



USDOT SMART Stage 1 Implementation Report

Community-Driven Regional Mobility Engine
for Multimodal Public Transportation in
Central Alabama



THE UNIVERSITY OF
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USDOT SMART Stage 1 Implementation Report

Project Title: Community-Driven Regional Mobility Engine for Multimodal Public Transportation in Central Alabama

Program: FY22 SMART Grants Program (Stage 1).

Award Number: 69A3552341008.

SMART Technology Area: System Integration

Stage 1 Award Amount: \$1,492,204

Recipient: Regional Planning Commission of Greater Birmingham (RPCGB). Technical work led by the Alabama Transportation Institute (ATI) at the University of Alabama (UA).

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Part 1 of 7: EXECUTIVE SUMMARY

This Stage 1 SMART project aimed to integrate public transportation in the Birmingham, Alabama region by combining a Regional Mobility Engine (RME) — an agent-based simulation and planning dashboard — with an EMtrac Transit Signal Priority (TSP) system covering 59 signalized intersections and 11 BJCTA buses. Technical work was led by the University of Alabama and the Alabama Transportation Institute (ATI). The pilot area covers ~390,000 residents across 112 census tracts in Jefferson and Shelby Counties, with 66 Historically Disadvantaged Community (HDC) tracts home to 230,000+ people. About 119,000 residents live in poverty and 20,000+ households have no vehicle. COVID-19 cut fixed-route service hours by ~61% and revenue miles by ~53%. The median paratransit passenger age is 70; ~49% use mobility devices; ~78% of their weekday trips are for essential purposes (medical, nutrition, dialysis).

Stage 1 Accomplishments

- Collected and integrated BJCTA/ClasTran ridership data and conducted a 1,035-response community survey; built a synthetic population database of 796,126 individuals and 2.7M+ daily trips.
- Built, calibrated, and validated a high-fidelity agent-based multimodal simulator.
- Developed the TransitView cyberinfrastructure platform integrating schedules, ridership, census, and network data into an interactive planning dashboard.
- Deployed EMtrac Transit Signal Priority (TSP) hardware at 59 intersections and 11 buses.
- Stage 2 application submitted August 14, 2024; no major deviations from project scope.

Key Findings

Latent demand analysis identified 49 underserved census block groups covering 98,000+ residents — including ~49,000 low-income residents not currently served. The system serves roughly 35% of potential demand today, suggesting ridership could roughly double under full integration. Integrated operation is projected to reduce on-demand travel time by ~54% and increase visits to key destinations (e.g., healthcare, places of employment) by 53%+.

Anticipated Costs and Benefits of At-Scale Implementation

At-scale implementation (i.e., Stage 2) is estimated at \$7.8M in federal support plus \$5M+ in committed local resources, covering 18-23 new ADA-compliant vehicles, additional TSP units at

30–50 intersections, and continued operations and engagement. Preliminary benefit-cost analysis estimates \$5.2M in annual monetized benefits, yielding a range of benefit-cost ratios from 1.4 to 2.5.

Part 2 of 7: INTRODUCTION AND PROJECT OVERVIEW

Project Description

This Stage 1 SMART was motivated to enhance public transportation services in the Birmingham, Alabama region. Specifically, the project set out to utilize *Systems Integration* and *Smart Technology Traffic Signals* to achieve the following outcomes:

- expand access and connect more people in the region to social and economic opportunity;
- improve reliability of the existing transit system; and, ultimately
- contribute to medium- and long-term economic competitiveness.

As such, the overall goal of the project was to develop a foundation for converting existing public transportation systems in Central Alabama into a fully integrated mobility system consisting of Bus Rapid Transit (BRT), fixed-route transit, on-demand shuttles, and demand response services.

The project explored the potential of *Systems Integration* concepts to build a community-based, data-driven tool to help the local transit provider, the Birmingham-Jefferson County Transit Authority (BJCTA). In particular, the tool was developed with the aim of assisting BJCTA in evaluating, planning, and implementing microtransit services (or modifying/ expanding existing ones) to better integrate them, and thus the riders they serve, with fixed route services, especially the new Bus Rapid Transit (BRT) system deployed in downtown Birmingham in 2022. Additionally, the project evaluated the deployment of transit priority systems (i.e. *Smart Technology Traffic Signals, Intelligent Sensor Based Infrastructure*) along fixed route corridors with an aim to better coordination of transfers between regular fixed route services and the BRT.

With regard to *Systems Integration*, the project developed a Regional Mobility Engine dashboard that can be used by transit agencies, in this case BJCTA, to examine scenarios for deploying microtransit and fixed route services to increase overall mobility in the Birmingham region with special attention in enhancing mobility opportunities for disadvantaged and underserved populations. The dashboard is based on a high-fidelity agent-based simulation model that was developed specifically for BJCTA using local transit data and travel behavior information collected through a community engagement process. A screenshot of the dashboard is shown in Figure 1 and the dashboard.

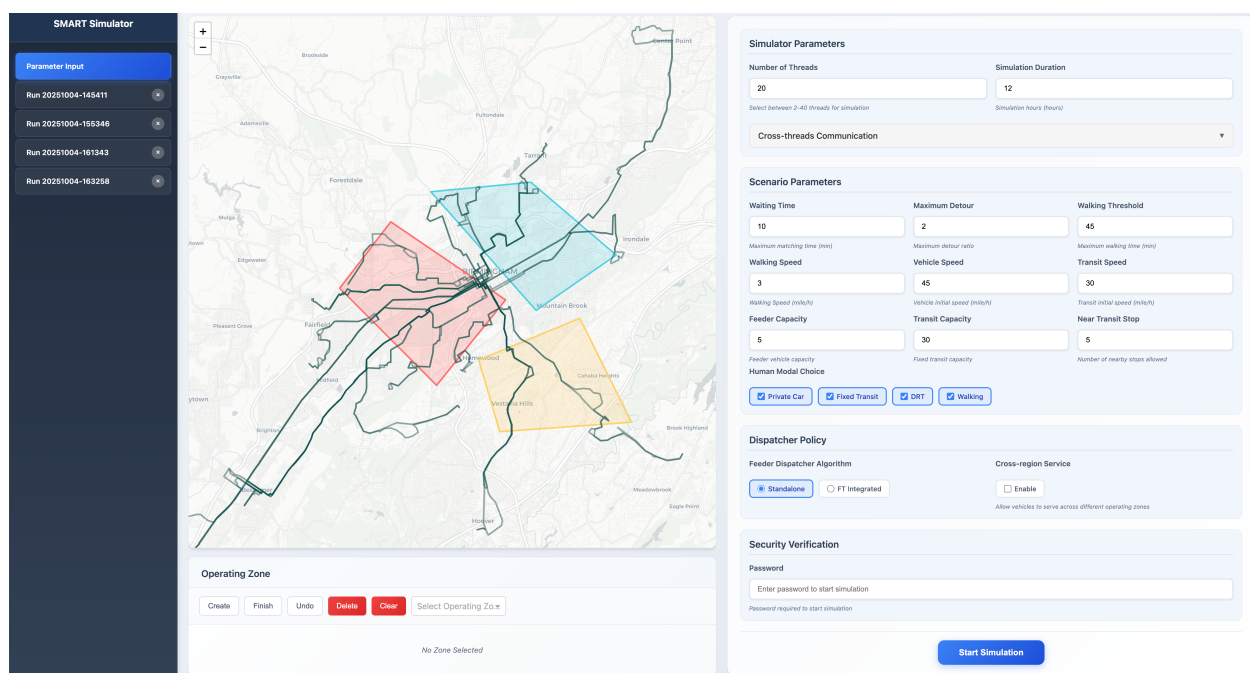


Figure 1 Regional mobility engine dashboard.

The Smart Technology Traffic Signals and Intelligent Sensor Based Infrastructure component of the project comprised the deployment of an EMtrac transit signal priority (TSP) system covering 59 signalized intersections and 11 BJCTA transit buses. Figure 2 shows the TSP coverage in the City of Birmingham. Figure 3 is a screenshot of the EMtrac Central Monitor located in the City of Birmingham Department of Transportation that illustrates one of the key fixed route corridors served by the TSP.

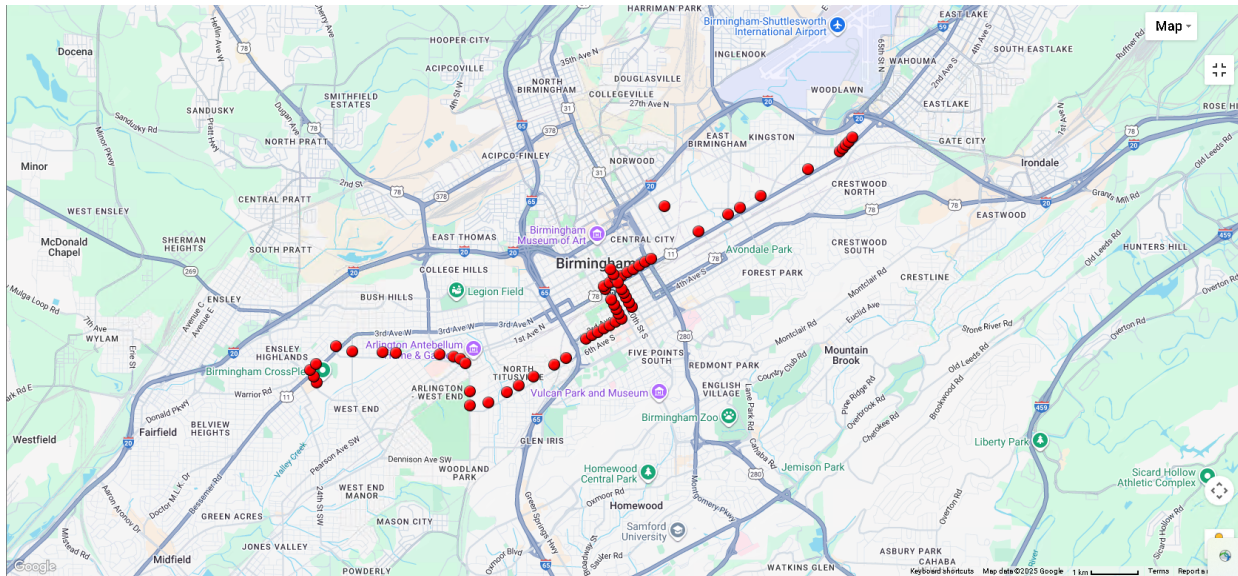


Figure 2. EMtrac Central Monitor system footprint across the City of Birmingham. 59 instrumented signalized intersections. Map data: Google.

