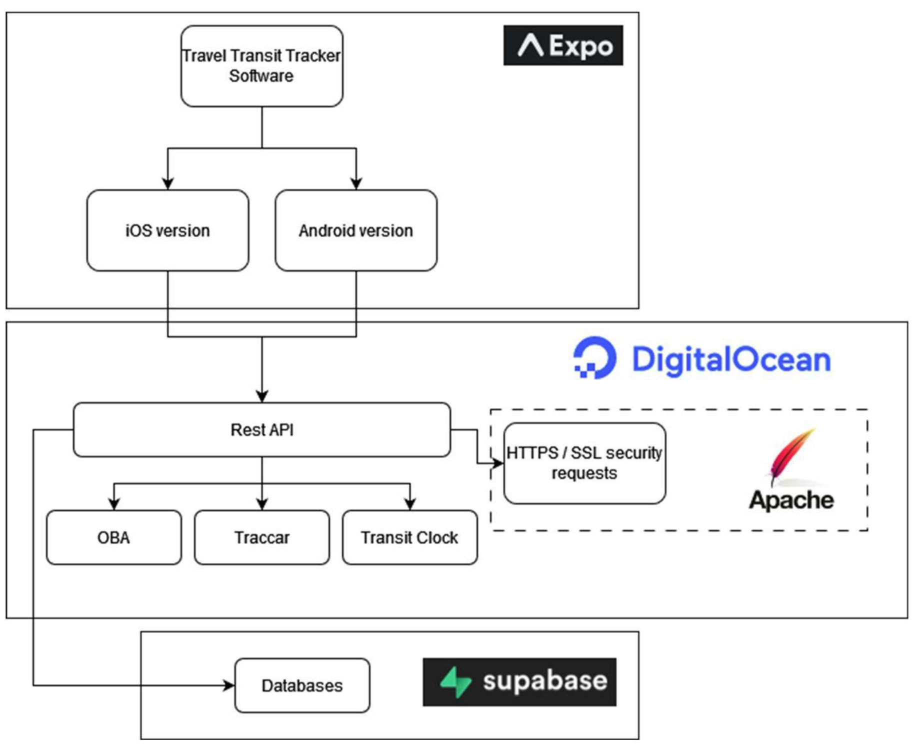

Figure 12. Travel Transit Tracker (TTT) Software Implementations.

JavaScript was used throughout the development of the Android and iOS versions of Travel Transit Tracker, and TypeScript was later implemented as the programming language. The goal was to ensure that the application meets essential requirements for user-friendliness and stability. Security was a top priority during the initial stages of development. A secure way to store user data and personal information was also needed. Apache software and Supabase were utilized to address this concern, and they effectively covered the security needs. When users login or register, their personal information - including their name, home location, and work location - is saved on Supabase. However, to prevent unauthorized access, the human-readable value is encrypted before being stored in the Supabase database portal, thus ensuring the security of account data and user information.

The key feature of the proposed app design that must be implemented is a map mounted with the stops, which shows the vehicle trips in real time. This feature will ensure the app completes recording and following the user through a vehicle trip. The status of the trip and any inconveniences should be noted through the application. The Mayagüez transit routes reflected a difficulty of device connectivity due to altitude and lack of internet provider signal in some regions. Due to this natural inconvenience, the software developer must account for an inconsistently connected device. During development, the issue was raised when the servers could not complete a reconnection to the mobile application due to prolonged disconnection of the user device.

Figure 13 displays an SSL error in the OBA application. This error was recurring during development in Mayagüez due to the expiration of a security certificate on the servers. Secure Socket Layer (SSL) is a critical server implementation that ensures secure communication through a port to the server. When developing servers in Digital Ocean and Apache, the firewall security needs to be revalidated every three months.

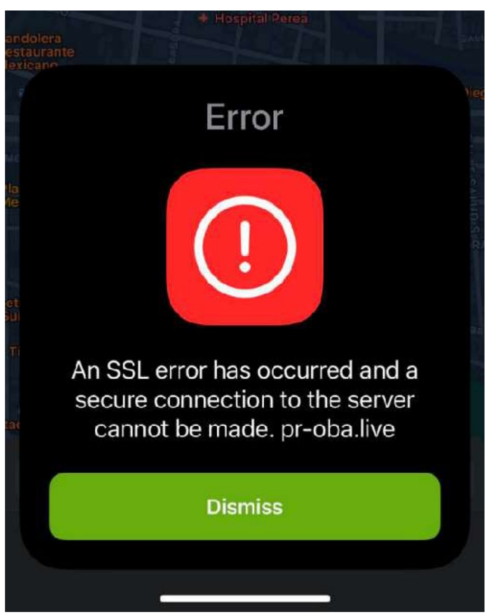

Figure 13. Secure Socker Layer (SSL) Error Visualization from OneBusAway.

Communication between the servers was facilitated using CRUD functionalities, which stands for create, read, update, and delete. These are the core functions required for transmitting information between services. The developed programs manage these functions using a REST API program. REST, which stands for

Representational State Transfer, is an architectural guideline that helps in managing communication on the internet. The Apache security methods mentioned earlier are crucial because information is represented in plain text. As a result, security implementation is essential to maintain information security when transmitting human-readable information between servers.

Travel Transit Tracker (TTT) and OneBusAway

When a user logs into the Travel Transit Tracker app, the app searches for and provides a series of information. The first accessible information for the user is the stops and their respective arrival times. The method created for users to maintain an active connection is received from the Digital Ocean server. The OBA information is filtered, recorded, and finally sent to the user from the server where the REST API is hosted. The application uses two connected servers through a REST API. Additionally, a third service hosts the user data and registration: Supabase, a cloud database provider. Figure 14 presents the server architecture with database communication. Four databases are used to complete the tasks required for the TTT application.

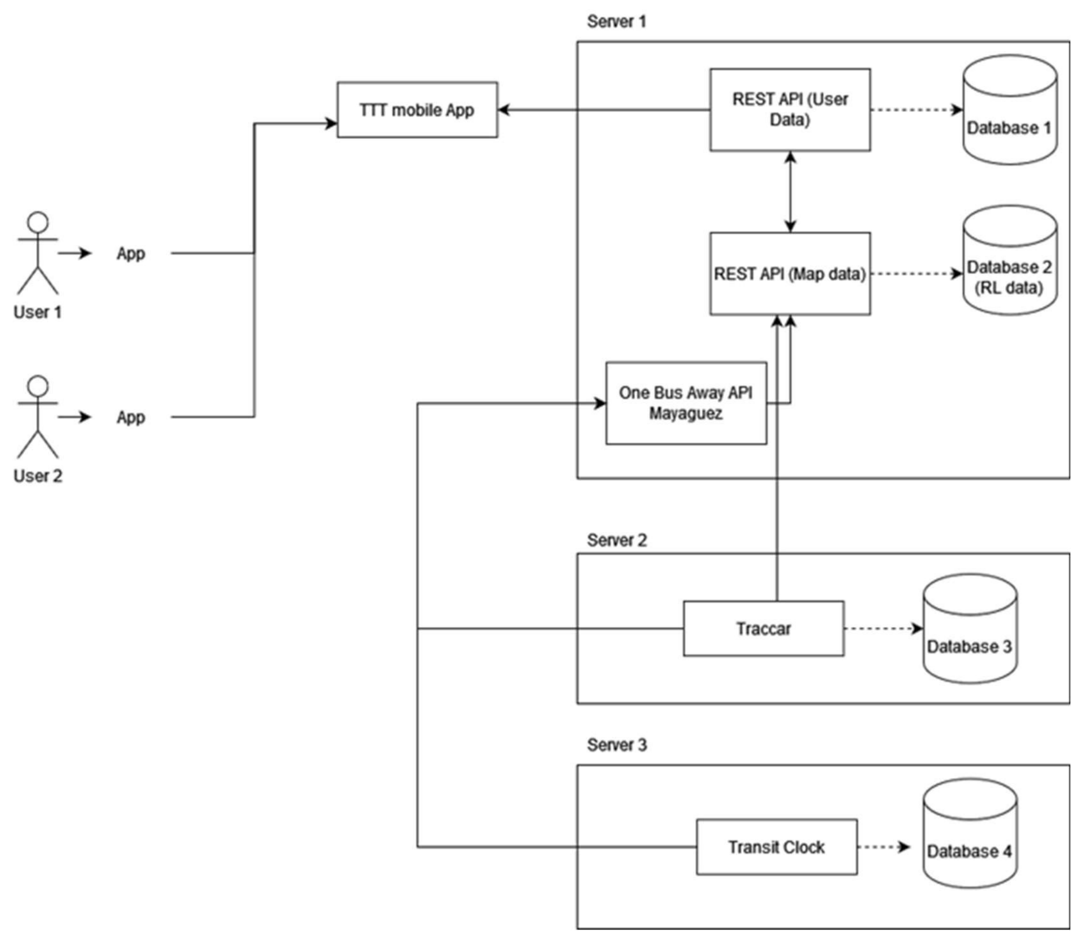

Figure 14. TTT Server Architecture with Database Communication.

Every software implementation has its own local database in PostgreSQL. Data from Traccar and Transit Clock is accessed through the Rest API, allowing the software to run while storing the information. Real-time data is filtered and stored in a separate PostgreSQL database when processed on the servers.

