



NATIONAL CENTER FOR TRANSPORTATION SYSTEMS PRODUCTIVITY AND MANAGEMENT

GRTA/GDOT Real-Time Tracking and Choice Data

Contract # DTRT12GUTC12 with USDOT Office of the Assistant Secretary for Research and Technology (OST-R)

Final Report

May 2017

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.: FHWA-GA-17-1225	2. Government Accession No.:	3. Recipient's Catalog No.: N/A	
4. Title and Subtitle: Real-time Tracking and Choice Data		5. Report Date: May 2017	
		6. Performing Organization Code:	
7. Author(s): Randall Guensler, Ph.D.		8. Performing Organ. Report No.: 12-25	
9. Performing Organization Name and Address: Georgia Transportation Institute/UTC Georgia Institute of Technology 790 Atlantic Drive Atlanta, GA 30332-0355		10. Work Unit No.: N/A	
		11. Contract or Grant No.: PI# 0011746 (RP 12-30)	
12. Sponsoring Agency Name and Address: Georgia Department of Transportation Office of Research 15 Kennedy Drive Forest Park, GA 30297-2534		13. Type of Report and Period Covered: Final; May 2011 – September 2014	
		14. Sponsoring Agency Code: N/A	
15. Supplementary Notes: Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.			
16. Abstract: The primary goal of this project was to demonstrate that smartphone travel activity monitoring systems that collect second-by-second data are capable of providing more reliable freeway and arterial travel time data than machine vision systems that collect spot-speed data. The report outlines project coordination with state agencies, app functions, and deployment efforts. The research team was required by the participating agencies to prepare outreach new materials, undertake additional human subject review, modify the look and feel of the app, release the app through the official Google beta testing service, and then release of the app through the Google Play Store. The team was also not allowed to contact agency express bus customers or tollway users directly to facilitate recruitment, either by mail or in person at the transit stops. Instead, the team was required to rely upon announcement of app availability through the agency blogs and e-mail newsletters. In all, three volunteers were obtained through the allowed recruitment mechanism. Participant recruitment efforts conducted in coordination with participating agencies was not successful; therefore the primary goals and objectives of the project could not be completed. Hence, this report describes the activities, summarizes lessons learned, and discusses future recruitment plans.			
17. Key Words: Travel Monitoring		18. Distribution Statement: No Restriction	
19. Security Classification (of this report): Unclassified	20. Security classification (of this page): Unclassified`	21. Number of Pages: 28	22. Price: N/A

GDOT Research Project No. RP 12-25
Project Report (Final)

Real-Time Tracking and Choice Data

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May 2017

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Executive Summary

The primary goal of this project was to demonstrate that smartphone-based applications that track second-by-second vehicle activity are capable of providing more reliable freeway and arterial travel time data than machine vision and other systems that collect spot-speed data. This project was also designed to monitor and assess real-time high-occupancy toll (HOT) lane corridor performance and GRTA Xpress Bus performance by monitoring Xpress bus riders with the smartphone app.

The team proposed to recruit 80 regular HOT corridor users, including Xpress bus riders, I-85 HOT lane users, and drivers who regularly use the I-85 general purpose lanes. The plan was to deploy the Commute Warrior application on the Android smartphones of these volunteers to collect second-by-second vehicle activity data on the I-85 HOT corridor and compare instrumented vehicle data with Georgia NaviGator ITS data and other data. The comparison of monitored second-by-second corridor traverse travel times with travel time estimates derived from NaviGator machine vision spot speed data would be used to assess the potential benefits of more widespread deployment of the Commute Warrior App throughout the region.

Recruitment of volunteers was coordinated directly with Georgia Regional Transportation Authority (GRTA) and the State Road and Tollway Authority (SRTA). The research team was required by the participating agencies to prepare outreach new materials, undertake additional human subject review, modify the look and feel of the app, release the app through the official Google beta testing service, and release of the app through the Google Play Store. The team was not allowed to contact GRTA Xpress bus riders or SRTA tollway users to facilitate recruitment, either by mail or in person at the transit stops. The team was required to rely upon agency announcements of app availability through their blogs and e-mail newsletters. In all, three volunteers were obtained through the allowed recruitment mechanism. Participant recruitment efforts conducted in coordination with participating agencies was not successful and resources were not available for a direct mail campaign to all commutershed residents; therefore the primary goals and objectives of the project could not be completed.

This report describes the activities and data sources, summarizes lessons learned, and outlines future recruitment plans. Although this project did not result in useful data for comparative analysis, the Commute Warrior Android app is being deployed in 2017 through a Department of Energy ARPA-E project. More than \$120,000 has been made available in the ARPA-E project for volunteer recruitment. Hence, data that would have been collected to perform the originally-proposed comparative research should become available by late 2017. The team still plans to perform the originally-proposed comparative analytical work and publish the results in a transportation journal.

1 Introduction

The primary goal of the HOT lanes constructed on the I-85 corridor was provide a more reliable and faster travel option through the congested corridor for express buses, vanpools, and 3-person carpools. This goal was to be accomplished while simultaneously ensuring that conditions did not degrade for users of the general purpose lanes. In the absence of an instrumented fleet that can be monitored from origin to destination, corridor travel times must generally be estimated using spot speed data collected by the intelligent transportation system at points along the corridor. With sufficiently accurate and temporally resolved spot speed data on the corridor, reliable corridor travel times can be estimated. Although accurate and reliable speed data are available for some specific locations on the corridor, the data are neither continuous nor reliable through the corridor (see Guensler, et al., 2013). Furthermore, there is a significant amount of weaving and vehicle interaction that occurs within each section that is not represented in the spot speed data (Toth, et al., 2014). Given the nature of congestion, it is difficult to know what happens to vehicle speeds between the locations where speed data are available, especially when these locations are separated by significant distances or data are missing from expected locations. Analysts have to assume that changes in spot speeds at multiple locations in the corridor serve as valid surrogates for changes in corridor travel time and reliability. Hence, the Georgia NaviGator data on this corridor are problematic and cannot be used to reliably estimate corridor travel times at the accuracy sufficient to assess HOT lane performance impacts on general purpose lanes. Continuous second-by-second traces from the Commute Warrior app could help overcome these problems and might also be used to correct counts from machine vision systems.

The primary goals of this project were: 1) to demonstrate the capabilities of smartphone systems to provide more reliable freeway and arterial travel time data than currently provided by NaviGator machine vision spot speed measurements, and 2) to facilitate the monitoring and analysis of real-time high-occupancy toll (HOT) lane corridor performance and GRTA Xpress Bus performance. The team proposed to recruit 80 regular HOT corridor users, including Xpress bus riders, I-85 HOT lane users, and drivers who regularly use the I-85 general purpose lanes. Recruitment of volunteers would be coordinated directly with Georgia Regional Transportation Authority (GRTA) and the State Road and Tollway Authority (SRTA). The team would deploy the Commute Warrior application on the Android smartphones of these volunteers to collect second-by-second vehicle activity data on the I-85 HOT corridor. The team proposed to compare monitored second-by-second corridor traverse travel times with travel time estimates derived from NaviGator machine vision spot speed data to assess the potential benefits of more widespread deployment of the Commute Warrior App throughout the region. The team also proposed to conduct focus groups with participants to gather information regarding the potential impacts of real-time data on their use of the HOT lanes and GRTA Xpress bus services.

The team proposed to monitor the activity of the 80 volunteers for six months to demonstrate system capabilities. The team proposed to compare monitored second-by-second corridor traverse travel times from Commute warrior with travel time estimates derived from NaviGator machine vision spot speed data. In addition, the team planned to put these corridor travel times in the context of complete total door-to-door commute times to assess whether differences in corridor travel times were still significant in the context of total home-to-work commute time.

