Evaluating the Impacts of I-24 Smart Corridor Strategies

Research Final Report

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DISCLAIMER

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16. Abstract

The I-24 Smart Corridor project, launched by TDOT since 2018, is a first-ever Smart Corridor study in Tennessee. This project integrates I-24 and SR-1, a parallel arterial roadway, with physical, technological, and operational enhancements to provide road users with accurate, real-time information and actively manage traffic. The I-24 project is conducted via three phases. At the time of this report, Phases 1 and 2 are complete, while Phase 3, targeted at long-term development, is still under design and deployment. This research project aligns with the project’s overarching goals, to assess the impacts of multiple strategies implemented during Phases 1 and 2, with particular emphasis on travel time reliability, safety, and mobility. Through comprehensive before and after evaluations and benefit cost analyses, this effort also aims to provide a data-driven foundation for future investments in Smart Corridor initiatives across Tennessee.

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Executive Summary

The purpose of this study is to assess the impacts of the strategies deployed as part of the I-24 Smart Corridor. Launched by Tennessee Department of Transportation (TDOT) since 2018, the I-24 Smart Corridor is the first such endeavor in the state of Tennessee. This project integrates Interstate 24 (I-24) and a major parallel arterial State Route 1 (SR-1) employing physical, technological, and operational enhancements, to provide road users with accurate real-time information and active traffic management. The whole project is conducted via three phases. Phase 1 and Phase 2 are complete, while Phase 3, targeted at long-term development, is still under design.

This study documented herein aligns with the I-24 Smart Corridor project's overarching goals to assess the impacts of various strategies implemented during Phases 1 and 2, with particular emphasis on travel-time reliability, safety, and mobility. Through comprehensive before-and-after evaluations and benefit–cost analyses, this effort also aims to provide a data-driven foundation for future investments in Smart Corridor initiatives across Tennessee**.**

Key Findings

- **Safety Improvement is Statistically Significant.**
    - After the signal system upgrades, many signalized intersections across the four connected cities demonstrated measurable safety improvements. Particularly, Nashville, Smyrna, and Murfreesboro showed statistically significant reductions in rear-end and sideswipe crashes. Additionally, these cities experienced notable decreases in property damage only (PDO) and injury crashes, with overall crash reductions ranging from 20% to 30%.
    - After the implementation of Variable Speed Limit (VSL) and Lane Control Signs (LCS), the safety benefits vary across the segments on I-24 Smart Corridor, but overall, suspect serious injury, suspect minor injury, possible injury, PDO crashes declined by 18.1%, 10.4%, 17.5% and 3.8%, respectively. Rear-end and sideswipe crashes decreased by 14.0% and 3.2%, respectively. The total number of secondary crashes reduced by 13.8%. The rate of secondary crash declined from 7.72% to 6.61%.
- **Travel Time Reliability Improved.**
    - Ramp extension strategy was found to be particularly effective in alleviating congestion and improving mainline traffic flow toward Nashville (Westbound), The average speed increased by 19.2% near the I-24W/Briley Pkwy exit ramp, followed by the I-24W/Bell Road entrance ramp, with a 12.3% improvement during peak hours. Correspondingly, the Buffer Time Index (BTI), a measure of extra time the traveler needs to add to their plan to ensure on-time arrival, reduced by 58.9% at I-24W/Briley Pkwy exit ramp, and by 15.3% at I-24W/Bell Road entrance. The benefits of the two ramp extensions on the Eastbound were comparably less notable, which might be due to less traffic exposures.
    - The implementation of the VSL/LCS systems has helped cool down the previously rising average travel time, even as westbound and eastbound Vehicle Miles Traveled (VMT) increased by 10.3% (approximately 80,000 vehicle-miles per day),

    and 3% (40,000 vehicle-miles per day), respectively, after the VSL/LCS implementation. Although average travel time and reliability initially declined during the first fiscal year of VSL/LCS deployment, notable improvements were observed in the second fiscal year (2024–2025). This trend suggests that VSL/LCS performed as intended, and drivers became familiar with the overhead gantry system and adapted to its operational patterns over time.
  - Traffic congestion during peak hours starts about 20-30 minutes earlier and persists about 30-60 minutes longer after the VSL implementation, which is likely to be because of the proactive and conservative settings of the VSL system.
- **Traffic Patterns Exhibited Directional Asymmetry.**
  - A much larger increase of VMT was observed in traffic towards Nashville (+10.3%, ~80,000 vehicle-miles per day) than the traffic towards Murfreesboro (+3%, ~40,000 vehicle-miles per day). This may suggest the growing economic attractions of Nashville city in recent years.
  - The eastbound traffic queue originates near the Davidson–Rutherford County boundary. By contrast, the end of Westbound traffic queue extends to the Sam Ridley Pkwy in Smyrna. It is also worth noting that westbound delay between Waldron Road and Sam Ridley Parkway has significantly improved following the implementation of the VSL/LCS system.
  - Ramp extension in Westbound particularly improved the travel time and travel-time reliabilities. By contrast, ramp extension in eastbound received less notable travel time improvement.
- **Economic Return on I-24 Smart Corridor Project is Remarkable.**
  - The return is **$1.13** for every dollar invested in the I-24 Smart Corridor project, assuming a 10-year service period and a 7% annual discount rate. This value is expected to increase as the service years extend and additional travel time savings materialize in the future.
  - The annual crash savings is estimated at **$10.1 million**, while the net annual return after operations and management costs is approximately **$1.2 million**.
- **Candidate Corridor for Future Investment in Tennessee.**
  - Based on the corridor benefits analyses, future investment priority of similar technologies should be given to I-40 in Knoxville, I-65 in Nashville, and I-24 in Chattanooga, in that order.
  - The I-65 corridor in Nashville and the I-24 corridor in Chattanooga are less suitable than the I-40 corridor in Knoxville because of the challenges with integrated management; typically, the presence of a viable parallel arterial route is needed for traffic diversion and coordination. Nonetheless, strategies such as VSL/LCS, ramp extension could still be implemented to mitigate the rear-end, sideswipe crashes and thereby improving the travel time reliability for those corridors.

Key Recommendations

The success of an Integrated Corridor Management (ICM) corridor relies on more than advanced technologies, it depends on strong data foundations, coordinated partnerships, consistent performance monitoring, and active public engagement. Each recommendation targets one of these core aspects to enhance corridor efficiency, transparency, and user compliance, ensuring that ICM investments achieve long-term operational and safety benefits.

- **Data quality assurance and system-wide data integration** are critical to the successful development and operation of the Smart Corridor. During the before-and-after analysis, the limitations of the legacy RDS data prevented a full representation of pre-implementation traffic conditions for the VSL/LCS system. Therefore, third-party probe data were utilized to ensure consistency and continuity in the analysis. Besides, the crash data are saved by different databases such as ETRIMS, TITAN, AASHTO and RITIS or SWCS. The differences between these are not fully known or reconciled. It is recommended to integrate all the key data sources and conduct a data quality assessment to ensure the quality of future performance monitoring efforts.
- **Data sharing across TDOT divisions and partner agencies** is highly recommended to enhance coordination and support performance evaluations. At present, much of the operational data is managed by external consultants or contracted data collectors, which makes access to crucial and already-collected data circuitous for the purposes of academic assessments and impartial evaluations. Establishing a centralized data-sharing framework would improve transparency, facilitate interagency collaboration, and strengthen data-driven decision-making.
- It is recommended that **targeted law enforcement or automated speed enforcement strategies be coordinated** during congestion periods to enhance compliance and improve overall corridor performance. Driver compliance with VSL/LCS is critical to achieving the intended safety and mobility benefits. If commuters adapt to “violating the VSL” due to a lack of enforcement, the effectiveness of the ICM system is likely to diminish.
- TDOT could benefit from **continuously monitoring the performance and adjusting the operation strategies,** as road users might get more familiar with the VSL/LCS, and travel time reliability might improve as a result. The previous trends of rapid rise in average travel time and decrease in travel time reliability appear to have been effectively curbed following the implementation of the VSL/LCS systems.
- **Public attitudes and sentiment matter**. TDOT can continue to conduct periodic surveys to assess traveler sentiment regarding perceived changes in travel time, delay, safety, and support for future investments**,** using these insights to guide outreach and operational refinements. Additionally, LLM-type social media sentiment assessment could provide unsolicited insights.
- **Conduct proper public outreach and education**, especially highlighting the corridor as an interdependent system. Educating road users to comply with the VSL/LCS can positively influence their driving behavior and thereby improve the performance of ICM strategies.

Conclusions

This study identified appropriate performance measures and secured relevant data to assess the impact and benefits of the I-24 Smart Corridor project. The analysis revealed that average westbound speeds improved by up to 19.2% near the I-24W/Briley Parkway ramp and 12.3% near Bell Road, with corresponding reductions in Buffer Time Index (BTI) by 58.9% and 15.3%, respectively. Signal system upgrades produced substantial safety benefits, rear-end crashes dropped by 21.6%-48.6% in four cities. Notably, in Murfreesboro, overall crashes across all severity levels declined by 24–34%. Following the VSL/LCS implementation, rear-end and sideswipe crashes decreased by 14.0% and 3.2%, respectively. The injury crashes also reduced by 10.4%-18.1%. The secondary crashes declined by 13.8%, and the rate of secondary crashes fell from 7.72% to 6.61%, despite increased VMT of 3–10%. Although corridor-level travel time savings were modest, the Benefit Cost Ratio considering the safety improvements reached **1.13** over a 10-year service life, with potential to grow as operational familiarity improves. The project also established a robust performance monitoring framework and identified three potential corridors for future ICM investment, with I-40 in Knoxville standing out as a particularly strong candidate.

The findings offer practical insights into the effectiveness of ICM strategies and establish a data-driven foundation for future Smart Corridor planning and investment. Lessons learned from this project can guide TDOT in refining operations, enforcement, and coordination, while the evaluation of three candidate corridors helps prioritize future improvements. The established Power BI dashboards further enable continuous performance monitoring and adaptive management for the I-24 Smart Corridor.