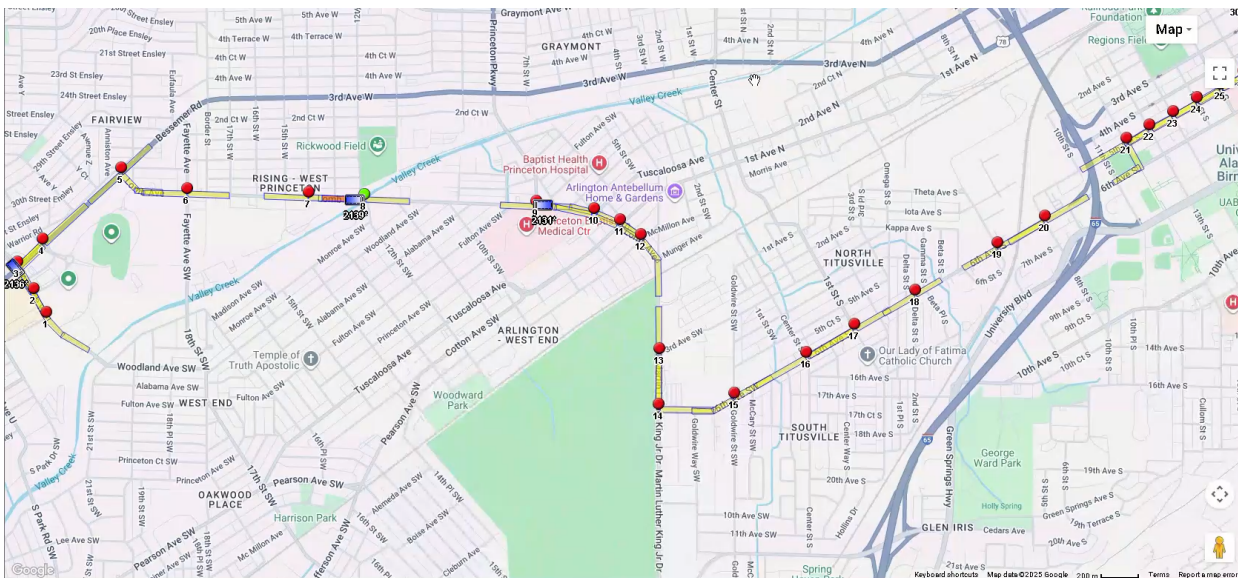


Figure 3. BJCTA bus route through the western portion of the instrumented corridor. Live capture from the EMtrac Central Monitor user interface, showing real time bus positions and signal phase state along the route. Map data: Google.

In live use the same view seen in Figure 3 animates continuously. Bus icons advance along the route as the in-vehicle Vehicle Computer Unit (VCU) reports updated Global Positioning System (GPS) positions through the 900 MHz radio link to the wayside Priority Detector (PD) and onward to the EMtrac Central Monitor service. Each instrumented intersection on the corridor carries a signal phase indicator that changes color in real time as the McCain traffic controller responds to

priority requests and resumes normal operation between calls. An operator watching the display can therefore see the full TSP request and response cycle as it happens at each intersection along the corridor: the bus approaching, the call arriving at the wayside, the controller granting an extended green or shortened red, the bus clearing the intersection, and the signal returning to its normal phase plan.

Communities impacted by at-scale implementation

At-scale implementation would serve the Birmingham region of Central Alabama, anchored in Jefferson and Shelby Counties and centered on the City of Birmingham. The full regional service area contains a population of approximately 898,000 people. The focused at-scale pilot area defined from Stage 1 modeling contains 112 census tracts and a population of approximately 390,000 people, of which 66 tracts are Historically Disadvantaged Communities (HDCs) home to more than 230,000 people.

The communities most affected are disproportionately low-income, older, and transit dependent. Across the region, roughly 119,000 residents live in poverty, and more than 20,000 households do not own a private vehicle. Since 2000 the regional population has grown some 13%. Yet fixed-route service coverage and alignments have not been substantially updated since the late 1990s, and microtransit has only been deployed in limited applications. The COVID-19 pandemic deepened the gap, producing reductions of roughly 61 percent in service hours and 53 percent in revenue miles for fixed-route transit, with the heaviest effect on riders from low-income households and HDCs.

Stage 1 directly targeted the mismatch between where service currently exists and where unmet need is concentrated. Stage 1 latent demand analysis identified 49 census block groups (CBGs) with positive unmet ridership potential, covering more than 98,000 residents, including roughly 49,000 residents with household incomes below \$35,000 who are not currently served. Transit-covered areas were found to have a lower median income than uncovered areas, confirming that expansion toward unmet demand reaches lower-income communities. The integrated design connects on-demand microtransit and paratransit to the fixed-route and BRT backbone so that travelers in underserved areas gain a practical path to jobs, education, healthcare, and essential services rather than isolated point service. Paratransit analysis showed the dependent nature of this population. The median paratransit passenger age is 70, about 49.1 percent require mobility devices, and roughly 78 percent of weekday trips are for essential purposes such as nutrition,

medical appointments, and dialysis. The human-centered operating design prioritizes these essential and time-sensitive trips, which is the population the at-scale system is intended to protect.

The nature of the impacted communities and how their perceptions and usage of transit in the region were examined via a comprehensive community engagement survey. The survey was conducted by the University of Alabama (UA) in conjunction with a local community-based non-profit from Birmingham. Institutional Review Board approval (IRB 23-12-7166) was obtained. A total of 1,035 survey responses were collected. Beyond demographic characteristics, the survey captured respondents' travel behaviors, mobility challenges, transit usage patterns, and perceptions of the existing transportation network in Birmingham, Alabama. Together, these responses paint a detailed picture of how residents interact with and evaluate the city's transit system. Key findings related to transit usage ridership

The high reliance on public transit among respondents reinforces the importance of a well-functioning transit system to a significant portion of Birmingham's traveling public. Nearly half of respondents reported commuting four or more days per week, while 13% commuted three days per week. Approximately 19% indicated they were unemployed or retired and therefore not commuting.

The most common one-way commute duration was 10-20 minutes, closely followed by 20-30 minutes. A combined 27% of respondents reported commutes exceeding 30 minutes, with 8% of individuals enduring trips longer than 60 minutes. Only 13% reported commutes under 10 minutes. These figures suggest that for many Birmingham residents, travel times are substantial, which may increase the importance of transit reliability and comfort.

Respondents were asked whether they had access to a personal vehicle. The sample was closely split, with 46% indicating they owned or had access to a vehicle and 48% reporting they did not. The high proportion of non-vehicle-owning respondents further underscores the essential role that public transit plays in meeting the daily mobility needs of a large segment of Birmingham's population.

A majority of respondents (70%) reported no mobility challenges. However, 11% indicated a mobility challenge affecting their ability to walk or move without assistance, 8% reported other mobility challenges, and 6% had a challenge affecting their ability to drive. These findings highlight that a meaningful proportion of Birmingham transit users have accessibility needs that must be considered in system planning and design.

When asked to rate Birmingham's transit environment in terms of friendliness and accessibility, respondents were largely critical. A combined 37% rated the system as somewhat or very unfriendly and inaccessible, while only 29% viewed it as somewhat or very friendly and accessible. The largest single group (35%) remained neutral, suggesting widespread ambivalence or dissatisfaction with the current state of transit accessibility in the city.

Respondents were also asked about their perceptions of safety within the transit system. Responses were more favorable here than on accessibility, with 27% rating the system as very safe (n=208) and 25% as somewhat safe. However, a substantial portion still expressed concerns, with 15% rating the system as somewhat unsafe and 12% as very unsafe. Roughly 24% remained neutral. These results suggest that while safety perceptions are modestly positive, there remains a significant minority of users who feel unsafe, pointing to areas where targeted improvements could meaningfully increase ridership and user confidence.

Respondents indicated which transit services they currently use. Fixed-route transit dominated, with 69% respondents reporting its use. Microtransit was used by 11%, while paratransit served a small but important 2%. Notably, 28% reported using none of these services, representing a potential market for expanded or improved transit offerings.

Fixed-Route Transit

The survey results indicate that fixed-route transit remains the most frequently used public transportation option among respondents. A substantial number of users reported utilizing fixed-route services daily or several times per week, demonstrating the importance of bus services in meeting mobility needs across the region. Most transit trips ranged between 15 and 60 minutes, with a considerable share of users reporting travel times exceeding one hour. Additionally, many riders experienced wait times between 10 and 30 minutes before boarding a bus. These findings suggest that while fixed-route transit serves a large user base, travel efficiency remains a concern.

Respondents identified several improvements that could enhance their transit experience. The most frequently cited needs included increased service frequency, more flexible schedules, real-time bus tracking applications, improved vehicle interiors, better schedule adherence, and reduced overall travel times. Concerns regarding inconsistent bus arrival times emerged as one of the strongest barriers to transit adoption, alongside total journey time and schedule inflexibility.

Encouragingly, many respondents indicated a willingness to walk a short distance if doing so would reduce waiting time, suggesting opportunities for route optimization and transit-stop consolidation strategies.

Microtransit Services

Microtransit services also demonstrated strong usage patterns among survey participants. Many respondents reported using microtransit either daily or several times per week. Typical trip durations were relatively short, with most journeys lasting less than 45 minutes. However, wait times emerged as a significant challenge, with many users reporting waits between 10 and 30 minutes before service arrival.

When asked about service improvements, respondents highlighted the need for reduced trip times, fewer intermediate stops, better vehicle quality, and improved schedule reliability. Timeliness was repeatedly identified as an important determinant of satisfaction. While safety concerns were not among the highest-ranked issues, service efficiency and reliability clearly influence user perceptions.

Analysis of barriers to microtransit use further revealed that excessive wait times and high costs were among the most discouraging factors. Accessibility challenges, vehicle cleanliness, and payment difficulties were generally viewed as less problematic but still influenced adoption decisions for some users.

Paratransit Services

Paratransit services serve a smaller but critically important segment of the population, particularly individuals with disabilities and mobility limitations. Survey responses revealed relatively low utilization rates, with many respondents indicating limited familiarity with eligibility requirements. A notable proportion of participants either did not know whether they qualified for paratransit services or incorrectly believed they were ineligible. This finding suggests a significant public awareness gap.