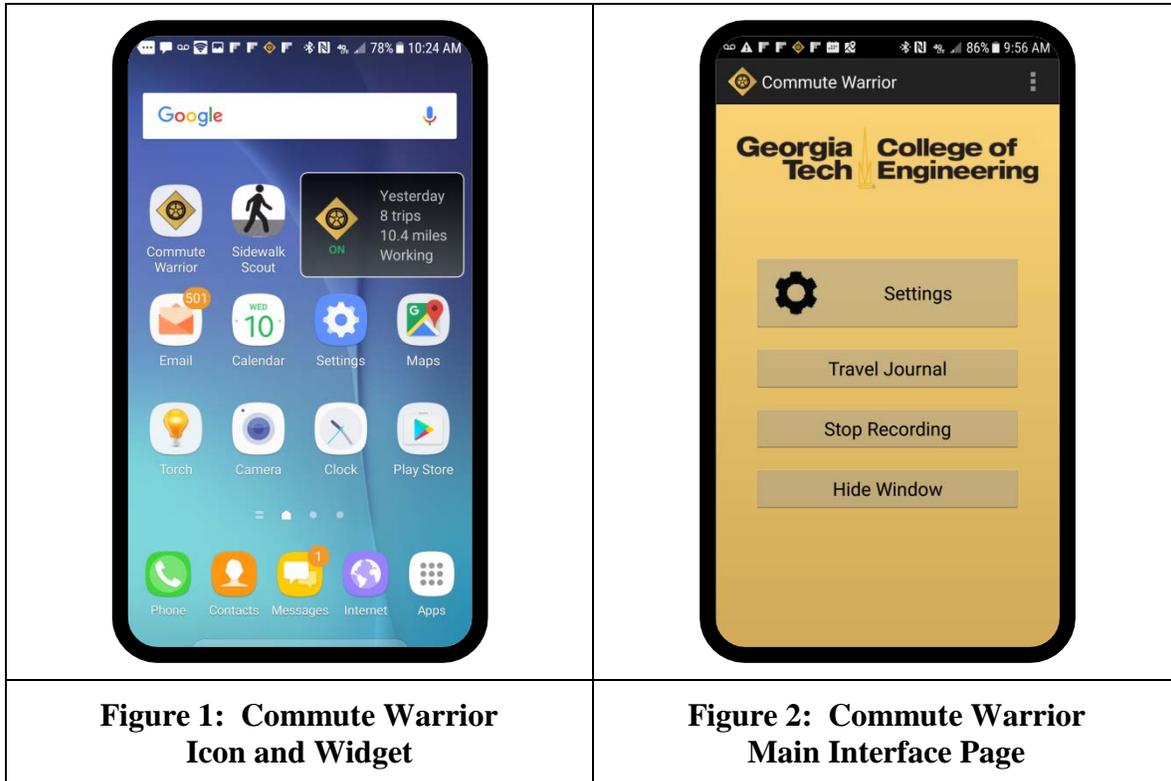
2 Commute Warrior Travel Monitoring System

Since 1996, Georgia Tech researchers have developed a variety of technologies for monitoring high-resolution vehicle activity and real-time travel behavior. The research focus of monitoring and equipment deployment has historically been to assess travel behavior, energy, emissions, and safety. In these various projects, the researchers monitored more than two million second-by-second trips, collected from 385 vehicles over 3-years in Commute Atlanta study, and from 500 Cobb County school buses over one year. Both of these major efforts involved the development and installation of power-connected equipment in vehicles, which significantly elevates project costs. Recent design improvements, and integration of more advanced GPS chipsets, has improved the quality of speed and position data collected by smartphones. Hence, the research team developed the Commute Warrior Android app for collecting and transmitting second-by-second data for use in travel behavior, energy, and emissions research. Server-side data management routines are coupled with advanced statistical tools, allowing researchers to assess personal and vehicle activity and changes in travel patterns over time.

The Commute Warrior Android app operates in background and does not require any ongoing interaction with the user. In 2013, battery draw was reasonable on a Samsung Galaxy S4 phone, and has remained reasonable through the Galaxy S7. Power draw is such that a typical user does need to recharge their phone in the early evening hours. Power consumption is dominated by GPS satellite search activity. A number of algorithms employed in the app put the app in a sleep mode when the phone is not in motion. During this project, the team explored the implementation of an iOS version of the app for iPhones. However, the team could not overcome the iOS limitation that prevents the third party Apple apps from operating continuously in background. The team created a communications version of the app in iOS that included the data communications elements for testing (no other app features). However, the iOS app was routinely shut down by the operating system and had to be manually restarted, creating an insurmountable user burden. The only solution that the team could identify to overcome the iOS limitation was to spoof the operating system into thinking that a music subscription service was running, which would have violated the iOS user agreement and would not be allowed by Georgia Tech. The remainder of this chapter describes the features of the Android app, the modifications made for this project, and app availability.

2.1 *Commute Warrior Android App*

The Commute Warrior app icon and widget (Figure 1, upper row left and right) lead to the main interface page (Figure 2). The optional widget indicates the data recording status and number of trips made yesterday. The main interface page (Figure 2) links to the settings page, links to a travel journal calendar page, allows the user to stop data recording (for privacy), allows the user to restart data collection if data collection is currently off (same button), and allows the user to hide the window (the app continues to run in background).



From the settings menu (Figure 3), the user can choose to operate on battery power and external power or only on external power. This option is provided for users who may only want to record their commute travel, while their phone is powered by a 12V outlet in the vehicle. The minimum battery level setting is the battery level at which point the app will hibernate, stop using satellites, and stop collecting data to conserve user battery life. This feature allows morning commute data to be collected while ensuring that battery draw does not exceed user expectations. Users can also choose to send and receive data via their cellular data plan or to operate on Wi-Fi only.

The travel journal calendar page is illustrated in Figure 4. This page opens from the main interface page and allows users to select a date for which they want to review their travel. A traditional calendar displays the days for which trip data were recorded (when the cell is highlighted in green). The user can page backward and forward by month and select any calendar date to view the daily trip journal for that day (Figure 5). Each daily trip journal page provides a list of all trips recorded for that date. For each trip, the app table displays the trip date/time, duration, and distance. The survey icon on the far right leads to a travel survey to collect trip purpose information. Users can select the map icon on the left to play back the trip on the trip viewer page (Figure 6).