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Glossary of Key Terms and Acronyms

Acronyms	Full term
ASSHTO	American Association of State Highway and Transportation Officials
AMS	Analysis, Modeling, and Simulation
ARM	Adaptive Ramp Metering
ATM	Active Traffic Management
BAA	Before After Analysis
BCA	Benefit Cost Analysis
BCR	Benefit Cost Ratio
BTI	Buffer Time Index
CRR	Crash Reduction Rate
CPI	Consumer Price Index
DMS	Dynamic Message Signs
DSS	Decision Support System
EAC	Equivalent Annual Cost
ETRIMS	Enhanced Tennessee Roadway Information Management System
FHWA	Federal Highway Administration
FY	Fiscal Year
HOV	High Occupancy Vehicle
HPMS	Highway Performance Monitoring System
HSR	Hard Shoulder Running
ICC	Incident Clearance Time
ICM	Integrated Corridor Management
IMS	Incident Management System
IT	Information Technology
ITS	Intelligent Transportation System
LCS	Lane Control Signs
MM	Mile Marker
MOE	Measures of Effectiveness
MPO	Metropolitan Planning Organization
NPMRDS	National Performance Management Research Data Set
PCE	Personal Consumption Expenditures
PDO	Property Damage Only
PDSL	Priced Dynamic Shoulder Lane
PI	Principle Investigator
PTI	Planning Time Index
QWS	Queue Warning Systems
RDS	Radar Detector System
RITIS	Regional Integrated Transportation Information System
RTIS	Real-time Information Sharing.
SR	State Route
SWCS	Smartway Central Software
SwRI	Southwest Research Institute

TDOT	Tennessee Department of Transportation
TI	Transit Integration
TITAN	Tennessee’s Integrated Traffic Analysis Network
TSM	Traffic Signal Management
TSMO	Transportation Systems Management and Operations
TTR	Travel Time Reliability
US	United States
USDOT	United States Department of Transportation
VMT	Vehicle Miles Traveled
VOT	Value of Time
VSL	Variable Speed Limit

Chapter 1 Introduction

“About 200,000 new residents are expected to move to the 10-county mid-state Nashville area over the next five years” said Ralph Schulz on January 24, 2022. That is an increase of near 110 new residents every single day and they will need to work, shop, go to school, entertain, and, in general, put increasingly more pressure on the Nashville transportation network, including the I-24 corridor.

Since 2018, the Tennessee Department of Transportation (TDOT) has been designing and deploying a I-24 Smart Corridor Project between Nashville and Murfreesboro. This project pairs I-24 with State Route (SR) 1 using connector routes between them. As **Figure 1-1** shows, I-24 project limit starts from I-24 at exit 53 in Metro Nashville to exit 81 in the City of Murfreesboro, which is approximately 28 miles. The paired SR-1 project also stretches from I-24 in Metro Nashville to SR-10 in the City of Murfreesboro, covering about 28.5 miles. There are 11 major connector routes between I-24 and SR-1, which extends for approximately 30 miles. The I-24 Smart Corridor project takes a comprehensive approach to improving the safety and travel time reliability along the corridor by managing existing infrastructure and using emerging technologies. A major strategy is the VSL/LCS system deployed since June 2023, which marks the beginning of Integrated Corridor Management (ICM) in Tennessee. This ICM limit is from mile markers 53 to 57. **Figure 1-2** shows the timeline of a series of intelligent strategies implemented on the I-24 Smart Corridor, these include:

- Emergency pull-offs
- Ramp extensions
- Connected vehicle infrastructure, fiber upgrade.
- Signal Systems upgrade
- Traffic detectors upgrades
- Dynamic Message Signs
- Lane Control Signs (LCS)
- Variable speed limits (VSL)
- Ramp metering (still in design)
- Choice lane (still in design)

The stated goals of I-24 Smart Corridor include:

- Increase travel time reliability
- Increase mobility of all modes
- Reduce the concentration of crashes, and
- Develop agency coordination

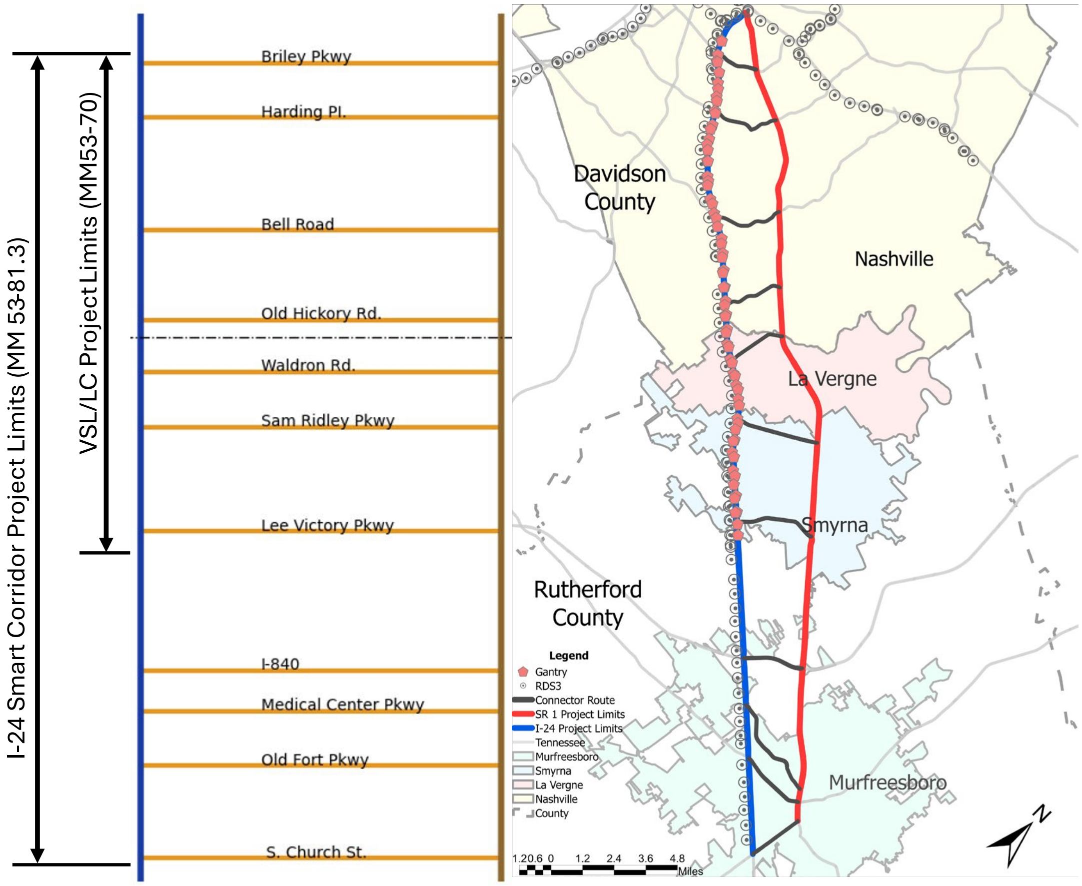

Figure 1-1 I-24 Smart Corridor Project Limits

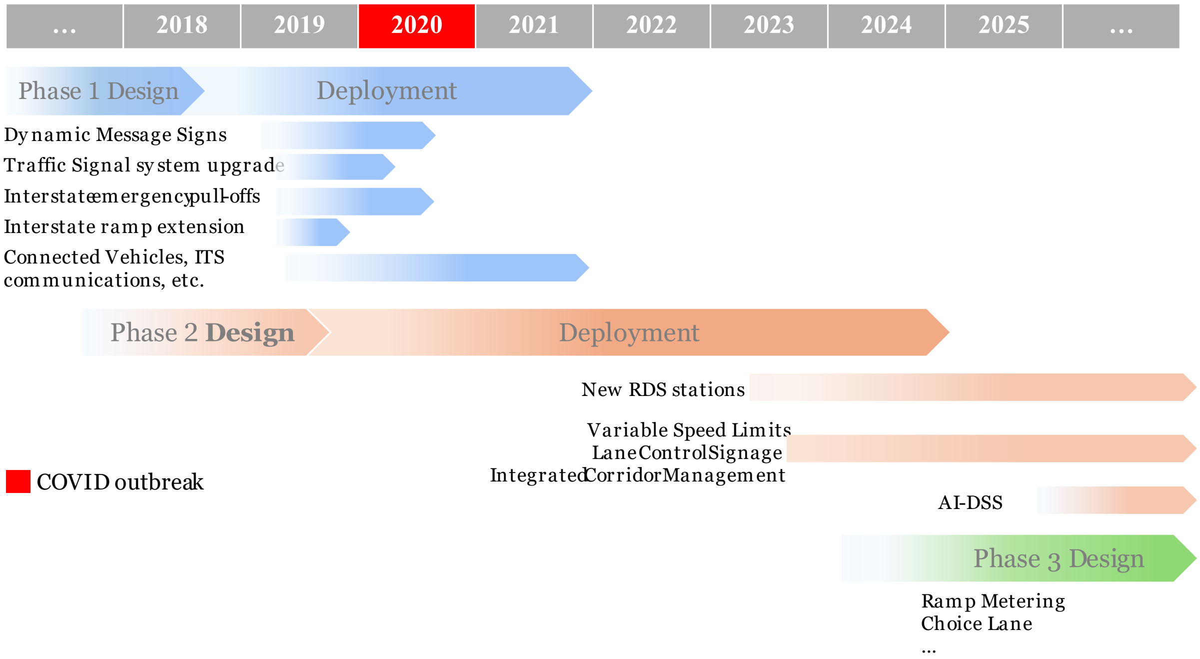

Figure 1-2. Timeline of I-24 Smart Corridor Project

1.1 Objectives of the Research

This research will identify performance measures and the necessary data to determine the impacts of the strategies deployed as part of the I-24 Smart Corridor. The research will also review before-conditions of all phases and after-conditions for phases 1 and 2 of each strategy deployed, and it will provide a Benefit Cost Analysis (BCA) of the Phase 1 and 2 strategies. The final report should provide information that will be useful in scoping future Smart Corridors. In general, the objectives of the research include:

- To establish performance metrics and identify data needed
- To measure the performance metrics before all phases
- To measure the performance metrics after all phases
- To perform before/after and benefit/cost comparisons for deployed strategies.
- To transfer the success/experience to other corridors.

1.2 Scope of Work

Based on the I-24 Smart Corridor initiatives, the following tasks were identified to ensure the success of the proposed study.

Task 1. Project management - During the life of the project, the PI maintained regular communication and reported project progress to TDOT technical and research staff through quarterly and ad hoc meetings. As a part of the team in this state's first-ever integrated corridor management project, our team was also actively coordinated with other TDOT partners such as Stantec, Arcadis, and Vanderbilt research team to ensure the successful implementation of the I-24 Smart Corridor project.

Task 2. Performance Measures and Data Needs – Based on the various strategies implemented in the I-24 Smart Corridor during Phases 1 and 2, an array of appropriate performance measures was identified and compared based on their appropriateness and data availability. In addition to TDOT's own RDS data, SmartWay CS incident data, ETRIMS data, TN-Times traffic data, and Emergency pull-off video data, the research team employed NPMRDS data and WAZE data to complement the speed information. Methodologies for using these heterogeneous data sets for calculating various performance measures were developed correspondingly.