When developing the mobile application using Expo, handling multiple server requests simultaneously was a major challenge. During certain development phases, updating information had to be delayed until the end of the trip due to the large amount of information being pushed to the server at once, resulting in the server tunnel being filled with traffic and causing some data to not be recorded or saved successfully. By adjusting the frequency of sending information to the server and dividing the updated information into bulks, the mobile app TTT successfully recorded all the required information from the users.

During the development of the Travel Transit Travel (TTT) application for both Android and iOS, the process had to be separated into two sections. The Android version was smoothly published on the Android Play Store, with specifications provided by the research developer. However, releasing the app on the App Store posed challenges for TTT. Because the app was developed using Expo, most of the code had to be compatible with both mobile stores. However, the process differed with the iOS store due to their policies, which didn't allow multiple releases of the TTT application. As a result, the development had to continue through an app called Test Flight for several months until the policy issue was resolved and the correct coding guidelines were implemented for the iOS app store release. The differences in privacy policy and user information usage required the development of two versions of TTT.

The TTT Android version comes with testing features, while the iOS version includes additional functions that are triggered when the user's location is updated. In the final iOS release, there are a series of prompts to confirm with the user that their location and mobile device information will be shared with the developers. It is important to note that the data collected from Android and iOS was the same, but the execution time varied based on the version.

The primary function of the Travel Transit Tracker application is to allow users to save their trips. This information can later be utilized to improve the OneBusAway service or enhance the transit system. Figure 15 demonstrates how this function is executed on the mobile application and how the information is sent to the server.

The code first prompts the user to select their preferred mode of transportation – car, bus, scooter, or walking. After the initial selection, the application begins to record the user's location locally, but this information is not sent to the server until the trip has officially started, in accordance with privacy policies. If the user chooses the bus as the transportation mode, they will be asked to select the origin, and destination stops for the trip. No stop selection is required for walking, driving, or using a scooter. During the active trip, the application sends location information to the server.

The function that sends server information begins by updating the user account and historical trips. This feature displays historical data from users, which is important because it allows them to plan future trips using their previous travel information. Access to this information benefits informed users in making better decisions while traveling. The user's access is limited to trip information, not the trip trajectory; only the trip's initial and final positions are shown. However, the real-time update of the user's location is stored separately and accessible to a server administrator, as the server structure is a series of APIs waiting for a connection to become available. It is possible to implement a feature or separate software to access this information.

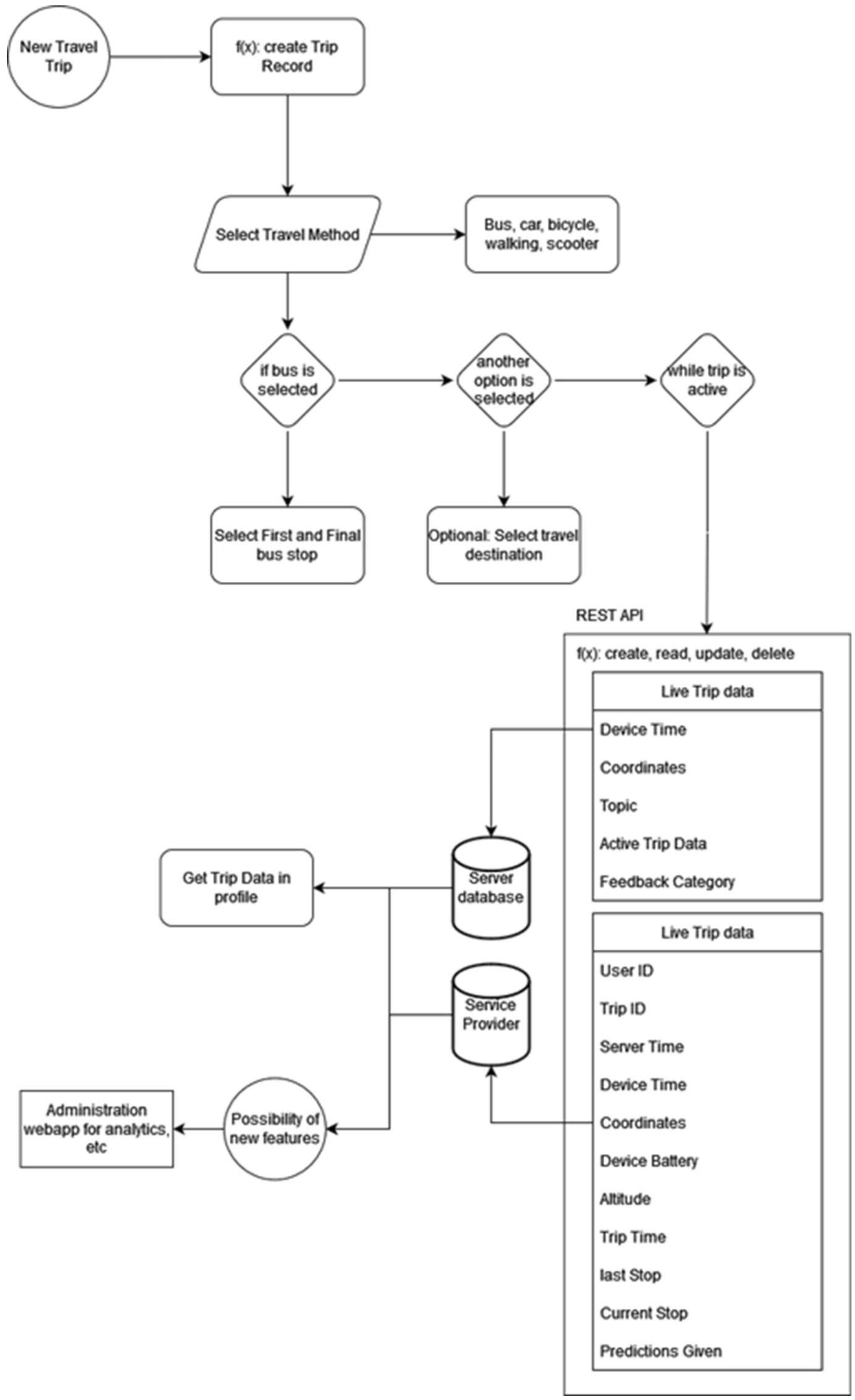

Figure 15. TTT Data Storage Code Functionalities.

Data Collection using Travel Transit Tracker (TTT)

Figure 16 presents a schematic of the sequence of events that occur during a user's trip who decides to complete it by bus. This figure also includes how TTT performs the data collection activities according to the events presented.

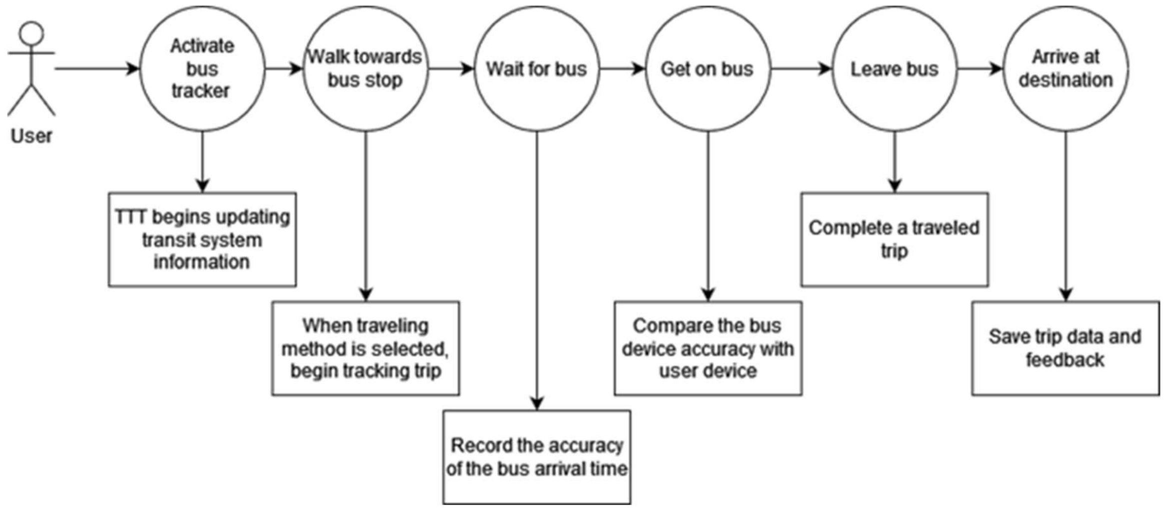

Figure 16. Events Executed by TTT when Users Complete a Trip.

For the Travel Transit Tracker app, specifying the method for retrieving key data is crucial as it involves extracting specific information. Once the app complies with the iOS and Android publishing guidelines and privacy protection measures, users can review or delete each recorded trip. The main feature of the app is a transit ticket system, which is initiated when the user searches for routes and the nearest bus prior to starting a trip.

Figure 17 presents a screenshot of the TTT app showing when a travel mode is selected. The user can choose to select the bus they traveled on before or after boarding. If they select the bus before boarding, it will provide a reference point to check the accuracy of the bus tracking software while the user is on the way to the stop. The segment of the trip from the initial recording until the user boards the bus is recorded as an additional traveling mode. While the user is active and on board, they can report any errors or inconveniences through the application, tracking service, or transit system. Finally, when the user arrives at the destination bus stop, they have the option to continue tracking the route or finish the trip at the bus stop.