Among current and potential users, the most frequently requested improvements included easier reservation processes, increased service frequency, faster service, and the implementation of real-time tracking technologies. These findings indicate that convenience and predictability are central to improving the attractiveness of paratransit services.

Similar to the microtransit findings, excessive wait times and high costs were identified as the strongest deterrents to paratransit use. Safety concerns and payment difficulties also influenced

ridership decisions, though to a lesser degree.

General Policy Implications

The findings suggest several opportunities for transit agencies in Birmingham. First, investments aimed at improving service reliability may yield substantial benefits in rider satisfaction and system usage. Second, implementing real-time information systems across all transit modes could address one of the most common concerns expressed by users. Third, targeted marketing and education campaigns may improve awareness of available transit services, particularly paratransit. Finally, efforts to reduce travel times through route optimization, improved scheduling, and operational efficiencies could strengthen the competitiveness of public transportation relative to private vehicle travel.

Scale of Deployment in Stage 1

The integrated design connects on-demand microtransit and paratransit to the fixed-route and BRT backbone so that travelers in underserved areas gain a practical path to jobs, education, healthcare, and essential services rather than isolated point service. Paratransit analysis showed the dependent nature of this population. The median paratransit passenger age is 70, about 49.1 percent require mobility devices, and roughly 78 percent of weekday trips are for essential purposes such as nutrition, medical appointments, and dialysis. The human-centered operating design prioritizes these essential and time-sensitive trips, which is the population the at-scale system is intended to protect.

Community input shaped the definition of benefits rather than simply validating a predetermined plan. RPCGB maintains a public involvement distribution list of nearly 2,500 individuals and has longstanding relationships with local governments, social service agencies, and groups representing the population of the City of Birmingham and surrounding region. Survey and engagement instruments were designed and reviewed by community engagement experts from the University of Alabama to ensure they were contextually appropriate and methodologically sound. Engagement was conducted at transit hubs, community centers and events, on board buses, and in some cases door to door, and was supported by the BJCTA marketing and outreach team, the Max Transit Ambassadors, and a local community-oriented non-profit engaged specifically to reach residents who are not current transit riders. The team met the Stage 1 community engagement target with 1,035 survey responses collected. The agent-based simulator and candidate service scenarios were presented and discussed in working meetings with the Metropolitan Planning

Organization, planning consultants, and the BJCTA, so that practitioner and community feedback informed the scenarios used to measure benefits. It is intended that these relationships be formalized into a community coalition that will oversee benefit definition and measurement during at-scale implementation.

The current TSP deployment scale is 59 instrumented intersections and 11 buses equipped with EMtrac VCUs, integrated with the City of Birmingham McCain traffic controllers and the EMtrac Central Monitor service. The EMtrac platform supports incremental growth without changing the in-vehicle hardware: the same VCU and antenna assembly that operates today can request priority at any future instrumented intersection. Additionally, the EMtrac system put in place can also be used to provide traffic signal preemption for emergency vehicles should they be equipped with VCUs in the future.

Summary of Stage 1 project activities

Stage 1 was organized around five tasks. Below is a consolidated summary of the milestones accomplished, the partners engaged, and the outcomes reported across the quarterly reports.

Key milestones accomplished

Task 1 (Data, demand, and community survey). Engaged the Birmingham-Jefferson County Transit Authority (BJCTA) and the regional paratransit operator, ClasTran, to obtain data on ridership and operations (hours of service, routes, etc.). A community survey was conducted to collect information on travel behavior, needs, and preferences – a total of 1,035 community survey responses were collected, meeting the engagement target. The transit and mobility data were assembled and integrated with community survey results to develop a synthetic regional population and activity database, which was then used to model latent demand for transit and microtransit services in the region.

Task 2 (Agent-based simulator). Built, optimized, calibrated, and validated a high-fidelity agent-based simulator of the integrated multimodal system for the Birmingham area, including fixed-route, BRT, microtransit, paratransit, and private vehicle behavior.

Task 3 (Cyberinfrastructure). Developed the TransitView cyberinfrastructure, including a multi-source data aggregator, the simulator back end, and an interactive front-end dashboard, and completed front-end to back-end integration with a results database.

Task 4 (Transit Signal Priority hardware). Selected candidate intersections, finalized

hardware specifications, procured TSP equipment and controllers, completed Advanced Traffic Controller cabinet training with traffic engineering personnel from the City of Birmingham Department of Transportation (BDOT), the Alabama Department of Transportation (ALDOT), and University of Alabama, and obtained access to the Birmingham TSP system for assessment.

Task 5 (Optimization and evaluation). Developed the route extension and integration optimization models and prepared simulation scenarios for before and after evaluation of system performance and efficiency.

Stage 2 preparation. Completed and submitted the draft implementation plan in July 2024 and submitted the SMART Stage 2 application on August 14, 2024.

Partners engaged

- **Public agencies.** RPCGB (lead and Metropolitan Planning Organization), the Birmingham-Jefferson County Transit Authority (BJCTA), ClasTran (regional paratransit), BDOT, and ALDOT.
- **Academic and research.** The University of Alabama and the Alabama Transportation Institute (ATI), including the Department of Civil, Construction and Environmental Engineering. ATI participates in the USDOT Region IV University Transportation Center (CR2C2) and the USDOT New Mobility Center of Excellence.
- **Community and workforce.** A local community-oriented non-profit was engaged for survey distribution and outreach, the Max Transit Ambassadors, and workforce development partners including Central Six Alabama Works, the City of Birmingham Department of Innovation and Economic Opportunity, and the Onin Group.
- **Industry and technology.** Emtrac and Utilicom (TSP systems and integration), McCain and Econolite (signal controllers), and PTV (Vissim microsimulation). Mobility and operations data were obtained from BJCTA, ClasTran, Ecolane, Azuga, OpenStreetMap, and SafeGraph.

Summary of Stage 1 project activities

The Stage 1 prototype produced a working, validated, and integrated planning and evaluation capability. The synthetic activity database represents 796,126 individuals from 337,738 households and more than 2.7 million daily activity and home trips. The agent-based simulator was calibrated against real-world demand-responsive transit data and reached close alignment with

observed operations. The latent demand analysis identified 49 underserved CBGs and more than 98,000 residents as priority candidates for service extension. The TSP subtask selected and verified candidate intersections along the 20th Street corridor connecting high-ridership fixed-route stops to the BRT line and advanced procurement, training, and system access. By the final quarters of the period of performance, Tasks 1 through 4 were complete and Task 5 evaluation was in its final stage.

The Stage 1 work has been presented to the following audiences:

- 2024 Annual Meeting of the Alabama Transportation Planners Association in Florence, AL;
- 2024 International Mobility Data Summit in Montreal, Canada; and
- 2026 ALTRANS and Transit Association of Alabama Spring Conference in Gulf Shores, AL.

Survey data and the simulator are being used to develop academic articles and additional conference presentations (e.g., TRB, ASCE) promoting the work and the SMART program. Additionally, the team has committed to presenting a poster in the Stage 1 project at the upcoming 2026 SMART Summit in Washington DC.

Major Deviations or Changes

There were no major deviations or changes form the project scope.

Part 3 of 7: PROOF-OF-CONCEPT EVALUATION FINDINGS

Findings on the performance of the dashboard prototype

The Evaluation Plan defined five evaluation questions, each with a performance measure and a target, to determine whether the prototype meets expectations and to inform realistic at-scale projections. The prototype is a data-driven planning and evaluation system rather than a public revenue service, so the performance measures were assessed primarily through the calibrated simulator, the latent demand models, and the engagement data collected in Stage 1. Table 1 below restates each measure and target and summarizes the Stage 1 finding. A discussion of data limitations follows.

Table 1. Stage 1 Performance Measures and Targets

Performance measure	Target	Stage 1 finding
Share of new potential riders over existing riders	Reach 50 percent new potential riders through integration	Latent demand modeling identified 49 underserved CBGs and more than 98,000 residents with unmet potential. Analysis indicated the current system serves roughly 35 percent of potential demand, implying ridership could roughly double under integration. More than 20 CBGs adjacent to the system showed at least 25 percent higher latent demand than served areas.
Average waiting time and delay in pickup and dropoff for on-demand service	Improve waiting time by 20 percent through TSP. Reduce on-demand pickup and dropoff delay by 20 percent through integration	Calibrated demand-responsive baselines were established (average wait 15.46 minutes, average in-vehicle time 10.53 minutes). Integration scenarios indicate on-demand mobility time could be reduced by about 54 percent. The TSP corridor and ten candidate intersections were selected and verified.
Efficiency of Travel (EoT), measured by detour rate and compared across different user groups (vertical) and communities (horizontal)	Improve worst-case EoT by 200 percent for disadvantaged groups. Prioritize seniors and healthcare trips. Close the EoT gap between communities	Stage 1 confirmed that some riders experience travel times 3 to 4 times longer than a comparable door-to-door trip (baseline detour ratio 1.59 average, 1.41 median). The priority vertical-efficiency population was characterized (paratransit median age 70, about 49.1 percent using mobility devices, about 78 percent of weekday trips for essential purposes). Modeling indicated worst-case travel times for affected riders could fall by up to 85 percent in the morning peak and about 60 percent overall.
New job and activity locations accessible, and additional population with access	Enable 30 percent of users to reach locations of interest. Cover an additional 20 percent of population from unserved communities	Extending service to the top candidate locations was estimated to increase visits to covered locations by more than 53 percent. About 58 percent of paratransit pickup and dropoff locations fall within five minutes of a transit station, of which about 32.6 percent could be accommodated by transit, affecting roughly 20 percent of total trips.
Operating cost, fares, and capital investment	Provide low-cost options for disadvantaged groups. Balance operating cost with ridership and efficiency. Quantify capital investment to inform Stage 2	Stage 1 quantified the prototype cost (\$1,492,204) and an at-scale capital estimate and produced a bi-objective optimization that yields Pareto-optimal trade-offs between benefit maximization and operating cost. An operating target of 70 percent fixed-route revenue miles and 30 percent microtransit and paratransit miles was defined to control cost while expanding coverage.