Task 3. Data Collection and Management – Depending on the actual implementations of the I-24 Smart Corridor strategies in Phases 1 and 2, as well as the COVID impacts, data deemed necessarily for calculating various performance measures were collected for different time span to eliminate the confounding or latent effects. Shapefiles for the entire corridor, including the segmentation of I-24, SR-1, and all the other connecting roadways were acquired with specific deployment location information of the strategies. To discern the contributing benefits of different strategies, the deployment details of them are meticulously logged. Our research team has already been collecting and archiving RDS, WAZE, and NPMRDS.

Task 4. Before After Analyses for deployed strategies – Applying the methodologies, with sensible modifications when necessary and employing the data sets collected, we calculated the performance measures including the travel time reliability, safety, mobility etc. for any periods data are available for strategies including emergency pull-offs, ramp extension, VSL and LCS, upgraded signal systems, and upgraded detectors. The data preprocessing such as RDS data quality check and imputation were conducted to exclude the negative impact of data issues on strategies evaluation. The year of 2020 which was affected by pandemic was not included in the prior analysis.

Task 5. Benefit Cost Analysis – Based on the Task 4 results, a comprehensive BCA was conducted by considering the project service year, inflation, and discounting factors. The Benefit contains the delay and crash savings, and the cost consists of the project construction, deployment, operation, and administrative cost which were obtained from TDOT.

Task 6. Candidate Corridors Evaluation & Recommendations – Based on the characteristics and initial results of I-24 Smart Corridor, a couple of candidate corridors in the state were examined for future strategy deployment. Measurement of Effectiveness analysis was conducted to provide the evidence for deploying any of strategies that have been implemented in I-24 Smart Corridor.

Task 7. Final Report and Workshop – All the important findings related to the before-after analysis (BAA), and BCA were wrapped up in the final report. Discussions, lessons, and recommendations for future improvement were also included. The technical product, such as performance measurement dashboards, will be shared with TDOT. A workshop was scheduled to brief on the important findings and transfer the technical product to TDOT.

1.3 Challenges of this project

The first challenge of this study is to identify appropriate performance measures for gauging the conditions of corridor traffic operations and crash safety. By comparing these performance measures before and after the deployment of various countermeasure strategies, one could evaluate the effectiveness and benefits of different strategies, or the combination of them. The primary focuses here are on traffic operation conditions (e.g., travel time reliability) and crash safety conditions (e.g., number of severe crashes and concentration of crashes) before and after the implementation of the strategies in Phases 1 and 2 (see **Figure 1-2**). Phase 3 of Smart Corridor is still under design, which is not considered in this project.

The next challenge is to devise methodologies and collect necessary data that could help accurately calculate the selected performance measures. FHWA's PM3 and TDOT's TSMO process have already given this study an excellent starting point.

A significant challenge to this study is recognizing the ongoing rapid growth in population and, hence, transportation demand, which has the potential of easily outpacing the benefits gained through improvement strategies implemented by TDOT. So, the study needs to factor the effects of rapidly growing demand into the BCA and help TDOT better understand the impacts of these improvements to inform future transportation projects.

Finally, it would be desirable to recommend candidate Tennessee corridors for the deployment of the Intelligent Transportation Systems (ITS) based on the findings of this study.

Chapter 2 Literature Review

The takeaway findings of literature review were presented first, followed by the detailed explanation and discussion of reviews in terms of previous ICM projects in the US, before after analysis and benefit cost analysis.

2.1 Summary of Important Findings

Integrated Corridor Management projects have shown measurable benefits in improving traffic reliability, safety, and multimodal performance in the US. Most deployed corridors integrate freeway and arterial operations using technologies such as Variable Speed Limits (VSL), Lane Control Signs (LCS), Dynamic Message Signs (DMS), and Queue Warning Systems (QWS). Many also apply dynamic shoulder or managed lanes to expand capacity during peak periods. Corridors like I-15 (San Diego), I-95 (Miami), and I-24 (Tennessee) have further advanced by adopting Decision Support Systems (DSS) and real-time data analytics for smarter operations.

Before and after evaluations consistently indicate reductions in crashes and improvements in travel time reliability, especially where HSR, VSL, or managed lanes were implemented. Safety gains have been notable, such as a 22% drop in total crashes and 62% fewer serious injuries on I-76 Smart Corridor (Philadelphia, PA). Benefit Cost Analyses demonstrate strong economic justification, with reported ratios ranging from 1.5 to 10 in real projects and up to 25 in simulation studies, mainly from time savings and crash reductions.

Key lessons emphasize that technology alone is insufficient; success depends on early multi-agency collaboration, real-time data sharing, and public acceptance. Unified operations centers enhance coordination and traveler communication, while visible and consistent enforcement ensures user compliance. Overall, the experience from existing ICM projects shows that combining advanced technologies with institutional cooperation and public trust is essential for sustainable and effective corridor management.

2.2 Previous Integrated Corridor Management Projects

Smart corridors take a comprehensive approach to managing existing infrastructure and communicate with road users. Generally, smart corridors strive to continuously monitor and smooth traffic flows, detect traffic incidents and coordinate the incident response, coordinate with other arterial routes, and eventually promote travel time reliability, safety, mobility, and multimodal traffic. The investment in smart corridors typically covers the roadway physical investments, infrastructure investments, and digital investments. Please note that different States may name such Smart Corridors implicitly and differently, but none or less, they are essentially centered on the development of ICM and ATM. A variety of geographically dispersed smart corridor projects are presented below, with the intent of providing insight into their locations, technologies implemented, and results. **Figure 2-1** presents a synthesis review of Smart Corridor projects that focus on ICM and ATM systems proposed or developed nationwide in the US (*1-6*). The USDOT started the ICM initiatives in 2006 (*7-9*). Currently, such programs are being set up more widely in heavily congested urban corridors nationwide. There were 13 pioneer sites proposed for ICM development, including the eight concept development sites (green), three analysis modeling, and simulation (AMS) sites (orange), and the two demonstration sites (blue). 13 sites received the planning grants, which are marked by red circles. Although many states are considering the development of Smart Corridors, this study summarizes 10 existing Smart Corridor projects, including the I-24 Smart Corridor, which are illustrated by the text boxes in **Figure 2-1.**

The key findings are summarized as follows:

- Many of those, like I-15 in San Diego, CA, I-80 in the Bay Area, CA, I-85 in Charlotte, NC, and I-24 Smart Corridor, are paired with parallel arterial corridors to address the regional traffic issues. Further strategies such as transit priority, traffic diversion, and signal timing and coordination are developed to manage the traffic between freeway and arterial corridors.
- On freeways, multiple technologies are often deployed together to maximize their combined benefits for traffic safety, mobility, and reliability. For example, Variable Speed Limits (VSL), Lane Control Signs (LCS), Dynamic Message Signs (DMS) and Queue Warning Systems (QWS), are frequently installed on the same gantry to alert drivers to slow down.
- Several ICM corridors employed dynamic shoulder lane operations through overhead gantries to increase peak-hour capacity. For instance, I-35W (Minneapolis, MN) and I-95 (Miami, FL) implement priced dynamic shoulders and HOV lanes, whereas I-66 (Northern Virginia) and I-76 (Philadelphia, PA) provide non-tolled shoulder access during congestion periods. Both operational strategies have demonstrated improvements in capacity utilization and congestion mitigation.
- With advancements in data collection, wireless communications, and artificial intelligence, Decision Support Systems (DSS) have been implemented to enhance the operational decision-making of Smart Corridors. Notable examples include the I-15 Smart Corridor in San Diego, CA, US-75 in Dallas, TX, and the I-24 Smart Corridor in Nashville, TN. From this perspective, the I-24 Smart Corridor is among the leading projects in the United States to deploy DSS technologies for optimizing incident response, traffic operations, and corridor management.

The Smart Corridors are built to improve the travel time reliability, safety, and multimodal traffic. The key effectiveness of developed Smart Corridors are summarized as follows, although the different evaluation periods and methods were used in different projects:

- **Both positive and negative changes in travel time reliability have been observed across Smart Corridor implementations. Improvements in travel time performance are largely attributed to the deployment of Hard Shoulder Running (HSR), managed lanes, and detour suggestion systems.** For example, on I-66 in Northern Virginia, weekday midday off-peak average travel times improved by 2–6%, whereas during weekday peak periods, benefits were limited due to continued growth in traffic demand. On weekends, however, approximately 10% improvement in average travel time and reliability was achieved because of HSR operations (*3*). Similarly, on I-95 in Miami, FL, average speeds in the HOV lanes increased significantly following the adoption of dynamic tolling (*6*). In Charlotte, NC, the ICM deployment reduced travel times along detour routes—particularly under high-demand conditions—while during off-peak periods, when traffic volumes were lower, the net benefits were less pronounced.

- **Many ICM corridors report the safety benefits**. For example, I-76 Smart Corridor average annual crashes reduced 22 percent, average annual rear-end crashes decreased 32 percent, average annual injuries decreased 20 percent, average annual serious injuries decreased 62%, despite the 10% growth of traffic demand after VSL implementation. Another study found that the I-80 corridor experienced a 5% reduction in Fatal crashes in the post-coordinated ramp metering implementation period (*10*).
- **The Integrated corridors also enable multimodal traffic, which is particularly effective for corridors with transit integration.** For example, on US-75 in Texas, transit ridership increased by up to +5.5% during a severe incident (*11*). In Miami, FL, transit ridership on the I-95 Express Bus Service increased by 57% after converting HOV lanes into express lanes (*6*).

The key lessons of developing Smart Corridors are summarized as follows:

- **Early and Continuous Multi-Agency Collaboration is Essential.** Successful Smart Corridors, such as I-15 in San Diego, CA, and US-75 in Dallas, TX, were built upon strong institutional partnerships between state DOTs, MPOs, transit agencies, and local municipalities from project inception.
- **Unified Operations Centers Foster Real-Time Data Sharing and Coordination**. Real-time information sharing is not only critical to the DSS system but also to road users with different travel modes. Those successful smart corridors adopted various information-sharing techniques such as DMS, mobile phone alerts, and websites to enhance the efficiency of communication with road users.
- **Public Perception, Attitudes, and User Acceptance are Critical to Long-Term Success.** Beyond interagency coordination**,** public perception plays a decisive role in the effectiveness and sustainability of Smart Corridor operations. Studies of corridors such as I-35W in Minneapolis, MN (*1*), and I-95 in Miami, FL (*6*) indicate that the success of well-designed operational strategies, such as HSR, VSL, and priced managed lanes, ultimately depends on the level of public understanding and trust.
- **Effective enforcement mechanisms are essential for translating Smart Corridor technologies into actual safety and mobility benefits.** While systems such as Variable Speed Limits (VSL), Lane Control Signs (LCS), and Hard Shoulder Running (HSR) provide dynamic guidance to drivers, their success depends heavily on user compliance, which in turn is strongly influenced by the visibility and consistency of enforcement. Experience from I-35W in Minnesota, I-66 in Northern Virginia, and I-95 in Miami, Florida, indicates that when enforcement policies were clearly defined and actively supported by state patrol or automated systems, compliance rates with posted speed limits, lane-use rules, and shoulder-lane restrictions were significantly higher. For example, MnDOT found that visible patrol presence and automated monitoring in conjunction with VSL and QWS deployments helped reduce rear-end conflicts and speed variability.