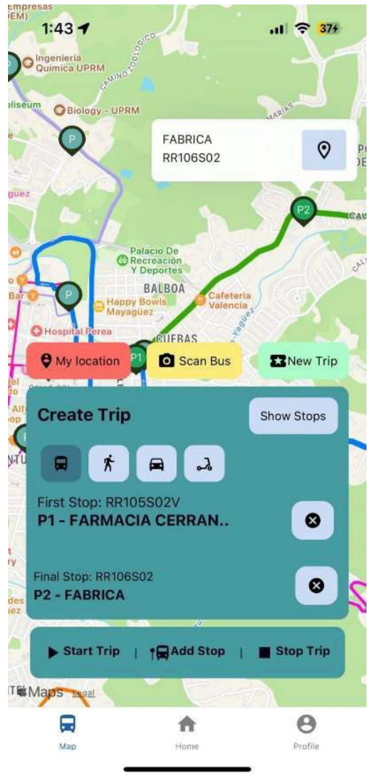

Figure 17. TTT Screenshot When a Travel Mode is Selected.

The user device information and tracking data could be compared with the tracking device on the moving vehicle. Because every request made to the server is recorded, a pre-trip preparation can be created in future developments so that a user can repeat a previously taken trip without re-adding all the information.

During the validation of the TTT application's data collection capabilities, a test was conducted with multiple users. The users used the Mayagüez Transit System for several trips on different routes. Figure 18 illustrates the trips taken by the users during the test. Before starting the test, the users were allowed to familiarize themselves with the application. The application tracked the users throughout their trips, following the functionalities mentioned in previous diagrams. TTT successfully collected the necessary data to track these trips.

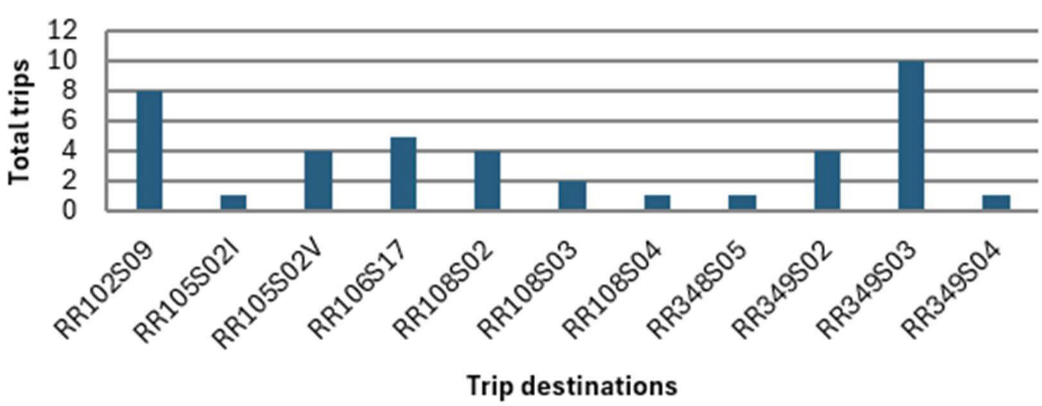

Figure 18. Trips Performed by Users During Test.

Table 6 provides an example of trip data collection from one of the TTT users, specifically stop arrival times. Figure 18 and Table 6 demonstrate how the TTT application replicated the data obtained from the OBA application. TTT utilized the raw data from OBA to develop a data-collecting application.

Table 6. Trip Data Collection of Stop Arrival Time from a TTT User

userId	firstStop	finalStop	route	startTime	stopTime	timeFram	lat	lon	travelMethod
3Hmf5uex	RR108S02	RR108S02	RR108	1682038172469.00	1682038188899.00	0:07:46	18.20129	-67.1387	AT_BUS
	RR349S03	RR106S17	RR106	1.68204E+12	1.68204E+12	0:21:05	18.20902	-67.0321	AT_BUS
	RR349S03	RR106S17	RR106	1.68204E+12	1.68204E+12	0:29:51	18.20903	-67.0321	AT_BUS
	RR105S02\	RR105S02\	T01	1.68204E+12	1.68204E+12	0:12:12	18.20483	-67.1391	AT_BUS
	RR349S04	RR349S04	T01	1.68204E+12	1.68204E+12	0:01:55	18.20479	-67.1385	AT_BUS
	RR106S17	RR106S17	T01	1.68204E+12	1.68204E+12	0:31:36	18.20475	-67.1385	AT_BUS
	RR105S02I	RR105S02I	T01	18.20091915	-67.13948515	0:42:24	18.20092	-67.1395	AT_BUS

The TTT application receives and sends information in real time during the data collection process. The TTT code was developed as one project because the software was designed to work with both Android and iOS. However, this approach limits the program's ability to fully utilize native device features on some Android devices, leading to delayed responsiveness. Despite this limitation, the application interface is designed to continue tracking users even during periods of lag or unresponsiveness.

As shown in Figure 19, tracking trajectories in the Mayagüez network sometimes exhibit jumping behavior, likely due to signal outages or elevated altitudes. The map in Figure 20 displays the tracking trajectories of bus devices using OBA during active service. Comparing Figure 19 and Figure 20 shows the difference in the recorded trajectories. The contrast demonstrates the improvement in recorded trip accuracy, which can be attributed to the updated OBA version 2.x and server docker containers. These updates allowed the servers to operate with lower latency, freeing up memory needed to process TTT requests.

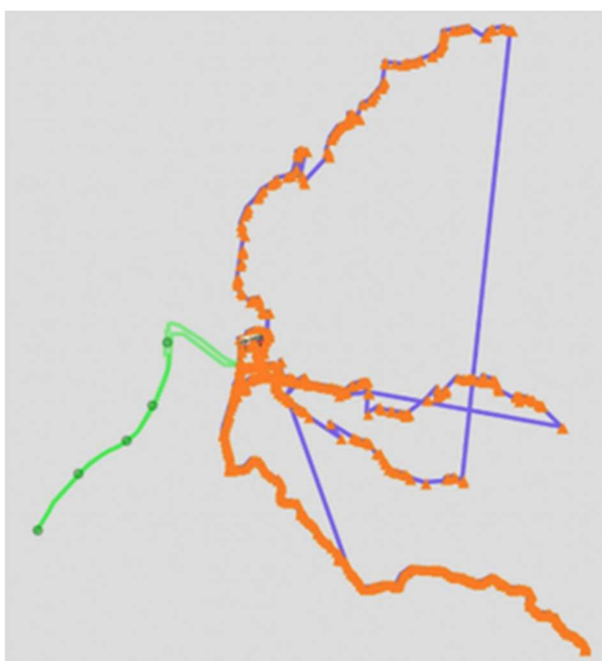

Figure 19. Map of Trip Trajectories During TTT Development.

The data collected by TTT overlaps with the data collected by OneBusAway. This is because the software maintaining both apps is almost the same, resulting in shared values in both outputs. The main difference in data collection lies in the manual input required in the TTT application. These additional steps in generating a user trip help validate OBA data.

As depicted in Figure 4, the GPS signal quality may diminish in certain regions of the municipality, potentially leading to disconnections in the OBA application. However, TTT, being a locally developed application, has been adapted to display the bus on the map even when the location and predictions are not available due to disconnection. This adaptability ensures that users are always informed about the bus's arrival, regardless of the signal quality.

Given that many of these areas are densely populated, the lack of GPS signal is likely also experienced by the user. However, TTT's user-friendly interface makes it easy for users to verify their activity manually. This feature allows for generating various parameters.

Data Before Trip

Users can choose from various modes of transportation. Although this feature creates a way to validate the change in transportation mode, it also allows for different ways to gather data. When a mode of transportation other than a bus is selected, the app gathers the user's location and traces the trip periodically. If a bus is chosen, the data collected can be compared directly with the GPS tracker. Figure 20 illustrates the contrast between a bus tracking application that only generates data for the bus trip and a general tracking application. The TTT application provides data that reflects the user's trip trajectory before and after using public transit.