To evaluate the dashboard prototype, we ran a no DRT baseline and four DRT operating-strategy experiments on the Birmingham metropolitan area. Each experiment simulates a representative 12-hour service day against the same synthetic regional travel demand (~324,000

daily trips) and the same calibrated road/transit network. The four DRT experiments conducted on a three-zone testbed are summarized in Table 2.

Table 2. DRT experiments conducted

Experiment	Scenario	DRT operating strategy
	Baseline	No DRT
1	DRT Baseline	Standalone DRT, service confined within each zone (10/10/10)
2	Cross-region	Standalone DRT permitted to serve trips across zone boundaries
3	Fleet right-sizing	Standalone DRT, fleet doubled in the highest-demand zone (20/10/10)
4	Fixed-route integration	DRT operates as a feeder integrated with fixed transit, cross-region enable

Performance metrics evaluated

The metrics below restate the performance measures established in the project's Evaluation Plan and map each to the corresponding output produced by the simulation platform. Table 3 describes the precise computed definition for the performance metrics evaluated and the key findings from these analyzes are summarized in Table 4.

Table 3. Definition for the performance metrics evaluated

Evaluation Plan	Simulation metric used	Definition as computed
Reliability / Delay	On-time performance; response time; expired requests	% of served DRT trips picked up within 30 min; mean seconds from request to vehicle assignment; count of requests not served within the 10-min maximum wait
Waiting time	Average wait	Response time + pickup wait, in min
Service efficiency	Vehicle utilization; passenger load	% of vehicle-operating time carrying ≥ 1 passenger; mean passengers on board
Efficiency of travel	Average detour ratio	Mean ratio of in-vehicle time to a direct car trip
Coverage	Service coverage	% of a zone's activity area within 500 m of an actual DRT pickup
Mode shift	DRT/FT service rate	Share of trips
Cost	Operating cost per trip	Mean fuel + labor cost per DRT trip

Table 4. Key findings from DRT experiments

Metric	No DRT	DRT baseline	Cross-region	Fleet right-size	FT integration
DRT trip served	0	2,745	2,765	2,816	3,533
Expired requests	0	967	0	174	345
On-time performance	-	64.7%	97.6%	93.8%	78.2%
Mean-response time	-	60.3 s	39.4 s	67.9 s	143.9 s
DRT utilization	-	41.7%	83.5%	48.2%	94.0%
Zone-1 average wait	-	16.9 min	14.8 min	11.6 min	19.8 min
DRT share	-	0.8%	0.9%	0.9%	0.7% + 0.4% (FT integrated)
Trip travel time	28.5 min	28.6 min	28.4 min	28.5 min	28.7 min

1. Allowing DRT to serve trips across zone boundaries is the single highest-impact operating decision: Enabling cross-region service (Scenario 2 vs. Scenario 1) eliminated all 967 unserved requests, raised on-time performance from 64.7% to 97.6%, cut mean response time by 35%, and roughly doubled fleet utilization. Pooling the fleet across boundaries lets idle vehicles in one zone answer demand surges in another.
2. Right-sizing the fleet relieves the worst-served zone: Doubling the fleet in the highest-demand zone (Scenario 3) reduced that zone's average wait from 16.9 to 11.6 minutes and cut region-wide unserved requests from 967 to 174. As expected, utilization fell, illustrating the efficiency-vs-service-level trade-off planners must balance.
3. Integrating DRT as a feeder to fixed transit maximizes coverage and ridership, at the cost of directness: The feeder model (Scenario 4) served the most trips at the highest utilization. The trade-off is longer wait times and transfers: response time rose to 143.9 s and detour ratios increased, reflecting the access/egress time inherent to a transfer-based model.
4. DRT is net-additive mobility and pulls trips off private cars: Compared with the no-DRT baseline, the DRT scenarios added new shared-mobility trips on top of a stable fixed-transit base. Tracing the mode shift, introducing cross-region DRT moved roughly 1,400 daily trips from private car to DRT, and the feeder model moved roughly 2,000 trips off private cars plus converted some fixed-transit riders into higher-value integrated journeys, all without degrading the region-wide average travel time.

Efficiency and Accessibility analysis

The Evaluation Plan defines Efficiency of Travel through the detour ratio, variation among zone and average wait times. The results are shown in Table 5.

Table 5. Efficiency and Accessibility results for the four DRT experiments

Scenario	Detour ratio	Inter-zone disparity	Average wait
DRT baseline	2.0 / 1.7 / 1.8	1.18	16.9 / 6.0 / 6.0
Cross-region	1.8 / 1.9 / 2.1	1.17	14.8 / 14.5 / 17.6
Fleet right-size	1.9 / 1.7 / 1.9	1.12	11.6 / 5.9 / 5.9
FT integration	2.5 / 1.8 / 2.7	1.24	19.8 / 19.0 / 20.6

Fleet right-sizing improved efficiency on both measures. It cut the worst-served zone's wait by 31% and narrowed the inter-zone detour disparity. The FT integration model widened the worst-case detour, an explicit efficiency cost of its broader coverage that planners must weigh. The Evaluation Plan's worst-case-for-disadvantaged-groups is challenging to be accurately evaluated at the current stage, since it requires more detailed socioeconomic survey data.

Two accessibility measures are evaluated. First, DRT spatial coverage: the share of each zone's activity area within 500 m of an actual DRT pickup, ranges 8-32%. Second, access to opportunities by trip purpose: the FT integration scenario newly enabled roughly 496 commute (jobs) trips and 520 business/shopping trips per day that the no DRT scenario did not serve. However, a formal cumulative-opportunity accessibility index (jobs or healthcare reachable within a travel-time threshold, with vs. without DRT) requires opportunity/point-of-interest data not available in the current stage.

Data collected and supporting evidence

The findings rest on several validated data products. The synthetic activity database covers 796,126 individuals (83.9 percent of residents) from 337,738 households (91.7 percent of households) and more than 2.7 million trips. It was validated against independent sources. The correlation between estimated CBG trips and SafeGraph foot traffic was 61.2 percent. The share of weekday trips was 80.2 percent in the synthetic data against 79.9 percent in the National Household Travel Survey, and major trip-chain shares deviated by less than 5 percent. Demographic attributes aligned closely, with a synthetic median age of 36.0 years against 36.2 years in the American Community Survey. The latent demand models were trained and tested on BJCTA ridership of 2,483,635 trips over the period July 2022 to June 2023. The classification

model reached about 70 percent accuracy, and the ridership estimation model achieved an R^2 of about 0.70. The simulator was calibrated using city-scale trip data, BJCTA General Transit Feed Specification data, and demand-responsive transit request data, and reached a demand modeling gap of about 6.7 percent for completed requests with consistent alignment of in-vehicle time, detour ratio, and wait time distributions. A spatial validation using PERMANOVA found no statistically significant difference between historical and simulated completed-trip patterns.

Data limitations

Several limitations should be read alongside these findings. First, the prototype was evaluated in a high-fidelity simulation environment calibrated to historical data rather than through a live revenue service, so the rider-facing targets reflect modeled outcomes and not observed operations. Second, the latent demand and ridership models were built on a single year of ridership and on third-party movement data (SafeGraph), which carries sampling and coverage limitations, and the classification accuracy of about 70 percent leaves residual uncertainty in which areas are classified as having unmet demand. Third, the TSP field results and the final Task 5 efficiency outcomes were still being finalized at the close of Stage 1, as noted in the placeholders above. Fourth, the community survey, while meeting its target of 1,035 responses, is a sample and may not fully represent every population group. These limitations are the reason the at-scale projections in Part 4 are framed qualitatively and are tied to baseline data that can be measured during Stage 2.

Findings on the performance of the TSP prototype

Operational data from the Birmingham EMtrac deployment is produced by the EMtrac platform itself. Each priority detector logs every call request received from each VCU equipped bus, the algorithm decision (priority, age, or all concurrent calls), and the resolution outcome at the local traffic controller. The EMtrac central monitor service ingests these events and stores them in a relational database for reporting. Where the Field Monitor Unit is present, the same database also stores NTCIP traffic controller telemetry, environmental telemetry from the cabinet, and any alerts generated by the cloud rule engine. Reports available out of the platform include textual reports such as alert history and command history, and graphical reports such as voltage, temperature, and humidity over time, with export to PDF, Word, Excel, and CSV.

Data limitations from the source material: the platform records call events and controller responses, but it does not by itself measure transit travel time or schedule adherence on the bus

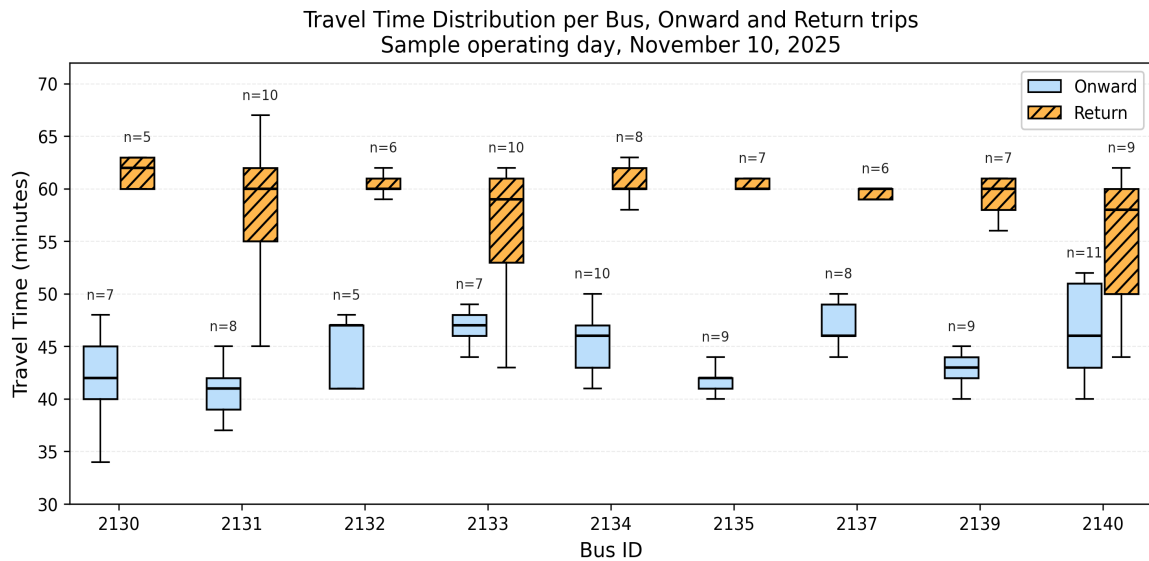
side. Some advanced settings on the platform are factory configured and password protected, which means certain low-level tuning is not changeable in the field without coordination with STC. The platform can also synthesize Automatic Vehicle Location (AVL) data from optical detector activity at instrumented intersections, but this synthesized AVL is not a substitute for vehicle generated AVL for performance metric calculation.