2.3 Previous Before-and-After Studies

The core objective of a before-and-after safety evaluation is to estimate the unbiased indicator (e.g., crash frequency) that would have occurred had the strategy (e.g., VSL) not been implemented. Such analysis includes the determination of baseline and treated period, treatment or comparison sites, the outcome indicators, and the approach.

- The selection of baseline and treatment periods should be made with caution, as an excessively high or confounded baseline condition could lead to underestimation or overestimation of the strategy's benefits. This concern was also noted in the I-80 Smart Corridor project in the Bay Area, CA, where corridor efficiency (VMT/VHT) slightly decreased compared to a reference corridor (*2*). The post-implementation evaluation period is also critical, as strategies such as VSL or LCS often require time for road users to become familiar with them. Consequently, the impacts of these strategies may not be immediately observable. This is a common issue observed in many existing smart corridor evaluations. For example, in the I-66 Smart Corridor in Northern Virginia, only three months of data were used to evaluate the effects of VSL and QWS, which makes it difficult to draw conclusive or statistically significant findings regarding their impacts (*3*).
- Treatment or comparison sites, the treatment sites refer to the location where strategies were deployed. By contrast, the comparison sites did not deploy any strategies, yet they share similar traffic characteristics with treatment sites. By differencing the performance post the implementation for both sites, one can estimate the net effectiveness of strategies.
- The outcome indicator refers to the selection of the outcome of interest aggregated by a segment or a route, for example, crash frequency by injury type, or collision type of the I-24 Smart Corridor.
- The overall evaluation approach includes observation-based, simulation-based, and causal inference methods. The observation-based approach cannot account for natural variations in outcomes (e.g., regression to the mean) or external confounding factors (e.g., COVID-19). The simulation-based approach can approximate real-world traffic conditions to some extent but cannot fully capture all influencing factors. In contrast, the causal inference approach is more complex but effectively addresses regression-to-the-mean and confounding effects, thereby providing the most reliable and unbiased estimates of treatment impacts.

2.4 Previous Benefit Cost Studies

While BCA is just one of many tools that can be used to support funding decisions for infrastructure investments, USDOT believes that it provides a useful method to evaluate and compare potential transportation investments for their contribution to the economic vitality of the Nation. The benefits of transportation projects primarily include the safety benefits, travel time savings, emission reductions, and operating cost savings. Meanwhile, the costs consist of the capital expenditures needed to build the project, operating and maintenance expenditures, residual value, and remaining service life.

Only a few BCA analyses for Smart Corridor projects were identified in the literature review, and they are listed below:

- Based on the simulation results, the estimated BCR for the deployment of I-15 Smart Corridor in San Diego, CA, is 9.7:1, considering the 10-year life cycle costs (*2*). The expected savings are attributed to the reduced travel times, reduced fuel consumption, and emissions.
- A study on the I-66 Smart Corridor in Northern Virginia reported a BCR of 1.54 for various ITS investments, including VSL, QWS, and HSR (*3*). It is worth noting that this BCR was

derived using conservative assumptions, as only weekend operational benefits were considered.

- Some studies applied Analysis, Modeling, and Simulation (AMS) methods to estimate the impact of proposed ICM solutions. Projected benefit-cost ratios range from 10:1 to 25:1 over 10 years (*9*). Note that this BCA values are entirely based on the simulation.

Please also note that often many institutional benefits are unable to be measured, especially for pilot deployments of new operational strategies. Besides, the way of monetizing the safety and travel time savings might be different from studies. Hence, the BCRs across the studies may not be comparable, yet they can provide support for funding decisions by continuously tracking them.

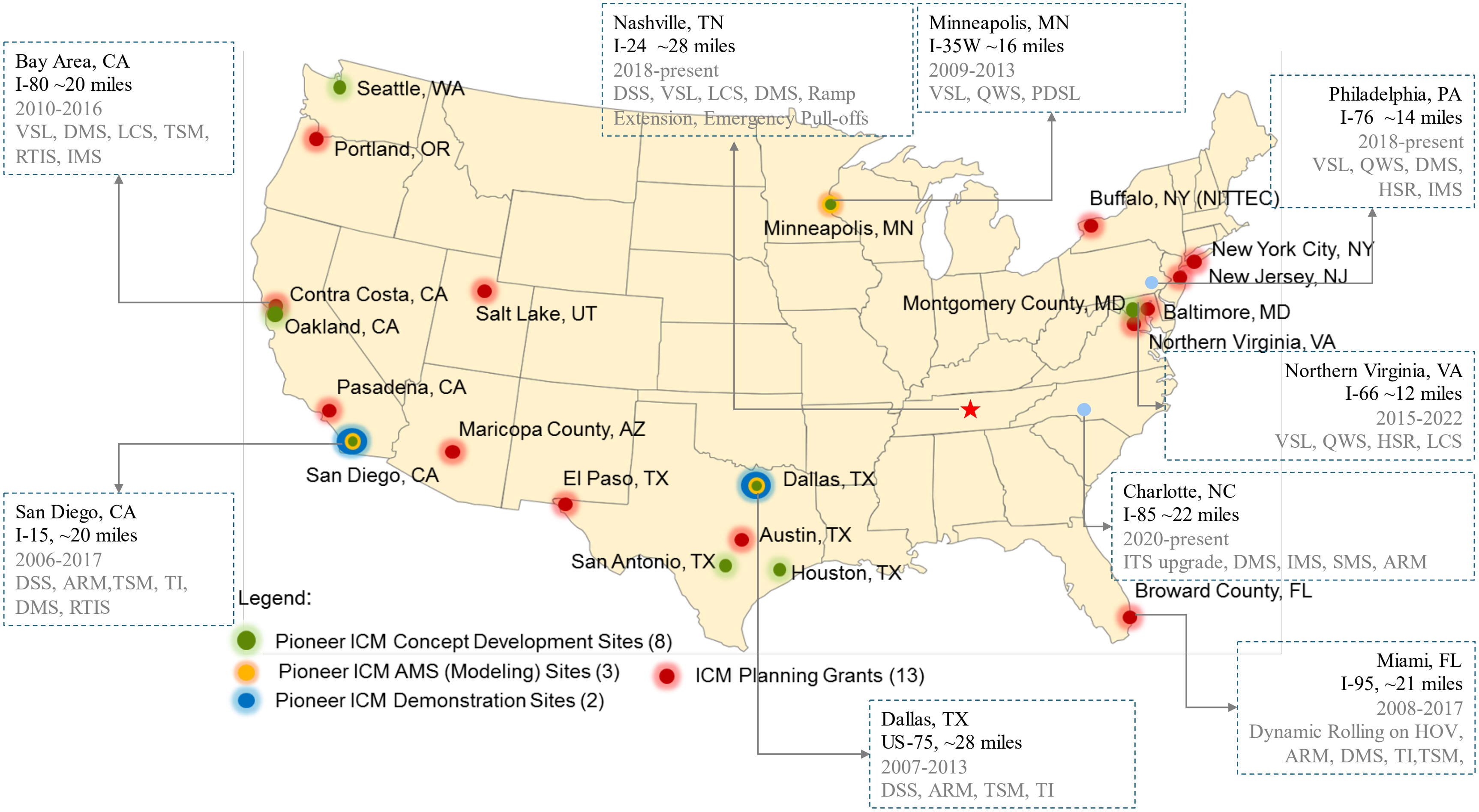

Figure 2-1. A Synthesis of ICM Projects in the US (Edited based on the 2018 USDOT ICM Project Map[1])

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[1] FHWA, 2020, Integrated Corridor Management (ICM) program: major achievements, Key Findings, and Outlook, https://ops.fhwa.dot.gov/publications/fhwahop19016/chapter2.htm

Chapter 3 Methodology

Performance measurements are the key components in the whole project evaluation, including the performance monitoring, before-and-after analysis, and benefit-cost analysis. This section describes the methodology for collecting 3.1 Data Source, determining appropriate 3.2 Performance Metrics, and performing 3.3 Before-and-after Study and 3.4 Benefit Costs Analysis.

3.1 Data Sources

Data used in this project are mainly divided into three categories based on their usage, which are:

First: the data used to compute the performance metrics. Table 3-1 summarizes the available data sources that the research team has been archiving for multiple years. In the prior projects and research, they have been frequently used to compute various performance metrics for continuously monitoring traffic. Among them, RDS, ETRIMS, TN-times, I-24 MOTION camera, and Pull-off videos are maintained by TDOT Information Technology (IT) sectors, whereas the NPMRDS, INRIX incident, and Waze data are obtained through third-party companies. They are freely available to reach team thanks to the partnership between TDOT and them. These data sources provide a comprehensive view of strategy performance, ranging from individual vehicles to stations and segments. In the temporal dimension, they capture traffic dynamics at resolutions from 25 hertz to seconds and minutes. By offering traffic characteristics at different spatiotemporal scales, they were flexibly used individually or in combination to ensure a more complete and accurate evaluation.

Table 3-1. Data Source for I-24 Smart Corridor Evaluation

Data source	*Parameters*	*Spatial Resolution*	*Temporal Resolution*
RDS	Speed, volume, and occupancy	Station	30 seconds
ETRIMS	Crash, roadway geometry	Segment/Station	timestamp
TN-times	AADT	Station	annual
I-24 Motion	Individual Vehicle Trajectories	Individual vehicle	25 hertz
Pull-off videos	Stop vehicle	Station	timestamp
CCTV	Stop vehicle, crash, congestion	Station	timestamp
NPMRDS	Speed, travel time	Segment	1/5/15 minutes
INRIX Incident	Traffic incidents	Station	timestamp
Waze	Speed, travel time	Segment	1 minutes

Second: construction, deployment, and operation information. Specifically, we requested the timeline and location of construction (i.e., as-built drawing), work activities, deployment, and logs of operations for the strategies, including signal upgrade, ramp extensions, emergency pull-offs, and VSL and LCS system. That information helped us establish the before-and-after period and locate the treatment sites in before after analysis. The cost data from construction to administration was also collected from TDOT and consulting companies for benefit-cost analysis.

Third: other miscellaneous data. On top of the data from TDOT and our own data, we collected supplementary information from the web to facilitate our evaluation. For example, the inflation data, e.g., Consumer Price Index (CPI), and Personal Consumption Expenditures (PCE) price index were collected from the US Bureau of Labor Statistics, and the crash unit was obtained from a 2018 FHWA freeway crash analysis report (*12*).