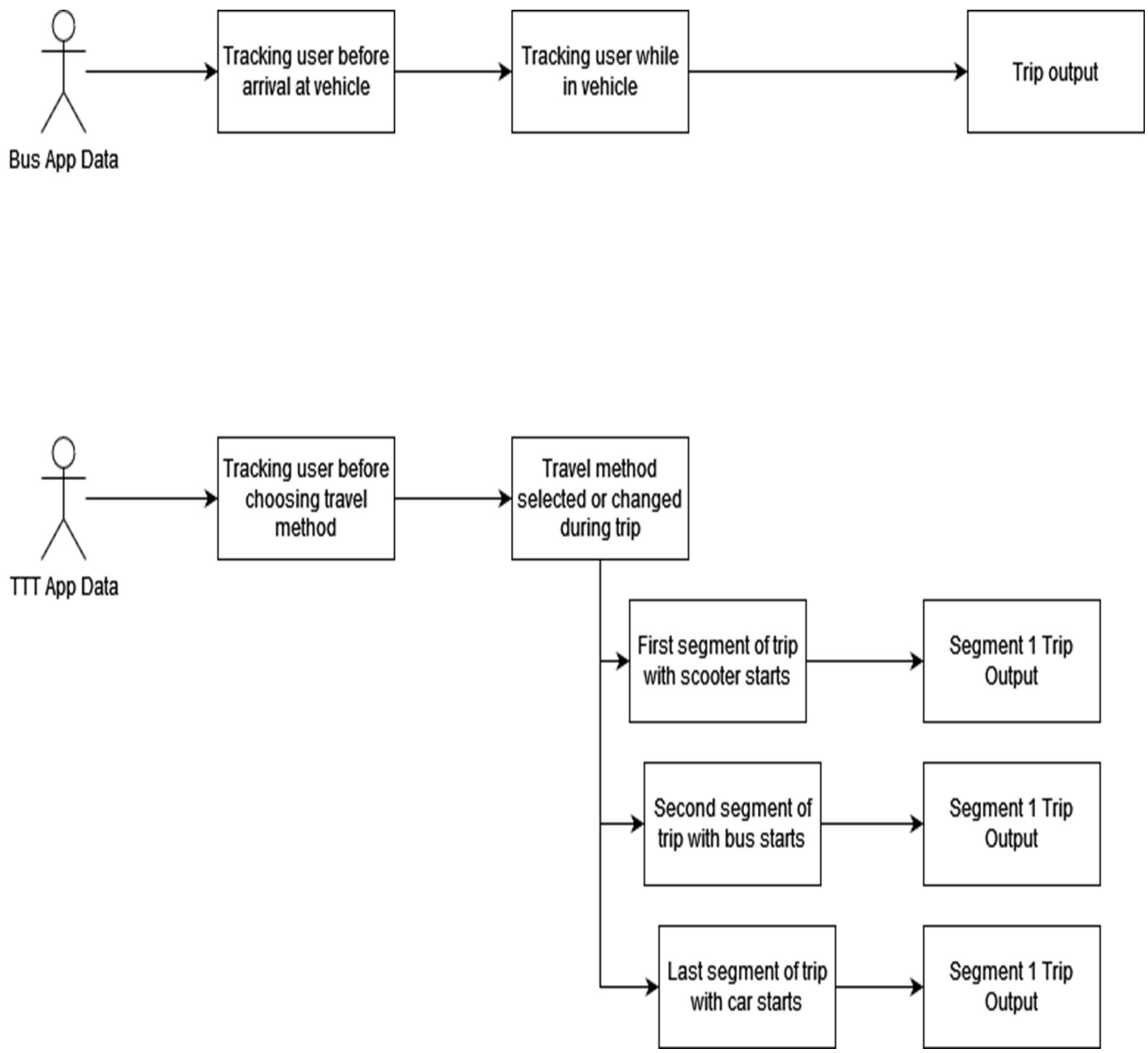

Figure 20. Data Collection Flow for Trip Management.

Chapter 6. Transportation Planning Modeling and the Implementation of the TTT Application

The TTT application data is a valuable resource that has the potential to provide essential insights into travel behavior in the city. However, as this data is user-specific, a significant number of application users need to contribute their information to generate enough data for comprehensive citywide insights on trip origin, destination, and modal split. This collective effort would significantly enhance demand models for city planning.

In the case of Mayagüez, the challenge is twofold because, on the one hand, the number of TTT users has been at an experimental level to validate the application. Therefore, having more system users provide information to modify the city's demand models would be necessary. On the other hand, it is necessary to develop the demand model, given that the city planning studies conducted so far have been very general to know the trips between cities or very specific for specific projects in some city sectors.

The research team had access to Puerto Rico's general planning data developed for the Long-Range Transportation Plan. With this information, a general planning model of the city of Mayagüez was developed using the TransCAD program. The aim is to have a planning model incorporating crowdsourcing information generated by the TTT application. The information provided by TTT corresponding to the transportation zones used for the planning model could then be used to modify the generation and modal split models corresponding to the city's general planning model.

This chapter presents the development of the four stages of the planning model for the city of Mayagüez using the TransCAD program and the Puerto Rico Long Range Transportation Plan database. The results for trip generation, distribution, modular split, and assignment of car and transit trips are presented as part of the planning model's development.

Definition of Transportation Zones for the Planning Model

The transportation zones used in the general planning model for the city of Mayagüez were based on the zoning obtained from the Census data. The transportation analysis zones were generated based on the centroids obtained from the Puerto Rico 2045 planning study (Puerto Rico Highways and Transportation Authority (PRHTA), 2018). Census blocks were grouped from the 2010 Puerto Rico census data files (*GOBIERNO DE PUERTO RICO*, 2010), using these centroids and considering possible zone boundaries such as highways, rivers, creeks, and other similar elements. The census zones were created to represent the areas from which population trips are generated. It is important to note that the centroids do not correspond to the exact middle of the geometry of the zone but are points that represent the trips generated or attracted within a given area (*Estrada*, 2008). Figure 21 displays the transportation analysis zones established for the project in the municipality of Mayagüez, with the zone centroids marked in yellow.

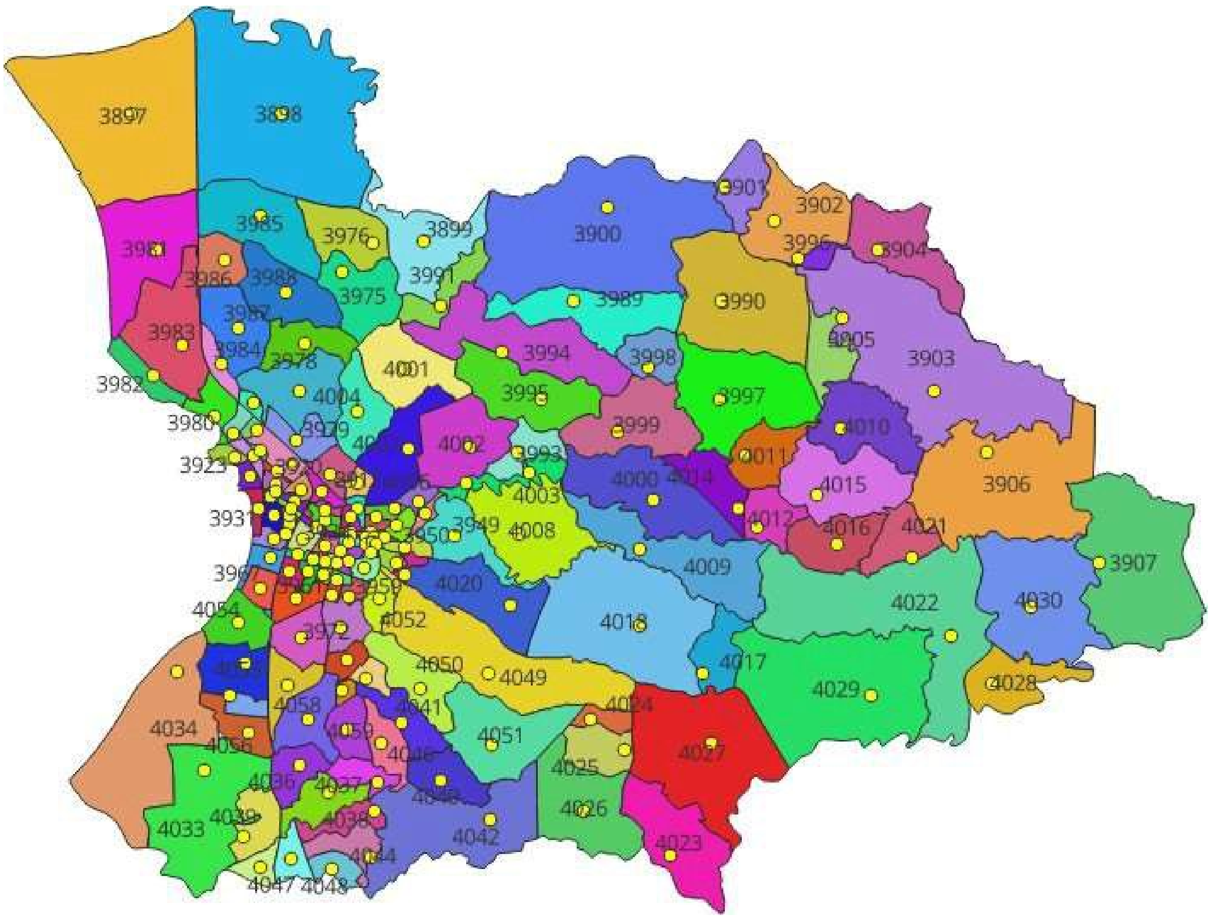

Figure 21. US Census Zones in the Municipality of Mayagüez.

Trip Generation and Trip Attraction

Various information sources could be used to gather the necessary data for the trip generation and attraction models. The Mayagüez Integrated Transit System (TIM) provided some general data, but it was insufficient for the city. Additionally, trip generation rates from the Institute of Transportation Engineers (ITE) could be used for travel generation locations. However, classifying buildings and their demand variables was time-consuming, requiring resources not available during the study.

The most accessible and reliable data was obtained from the Long-Range Transportation Planning study conducted by the Planning Division of the Puerto Rico Highways and Transportation Authority, which projected data up to 2045. This study provided information about transportation analysis zones and the number of trips generated and attracted, which was crucial for creating an origin-destination matrix, an essential component for a transportation planning model in Mayagüez.

With the origin-destination information in place, most of the data needed for the demand model was ready. The last piece of data was the modal split information that was also taken from the Transportation Plan. However, the data for the 2045 Long-Range Transportation Plan was particularly succinct for the modal split model. Therefore, an application such as TTT could be beneficial for collecting data, particularly information about modes of transportation used by the population. This information is essential for an efficient application intended for this purpose. Figure 22 was developed using TransCAD to graphically represent the volume of trips generated in each zone according to the population.