Preliminary analysis of Birmingham field data

A preliminary analysis of EMtrac Central Monitor event log data for a sample operating day in November 2025 was conducted by the project team. The analysis confirmed the end-to-end data pipeline from the wayside priority detectors and Field Monitor Unit through the central monitor service into a structured event log suitable for performance evaluation. The metric examined was approach zone duration, defined as the elapsed time between the first VCU priority request packet received by the priority detector or FMU and the last packet received while the bus remained inside the configured approach zone for the intersection. The approach zone is the geographic boundary around each intersection within which an equipped bus is detected, and a priority request is generated. Approach zone duration therefore represents how long the bus is in the priority request window before clearing the intersection. A longer duration means either the zone is physically larger at that intersection or the bus is being held up inside the zone while waiting for the signal to clear.

The preliminary findings, presented qualitatively, are as follows. First, approach zone duration varied measurably across the 59 instrumented intersections, with median values clustered in the lower end of the observed range and a smaller number of intersections showing consistently longer durations and a longer tail of outlier events. The pattern indicates that the priority detection zones are not uniform in length across the corridor, which is expected because approach zones are configured per intersection based on local geometry and speed.

Second, corridor travel time varied by vehicle and by direction, with return trips consistently slower than onward trips across the vehicles in the sample. Figure 4 shows the travel time distribution by bus for the corridor. Note that the results indicate that Return medians sit higher than onward medians across all nine buses. Approximate quartile values read from the source chart pending full data access for re-analysis.



Each bus has two boxes: Onward (left, solid light blue) and Return (right, hatched orange). Hatch pattern is a redundant cue alongside colour and left-right position.

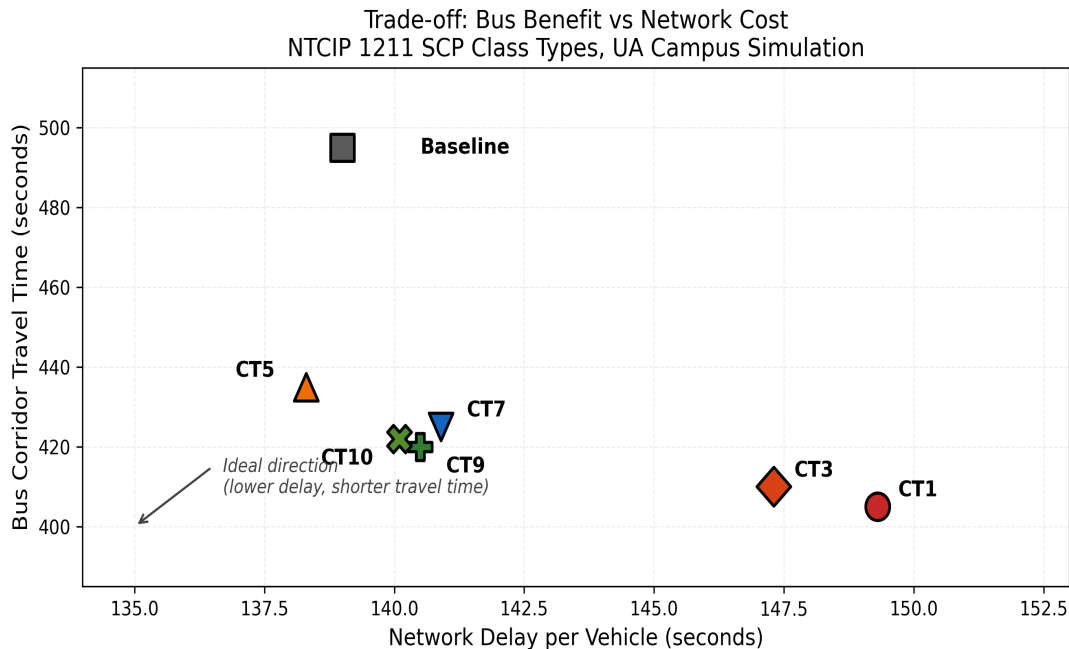
Figure 4. Travel time distribution per bus, onward and return trips, sample operating day November 10, 2025.

Supporting evidence from the UA campus NTCIP 1211 simulation

In addition to the Birmingham EMtrac field context above, an independent simulation study produced controlled evidence of TSP behavior using the standardized NTCIP 1211 SCP protocol on a four-intersection coordinated corridor on the University of Alabama campus. This evidence is not from the Birmingham deployment and does not use EMtrac hardware and is included here as supporting research only.

All six TSP class types tested produced statistically significant reductions in bus corridor travel time on the test corridor. The aggressive classes produced the largest gains and were statistically indistinguishable from each other. The moderate class produced a smaller but still measurable gain.

Network impact differs sharply across class types and is what makes the choice of class type an engineering decision rather than a default to the most aggressive option. In the simulation, the aggressive Class 1 produced the largest bus travel time gain but also the largest increase in network wide delay versus the no TSP baseline. The moderate Class 5 produced essentially no change in network delay versus baseline while still delivering a measurable bus travel time reduction. Figure 5 plots the bus benefit against the network cost for all seven scenarios so the tradeoff can be read at a glance. Interpretation of Figure 5 is such that results in the lower left indicate better performance.



Marker shapes: square = Baseline, circle = CT1, diamond = CT3, upward triangle = CT5, downward triangle = CT7, plus = CT9, cross = CT10. Lower left is better.

Figure 5. Bus benefit versus network cost tradeoff for the seven simulation scenarios.

The trade-off pattern in Figure 5 is relevant to the Birmingham wayside priority detector, which is a combined transit signal priority and emergency vehicle preemption device. The two services have different objectives and therefore different operating regions on the chart.

On the simulation corridor, the moderate Class 5 sits closest to the lower left region of the chart, delivering bus travel time reduction with essentially no change in network delay. The Birmingham deployment is operating under the simplest priority configuration, with priority requested rather than imposed and the McCain controller retaining final authority. The specific NTCIP 1211 SCP class type configured in Birmingham is not in the available source material.

For the emergency vehicle preemption capability, the desirable region of the chart is the lower right, where the equipped emergency vehicle gets a sharp travel time drop and the network accepts the additional delay. EVP benefits from longer detection range than TSP, which is consistent with aggressive call handling on the controller side. How the McCain controller in Birmingham is configured for TSP versus EVP calls is not in the available source material.

The simulation also examined how long the priority call remains active on the controller. Class 3, which is subject to the NTCIP 1211 recovery cycle, holds the controller for a measurably shorter window per request than Class 1, which is exempt from recovery. The shorter window helps

explain the smaller network delay impact of the recovery cycle class types.

A conditional activation strategy that only requested TSP when a bus was behind schedule did not improve corridor travel time on this small test corridor, because most buses arrived during favorable signal phases without needing priority. Conditional activation may behave differently on longer or more congested corridors. The simulation corridor is short (four intersections over approximately two kilometers) and uses a single bus route, so its results describe behavior on that test corridor and are not a projection for the 59 intersection Birmingham deployment.

How the prototype met the original expectations and statutory goals

The original proposal set out to build and validate a Regional Mobility Engine, a data-driven prototype that could profile community mobility demand, simulate an integrated multimodal system at the individual traveler level, and identify where targeted investment would most improve efficiency. Stage 1 met that core expectation. The prototype delivered the four building blocks the proposal promised, namely a calibrated and validated high-fidelity simulator, a multi-source cyberinfrastructure with an interactive front end, optimization models for route extension and integration, and a behavior and demand evidence base drawn from synthetic activities and a community survey. The proposal also committed to a small-scale demonstration of transit signal priority to support BRT and fixed-route transfers, and Stage 1 advanced that demonstration through intersection selection, procurement, training, and system access along the 20th Street corridor. The prototype therefore moved the concept from proposal to a working, evidence-backed system ready to inform an at-scale pilot.

Statutory goal data, as applicable (IIJA Section 25005 F(1)(B)(i)). The following addresses the specific statutory goals originally set out for the Stage 1 prototype project.

- **Reducing traffic-related fatalities and injuries.** Safety was not a primary measured goal of the Stage 1 prototype, and no fatality or injury performance data were collected. Secondary safety benefits are anticipated at scale through smoother signalized transit movements, and these are discussed in Part 4 rather than claimed here.
- **Reducing traffic congestion or improving travel-time reliability.** The prototype quantified the reliability problem and the levers to address it. Baseline fixed-route headways range from about 30 to 100 minutes, and demand-responsive detour ratios average 1.59. The TSP design targets smoother transit progression and protected transfers, and the simulator

estimated that integrated operation could cut on-demand mobility time by about 54 percent, which directly supports travel-time reliability.

- **Providing access to real-time integrated traffic, transit, and multimodal information.** The TransitView cyberinfrastructure integrates General Transit Feed Specification schedules, stop-level ridership, points of interest, census block group data, jobs data, and the road network into one platform with vehicle playback and interactive statistics. This is the prototype of the integrated multimodal information capability called for in the proposal.
- **Reducing barriers or improving access to jobs, education, and essential services.** The latent demand analysis identified more than 98,000 underserved residents and the essential-trip profile of dependent riders, and the optimization models showed that targeted extension could increase visits to key destinations by more than 53 percent, demonstrating a clear path to reduced access barriers for jobs, healthcare, and other essential services.

Improvement demonstrated in the statutory benefit areas

The following maps Stage 1 progress to the statutory benefit areas of IIJA Section 25005 D(3)(ii) that are relevant to this project.

- **Reduce congestion and delays for commerce and the traveling public.** Demonstrated in modeling. Integrated operation and signal priority were shown to reduce on-demand mobility time and to support protected transfers, reducing rider delay. The EMtrac priority detector grants a green extension or early green to equipped buses at instrumented intersections, which reduces control delay at signalized intersections for in service buses.
- **Improve safety and integration of transportation facilities and systems.** Integration demonstrated. The prototype unified fixed-route, BRT, microtransit, and paratransit into one planning and operating model. The TSP platform integrates the wayside priority detector with the City of Birmingham McCain traffic controllers under the controllers' own decision logic, so the controller retains final authority over phase changes. Priority is requested, not imposed. The EMtrac platform also supports linked alerting, where for example a cabinet door open event creates an alert that is auto cleared when the door closes, which gives operators a real time view of cabinet integrity without alert clutter. Additionally, the EMtrac system put in place can also be used to provide traffic signal preemption for emergency vehicles should they be equipped with VCUs in the future.