3.2 Performance Metrics

Performance metrics lay the foundation for performance monitoring and project evaluation. Hence, they are selected carefully based on the ease of understanding and available data. Based on the initiatives of the I-24 Smart Corridor project, the measurements of effectiveness used in this study are categorized into four types: safety, mobility, traffic operations, and other measures, which are shown in Table 3-2.

Table 3-2. Summary of Performance Measures

Performance category	*Performance measures*	*Data source*	*Explanation*
Safety	①Total crash (rate) ②Crash (rate) by injury type ③Crash (rate) by collision type ④Secondary crash (rate)	• ETRIMS • INRIX Incident database	A lower value indicates a safer situation.
Mobility	⑤Travel Time ⑥Buffer Time ⑦Buffer Index	• NPMRDS • RDS • WAZE	A lower value indicates a more reliable trip
Traffic Operations	⑧Delay (Per VMT) ⑨Delay Cost (per VMT) ⑩Compliance Rate (VSL)	• INRIX Incident database • NPMRDS • RDS • VSL log	A lower value indicates a more efficient operation except for the compliance rate of VSL.
Other measures	⑪Benefit Cost Ratio ⑫Vehicle Miles Traveled	• US Bureau of Labor Statistics • RDS • NPMRDS • ETRIMS • TN-times	A larger BCR value indicates a larger return on investment, so the higher, the better

The definition and calculation of above above-listed performance metrics are presented in a sequential order:

①**Total crash (rate),** ②**Crash (rate) by injury type, as well as** ③**Crash (rate) by collision type**.

The raw crash frequency by type of segment is the total number of crashes that happened in a month, quarter, calendar year, or fiscal year, which depends on the analysis or visualization granularity. By contrast, due to the traffic exposure difference, crash frequency is typically normalized by the volume and segment length for the appropriate comparison, which is the so-called crash rate (CR). The common practice of defining crash rate is crash frequency per 100 million vehicle-miles of travel, which is written in equation (1)

$$\mathrm{CR} = \frac{N \ \times 10^6}{AADT \ \times 365 \times L} \tag{1}$$

Where N is the number of crashes, AADT is the annual average daily traffic, and L denotes the segment length.

④Secondary crash (rate)

Most secondary crashes occur due to traffic queues, lane-changing maneuvers, and speeding behaviors. Those factors might be alleviated by the VSL and LC systems as they proactively slow the traffic upstream congestion. Aligning with prior studies, secondary crashes were identified if two crashes happened within 2 miles and incident clearance time. Two minor secondary crash indicators were also developed to measure the effectiveness of VSL and LC systems. The first is the secondary crash rate, which is defined by the secondary crash per total number of crashes. This measures the likelihood of a secondary crash. The other is the rate of secondary crashes over the primary crash, that is, the number of secondary crashes caused by the primary crash.

⑤Travel Time

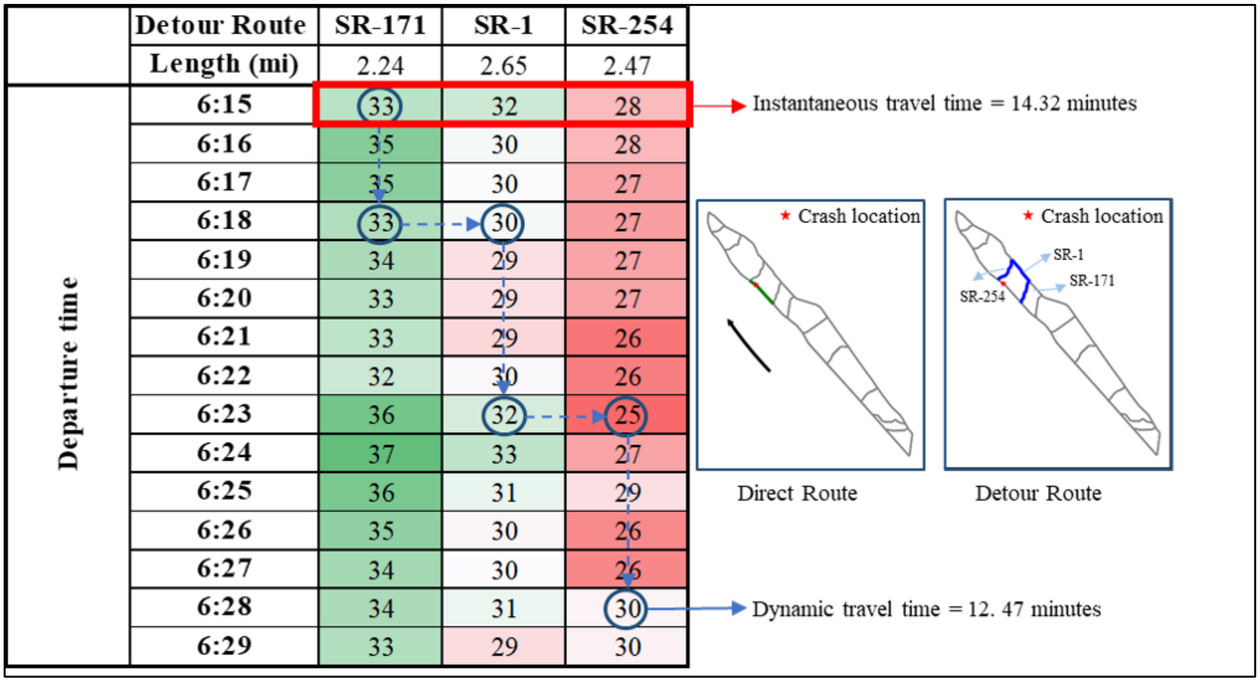
Travel time is computed by using the segment speed provided by the NPMRDS. Please note that NPMRDS provides travel time for segments, neither the corridor nor trips. However, traffic conditions vary as vehicles traverse the segment. Therefore, we calculated the dynamic travel time to account for the varying traffic conditions based on the previous study (*13*). **Figure 3-1** illustrates the method of calculating the dynamic travel time, compared to the instantaneous travel time, which is the straightforward summation of segment travel time. The dynamic travel time reflects the travel time of a trip that departs at a specific time and dynamically updates the speed information by the time of arrival at the next segment. As such, the dynamic travel time is closer to reality.

⑥Buffer Time and ⑦Buffer Index

Buffer time represents the extra time (or time cushion) that travelers must add to their average travel time when planning trips to ensure on-time arrival, where the planning trips are typically measured by the 95th travel times. Buffer time index is the normalization of buffer time, which is used to describe the travel time reliability for segments of different lengths. The buffer time index is calculated via comparing the 95th travel time, TT_{95} With average travel time, TT_{avg}., which is written by equation (2):

$$\mathrm{BTI} = \frac{TT_{95} - TT_{avg}}{TT_{avg}} \tag{2}$$

Buffer time and buffer time index are easily understandable and measurable. For example, a buffer index of 40 percent means that for a trip that usually takes 20 minutes a traveler should budget an additional 8 minutes to ensure on-time arrival most of the time. Hence, the higher the buffer time index, the less reliable the traffic.



	Detour Route	SR-171	SR-1	SR-254
	Length (mi)	2.24	2.65	2.47
Departure time	6:15	33	32	28
	6:16	35	30	28
	6:17	35	30	27
	6:18	33	30	27
	6:19	34	29	27
	6:20	33	29	27
	6:21	33	29	26
	6:22	32	30	26
	6:23	36	32	25
	6:24	37	33	27
	6:25	36	31	29
	6:26	35	30	26
	6:27	34	30	26
	6:28	34	31	30
	6:29	33	29	30

Figure 3-1 Graphical Visualization of Dynamic Travel Time Estimation

⑧Delay

Travel delay is the extra time a traveler spends compared with the chosen expected time, such as free-flow time and historical average time. Travel delay can be caused by both recurring (e.g., peak hour traffic) and nonrecurring traffic incidents (e.g., crash, work zone). It is a critical indicator that measures travel time reliability. For a single user, the delay of a trip or on a segment during period t is calculated by equation (3):

$$\mathrm{D(t)} = \max\{0, (TT - TT_{exp})\} \tag{3}$$

It takes the maximum value between 0 and the subtraction between actual travel time TT and expected travel time TT_{exp} because actual travel time may be shorter than expected travel time if traveling fast. Because vehicle classes differ in operating characteristics, typical occupancy, the number of economic activities they are involved in, and the value of time (VOT), travel delay is usually reported separately for passenger vehicles and commercial vehicles. Total delay by vehicle type is the summation of individual vehicles' delay on the trip or segments R across a period T, which is written by Equations (4) and (5):

$$DP_{RT} = \sum_{j\in R}\sum_{t\in T}(V_j(t) \times P_p \times D_j(t)) \tag{4}$$

$$DT_{RT} = \sum_{j\in R}\sum_{t\in T}(V_j(t) \times P_c \times D_j(t)) \tag{5}$$

Where DP_{RT} and DT_{RT} are the delays of passenger and commercial vehicles separately. $V_j(t)$ is the traffic volume of segment j during interval t. P_p and P_c are proportions of passenger vehicle and commercial vehicles in the mixed traffic flow. In this project, we used our algorithm to extract the truck traffic from the RDS volume (*14*), which would be much more accurate than that using empirical values or default values from HPMS or NPRMDS, $D_j(t)$ is the delay per vehicle on segment j during interval t. Further, to have a better understanding of delay, we calculate the delay per VMT, that is the delay per vehicle mile traveled.

⑨Delay Cost

Further, the total delay cost of passenger vehicles ($\mathrm{DPCC_{RT}}$) and commercial vehicles ($\mathrm{DCTC_{RT}}$) on a route *R* and over a period *T* can be represented by equations (6)(7):

$$\mathrm{DPCC_{RT}} = \sum_{j \in R} \sum_{t \in T} (V_j(t) \times P_p \times D_j(t) \times AVO_p \times VOT_p) \tag{6}$$

$$\mathrm{DCTC_{RT}} = \sum_{j \in R} \sum_{t \in T} (V_j(t) \times P_c \times D_j(t) \times AVO_c \times VOT_c) \tag{7}$$

Where AVO is the average vehicle occupancy, in this study, we set passenger vehicle occupancy AVO_p as 1.7 and commercial vehicle occupancy AVO_c as 1, separately, to reflect the amount of people impacted by the delay. The value of VOT for The value of VOT for passengers VOT_p and commercial vehicles VOT_c are provided in **Table 3-3**, which refers to the study from Texas A&M Transportation Institute. Note that the value of time for year of 2023 and 2024 is projected.