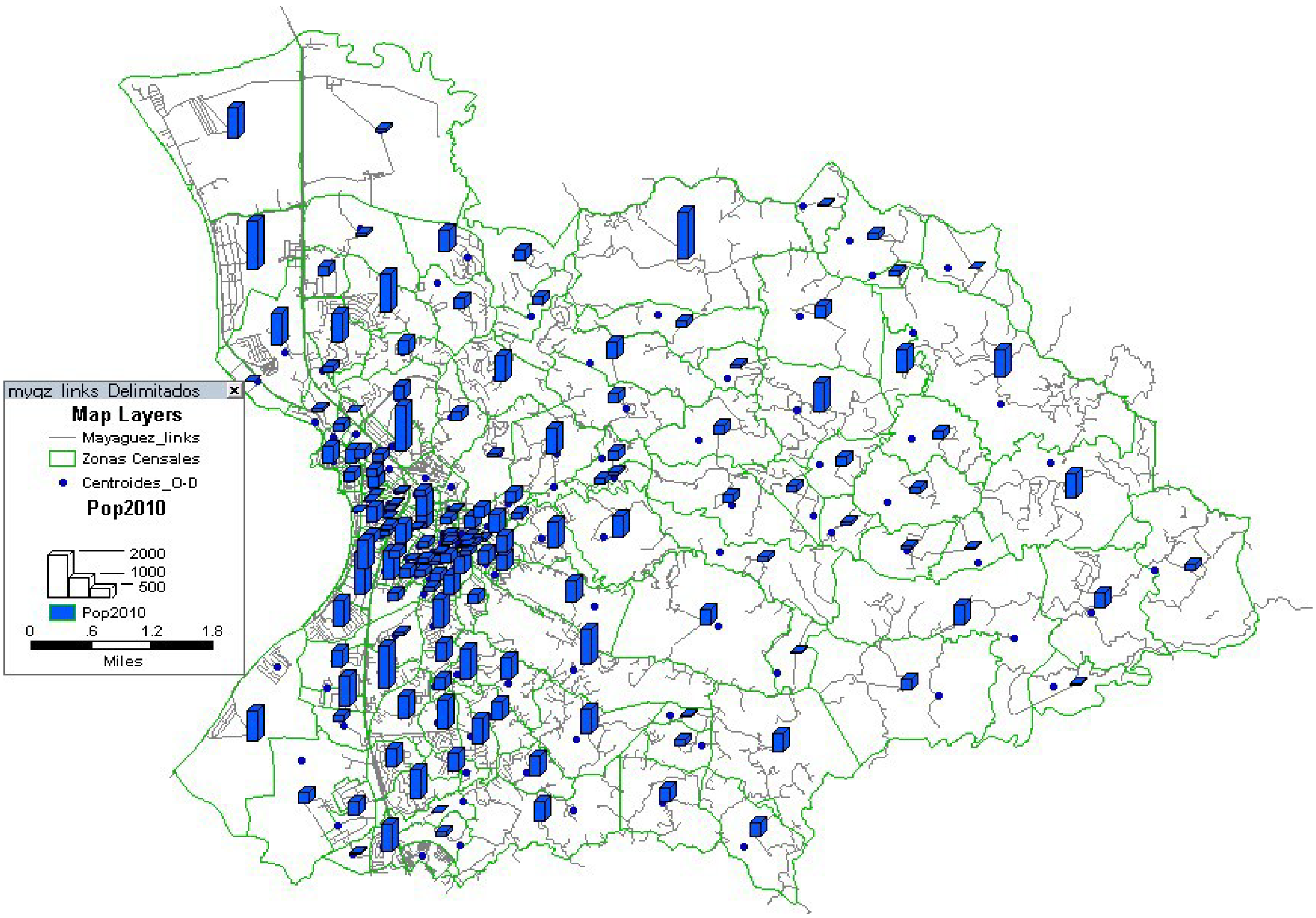

Figure 22. Generation of Trips by Zone.

O-D Matrix

After identifying the various transportation analysis zones within the municipality, the data on the number of trips in each zone was identified in the study and entered in the TransCAD model. This allowed us to determine how many trips were either generated within each zone or attracted to other zones within the municipality. Using this information, the origin-destination matrices were created. The O-D matrix is visually depicted in Figure 23, showing the connections between origins and destinations from one zone to another.

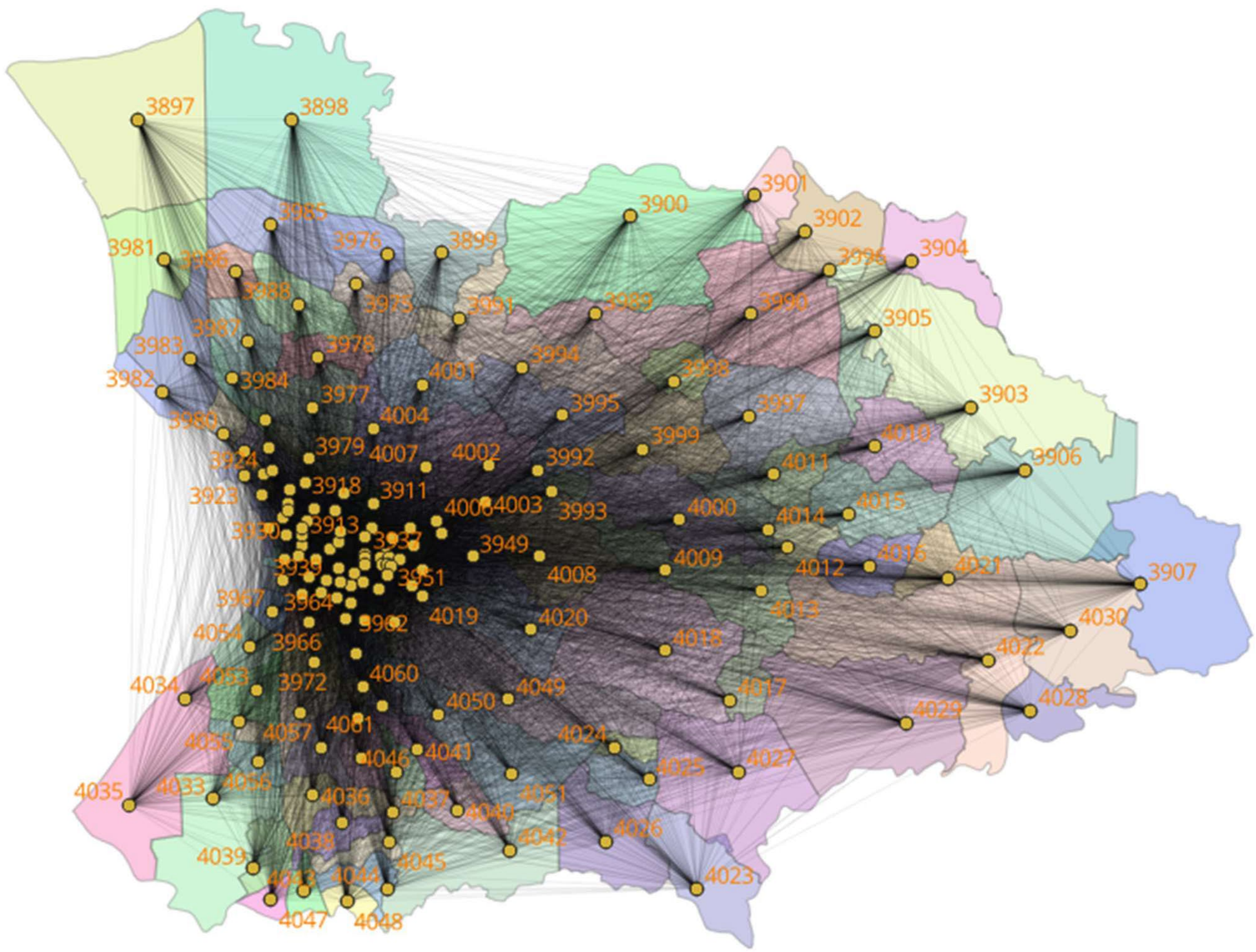

Figure 23. O-D Matrix.

Transportation Network for Traffic Assignment

The transportation network in the Municipality of Mayagüez was created manually in TransCAD. This involved representing routes, creating nodes and links, and defining their characteristics. The network connects centroids to routes, enabling communication between trips from an origin to a destination. Afterward, the traffic model is used to determine the traffic assignment for all trips in the origin-destination matrix. Figure 24 shows the visual representation of the route network in Mayagüez, which includes nodes, centroids, links, and zones.