- **Improve access to jobs, education, and essential services, including health care.** Demonstrated. Latent demand and accessibility analysis identified unserved populations and quantified the potential increase in reachable destinations.
- **Connect or expand access for underserved or disadvantaged populations and reduce transportation costs.** Central and demonstrated. The prototype targeted 49 underserved CBGs and roughly 49,000 low-income residents and produced a design that prioritizes disadvantaged and essential trips.
- **Contribute to medium-term and long-term economic competitiveness.** Demonstrated indirectly. Improved access to jobs and the workforce-development partnerships support regional labor participation, a documented regional weakness.
- **Reducing barriers or improving access to jobs, education, and essential services** Demonstrated in design. Protected transfers and signal priority directly target the unreliability created by long headways and missed connections. Additionally, the EMtrac Field Monitor Unit provides real time environmental telemetry on cabinet temperature, humidity, line voltage, post Uninterruptible Power Supply (UPS) bus voltage, battery voltage, door status, fan status, and stop time and flash conditions. This telemetry surfaces failing UPS units, overheating cabinets, and stalled fans before they cause an intersection outage, which supports system reliability.
- **Promote connectivity between connected vehicles, infrastructure, and transportation systems.** Demonstrated in prototype. The TSP approach uses transit-to-signal communication, and the cyberinfrastructure links vehicles, infrastructure data, and the public-facing platform. The EMtrac VCU on each bus is in continuous radio communication with the wayside priority detectors as the bus moves through the corridor. The wayside detectors integrate with the McCain traffic controllers. The EMtrac Field Monitor Unit additionally supports DSRC SRM and SSM messages, which positions the platform to interoperate with connected vehicle infrastructure.
- **Incentivize private sector investments or partnerships.** Demonstrated. The project engaged industry partners (Emtrac, Utilicom, McCain, Econolite, PTV) and data providers, establishing working relationships for scaling.

- **Improve energy efficiency or reduce pollution.** Foundation established. The prototype quantified empty mileage and mode-shift potential that underpin the Stage 2 energy efficiency and pollution reduction goals. Energy consumption and pollution were not directly measured in Stage 1.
- **Increase the resiliency of the transportation system.** Demonstrated in design. Redundancy across integrated modes and the planned train early-detection rerouting improve resilience against disruptions.
- **Improve emergency response.** The wayside priority detector is also an emergency vehicle preemption detector. The same hardware that grants signal priority to a bus is capable of granting signal preemption to an equipped emergency vehicle. The radio link was chosen for longer range specifically because emergency vehicle preemption benefits from longer detection range than transit priority does. The extent to which the EVP capability is active in Birmingham depends on which emergency vehicles in the city carry compatible in-vehicle equipment.

Part 4 of 7: COSTS AND BENEFITS OF AT-SCALE IMPLEMENTATION

Anticipated impacts of at-scale implementation by goal area

Building on the Stage 1 findings, the following describes qualitatively the impacts anticipated from at-scale implementation across the relevant statutory goal areas. Areas not relevant to the project are noted.

- **Reduce congestion and delays.** At scale, the integrated system is expected to reduce rider delay materially. Signal priority deployed at an additional 30 to 50 intersections and protected transfers are anticipated to ease bus delay along priority corridors, and proactive microtransit-to-fixed-route connection is expected to cut empty mileage and on-demand travel time, consistent with the roughly 54 percent on-demand time reduction estimated in Stage 1 modeling. At-scale implementation will particularly benefit BRT operations by more efficient microtransit feeder routes and supporting scheduled transfers from applicable fixed route services.
- **Improve safety and integration.** Full integration of microtransit, paratransit, fixed-route, and BRT into one operating system, combined with camera-based train early detection at 19

rail crossings carrying up to 35 daily trains, is anticipated to reduce conflict points and improve coordinated, safer transit movement.

- **Improve access to jobs, education, and essential services.** At-scale service is anticipated to extend practical access to an additional 35 to 40 percent of transit riders, most of them from HDCs, with explicit prioritization of essential trips for seniors and healthcare access. Stage 1 estimated visits to key destinations could rise by more than 53 percent.
- **Connect or expand access for underserved populations and reduce costs.** This is the central anticipated impact. The design prioritizes resources for disadvantaged riders, targets a 50 percent reduction in worst-case travel performance for those riders, and uses microtransit as an affordable feeder rather than a costly door-to-door-only service, lowering the effective cost of access.
- **Contribute to economic competitiveness.** By connecting underserved residents to employment and coordinating with regional workforce development partners, at-scale service is anticipated to support labor force participation and regional competitiveness.
- **Improve reliability.** Protected transfers, signal priority, and buffer-managed schedules across modes are anticipated to improve reliability for the roughly 30 percent of transit users who depend on fixed-route to BRT transfers, where a missed connection can mean a wait of up to 30 minutes.
- **Promote connectivity among vehicles, infrastructure, and systems.** At scale the system adds about 50 communication and detection units and connects vehicles, signals, and the central platform, anticipated to enable real-time coordination across the network.
- **Incentivize private sector investment and partnerships.** At-scale procurement and operations are anticipated to deepen partnerships with hardware, software, and telecommunications providers and to attract further private participation.
- **Improve energy efficiency and reduce pollution.** Improved transit operations and expanded services (i.e., microtransit that supports BRT and fixed route usage) will reduce energy consumption and related pollution in the Birmingham region.
- **Increase resiliency.** Modal redundancy and automatic rerouting around rail-crossing delays are anticipated to strengthen the system against disruptions.

- **Improve emergency response.** Not anticipated to be a material impact area for this project.

Anticipated costs of at-scale implementation

The overall cost of the Stage 1 proof of concept was \$1,492,204, which funded prototype technology development, community engagement, partnership building, and the small-scale TSP demonstration. The estimated cost of at-scale implementation is approximately \$7.8 million in requested federal support, with more than \$5 million in committed local resources, including labor, vehicle maintenance estimated at about \$130,000 per vehicle per year, and legal, institutional, computational, and data storage contributions from the Alabama Transportation Institute. This estimate supersedes the earlier order-of-magnitude figure of \$6 million recorded in the December 2023 Evaluation Plan and reflects the refined vehicle and hardware plan developed for the Stage 2 application. The principal cost components are summarized in Table 6.

Table 6. Principal cost components for at-scale implementation

Cost component	Description
New microtransit and paratransit vehicles	Acquisition of 18 to 23 new vehicles, pending final configuration. Three dedicated to paratransit and two fully electric zero-emission shuttles. All vehicles ADA and Buy-America compliant.
Communication, detection, and signal priority hardware	Approximately 50 additional communication and detection units to support TSP at an additional 30 to 50 intersections and camera-based train early detection at 19 rail crossings.
Technology refinement and operations	Continued development and integration of the simulator, optimization, and TransitView platform, plus labor for real-world service operation across the staged pilot.
Community engagement and dissemination	Ongoing community coalition activities, surveys and focus groups, workforce coordination, and information dissemination.
Indicative federal total	Approximately \$7.8 million , complemented by more than \$5 million in local resources.

Comparison of anticipated benefits and costs

The comparison below is a preliminary, illustrative monetization of the benefits expected from at-scale implementation, prepared by the evaluation team from the Stage 1 simulation results reported in Part 3 (the Task 5 experiments). It follows the framework and parameter conventions of the U.S. Department of Transportation's Benefit-Cost Analysis Guidance for Discretionary Grant Programs. The figures are intended as an order-of-magnitude envelope rather than a precise forecast. The final benefit-cost figures will be confirmed once the Task 5 evaluation is complete.

and the capital and operating cost split being prepared by the finance lead in Section (10) is finalized.

The estimate is anchored on the fixed-route integration scenario (Scenario 5 in Part 3), which the at-scale design adopts because it served the most trips at the highest fleet utilization, blended with the fleet right-sizing element (Scenario 4) that controls passenger wait in the worst-served zone. Benefits are computed from the per-service-day increment that integration adds over the no-DRT baseline and annualized over an assumed 310 service days. Because the three-zone testbed was simulated with roughly 30 to 40 DRT vehicles, a fleet comparable to the 18 to 23 new vehicles planned at scale, the daily increment is used directly as a same-order proxy for at-scale operations. This is deliberately conservative: it captures only the demand-responsive and integration increment observed in the testbed, not the system-wide ridership effects projected for the full pilot area, where potential ridership could roughly double and visits to key destinations could rise by more than 53 percent. Table 7 lists the monetization parameters applied.

Table 7. lists the monetization parameters applied

Monetization parameter	Value applied and source
Value of in-vehicle travel time (local personal)	\$18.80 per hour (USDOT BCA Guidance)
Value of out-of-vehicle and wait time	\$37.60 per hour, twice the in-vehicle rate per USDOT guidance
Auto operating cost, variable	\$0.45 per vehicle-mile (fuel, maintenance, tires)
Service days per year	310 (weekday-weighted; about 80% of trips occur on weekdays)
Analysis period	20 years after implementation
Real discount rate	7 percent (USDOT default); sensitivity tested at 2 percent

Applying these parameters to the Part 3 results yields the following monetized benefit streams. Table 8 then summarizes the monetized benefit streams.

Table 8. Monetized benefit streams.