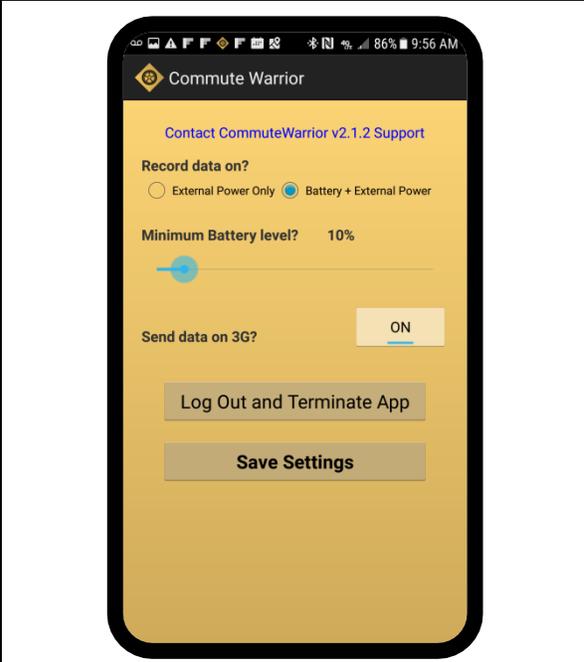


Figure 3: Commute Warrior Settings Page

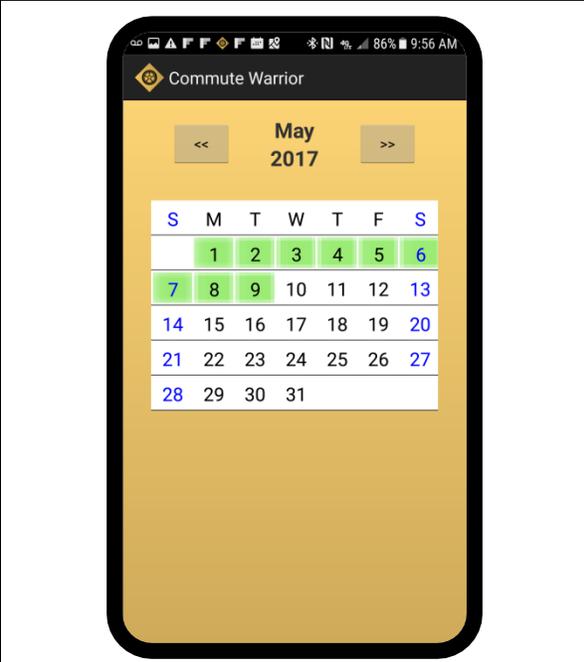


Figure 4: Commute Warrior Travel Journal Calendar Page

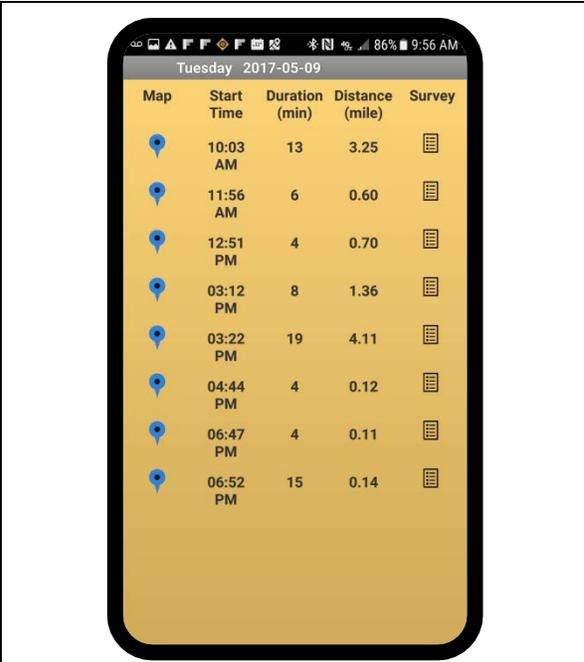


Figure 5: Commute Warrior Daily Trip Journal Page

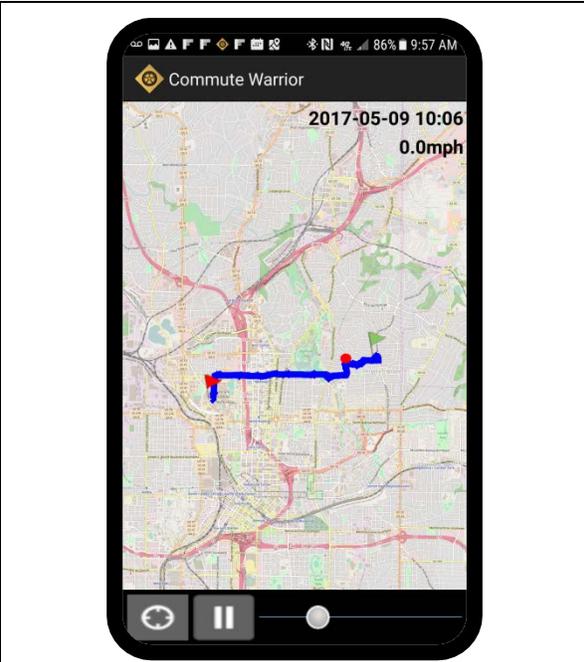
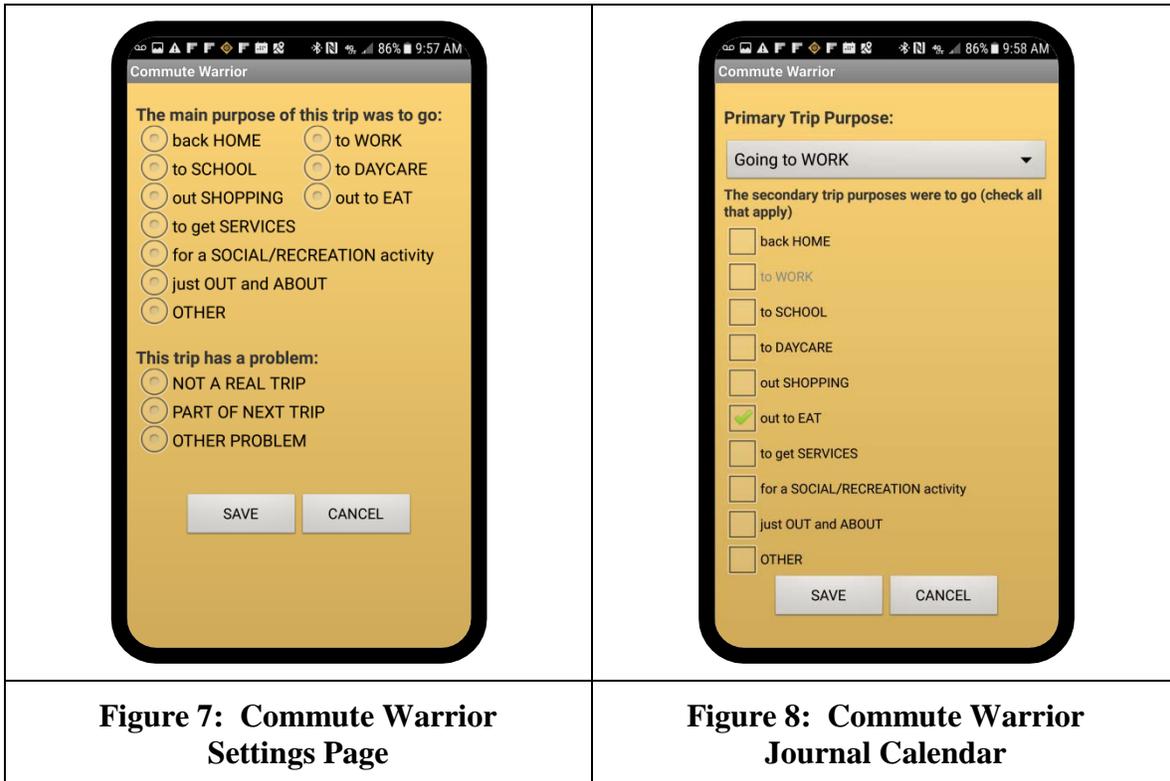


Figure 6: Commute Warrior Trip Viewer Page

If the user selects the travel survey icon, two pages are presented to collect the primary and secondary trip purpose information. On the primary purpose page (Figure 7), the user specifies the primary reason for the trip (e.g., going to work). The secondary trip purpose page (Figure 8) appears immediately after the primary purpose is entered. This page is used by the traveler to record additional reasons for making the trip, or incidental activities undertaken along the way. For example, a trip to work where the user stopped for coffee would be recorded with a primary trip purpose of going to work and a secondary trip purpose of going out to eat. Users can select multiple secondary trip purposes and easily change the primary trip purpose. Users can also report data errors. The Commute Warrior Web interface provides a long form survey in which users can specify other trip data, such as number of passengers and reasons for taking a route.



Vehicle data are collected second-by-second (Figure 9), and a playback of trips over time can help researchers better understand household travel behavior (Figure 10).