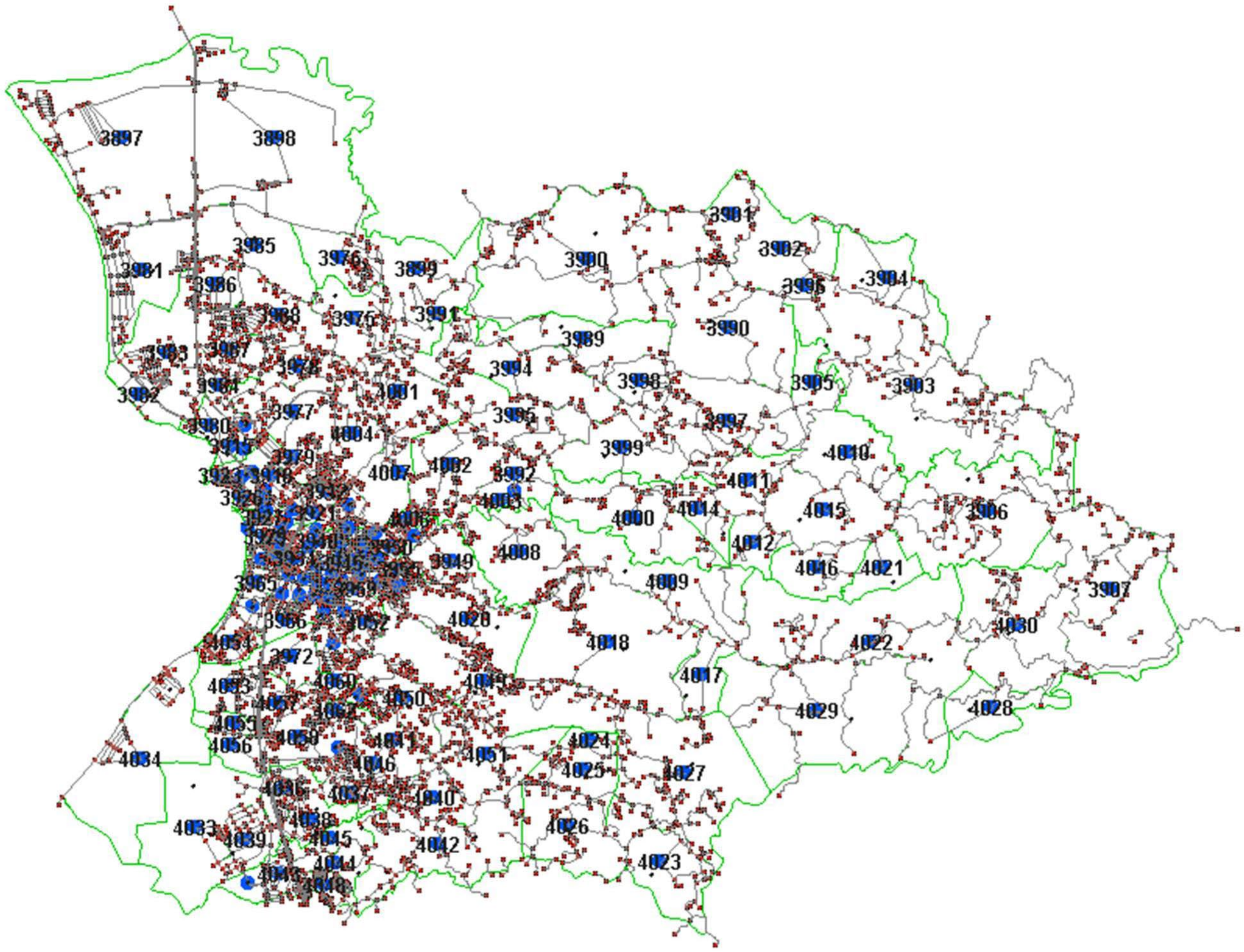

Figure 24. Road Network in the Municipality of Mayagüez.

In addition to building the street network, the corresponding routes for the Mayagüez integrated transportation system (TIM) must be provided to TransCAD. The transit network was built according to information provided by the company administering the transit system. The transit network creates the shapefiles used in TransCAD and is used to load the origin-destination matrix corresponding to the public transportation system. Figure 25 shows the routes created for the transit system (TIM).

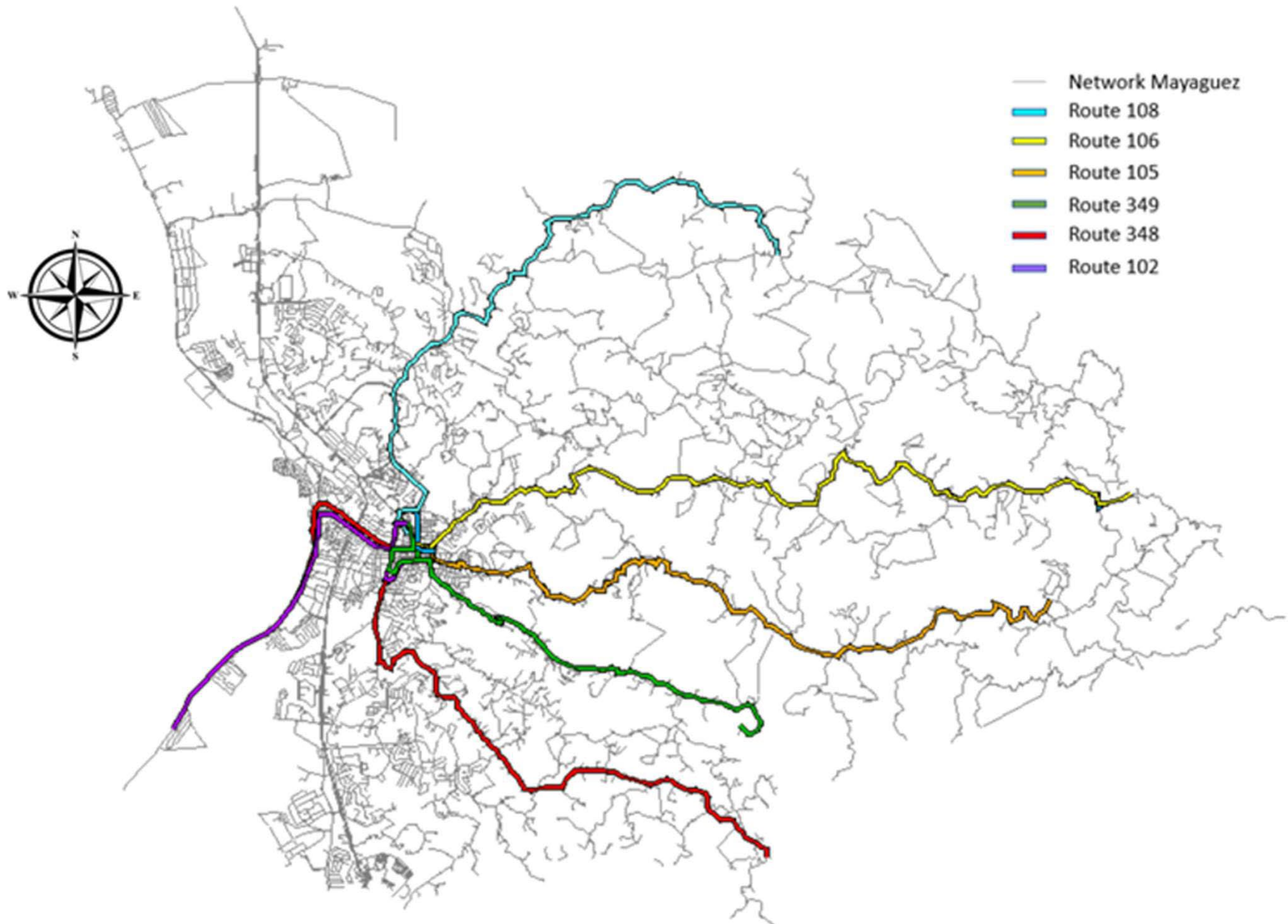

Figure 25. Rural TIM Bus Routes.

Traffic Assignment

The final step in the planning model involves assigning trip flows to the transportation network. TransCAD uses the results of previous steps to define the demand modeling and load the trips onto the transportation network, including both car and transit trips. Figure 26 shows the results of the traffic assignment step in TransCAD. This figure illustrates the flows circulating through the Mayagüez network, including the Rural TIM routes and the flows on each network link. It provides a graphical representation of the flow on links, including those with low flow, high flow, and transit routes.