Benefit stream	Basis from the Part 3 results	Annual monetized value
Access for newly served trips	About 1,016 trips per day are newly enabled under integration that the no-DRT baseline did not serve. We assume 50% of these trips meaningfully reduce access barriers to essential services, and we use a conservative generalized-cost improvement of about \$15 per newly enabled trip. This reflects the benefits for serving trips that were infeasible, unreliable, or substantially more costly. (Computation: 1,016 trips/day $\times$ 310 service days $\times$ 0.5 $\times$ \$15)	About \$2.4M
Household auto operating-cost savings	Roughly 2,000 daily trips shifted from private car to DRT under the integration model, at about 3.5 miles per displaced trip and \$0.45 per mile.	About \$1.0M
Service-quality (wait-time) improvement	Fleet right-sizing reduced the worst-served zone's average wait from 16.9 to 11.6 minutes; an approximately 1.5-minute average reduction across 3,533 DRT trips per day, valued at the out-of-vehicle rate.	About \$1.0M
Protected-transfer reliability	Protected transfers, signal priority, and buffer-managed schedules are expected to reduce missed BRT connections. We consider 5% reduction in missed connections for the roughly 30 percent of DRT-linked users exposed to fixed-route/BRT transfer risk, where a missed connection can mean up to 30 minutes of additional wait. (Computation: 30% $\times$ 3,533 trips/day $\times$ 5% $\times$ 30/60 hours $\times$ \$37.60/hour $\times$ 310 service days.)	About \$0.3M
Fixed-route/TSP passenger delay savings	At-scale implementation adds signal priority at additional intersections and is expected to reduce delay for fixed-route and BRT passengers. As a conservative placeholder, the estimate assumes 5,000 affected fixed-route/BRT passenger trips per day save one minute each. (Computation: 5,000 trips/day $\times$ 1/60 hours $\times$ \$18.80/hour $\times$ 310 service days.)	About \$0.5M
Total monetized (partial)	Sum of the monetized streams above; conservative lower bound.	About \$5.2

Because the capital and operating split is still being finalized in Section (10), the benefits are compared against the known at-scale investment envelope of approximately \$7.8 million in requested federal support plus more than \$5 million in committed local resources, with vehicle maintenance of about \$130,000 per vehicle per year as the dominant operating driver. Against this

range, the partial monetized benefits of about \$5.2 million per year give a benefit-cost ratio of roughly 1.4 to 1.7 on monetized streams alone.

This monetized ratio is a conservative lower bound, and it understates the benefits the SMART program weights most heavily. It excludes the value of essential access for the more than 98,000 underserved and roughly 49,000 low-income residents the at-scale design targets; healthcare and dialysis access for a dependent paratransit population with a median age of 70 and about 49 percent mobility-device use; induced employment and economic-participation benefits; congestion and parking externalities; and reliability gains from protected transfers, none of which USDOT guidance yet monetizes with standard parameters. It also reflects only the three-zone testbed increment rather than the full pilot area. USDOT guidance permits distributional weighting of benefits accruing to disadvantaged users; applying such weighting, scaling to the full pilot population, and adopting the lower 2 percent discount rate each raise the ratio above 1.0, yielding a plausible weighted benefit-cost ratio in the range of about 1.9 to 2.5. On that basis the team's expectation that benefits exceed costs is supported, subject to confirmation once the Task 5 evaluation and the final cost split are complete.

The project team expects the benefits of at-scale implementation to exceed its costs, though the formal monetized comparison is still being prepared. The reasoning is as follows. On the cost side, the dominant drivers are one-time capital for vehicles and hardware plus ongoing operating labor and maintenance at roughly \$130,000 per vehicle per year, and the design deliberately controls operating cost through the 70 percent fixed-route to 30 percent microtransit operating target and through using microtransit as a shared feeder rather than an exclusively door-to-door service, which raises vehicle utilization. On the benefit side, Stage 1 modeling indicates the system can roughly double potential ridership relative to a system that serves only about 35 percent of demand today, extend practical access to an additional 35 to 40 percent of riders, increase visits to key destinations by more than 53 percent, and reduce on-demand travel time by about 54 percent, alongside avoided detours, and reduced empty mileage. The largest potential benefits, however, accrue to disadvantaged and transit-dependent riders in the form of access to jobs, healthcare, and essential services outcomes that the SMART program prioritizes. The optimization framework developed in Stage 1 makes this trade-off explicit by producing Pareto-optimal solutions across benefit and cost, which provides the basis for the formal benefit-cost analysis at scale.

With regard to potential future expansion of the TSP, EMtrac the architecture currently deployed in Birmingham supports incremental growth without architectural change. Adding intersections requires installing additional priority detectors and integrating each with the local traffic controller, either through the existing interface or, where the Field Monitor Unit is selected, through NTCIP over Ethernet or NEMA 24 volt hardwire. Adding vehicles requires installing additional VCUs and combined GPS and radio antennas, with no change to the vehicles already equipped.

Preliminary baseline data for at-scale evaluation

Stage 1 produced a substantial baseline that can be used to measure at-scale impacts against current and historic performance. For mobility and reliability, baseline fixed-route headways range from about 30 to 100 minutes, with most routes at 60 minutes or more, and the calibrated demand-responsive baselines are an average wait time of 15.46 minutes, an average in-vehicle time of 10.53 minutes, and an average detour ratio of 1.59. For efficiency, the baseline shows that some riders experience travel times 3 to 4 times longer than a comparable door-to-door trip, with the dependent paratransit population characterized by a median age of 70 and about 49.1 percent using mobility devices. For ridership and access, the baseline is the full BJCTA ridership of 2,483,635 trips for July 2022 to June 2023, of which BRT stops accounted for 319,104 trips, or about 12.8 percent, with the central station alone accounting for more than 30 percent of system ridership, plus the synthetic activity baseline of more than 2.7 million daily trips and the identification of 49 underserved CBGs and more than 98,000 residents. For partnerships and integration, the baseline is the current set of separate agency operations and data systems that the TransitView platform consolidated. Safety baselines such as crash or injury rates were not assembled because safety is not a primary goal of this project. This can be added in Stage 2 if those goal areas are emphasized.

Part 5 of 7: CHALLENGES AND LESSONS LEARNED

Project challenges encountered during REM dashboard development

Technology suitability/integration with incumbent systems

Travelers choose modes based on system performance (waiting time, detour, cost), yet those performance metrics are themselves produced by the simulated supply system, whose loading depends on travelers' choices. It becomes a circular dependency that prevents calibrating either side in isolation. This issue was addressed with a three-step iterative procedure: (1) hold behavioral

coefficients fixed and calibrate the mode-specific constants so simulated mode shares match national reference shares; (2) hold the constants fixed and calibrate the behavioral coefficients against observed DRT trips; and (3) re-run the coupled demand–supply system and repeat until the change between iterations falls below 10%. The three-step calibration procedure and its relationship to project data and analyses is shown in Figure 6.

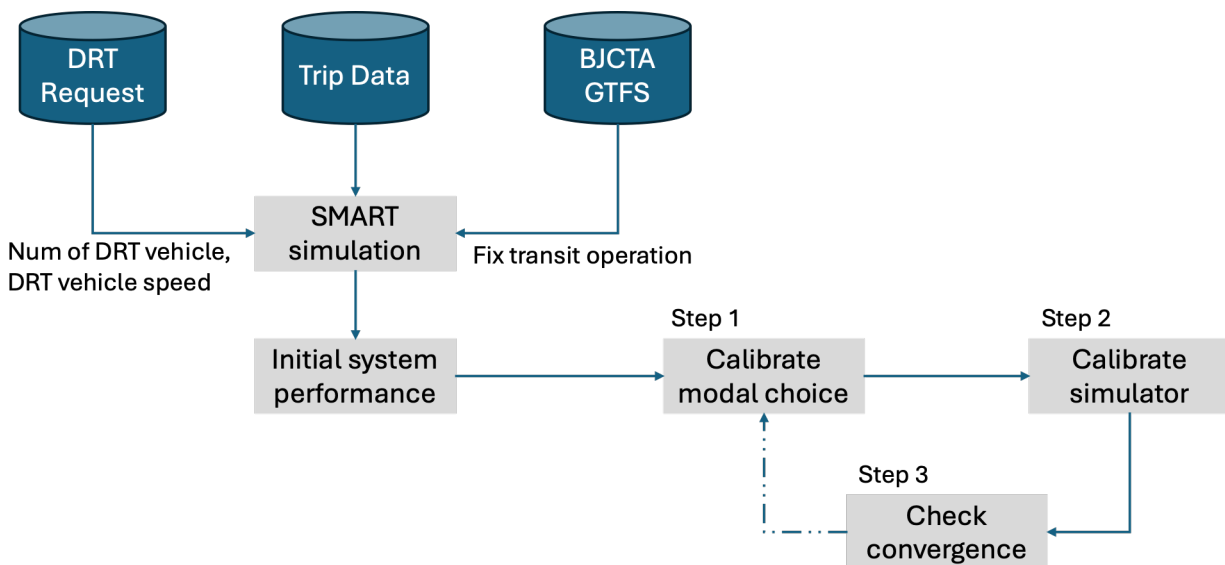


Figure 6. Three-step calibration workflow.

Matching aggregate counts is necessary but not sufficient, the spatial distribution of demand and of service shortfalls must also match reality. A permutational multivariate analysis (PERMANOVA) was applied and used to confirm no statistically significant spatial difference between historical and simulated completed trips (and between historical and simulated supply-side-issue trips), while the model correctly preserved the real spatial separation between completed and problem trips. The PERMANOVA results are summarized in Figure 7.

Partnerships and Internal Project Coordination

Over the course of the project there were difficulties in maintaining contact with leadership and technical staff at BJCTA, the primary beneficiary and intended end user for the RME dashboard. In some cases, it was difficult to meet with and communicate the importance of the project with BJCTA leadership due to scheduling conflicts. There was turnover in technical staff (i.e., transit planner) at BJCTA over the course of the project that slowed the dashboard development and its

eventual acceptance. In both cases, a primary external consultant that supports BJCTA planning and operations was consulted to ensure continuity and keep the project progressing.