Table 3-3. Value of Time (VOT), Dollars Per Hour

VOT	2021 (TTI)	2022 (TTI)	2023 (Projection)	2024 (Projection)
Passenger	22	23.12	24.29	26.83
Truck	62.43	64.68	67.01	71.93

Likewise, the delay cost per VMT is obtained by dividing the annual vehicle-hours-of-delay cost by the annual vehicle miles traveled, which serves as an indication of the delay cost associated with each vehicle mile traveled.

⑩Compliance Rate (VSL)

The compliance rate is a critical factor in the performance of VSL and LCS systems. VSL and LCS systems are more likely to obtain the expected travel time and safety benefits if commuters follow the signs strictly. It can also be used to explain any safety and mobility-related issues. The ideal data used to compute the compliance rate is an individual's trajectory. However, due to the data limitations, we proposed a surrogated measurement using RDS 30-second data. The compliance rate in this study is the percentage of time intervals when speed is less than 5 mph of the posted variable speed limits.

⑪Benefit Cost Ratio

The Benefit Cost Ratio is calculated by dividing the total benefits from delay and crash savings by the total cost for construction, operation, deployment, and administration.

⑫Vehicle Miles Traveled

VMT is the total miles driven by all vehicles over a route during a period. It measures the traffic exposure. It is formulated as:

$$\mathrm{VMT_{RT}} = \sum_{j\in R}\sum_{t\in T}(V_j(t) \times L_j) \tag{8}$$

3.3 Before-and-after Study

In this project, a Full Bayesian (FB) before-after framework was established to address two common issues: regression to mean and negative impact from confounding factors. The FB framework estimates the expected distribution of crash frequency on treatment sites by accounting for the uncertainties and variations of crash data. Poisson-Lognormal and Poisson-Gamma models are two common models integrated with the Bayesian framework in earlier studies. The Poisson-Gamma model, with its ability to incorporate time-varying coefficients and accommodate temporal variations in various factors, is preferred for before after FB analysis due to its lower Deviance Information Criterion value (*15-18*). A Poisson-Gamma model is defined as follows:

$$Y_{i,t} \sim Poisson(\delta_i \lambda_{i,t}) \tag{9}$$

where $Y_{i,t}$ is the observed crash frequency at site i in year t. δ_i captures the random effect of the site i for accommodating the unobserved heterogeneity between sites. In a Poisson-Gamma model, δ_i is distributed as $Gamma(\varphi, \frac{1}{\varphi})$, where the shape parameter φ follows $Gamma(1,1)$ distribution so that the random effect has a mean of 1 and variance $1/\varphi$. The conjugate Poisson-Gamma function with such prior becomes a negative binomial distribution (*19*). Considering different time trends, the expected crash frequency at site i and year t is formulated with respect the traffic exposure x_i and time indicators t.

$$\ln(\lambda_{i,t}) = \beta_0 + \beta_i x_i + \beta_4 t \tag{10}$$

The crash reduction rate (CRR) is used to measure the safety effectiveness of strategies employed on I-24 Smart Corridor. The CRR represents the crash reduction rate by comparing the expected crash frequency, assuming the strategies had not been deployed, with the actual crash frequency after deployment, which is written by Equation (11).

$$\mathrm{CRR} = \frac{N_{exp} - N}{N} \tag{11}$$

3.4 Benefit Costs Analysis

Benefit-cost analysis includes the estimation of benefits resultant from the enhancement and cost spent on the enhancement. The benefits related to the traffic typically include the travel time savings, crash prevented and their extended benefits such as emission reductions (*20*). The cost primarily come from the project planning, design, procurement, infrastructure construction, as well as post-operations and management related to the I-24 Smart Corridor. The cost was directly extracted from the invoice provided by TDOT. Hence, the BCR can be expressed by the equation (12).

$$\mathrm{BCR} = \frac{(monetized\ delay\ savings + crash\ savings)}{(construction, deployment, operation\ and\ adminstrative\ cost)} \tag{12}$$

To reflect the state economics, we firstly convert the available FHWA nationwide average comprehensive crash unit costs (year of 2016) to Tennessee specific values by using the FHWA adjust tools provided in report *Crash Costs for Highway Safety Analysis* (*12*). Following that, we use CPI of US southeast region, which is obtained from U.S. Bureau of Labor Statistics[2], to convert the 2016 dollars to 2023 dollars.

In line with FHWA guidelines, three key factors are considered in the benefit–cost analysis: inflation, discounting, and project lifespan. To ensure comparability, all benefits and costs are expressed in constant dollars; in this study, 2023 is used as the base year for dollar conversions. This is because the major component of the I-24 Smart Corridor, VSL/LC systems, were deployed in 2023. After adjusting for inflation, discounting is applied to reflect the time value of money, with a recommended real discount rate of 7% per year for USDOT discretionary grant programs. Finally, the expected service life of intelligent transportation system investments is generally somewhat less than 20 years and may be short as 7-10 years for some types of technologies. Hence, the lifespan of the project is initially set by 10 years for I-24 Smart Corridor project (*21*).

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[2] U.S. Bureau of Labor Statistics, Consumer Price Index, https://www.bls.gov/cpi/data.htm

Chapter 4 Results and Discussion

This section first summarizes the takeaway findings of this evaluation project, followed by the detailed results and discussion of major enhancements of I-24 Smart Corridor project, including RDS detector upgrade, ramp extension, emergency pull-offs, arterial signal system upgrade, variable speed limits and lane control signs. Following that, the candidate corridors are also examined for guidance of future deployment. Finally, the benefits to TDOT and implementations of this project are summarized.

4.1 Summary of Findings

- The upgraded RDS detectors significantly improved the speed accuracy. The volume data output from the old RDS detectors appears to be reliable for performance measurement.
- The average speed increased by 19.2% at I-24W/Briley Pkwy exit ramp, and by 12.3% improvement at I-24W/Bell Road during the peak hours. BTI was reduced by 58.9% at the I-24W/Briley Pkwy exit ramp, and by 15.3% at I-24W/Bell Road entrance.
- Only 17% of stopped vehicles in pull-offs resulted in significant speed changes in mainlines; however, 40% of vehicles stopped on shoulders led to significant turbulence to mainline traffic flow.
- Over 50% of signalized intersections showed measurable safety improvements. Rear-end crashes dropped significantly, with a range of 21.6% to 48.6% among four cities. PDO crashes also significantly decreased in Nashville and Murfreesboro, with a reduction rate of 27% and 24.6% separately.
- VMT increased by 3% (+40,000 vehicle-miles per day) and 10.3% (+80,000 vehicle-miles per day) in the eastbound and westbound directions, respectively.
- After VSL/LCS implementation, the suspect serious injury, suspect minor injury, possible injury, and PDO crash declined by 18.1%, 10.4%, 17.5% and 3% respectively. Rear-end and sideswipe crashes decreased by 14.0% and 3.2%, respectively.
- The westbound average travel time increased from 26 minutes before the VSL/LCS implementation to 32.5 minutes in the first fiscal year and then remained steady in the second fiscal year. In contrast, the eastbound average travel time rose modestly from 23.9 minutes to 25.3 minutes by FY (Fiscal Year) 2023–24 and remained stable through FY 2024–25.
- The rate of secondary crash declines from 7.72% to 6.61%.
- The total number of crashes reduced by 13.8% after the VSL/LCS implementation.
- The return is **$1.13** for every dollar invested in the I-24 Smart Corridor project, assuming a 10-year service period and a 7% annual discount rate. This value is expected to increase as the service years extend and additional travel time savings materialize in the future.
- The annual crash savings is estimated at **$10.1million**, while the net annual return after operations and management costs is approximately **$1.2 million**.
- I-40, paired with Kingston Pike, in Knoxville could be given priority for the future Smart Corridor Investment, compared with Chattanooga I-24, and Nashville I-65.

4.2 Radar Traffic Detector Upgrade

Real-time traffic data is critical to the VSL and lane control signs. TDOT installed many new detectors near the mainline and ramps and upgraded existing detectors since March 2023. **Figure 4-1** shows the number of traffic detectors gradually added onto the I-24 Smart Corridor from March to May 2023. The new detectors were installed every 0.5 miles, which can well capture the traffic variations between VSL/LCS gantries.

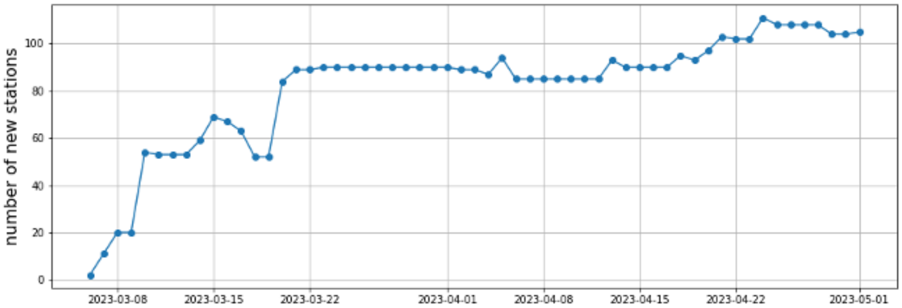


Figure 4-1. Number of traffic detectors on I-24 Smart Corridor

On the other hand**,** data quality plays a critical role in evaluating the effectiveness of enhancements. Therefore, we assessed both the old and new RDS data to determine its suitability for analysis.

First, **Figure 4-2** compares the speed differences between RDS and probe vehicle data from NPMRDS for the westbound direction. The green box represents the differences using old RDS data from 2022, while the purple box shows the differences for new RDS data collected after March 2023. Positive values indicate that RDS speeds are higher than NPMRDS speeds. As shown, the new detectors produce speeds that are highly consistent with NPMRDS, with minimal variance. In contrast, the old detectors, particularly near the Nashville and Murfreesboro areas, often reported speeds that were either much higher or lower than NPMRDS speeds. Given these discrepancies, NPMRDS speed data was used for travel time reliability measurements for the scenarios where prior situation needs to be measured before 2023.

Second, for traffic volume, we compared the old RDS output with the I-24 Motion trajectory data collected during the week of November 21, 2022. The I-24 Motion data, captured individual vehicles using high-resolution cameras, served as the ground truth for this evaluation. To ensure consistency with the RDS format, the trajectory data was aggregated into 30-second intervals matching the RDS time slots. **Figure 4-3** illustrates the comparison at mile marker 60.7 westbound, where the orange lines represent camera-based volume, and the green lines represent RDS volumes for each lane. Overall, the RDS volumes closely align with the ground truth, although slight discrepancies are observed in specific lanes, such as lane 3, where deviations are more noticeable. These results suggest that RDS volume data might be reliable for estimating delay, AADT, and VMT, despite minor lane-level variations.