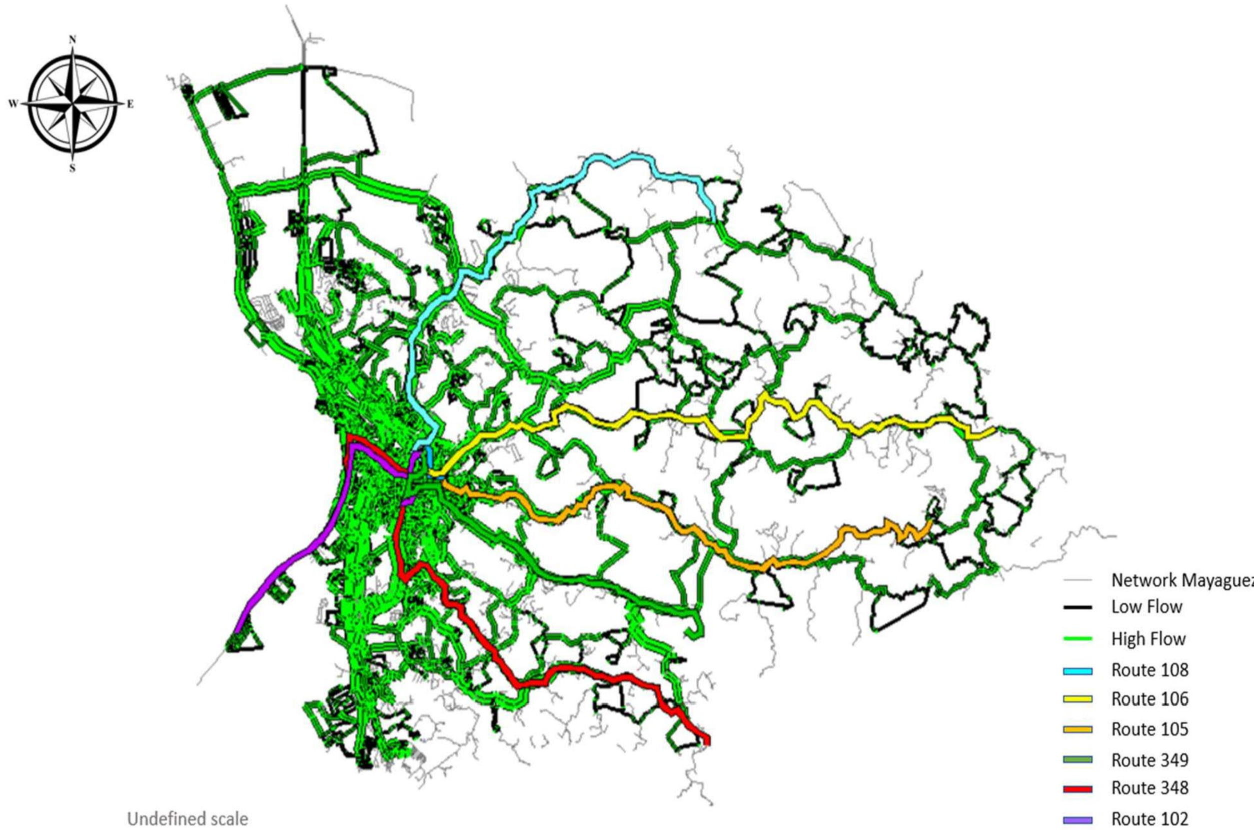

Figure 26. Flow Assignment.

Based on the traffic flow data, congestion is most common in downtown areas and along Highway PR-2. The transportation patterns show that people from rural areas tend to travel towards downtown or Highway PR-2 in the southern part of the municipality. This indicates that people's movement is primarily directed towards specific areas such as commercial districts, workplaces, hospitals, and the UPRM University area.

The concentration of high traffic volumes on PR-2 causes a lot of congestion in Mayagüez. Despite undergoing several studies and improvements, PR-2 remains a controlled arterial road with traffic lights at major intersections and only one viaduct at an intersection with the main streets connecting the Mayagüez city center from east to west. Recently, planning processes have led to the proposal of overpass projects with specifications like those of an expressway to address conflicts at other intersections with high vehicular flow. However, the presence of significant urban development with commercial establishments on both sides of PR-2 complicates the construction of overpasses. In some segments, there is not enough space to develop the frontage roads needed to accommodate local urban traffic, including the potential development of a mass transit service along PR-2. These challenges would result in high costs for the conversion of this arterial road into an expressway in Mayagüez.

The downtown area experiences a high volume of trips, as it serves as a central hub for travel from various parts of the municipality. Operational changes to the downtown roads and control system are necessary to improve mobility and encourage the use of alternative modes of transportation over private cars.

In recent years, the use of alternative modes, such as e-scooters and bicycles for short trips in the urban area of

Mayagüez, has increased. With the implementation of complete streets concepts, these alternative modes are expected to be adequately incorporated into the other available modes for commuting to study and work. Therefore, it is essential to understand how the distribution of transportation modes is changing in the city.

The TTT application developed in this study has the potential to provide the information needed to understand system user behavior and changes in modal split. When used in conjunction with the planning model, it can help test potential solutions to congestion problems and assess the impact of new transportation modes on congestion reduction.

Continuous Improvement Process Integrating Crowdsourced Data and Transportation Planning Modeling

Using crowdsourced data in urban planning can assist transportation planners in testing integrated strategies to reduce urban congestion and improve mobility. Figure 27 shows a suggested cyclical process that can help generate effective strategies by incorporating data obtained from numerous users through OBA and TTT.

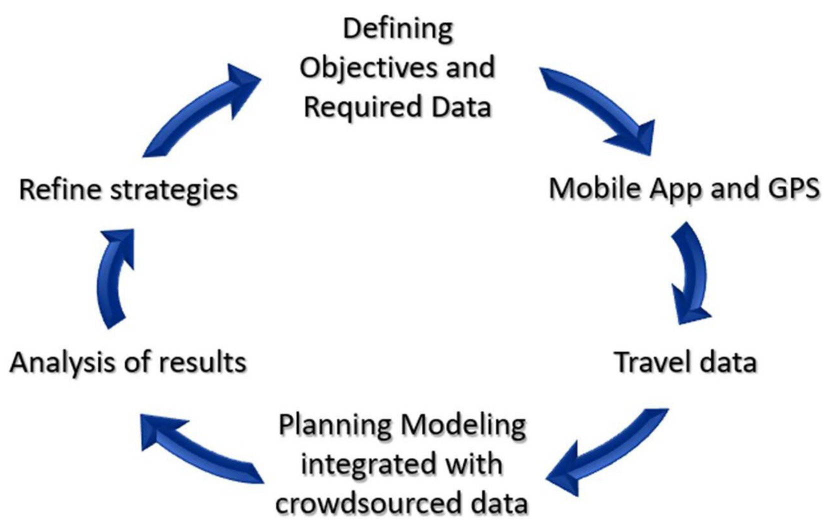

Figure 27. Intelligent Model development Cycle.

A cyclical process is recommended to integrate crowdsourced data in the planning models. It begins with defining the planning objectives and necessary data and ends with developing strategies based on the results of the planning model. The stages of the process are illustrated in Figure 27 and include the following:

- Defining Objectives and Required Data: This process involves outlining the city's goals for multimodal mobility, developing potential strategies to achieve these objectives, and identifying the necessary data to analyze user behavior. This process includes considering information on various multimodal travel variables.
- Mobile App and GPS: Planning models can utilize information from various sources. This project emphasizes the use of GPS-enabled mobile applications such as OBA and TTT to gather multimodal travel information data.

- Travel data: Mobile applications such as OBA and TTT collect and process multimodal travel information from each system user. They generate crowdsourced databases that can be used as part of the data for planning models.
- Planning Modeling integrated with crowdsourced data: Planning models are integrated with crowdsourced data for determining expected trips in the transportation system based on the strategies to be tested.
- Analysis of results: The results of the travel modeling for each strategy are analyzed and summarized based on the city objectives set at the beginning of the cycle.
- Refine strategies: The obtained results will be used to refine the proposed strategies for improving multimodal mobility in the city. Specific data can be collected, if needed, to repeat the process and verify whether the proposed strategy enhances mobility and achieves other city objectives. Once the best results are achieved, detailed strategies will be formulated for implementation.

This process can be repeated multiple times to refine a series of strategies, considering the typical data used in the planning models and the crowdsourced data obtained through the implementation of applications such as OBA and TTT.

Chapter 7. Conclusions and Recommendations

Conclusions

During the implementation of the OneBusAway (OBA) application as a user trip information system, the team gained valuable insights into the unique dynamics of the Mayagüez's transportation system. While adjusting the software, it became evident how factors such as topography and climate affected the app's performance.

The study demonstrated the practicality of mobile applications in collecting real-time data on user travel behavior, especially when combined with GPS technology. This technology enables more precise transportation planning, leading to smarter solutions for reducing traffic congestion.

The OBA app collected travel data successfully. However, it became evident that more fixes were needed due to issues such as inaccurate GPS readings and incomplete trip registrations. These problems emphasized the importance of improving data collection techniques to ensure more reliable outcomes.

The research team created the Travel Transit Tracker (TTT) app to improve OBA's limitations in providing information about the use of different transportation modes during a trip. TTT improved data accuracy by allowing users to manually confirm and log their stops in addition to the automatic data collection process. This app effectively enhanced the quality of the data, which could potentially aid in the transportation planning process in Mayagüez.

During the testing of the TTT app, it was confirmed that OBA could function effectively as a supplementary software. However, challenges arose when cleaning and selecting the correct routes due to incomplete trips and recurring GPS errors. While OBA's raw data contains rich information and plays a crucial role in identifying travel routes, modifications were necessary to adapt the system to the specific needs of Mayagüez. As a result, TTT was developed to access data beyond the range of OBA.

The research team developed TTT for both Android and iOS platforms. Two versions of the app were released to comply with each store's security and GPS tracking requirements. This implementation demonstrated that an app designed to track public transportation and provide real-time information could be successfully used as a base to develop other apps, such as TTT, with broader reach. Tests confirmed that the app could identify trip destinations based on user input.

The study emphasizes the need for continual data validation, especially in areas with challenging geographical features that compromise GPS accuracy. Further improvements to the OBA and TTT systems are necessary to ensure comprehensive data collection and more effective congestion reduction strategies.

The approach used in this study of using mobile data for urban transportation planning can serve as a model for other cities facing similar traffic and congestion challenges. The knowledge gathered from this study could be applied to different urban settings to improve mobility.

Recommendations

In future updates, the TTT app and related resources should focus on improving GPS accuracy, especially in areas with difficult terrain or poor signal reception. This can be achieved by utilizing advanced GPS technology or by enhancing location accuracy using additional data sources such as Wi-Fi or Bluetooth.

It is crucial to streamline the process of collecting and validating user trip data. To reduce errors, such as missing or duplicate trip data, future versions of the OBA and TTT apps should include automatic data cleaning tools and algorithms. This will improve the accuracy of the collected information.