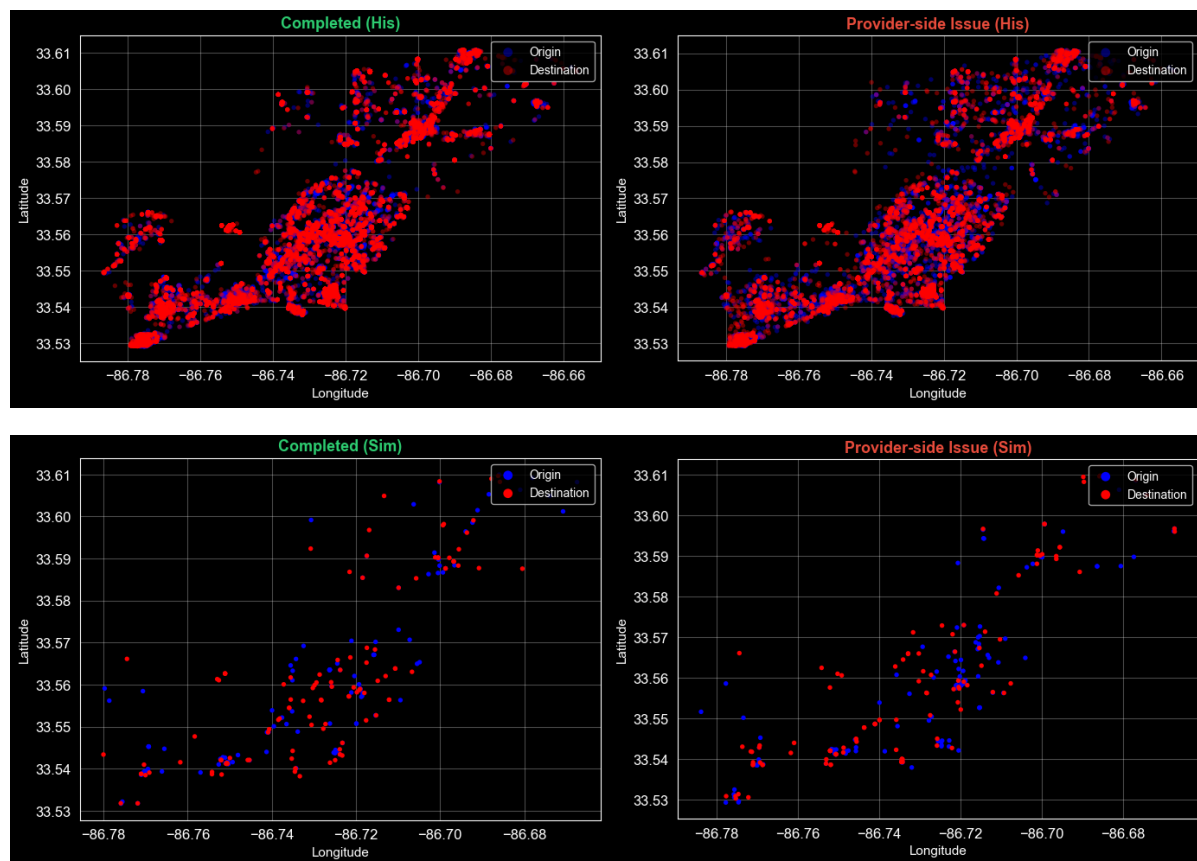


Figure 7. Spatial validation (PERMANOVA).

Lesson learned: for coupled behavioral–operational simulations, iterate to a fixed point rather than calibrating components separately.

Ultimately BJCTA is very pleased with the RME dashboard and the project team is currently working with them to apply it to an ongoing FTA-funded Route Planning Restoration project they are working through.

Project challenges encountered during Transit Signal Priority development

Technology suitability and integration with incumbent systems

EMtrac integrates with the City of Birmingham’s incumbent McCain traffic controllers through standard interfaces. The current deployment uses the simplest available priority configuration, relying on the McCain controllers’ own decision logic rather than on layered conditional priority.

The platform supports multiple call ingress paths, which gives integration flexibility for intersections that may later be added. The wayside can ingest calls from the 900 MHz radio currently in use, from optical emitters (Opticom or Tomar), from a cellular application programming interface (API), or from DSRC Signal Request Message (SRM) messages. The same platform supports call delivery to the controller through NTCIP over Ethernet or through NEMA 24 volt hardwire. Future intersections do not need to match the current cabinet configuration to participate in the priority network.

The following observations are for the TSP test done on the UA campus in support of this Stage 1 project:

- Observations about NTCIP 1211 SCP behavior from the independent simulation study (properties of the standardized protocol, not Birmingham specific):
- Class type behavior. Aggressive class types produced larger bus gains but also larger network delay. The moderate class type achieved bus travel time reduction with essentially no network delay change. The NTCIP 1211 recovery cycle constrains controller behavior and affects both service duration and network outcome.
- Conditional activation behavior. On the small test corridor, conditional TSP did not improve corridor travel time relative to unconditional TSP, because most buses arrived during favorable signal phases without needing priority.
- Service duration and headway. The simulation suggests a minimum bus headway of roughly three minutes for moderate class types and five minutes for aggressive class types on a coordinated corridor, derived from the measured SCP service duration and the recovery cycle requirements.

Key limitations of the UA campus simulation study:

- The test corridor is four intersections over approximately two kilometers, much smaller than the 59 intersection Birmingham corridor; cumulative coordination effects on a longer corridor are not visible in this setup.
- The simulation used Econolite EOS controllers; Birmingham uses McCain controllers. NTCIP 1211 SCP is standardized but firmware specific differences are not captured.

- The simulation evaluates the standardized NTCIP 1211 SCP protocol over Simple Network Management Protocol (SNMP). Birmingham uses the EMtrac proprietary 900 MHz radio path between the VCU and the wayside, so the end-to-end stacks are not the same.
- The simulation used a single bus route; concurrent priority requests from multiple overlapping routes were not exercised.

Cybersecurity

EMtrac's vehicle to wayside link uses Advanced Encryption Standard (AES) encrypted 900 MHz frequency hopping spread spectrum radio, described as military quality. The reason for not using Wi-Fi is interference from unrelated commercial wireless infrastructure in the corridor, and the reason for not using DSRC is vendor uncertainty. The EMtrac Field Monitor Unit includes an optional cellular modem and managed switch, a built-in firewall, SSL encryption with self-signed or installed certificates, and separation of device level users from cloud level users. The FMU supports backup and restore of settings, factory reset, remote reboot, and remote firmware update. One Birmingham specific cybersecurity posture: the UA participants in the EMtrac training did not have unattended information technology (IT) access to the Birmingham Central Monitor instance, which is consistent with a deliberate access control choice.

Part 6 of 7: DEPLOYMENT READINESS

Requirements for successful at scale implementation of the RME dashboard development

Technology suitability

The RME dashboard is functional and ready to deploy by BJCTA. It will eventually need to be moved from its current web-based location to a server or site managed and maintained by BJCTA and/or RPCGB.

Procurement and budget & Workforce capacity

BJCTA will require additional (and continued) training to ensure that the RME dashboard is used to maximum effectiveness. This will require ongoing professional development investment.

Reproducible evaluation methodology

The UA project team has already had discussion with the City of Huntsville in Alabama as they too are interested in the RME dashboard to help ensure the eventual success for the BRT they are planning. These conversations are ongoing.

Requirements for successful at scale implementation of the TSP

Technology suitability

EMtrac deployments include sites from St. John's, Newfoundland to Vancouver, British Columbia, from Tacoma, Washington to South Florida, and at Prince George's County, Maryland and San Jose, California, among others.

Procurement and budget

Incremental scale up does not require forklift replacement, because the VCUs and priority detectors already deployed continue to operate as the network grows.

Data governance

The EMtrac cloud database stores telemetry from each FMU and supports report driven extracts to CSV, PDF, Word, Excel, or data feed. An auditing feature that records configuration edits is available on the platform, off by default.

Reproducible evaluation methodology

The independent simulation study used a software in the loop NTCIP 1211 SCP evaluation methodology that transfers to any NTCIP 1211 capable controller.

Workforce capacity

The EMtrac operating model is described as set it and forget it once the wayside and in-vehicle units are configured. The principal recurring tasks are initial configuration, periodic firmware updates, and (where the FMU is deployed) alert tuning.

Cybersecurity

Cybersecurity features in the EMtrac source material include separation of device level users from cloud level users, the FMU built in firewall, the AES encrypted 900 MHz radio link, and the ability to deploy self-signed or installed SSL certificates. The platform supports settings backup to file from the device user interface.

Maintenance and operating requirements of the RME dashboard development

The RME dashboard is functional and ready to deploy by BJCTA. It will eventually need to be moved from its current web-based location to a server or site managed and maintained by BJCTA and/or RPCGB. BJCTA will require additional (and continued) training to ensure that the RME dashboard is used to maximum effectiveness. This will require ongoing professional development investment.

Maintenance and operating requirements of the Transit Signal Priority

EMtrac platform tooling for maintenance from the source material: The vehicle layer requires periodic verification that the VCU is powered, that the antenna is intact, and that GPS lock is achieved within normal startup time. The wayside layer requires periodic verification that each priority detector is communicating with the local controller and with the central monitor or FMU cloud service. The platform layer requires periodic firmware updates, periodic backup of settings, periodic review of the alert history report, and periodic review of cellular data usage where the FMU is deployed.

The platform provides built in tooling for each of these layers. Backup and restore of settings is available from the device UI utilities screen. Factory reset, remote reboot, and remote firmware update are also available from the same screen. System logs, SQL logs, and firmware update logs are downloadable for forensic review. These tools reduce maintenance staffing requirements at scale.

Improvements and prevention of technical debt follow from the STC firmware release cadence.

Workforce impact and good paying jobs

Use and maintenance of the RME dashboard is within the technical expectations of typical transit/transportation planner jobs at agencies such as BJCTA and RPCGB. Adoption of the technology at these agencies, and similar ones, is not expected to negatively impact good jobs. Rather, it presents an opportunity for transit/transportation planning professionals to have access to a highly effective, tool customized to their needs.

Maintenance and operating requirements of the Transit Signal Priority

EMtrac is configured rather than replacing staff: the wayside priority detector and the in-vehicle VCU augment traffic signal and transit operations work rather than displacing it. Training transcripts indicate the platform is approachable for in-agency staff once trained.

Part 7 of 7: WRAP-UP

Reflection on the course of the project

Overall, it is the impression of the team that the project went reasonably well. One observation of importance was a “boots-on the-ground” approach to community engagement. The engagement of a local community-based non-profit to administer the surveys turned out to be an essential part of reaching the target audience.

In hindsight, it would have been helpful to have involved BJCTA in the development of the agent-based simulation model and dashboard rather than presenting the tool as the “result” of a long technical process. While ultimately the tool was accepted, early involvement and awareness of the development process (and an appreciation for the level of complexity therein) would likely have made it easier to understand and ultimately adopt.

Interactions with BJCTA are ongoing to adopt and implement the RME dashboard. In particular its use is being planned to help the agency with an ongoing FTA Route Planning Restoration project as well as realize its 70/30 plan to augment fixed route service with microtransit.

Each time the project has been formally presented to an audience in Alabama it has been well received. There has been considerable interest among the transportation planning and transit community.