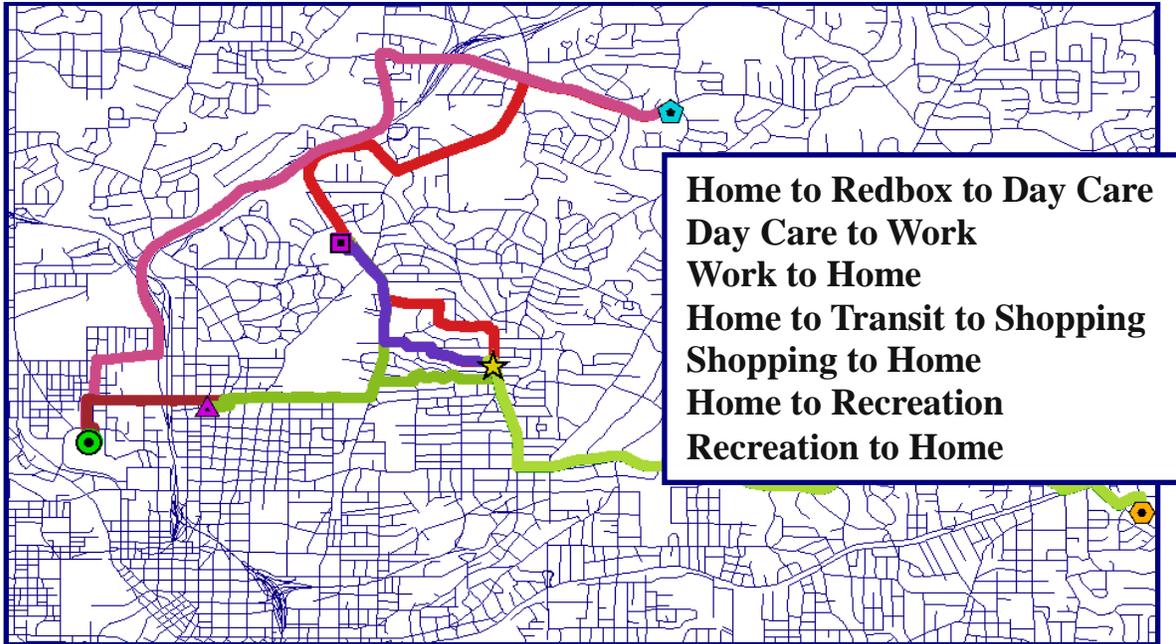


Figure 9: Vehicle Traces Provided by Second-by-second Travel Monitoring

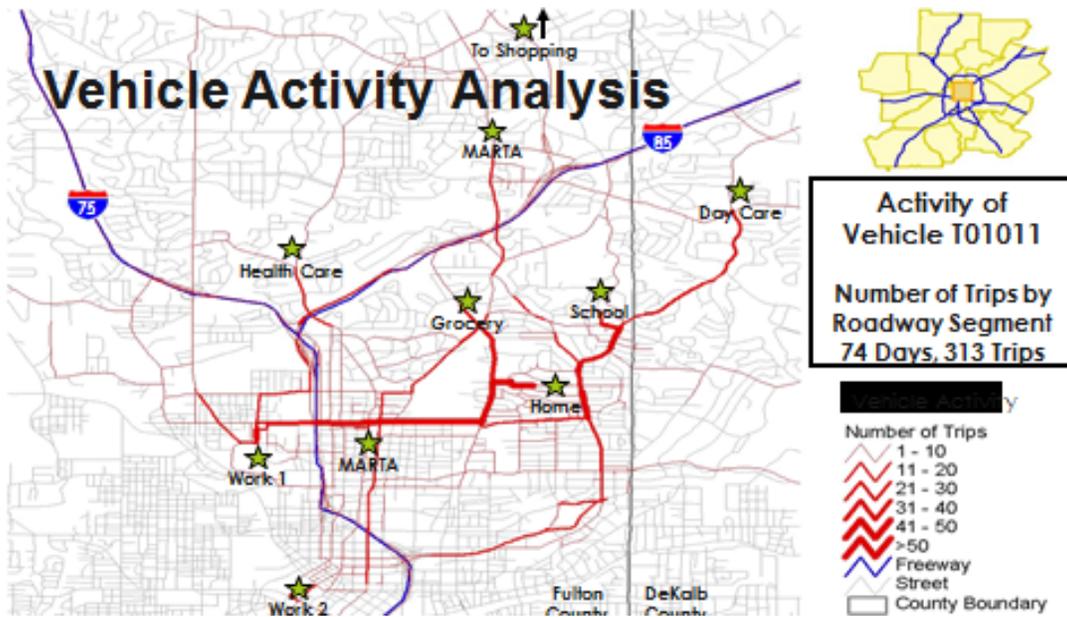


Figure 10: Travel Patterns Revealed by Continuous Travel Monitoring

2.2 Commute Warrior Android App Availability

In 2013 and 2014, the initial rollout of the Commute Warrior app was handled via direct distribution of the compiled app as an e-mail attachment and posting of a compiled app to an official Georgia Tech website (<http://transportation.ce.gatech.edu/commutewarrior>). It is relatively easy for any user to directly install an .apk file on their Android phones. However, this does require the user to acknowledge that the app is not distributed through the Google Play Store and to click on an Android installation button indicating that they are willing to temporarily override Android settings on their phone to allow an app to be installed manually. While the team's approach of direct distribution worked fine for initial beta testing, the initial thought that consumers would be willing to trust an app distributed through an official Georgia Tech website was proven over time to be untrue, given that so few volunteers downloaded the app from the website. Furthermore, the State agencies (GRTA and SRTA) were not willing to have their names associated with an app that was not distributed through an official Google app outlet. The online app that was originally placed online has since been replaced by a link to the app in the Google Play Store. However, before reaching that stage, the team distributed the app through Google's beta testing outlet for a number of months.

To address agency concerns, the second step taken in app deployment was to launch an official beta version of the app through Google's official alpha and beta testing service. This beta release and testing service is now managed via the Google Play Developers Console (<https://accounts.google.com/signin>). However, when the app was initially deployed for the project, the beta testing service allowed developers to run beta testing with a large group of individuals, without appearing on the Google Play Store (which is now supported by the developer's Console). Beta testers were managed by user e-mail address and users had to sign up on the site to download the app. An opt-in web address was made available to agency beta testers. However, the overall user experience associated with interacting with the Google website beta testing site, signing up, obtaining and installing the app, and interacting via e-mails was a complete disappointment. After experiencing the beta testing service, agency staff members understandably elected not to encourage their customers to sign up for the app through the beta testing service. The team had to move the app into final form and release the app on the Play Store. Modifying the materials for distribution through Google's Beta Testing site was unsuccessful.

Georgia Tech faced some significant internal hurdles in preparing the app for official Play Store distribution. The primary impediment was the lack of infrastructure support within the University for Android and iOS app deployment. Officially, all university-developed apps are institutional property that must be centrally managed and 'signed' (with the single official university developer ID) by the Office of Information Technology. At the time of this project there was no university official in charge of testing, approving, and submitting apps to the Google Play Store or Apple App Store. This project played an important role in the university's technology development, in that we now do have an assigned official hired in 2016 to support these activities. The Commute Warrior Android only became available through the Google Play Store at the end of the study. The latest version of the app can be found in the Google Play Store (Figure 11) at: <https://play.google.com/store/apps/details?id=com.gatech.cw3>. The Commute Warrior app will be used in widespread Atlanta regional deployment in a Department of Energy ARPA-E project known as TRANSNET-Atlanta.

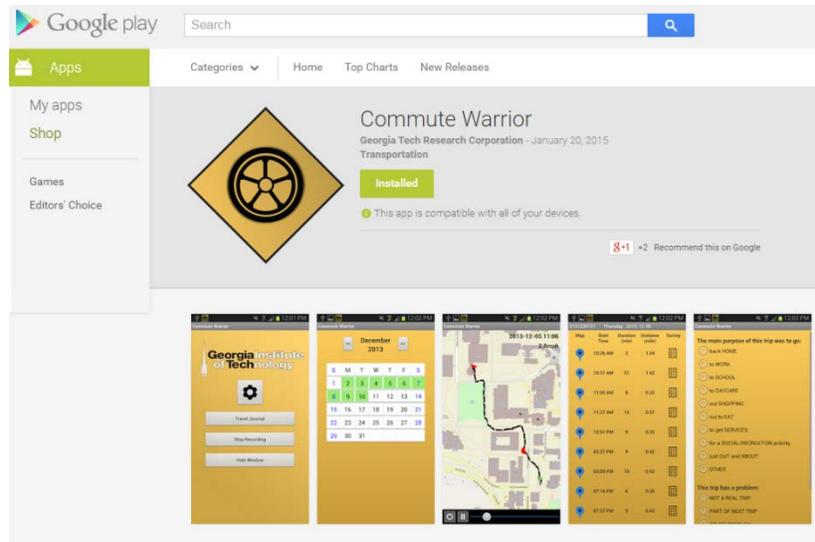


Figure 11: Current Google Play Commute Warrior Page

The Commute Warrior app collects second-by-second speed and position data from the Android phone while operating continuously in background. The app is fully functional and is currently available on the Google Play Store. However, as will be described in the next chapter, the initial rollout of the Commute Warrior app for this project via direct distribution on the Georgia Tech website, coupled with GRTA and SRTA online outreach, was not successful in recruiting participants into the project.