Future studies should increase user participation and engagement to acquire more thorough and representative data. This might be done by working with regional transportation authorities, offering incentives for using the app, and conducting public outreach campaigns to promote the widespread use of these data collection instruments.

Transportation planners should consider integrating data from transportation apps with other city programs and public transportation networks. By combining crowdsourced data and existing infrastructure information, they can gain a comprehensive understanding of urban mobility. This can help reduce congestion and improve traffic flow in cities.

It is essential to work closely with transportation officials and urban planners to ensure that the data collected by these apps is valuable and aligns with the city's goals for reducing traffic, introducing new transportation modes, and optimizing public transit.

It is important to start implementing continuous monitoring from the beginning. This will help in detecting any data variations and taking corrective actions promptly. Carrying out these initial activities is essential to ensure the reliability of the data throughout the project.

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Appendix A

Table A.1. Information Manually Recorded "Ground Truth Data"

GT_Collector	GT_TourID	GT_TripID	GT_Mode	GT_Mode_Original	GT_Date	GT_TimeOrig	GT_TimeOrigMinuteRounded	GT_TimeZone	GT_LatOrig	GT_LonOrig	GT_LocationOrig	GT_TimeDest	GT_TimeDestMinuteRounded	GT_LatDest	GT_LonDest	GT_LocDest
Giraldo	GIR_1	1	WALKING	WALKING	6/9/2022	9:57:00 AM	0	America/PuertoRico	18.216369	-67.148244	Location 1	10:15:00AM	0	18.214297	-67.141231	Location 2
Giraldo	GIR_1	2	STILL	WALKING	6/9/2022	10:15:00AM	0	America/PuertoRico	18.214297	-67.141231	Location 2	10:21:00AM	0	18.215122	-67.139288	Location 3
Giraldo	GIR_1	3	STILL	WALKING	6/9/2022	10:21:00AM	0	America/PuertoRico	18.215122	-67.139288	Location 3	10:43:00AM	0	18.214297	-67.141231	Location 2
Giraldo	GIR_1	4	WALKING	STILL	6/9/2022	10:43:00AM	0	America/PuertoRico	18.215122	-67.1392288	Location 2	11:05:00AM	0	18.215136	-67.139379	Location 4
Giraldo	GIR_1	5	IN_VEHICLE	IN_VEHICLE	6/9/2022	11:05:00AM	0	America/PuertoRico	18.214297	-67.139379	Location 4	11:51:00AM	0	18.214585	-67.141197	Location 5
Giraldo	GIR_1	6	WALKING	WALKING	6/9/2022	11:51:00AM	0	America/PuertoRico	18.214585	-67.141197	Location 5	1:15:00 PM	1	18.216369	-67.148244	Location 1
Giraldo	GIR_2	1	WALKING	WALKING	8/9/2022	9:38:00 AM	0	America/PuertoRico	18.214297	-67.141231	Location 2	9:47:00 AM	0	18.215122	-67.139288	Location 3
Giraldo	GIR_2	2	STILL	WALKING	8/9/2022	9:47:00 AM	0	America/PuertoRico	18.215122	-67.139288	Location 3	10:36:00AM	0	18.215136	-67.139379	Location 4
Giraldo	GIR_2	3	IN_VEHICLE	IN_VEHICLE	8/9/2022	10:36:00AM	0	America/PuertoRico	18.215136	-67.139379	Location 4	11:22:00AM	0	18.214585	-67.141197	Location 5
Giraldo	GIR_2	4	WALKING	WALKING	8/9/2022	11:22:00AM	0	America/PuertoRico	18.214585	-67.141197	Location 5	11:32:00AM	0	18.214297	-67.141231	Location 2
Giraldo	GIR_3	1	WALKING	WALKING	12/9/2022	8:29:00 AM	0	America/PuertoRico	18.214297	-67.141231	Location 2	8:32:00 AM	0	18.215122	-67.139288	Location 3
Giraldo	GIR_3	2	STILL	WALKING	12/9/2022	8:32:00 AM	0	America/PuertoRico	18.215122	-67.141231	Location 3	9:00:00 AM	0	18.214297	-67.141231	Location 2
Giraldo	GIR_3	3	STILL	WALKING	12/9/2022	9:00:00 AM	0	America/PuertoRico	18.214297	-67.141231	Location 2	9:12:00 AM	0	18.215136	-67.139379	Location 4
Giraldo	GIR_3	4	IN_VEHICLE	IN_VEHICLE	12/9/2022	9:12:00 AM	0	America/PuertoRico	18.215136	-67.139379	Location 4	10:01:00AM	0	18.214641	-67.141018	Location 6
Giraldo	GIR_3	5	IN_VEHICLE	IN_VEHICLE	12/9/2022	10:01:00AM	0	America/PuertoRico	18.214641	-67.141018	Location 6	10:29:00AM	0	18.214641	-67.141018	Location 7
Giraldo	GIR_3	6	IN_VEHICLE	IN_VEHICLE	12/9/2022	10:29:00AM	0	America/PuertoRico	18.214641	-67.141018	Location 7	10:34:00AM	0	18.214297	-67.141231	Location 2
Giraldo	GIR_4	1	WALKING	WALKING	09/13/2022	10:49:00AM	0	America/PuertoRico	18.215122	-67.139288	Location 3	10:52:00AM	0	18.214297	-67.141231	Location 2
Giraldo	GIR_4	2	STILL	WALKING	09/13/2022	10:52:00AM	0	America/PuertoRico	18.214297	-67.141231	Location 2	11:05:00AM	0	18.215136	-67.139379	Location 4
Giraldo	GIR_4	3	IN_VEHICLE	IN_VEHICLE	09/13/2022	11:05:00AM	0	America/PuertoRico	18.215136	-67.139379	Location 4	11:53:00AM	0	18.214641	-67.141018	Location 6
Giraldo	GIR_4	4	IN_VEHICLE	IN_VEHICLE	09/13/2022	11:53:00AM	0	America/PuertoRico	18.214641	-67.141018	Location 6	12:23:00PM	0	18.214641	-67.141018	Location 8
Giraldo	GIR_4	5	IN_VEHICLE	IN_VEHICLE	09/13/2022	11:23:00AM	0	America/PuertoRico	18.214641	-67.141018	Location 8	1:11:00 PM	0	18.214641	-67.141018	Location 6
Giraldo	GIR_4	6	WALKING	WALKING	09/13/2022	1:11:00 PM	0	America/PuertoRico	18.214641	-67.141018	Location 6	1:44:00 PM	0	18.216369	-67.141018	Location 1
Giraldo	GIR_4	7	WALKING	WALKING	09/13/2022	1:44:00 PM	0	America/PuertoRico	18.216369	-67.148244	Location 1	2:43:00 PM	0	18.214297	-67.141231	Location 2
Giraldo	GIR_4	8	WALKING	WALKING	09/13/2022	2:43:00 PM	0	America/PuertoRico	18.214297	-67.141231	Location 2	2:46:00 PM	0	18.215122	-67.139288	Location 3
Giraldo	GIR_5	1	WALKING	WALKING	09/15/2022	8:19:00 AM	0	America/PuertoRico	18.216369	-67.148244	Location 1	9:08:00 AM	0	18.214297	-67.141231	Location 2
Giraldo	GIR_5	2	STILL	WALKING	09/15/2022	9:08:00 AM	0	America/PuertoRico	18.214297	-67.141231	Location 2	9:11:00 AM	0	18.215136	-67.139379	Location 4
Giraldo	GIR_5	3	IN_VEHICLE	IN_VEHICLE	09/15/2022	9:11:00 AM	0	America/PuertoRico	18.215136	-67.139379	Location 4	9:58:00 AM	0	18.214641	-67.141018	Location 6
Giraldo	GIR_5	4	IN_VEHICLE	IN_VEHICLE	09/15/2022	9:58:00 AM	0	America/PuertoRico	18.214641	-67.141018	Location 6	10:00:00AM	0	18.214641	-67.141018	Location 9
Giraldo	GIR_5	5	IN_VEHICLE	IN_VEHICLE	09/15/2022	10:00:00AM	0	America/PuertoRico	18.214641	-67.141018	Location 9	10:59:00AM	0	18.214641	-67.141018	Location 6
Giraldo	GIR_5	6	IN_VEHICLE	IN_VEHICLE	09/15/2022	10:59:00AM	0	America/PuertoRico	18.214641	-67.141018	Location 6	11:00:00AM	0	18.214641	-67.141018	Location 10
Giraldo	GIR_5	7	IN_VEHICLE	IN_VEHICLE	09/15/2022	11:00:00AM	0	America/PuertoRico	18.214641	-67.141018	Location 10	12:16:00PM	0	18.214641	-67.141018	Location 6
Giraldo	GIR_5	8	WALKING	WALKING	09/15/2022	12:16:00PM	0	America/PuertoRico	18.214641	-67.141018	Location 6	12:51:00PM	0	18.216369	-67.148244	Location 1

The National Institute for Congestion Reduction (NICR) will emerge as a national leader in providing multimodal congestion reduction strategies through real-world deployments that leverage advances in technology, big data science and innovative transportation options to optimize the efficiency and reliability of the transportation system for all users. Our efficient and effective delivery of an integrated research, education, workforce development and technology transfer program will be a model for the nation.

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