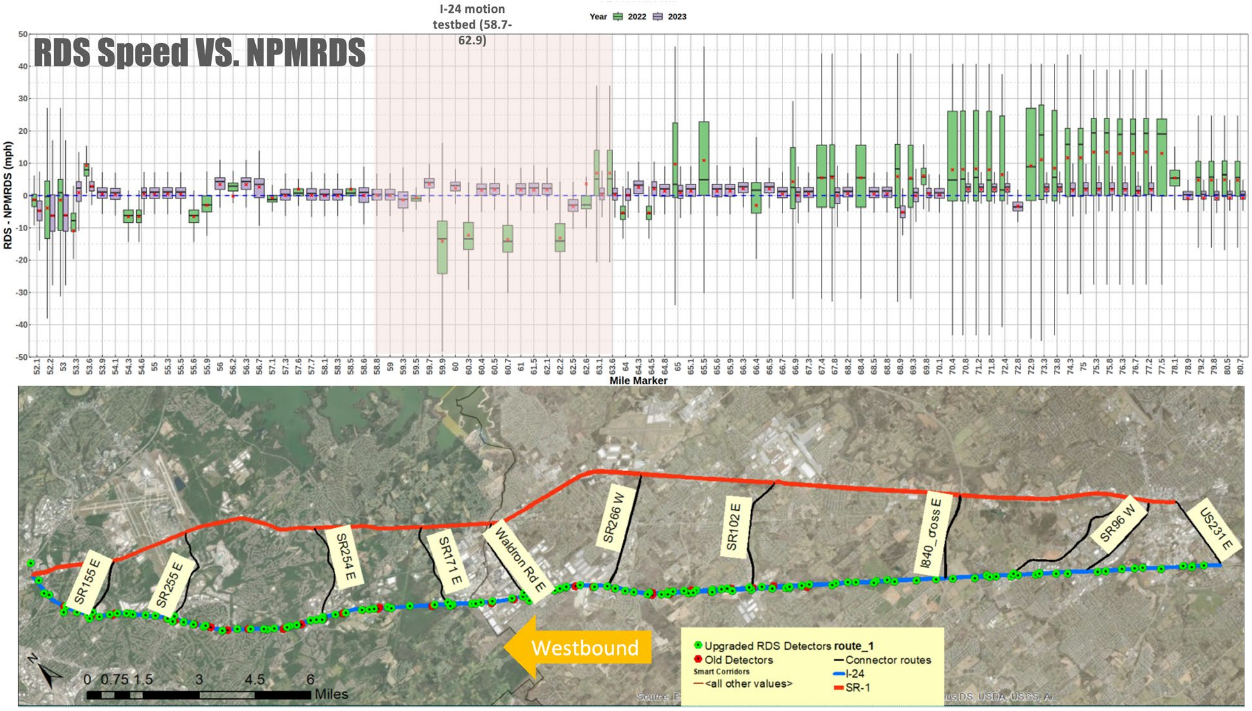


Figure 4-2. Difference between RDS Speed and NPMRDS Speed for both Old and New Detectors

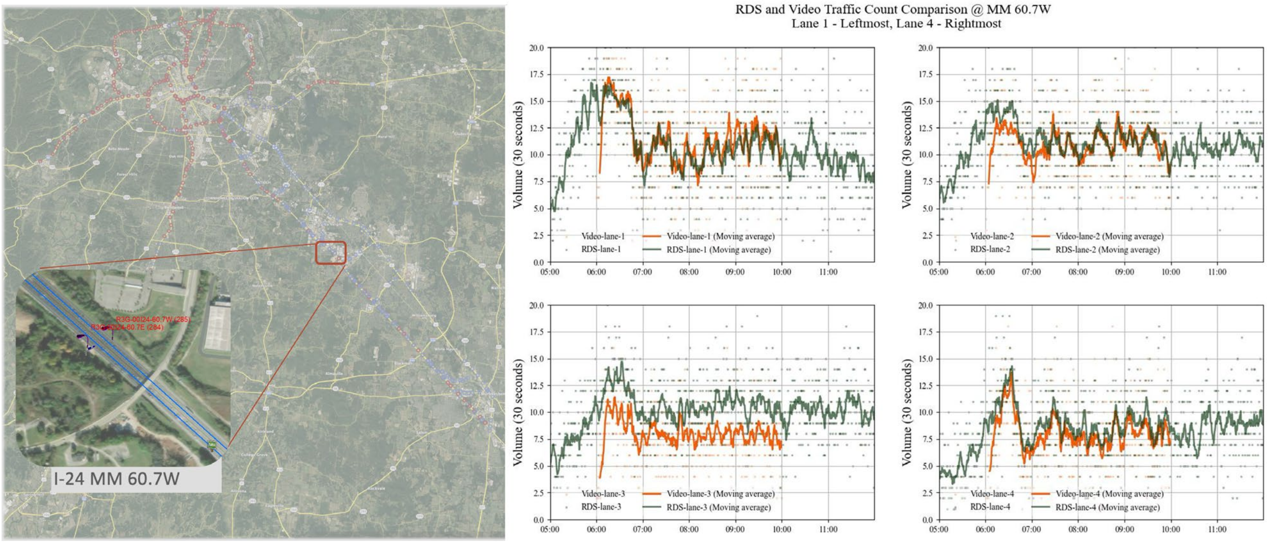


Figure 4-3. Traffic Volume Comparison between RDS and I-24 Motion Trajectory Data

4.3 Ramp Extension

During Phase 1 of the I-24 Smart Corridor project, TDOT extended the deceleration lanes at I-24W/Briley Pkwy, I-24E/Harding Pl, and I-24E/Bell Road, and added one acceleration lane at I-24W/Bell Road, as shown in **Figure 4-4**. Construction at Bell Road (both directions) lasted from September 2019 to July 2020, while the Harding Pl and Briley Pkwy ramps were under construction from July 2019 to August 2020. For I-24E/Bell Road, an additional exit ramp lane was added in 2022. The change of ramp profile is summarized in Table 4-1. Note that Bell Road Exit Ramp was significantly extended by 0.4 miles, while other ramp only extended by 0.08 miles (equivalent to 422 feet). Therefore, the before period is defined as the two years prior to September 2019, and its "after" period as the year following July 2020. For the other three ramps, the "after" period covers the two years following construction completion. None of the after periods overlap with the VSL/LC implementation which went online in June 2023. Finally, the travel time reliability and safety effectiveness of ramp extension were examined.

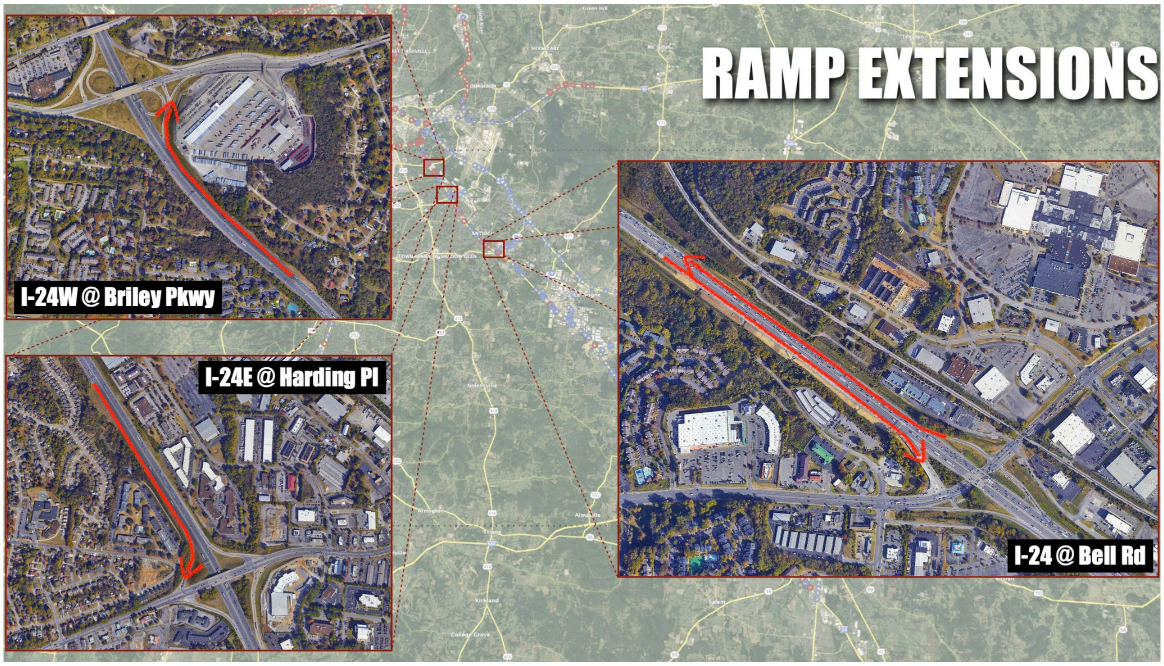


Figure 4-4. Locations Of Ramp Extension

Table 4-1. Ramp Profile Before and After Extension

Ramp extension	Attributes	Before	After
I-24W/Briley Pkwy Exit	Length	0.311 miles	+0.08 miles
	deceleration lanes	1	1
	ramp lanes	2	2
I-24E/Harding Pl Exit	Length	0.345 miles	+0.08 miles
	through lanes	4	4
	deceleration lanes	1	1
	ramp lanes	3	3
I-24E/Bell Road Exit	Length	0.139 miles	+0.4 miles
	deceleration lanes	1	2
	ramp lanes	3	4
I-24W/Bell Road Entrance	Length	0.16 miles	+0.076 miles
	acceleration lanes	1	1
	ramp lanes	1	1

The **Figure 4-5** compares the arrival traffic speed distributions at four I-24 ramps during peak hours across three time periods: before construction (green), during construction (gray), and after construction (red). **Table 4-2** summarizes the average speed during the peak hours. It is found that:

- The I-24E/Bell Road Exit ramp experienced a modest improvement, with average peak-hour speed increasing from 48.97 mph before construction to 52.66 mph after construction, representing a 7.5% gain.
- The I-24W/Bell Road Entrance ramp showed a more substantial improvement, rising from 47.42 mph to 54.80 mph, a 15.6% increase. Similarly, the I-24E/Harding Pl exit ramp increased from 32.22 mph to 36.27 mph, a 12.3% improvement.
- The most significant change occurred at the I-24W/Briley Pkwy Exit ramp, where speeds increased from 46.77 mph to 55.77 mph, a 19.2% rise.
- These results suggest that while all ramps experienced some level of improvement following construction, **the benefits were most evident at the Bell Road westbound and Briley Parkway westbound ramps, suggesting that the ramp enhancements were particularly effective in alleviating congestion and improving traffic flow toward Nashville, especially amid increasing travel demand to Nashville**.