3 App Deployment

GRTA and SRTA staff required the research team to meet a number of conditions before agency staff would be willing to have the agency names associated with the research project and app deployment. At the time the project began, SRTA staff was in the process of working with a consultant to update their toll app. Based upon agency customer experience with their existing app, the agency would require the Georgia Tech team to modify the look and feel of the Commute Warrior user experience (UX) in response to agency staff input. When the project began, the Commute Warrior was being distributed by website link. Users downloaded the app from the Georgia Tech website (or by e-mail attachment) and installed the app on their Android phones. However, agency staff did not want the app to be distributed outside of Google's official app distribution processes. As discussed later, the team was first required to publish the app through the official Google beta testing service (which turned out to be very problematic from a user experience perspective). GRTA also required that all consent forms be accessible from within the app and by e-mail delivery, not just through the app website. This was handled through an app modification and linkage to a web mail server created for the project. The agencies required the development of a splash page on installation indicating to users that Commute Warrior was running in background, recording activity data, and that data are processed at night by the server, meaning that details about today's trips are made available the following day. Finally, the agencies required the team to develop a variety of customer outreach materials to be made available online for interested GRTA and SRTA customers. The outreach materials needed to include:

- Statement of community benefits
- Statement of user benefits and forthcoming systems
- Installation instructions
- Written operating instructions
- PPT operating instructions
- Links to papers and projects
- The Google site link

All materials described above were required to undergo the human subjects review process managed by the Institutional review Board, which took a couple of months. The team spent a considerable amount of time and resources associated with meeting all of the conditions outlined above; however, all of the requirements were ultimately met, and agency staff was satisfied that the agency names could be associated with the app for deployment in the commutershed. All of the materials described above that were prepared for agency approval can be found on the Commute Warrior website, although some materials have been updated since the initial rollout (<http://transportation.ce.gatech.edu/commutewarrior>).

3.1 Initial Deployment

The initial deployment announcement was handled by the agency staff through their blog and e-mail newsletter in the first quarter of 2014. The announcement prepared by GRTA staff is provided below:

Wanted: Commute Warriors

One of the best ways to help improve Atlanta's traffic and your commute options is to help researchers gather data about your travel patterns.

There's currently an opportunity for *Xpress* riders to do just that. Georgia Tech's Civil Engineering Drive Lab is looking for volunteers. You'll install an app that runs in the background of your mobile device and records data about your trip, such as speed and total distance. This kind of information is valuable for helping engineers analyze congestion patterns and improve the transportation planning process.

If you're interested in participating, [visit their website here](#). Participation is voluntary and you can opt out at any time by uninstalling the app.

The blog was relatively new and had very few hits according to the agency. However, the e-mail newsletter was sent out to about 3,500 GRTA customers. Despite the wide circulation of the e-mail newsletter, the team was only able to recruit three users. A fourth user wanted to sign up but did not have an Android phone. Given the low signup rate experienced, the team met with the agencies to pursue alternative recruitment arrangements.

3.2 Secondary Deployment Efforts

At this point in the project, the team asked the agencies to partner on outreach again to the GRTA *Xpress* Bus commuters and SRTA customers. Given the low response rates from the initial recruitment, the team concluded that the best recruitment approach would be to develop project information and contact cards containing a detailed description of the research and the Play Store app, and to hand these cards directly to *Xpress* bus customers. In this manner, team members could describe the research effort to bus riders at the park-and-ride stops and encourage them to download the app from the Play Store and participate in the study. The team also proposed sending a mailer directly to the homes of registered HOT lane users.

Although the team communicated that we "...do not think we are going to get much traction without getting something into the hands of the riders", the agencies would not approve direct customer contact for this research project. The basic problem was that if the agency provided Georgia Tech researchers with permission to directly contact *Xpress* bus or HOT lane customers, they would be in a position where they would have to potentially approve similar requests from other parties. "We try to avoid allowing third parties to hand out flyers to our customers in order to prevent our customers from commercial solicitation and avoid confusion on what messages are coming from/endorsed by us vs. other interests (Markham, 2013). Similarly, the agencies would not provide permission to send mail directly to their customers.

The team ultimately moved the final app into the Google Play Store through the Georgia Tech process (which took months to navigate). However, the team could not connect GRTA and SRTA customers to the app without agency permission. Funding was not available to recruit via alternative means and no funding was available or allowed to be used as participation incentives. Given the lack of participants in the study, the team was unable to collect the data required to perform the comparative analyses and to conduct the four customer focus groups to assess their potential use of real-time information and the potential impact that such data may have on their use of HOT lane and express bus services.

The team was able to collect and archive HOT lane general purpose lane performance data from the GDOT and SRTA intelligent transportation systems. The team was also able to establish the commutershed demographics for use in future analyses. The vehicle activity and demographics data sets facilitated the development of two dissertations of interest to the sponsoring agencies (Khoeini 2014; Sheikh, 2015). These data also contributed to two related publications on HOT lane performance (Sheikh, et al., 2014; Sheikh and Guensler; 2014). Proving that these data sources were valid also ultimately contributed to the completion of a separate GDOT project (Guensler, et al., 2016).

4 I-85 Corridor Operations Data

When the project was initially proposed, the team envisioned only using the data from the GDOT NaviGator intelligent transportation system (ITS). However, as the team prepared for implementation, and as reported in the HOV-to-HOT analytical work (Guensler, et al., 2013), NaviGator data were not always continuous and reliable through the corridor. Problems with data discontinuity (sporadic equipment outages), calibration, and perhaps to some extent the nature of data processing algorithms make using the NaviGator data to estimate traverse times somewhat difficult. Given that Atlanta is significantly expanding managed lanes systems in the region over the coming decades, and given that RFID tag readers have been placed in general purpose lanes, a new source of vehicle traverse speed data may become more widespread. Given that the team already had already arranged access to SRTA's real-time transponder readings data feed for the I-85 corridor, which was being used to some extent in the pre-post HOV-to-HOT analysis, the team also adapted this data source for this project. This data source proved useful for a variety of follow-on projects. Sheikh's dissertation (2015) provides an overview of the data sources and the processing methods used to construct the analytical data set that would ultimately be used across multiple research projects.

4.1 Georgia Tech Data Warehouse and GDOT NaviGator Data

Georgia NaviGator data serve as public baseline performance data for Atlanta's freeway corridors. The GDOT Traffic Management Center (TMC) uses closed-circuit pan-tilt-zoom (PTZ) and fixed-view cameras for incident identification and quick response dispatch of Highway Emergency Response Operators (HERO) units. Traffic volumes and speeds for the I-85 HOT corridor are automatically derived by processing the video from fixed camera locations using machine vision software. Video-based machine vision systems are connected to monitoring stations. Changes in pixel colors within the video field of view are used to detect the passage of each vehicle. Establishing two detection zones at a known distance apart provides an estimate of speed data.

Fixed-view camera clusters for machine vision processing are located about every 1/3 mile along the corridor. Cameras are usually mounted on 60' poles and pointed downward at the traffic. The location of the cameras relative to the lane monitored can significantly impact the accuracy and reliability of the data being collected. The accuracy of speed and volume data from machine vision systems varies significantly by location, as a function of video resolution, light level, field of view, calibration, camera height and angles impacting vehicle occlusion, percentage of large trucks impacting occlusion, road curvature, etc. (Grant, et al., 1999). Calibration efforts must be undertaken on a regular basis to ensure values remain within $\pm 10\%$. More information regarding data quality assurance procedures, data accuracy, and the use of NaviGator data in research is provided in Guensler, et al. (2013).

The volume and speed data are archived in real time from the Georgia NaviGator system for more than 220 miles of freeway in Metro Atlanta. Figure 12 provides an overview of the NaviGator system (Guensler, et al., 2013). GDOT NaviGator system data include: traffic volumes in the managed lane, traffic volumes in each general purpose lane, vehicle speeds in the managed lane, and vehicle speeds in each general purpose lane (Guensler, et al., 2013). Figure

13 illustrates the web interface provided by GDOT for the public to access camera views and visualize congestion conditions on the roadway.



Figure 12: Overview of the NaviGator System

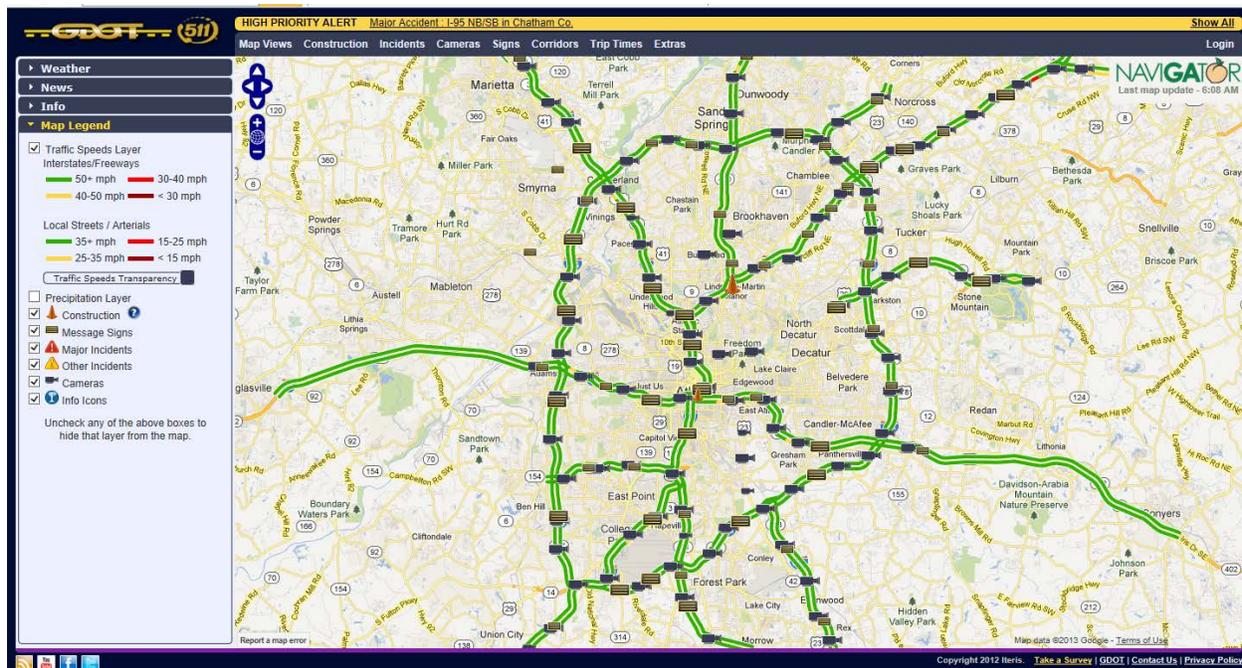


Figure 13: NaviGator Web Interface

It should be noted that traffic vehicle volume counts collected by SRTA’s monitoring system (separate from the GDOT monitoring system) for the HOT lane are more accurate than the counts from the NaviGator system. This is because a laser detection system is used to trigger RFID tag reads (Guensler, et al., 2013).

The PTZ cameras located along the corridor can also be used to collect traffic count data. Such data have been employed in the assessment of HOT lane weaving and effective capacity analysis (Guin, et al., 2008; Toth, et al., 2014). Cameras locations along the corridor that are at a high-enough resolution to count vehicles and weaving activity are identified in Figure 14. The areas between the yellow and the white lines (in the donut) in Figure 14 are the zones in which vehicles can be tracked using Georgia Tech traffic monitoring software (Guensler, et al., 2013). The yellow line has a radius of 400', while the white line has a radius of 1000'. To obtain the maximum vehicle tracking distance, the camera must be pointed at this 600' area. The PTZ cameras only cover about 25% of the corridor (Guensler, et al., 2013). For the purposes of the vehicle throughput study, the use of video-based traffic volume data taken from these PTZ cameras was not a practical consideration. Hence, the team would need to rely on the basic machine vision data collected about every 1/3 of a mile.

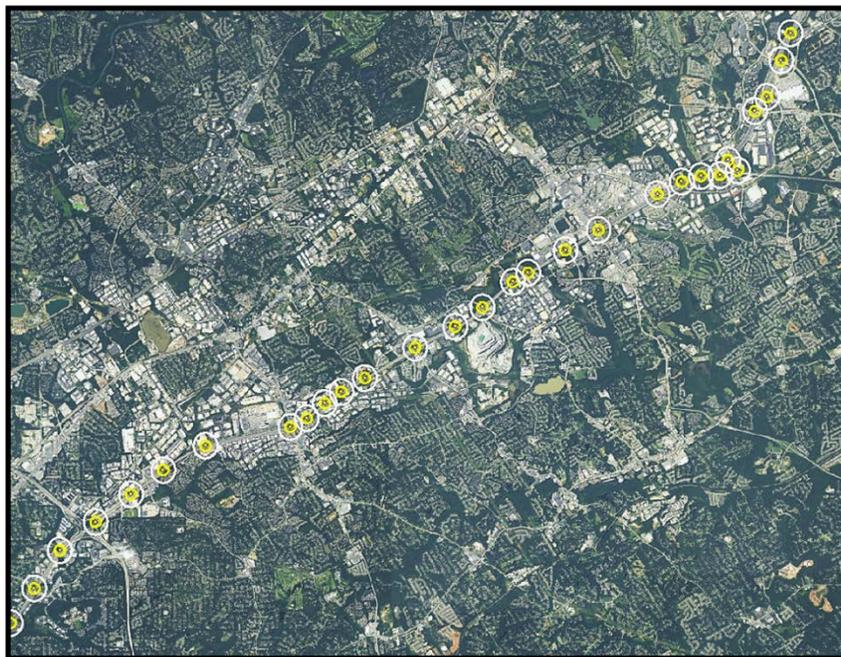


Figure 14: Locations of NaviGator PTZ Cameras on the HOT Corridor

The NaviGator data flow from the TMC directly to the Georgia Tech School of Civil and Environmental Engineering's Transportation Research Laboratory (TRL) and into the Georgia Tech NaviGator archive. The TRL is an official GDOT station, located at the endpoint of a fiber-optic connection between the TMC and Georgia Tech. The TRL monitoring station is isolated from the Georgia Tech network to maintain system security. The NaviGator data feed includes traffic volumes and spot speed data, by lane, at 20-second resolution. The research team manages an analytical archive of the TMC data, including the raw and processed 20-second data, aggregation of data to 5-minute bins, 15-minute bins, and hourly volumes. The Georgia Tech archives include 15-minute data, from January 2000 to date, and 20-second data, from October 2007 to date. The data are archived in near-real-time, with 20-second bin data arriving within 2 minutes of machine vision processing. The research team also processes the 20-second machine vision data through a series of quality control measures to identify and eliminate highly improbable values. Gaps in real-time data do occur and are attributable to several different

factors, such as sensor failures, data communications interruptions, etc. Georgia Tech researchers also process the 20-second data to impute missing data. After filtering and imputation, the 20-second data are re-aggregated to 5-minute and one-hour bins and retained in the separate analytical archive for use in research activities.

The Georgia Tech Transportation Research Laboratory supports research in transportation system surveillance, evaluation, and control. The ITS data warehouse receives, processes, and archives real-time data from multiple agencies, including the Georgia Department of Transportation (GDOT), Georgia State Road and Tollway Authority (SRTA), and Metropolitan Atlanta Rapid Transit Authority (MARTA). The laboratory also houses a remote control station that provides access to the pan-tilt-zoom cameras along the Atlanta freeway system, so that video can be recorded for later analysis. The ITS data-warehouse incorporates data from numerous detection systems, including spot vehicle detection data from Video Detection System, microwave radar stations, probe data from Radio Frequency Identification (RFID) systems, and National Oceanic and Atmospheric Administration (NOAA) weather data.

4.2 *SRTA Data*

In 2010, the USDOT awarded the Georgia Department of Transportation (GDOT), the State Road and Tollway Authority (SRTA), and the Georgia Regional Transportation Authority (GRTA) a \$110 million Congestion Reduction Demonstration Program grant to convert over-subscribed HOV lanes on I-85 (Guin, et al, 2008) into value-priced HOT lanes. The majority of the funding was dedicated to development of park-and-ride facilities and increased bus service on the corridor. The HOV-to-HOT project converted more than 15 miles of HOV 2+ carpool lanes into HOT lanes, one in each direction, between Chamblee Tucker Road (south of I-285) to Old Peachtree Road to the north. Figure 15 illustrates the primary HOT lane corridor (Sheikh, 2015). The I-85 HOT lanes opened on October 1, 2011.

SRTA's Express Lanes are divided into six segments: Interstate 285 (285), Jimmy Carter Boulevard (JC), Indian Trail-Lilburn Road (IT), Pleasant Hill Road (PH), Old Peachtree Road (OP), and State Route 316 (SR316). These segments range from 1.8 miles to 3.6 miles in length. Drivers are allowed to access the HOT lanes via five ingress/egress sections marked by dashed lines. Rumble strips are present along the striping in between the dashed sections to discourage weaving in these areas. The weaving sections are purple Figure 16 (Sheikh, 2015).

The HOT lanes are equipped with automatic vehicle identification (AVI) radio frequency identification (RFID) transponder systems that read the identification number of each user's Peach Pass at various locations along the corridor. Thirty-five HOT lane gantries are equipped with RFID tag readers. In addition, thirteen tag readers (seven northbound and six southbound) cross the entire roadway section, to detect transponders on general purpose lanes (Sheikh, 2015).

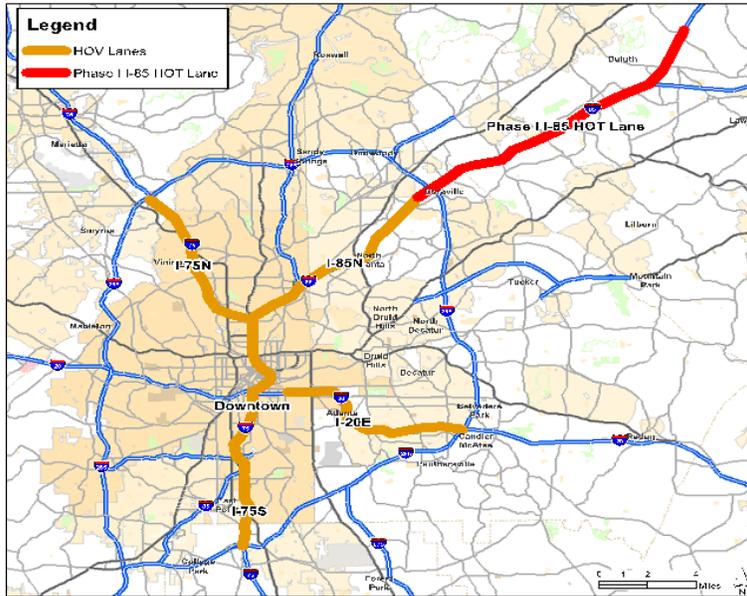


Figure 15: I-85 Express Lanes (GDOT, 2015)

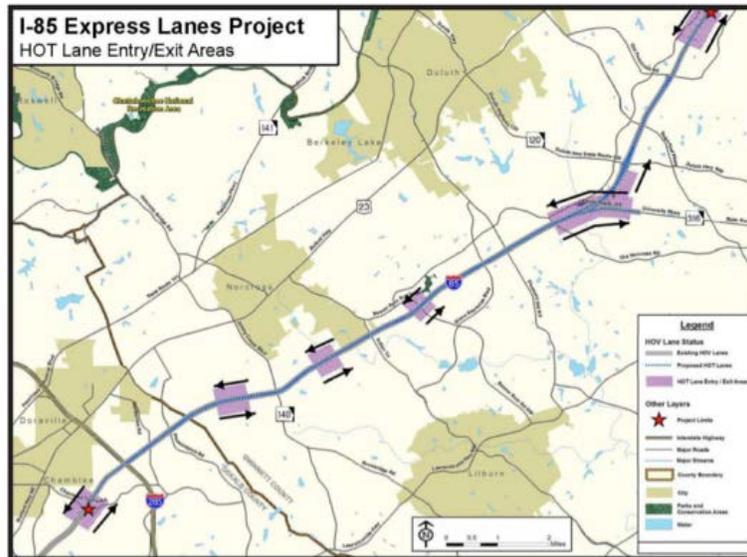


Figure 16: I-85 Express Lanes Weave Zones (GDOT, 2015)

Atlanta’s I-85 HOT corridor is unique, in that RFID tag reads are taken from the toll lanes as well as from the unpriced General Purpose (GP) lanes. This means that analysts can assess individual user choices to use, or not to use, the HOT lanes as a function of price and traffic conditions (Sheikh, 2015). Two additional features of the SRTA toll lane data stream provide very useful data for corridor performance analyses: 1) the data stream includes partial corridor trips (the majority of the trips on the corridor do not traverse all 15+ miles), and 2) the data

stream includes repeat user data. For each transponder, records typically exist for operation in the HOT lane as well as in the general purpose lanes, because users choose whether to pay to use the HOT lanes or to use the free general purpose lanes. Some users almost always use the HOT lanes, and some users almost never use the HOT lanes, but most users employ the HOT lanes occasionally (Sheikh, 2015). The SRTA data stream also includes trip lengths, toll amounts, start and end times, and whether the trip was in carpool or toll mode; rarely available for HOT lane studies in other regions.

Sheikh's dissertation (2015) describes the detailed methods for creating the analytical data sets for use in comparative analyses, including the method for aggregating individual vehicle detections into vehicle trips, calculation of average travel times, counting detected transponders along the corridor, and joining constructed trips to the other elements in the SRTA data stream. The I-85 Express Lane corridor provides ten different streams delivered automatically to Georgia Tech's servers by ETCC, one of SRTA's contractors. The data arrive as XML files at varying frequency, from files received every twenty seconds to those received every seven days. This is a big data analysis. In 2012, more than 78 million RFID readings were collected from the HOT lanes and more than 44 million from the General Purpose lanes.

For each RFID tag number and traverse time, the series of RFID detections are assembled into trips traversing the corridor. Table 1 shows the number of total trips each year for HOT-lane-only trips, GP-lane-only trips, and mixed trips in 2012, 2013, and 2014 (Sheikh, 2015). The number of trips by Peach-Pass-equipped vehicles increased significantly each year. About 25% of the vehicles using the corridor switch between HOT lanes and general purpose lanes during a single trip (mixed trips). In addition, more than 30,000 vehicles use both the HOT lanes and general purpose lanes each month (between 28.1% and 33.4% of the unique corridor users) meaning that many users are making decisions to use or not use the HOT lane as a function of toll price and operating conditions (Sheikh, 2015). However, it is also true that the 20% of transponders with the highest individual use of the HOT lanes make than 80% of the total HOT lane trips (Sheikh, 2015). That is, regular daily users dominate overall HOT lane use.

Because the time of each RFID transponder read is contained in the data stream with each tag number, the average speed of vehicles between each RFID tag reader can be derived from the known distance separating the transponder reader locations. As an example of data availability and application, Figure 17 below (Sheikh, 2015) provides the kernel density distribution of constructed trip speeds for all southbound morning peak period trips in March, 2012 (HOT lane trips are in green, GP-lane trips are in red, and mixed trips are in blue). HOT lane speed benefits are evident, with HOT speeds shifted toward the higher end of the speed distribution, and with few HOT lane trips observed in the lower speed range where most GP lane trips are observed.

Table 1: Number of Constructed Trips by Year (Sheikh, 2015)

	2012	2013	2014
Total Observed Trips by Peach Pass Vehicles	11,188,848	13,903,170	15,250,085
HOT-only Trips	1,540,232 (13.8%)	1,683,636 (12.1%)	2,169,130 (14.2%)
GP-only Trips	7,059,956 (63.1%)	8,854,212 (63.7%)	9,480,632 (62.2%)
Mixed HOT-GP Trips	2,588,660 (23.1%)	3,365,322 (24.2%)	3,600,323 (23.6%)

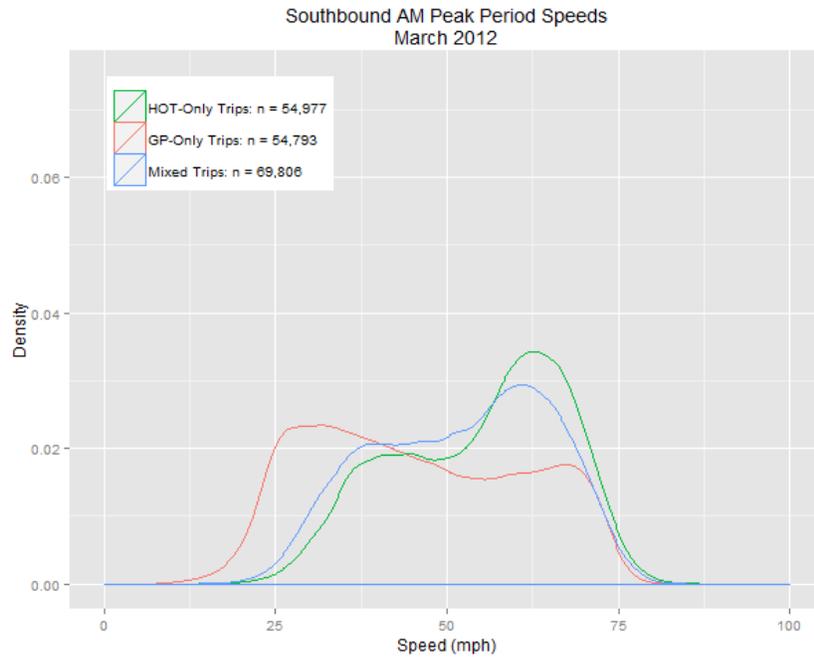


Figure 17: Speed Distributions for March 2012 SB AM Peak Period Trips (Sheikh, 2015)

All SRTA data beginning in October 1, 2011 and continuing through 2014 were processed for this project and remain available for any number of research projects.

5 Conclusions and Recommendations

The primary goal of this project was to demonstrate that smartphone-based applications that track second-by-second vehicle activity are capable of providing more reliable freeway and arterial travel time data than machine vision and other systems that collect spot-speed data. The project was to include a comparative assessment of real-time HOT lane corridor performance and GRTA Xpress Bus performance by recruiting and monitoring 80 regular HOT corridor users. The Commute Warrior application on the Android smartphones of the volunteers could collect second-by-second vehicle activity data on the I-85 HOT corridor so that instrumented vehicle data could be compared with Georgia NaviGator ITS data and SRTA data. Comparing monitored second-by-second corridor traverse travel times with travel time estimates derived from machine vision spot speed data would be used to assess the potential benefits of more widespread deployment of the Commute Warrior App throughout the region.

The team successfully monitored the onroad operating conditions of the HOT corridor through direct data feeds to the GDOT NaviGator system and the SRTA toll operations system. However, the team was unsuccessful in recruiting the Commute Warrior participants for comparative analysis. Recruitment of volunteers was coordinated directly with Georgia Regional Transportation Authority (GRTA) and the State Road and Tollway Authority (SRTA). The research team was not allowed to contact GRTA Xpress bus riders or SRTA tollway users to facilitate recruitment, either by mail or in person at the transit stops. The team was required to rely upon agency announcements of app availability through their blogs and e-mail newsletters. Participant recruitment efforts conducted in coordination with participating agencies was not successful and resources were not available for a direct mail campaign to all commutershed residents; therefore the primary goals and objectives of the project could not be completed.

Nevertheless, the research team was able to accomplish a number of project objectives and develop data processing routines and data sets that would prove very useful for other research efforts. The data sets developed in this research directly contributed to the completion Sheikh's dissertation (2015) which employed all of the traffic operations data in the assessment of consumer value of time and response to toll pricing. Sheikh's dissertation involved the "development of a host of data processing and modeling scripts that serve to: construct trips from disaggregated vehicle detections, estimate corridor conditions such as travel speeds and travel time reliability, and pair trip records with account, toll, and demographic data to provide a comprehensive overview of user characteristics and operating conditions at the time of each individual trip."

Although Commute warrior was not successfully deployed for this project, the Android app is currently being deployed for a Department of Energy ARPA-E project, where more than \$120,000 has been made available to support volunteer recruitment. Hence, data that would have been collected to perform the originally-proposed comparative research should become available by late 2017. The team does plan to perform originally-proposed comparative analytical work in 2017 and publish the results in a transportation journal.

In terms of field experience, the research team experienced a number of issues that should be considered in conducting similar research and deployment of app-based monitoring systems:

- Recruitment for monitoring studies simply cannot rely upon agency blogs and e-mail newsletters. In future studies, it will be critical that the research team obtain explicit advance permission in writing from agency heads granting permission to contact agency stakeholders via direct mail and person-to-person contact. Traditional travel diary studies employ a multi-contact approach that includes multiple mailers and a telephone contacts. These mechanisms should be employed.
- Future research should be staged, so that apps employed in research are fully vetted by the participating agencies so that any resources that will be required to meet agency expectations are identified in advance of contracting. This includes the development of any new outreach materials which require human subjects review and approval by the Institutional Review Board.
- Social media outreach should be considered as a component of recruitment efforts. This will require the participation of social media outreach experts on the research team.
- Visual advertising directly to potential participants should be considered. For example, overhead advertising placard space may not be available on luxury buses, but might be an option for future MARTA customer recruitment.
- Field research in travel behavior is currently inhibited by state and federal policies and contract provisions that prohibit the use of monetary incentives for recruitment and research participation. Changing the policies and/or regulations that are preventing the use of participation incentives is expected to improve research effectiveness. Alternatively, future research proposals may want include the participation of corporate or non-profit partners willing to provide recruitment incentives in exchange for sponsor-desired analysis of the data. Significant privacy issues will likely arise in such teaming efforts that will need to be addressed directly in the research plan during the Human Subject Review Board process.
- Traffic data archives such as the GDOT NaviGator archive and the SRTA operations archive should be continuously maintained. Archives allow researchers to automatically identify significant changes in operating conditions that might be attributed to critical infrastructure issues or changes in travel behavior. This requires that the archive maintenance team continuously support all of the necessary data connections and post-processing routines (such as those described for the SRTA data that process and link ten different files into a single analytical archive). The data flowing into these archives also need continuous QA/QC assessment. There is currently no dedicated funding source to ensure that high quality research data are archived and made available on demand for analysis. This will likely require the implementation of updated data sharing agreements.

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