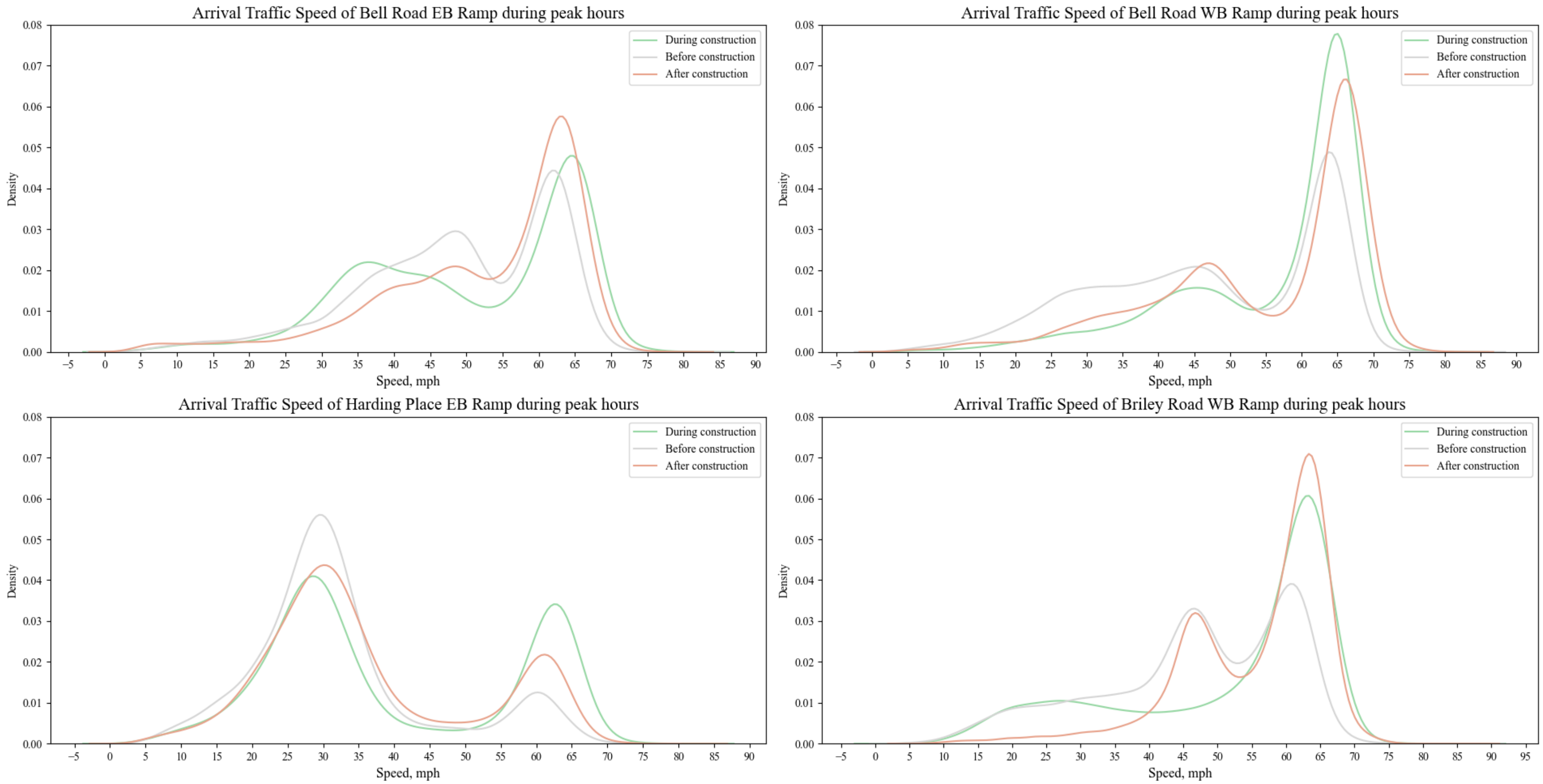
The **Figure 4-6** and **Table 4-3** illustrate the arrival traffic speed distributions at four I-24 ramps during off-peak hours, comparing the periods before, during, and after construction.

- Unlike peak-hour conditions, the differences across periods are relatively minor, indicating that construction primarily influenced congestion during high-demand periods. At the I-24E/Bell Road Exit ramp, average off-peak speed remained stable, shifting slightly from 64.29 mph before construction to 64.08 mph after, representing a negligible 0.3% decrease.
- The I-24W/Bell Road entrance ramp showed a small improvement, with speeds increasing from 64.14 mph to 65.54 mph, a 2.2% gain, while the I-24W/Briley Parkway Exit ramp experienced the highest increase, rising from 62.68 mph to 64.63 mph, a 3.1% improvement.
- In contrast, the I-24E/Harding Pl exit ramp showed virtually no change, decreasing slightly from 60.91 mph to 60.85 mph. The narrow, overlapping distributions in the plots confirm these minimal changes, indicating that off-peak traffic flow was already smooth and largely unaffected by the ramp construction projects.
- **Overall, the results suggest that while the ramp enhancements significantly benefited peak-hour congestion, they had little impact on off-peak travel speeds.**

The **Figure 4-7** and **Table 4-4** illustrate the buffer time index at four improved ramps during peak hours. Note that a lower BTI reflects more consistent travel times and reduced congestion variability. It is found that:

- **The most significant improvement occurred at the I-24W/Briley Pkwy exit ramp, where the BTI dropped sharply from 0.90 before construction to 0.37 after construction, representing a 58.9% reduction.** This is also a positive sign, as Briley Parkway (SR-155) functions as a city bypass. Its improvement in travel time reliability could help divert or relieve traffic demand that would otherwise flow into Nashville.
- The I-24W/Bell Road entrance ramp also showed a notable improvement, decreasing by 15.3% from 0.72 to 0.61. Harding Pl eastbound experienced a modest decline of 6.3%, from 0.74 to 0.69. In contrast, the I-24/E Bell Road exit ramp remained essentially unchanged, staying at 0.70 before and after construction.

- These patterns are reflected in the hourly plots, where the Briley Parkway ramp displays a clear reduction in peak-hour variability, while other ramps exhibit smaller or negligible changes. Overall, these results highlight that the construction work was especially effective at improving travel reliability at I-24W/Briley Pkwy exist ramp, with more moderate or localized benefits observed at the other sites.



Arrival Traffic Speed of Bell Road EB Ramp during peak hours

Arrival Traffic Speed of Bell Road WB Ramp during peak hours

Arrival Traffic Speed of Harding Place EB Ramp during peak hours

Arrival Traffic Speed of Briley Road WB Ramp during peak hours

Figure 4-5. Peak Hour Speed Comparison Before and After The Ramp Extension.

Table 4-2. Average Speed During Peak Hours, mph

Period	I-24E/Bell Road Exit	I-24W/Bell Road Entrance	I-24E/Harding Pl Exit	I-24W/Briley Pkwy Exit
Before	48.97	47.42	32.22	46.77
During	50.63	56.35	39.64	51.92
After	52.66	54.80	36.27	55.77
Change	+7.5%	+15.6%	+12.3%	+19.2%

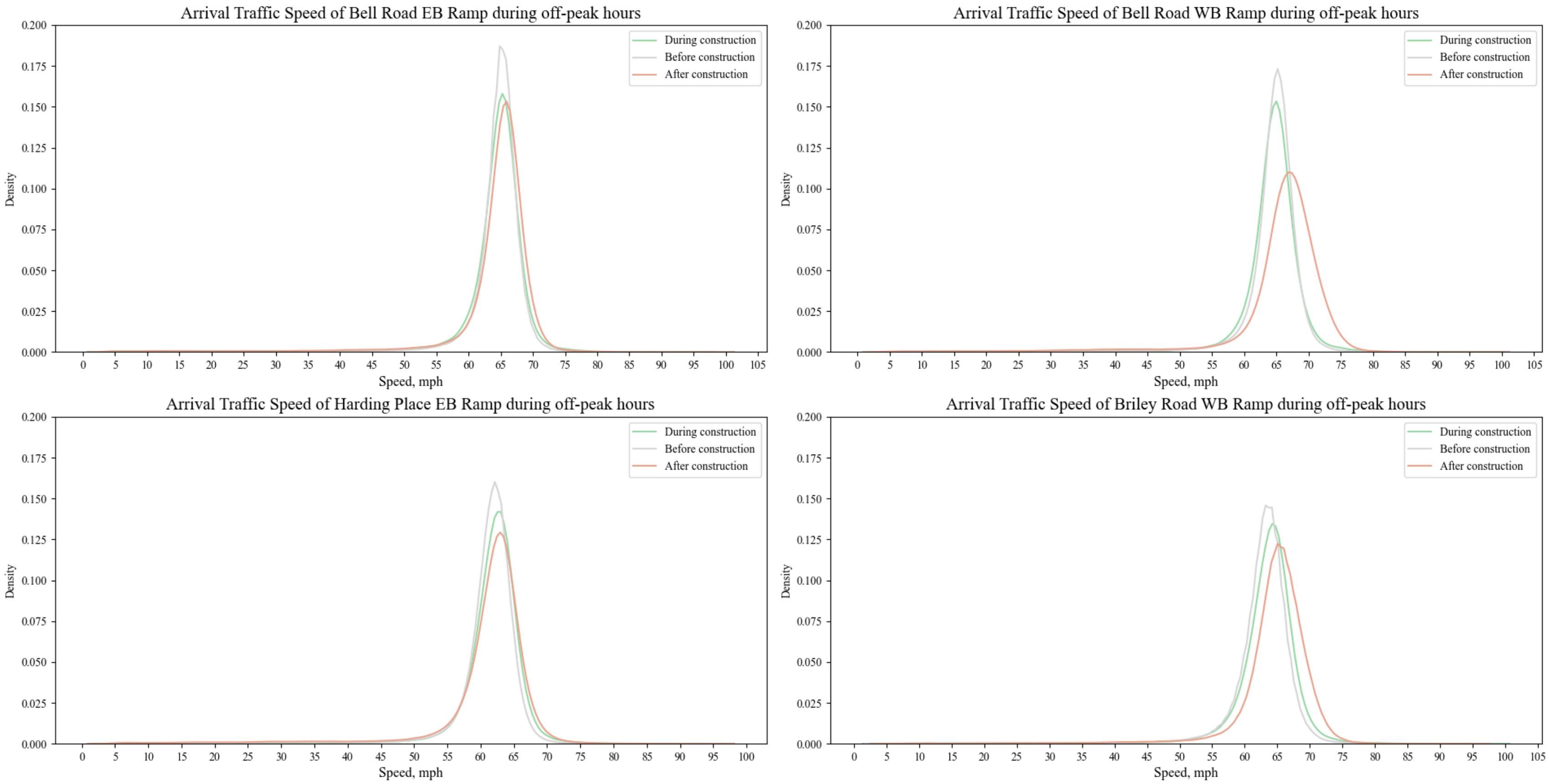


Figure 4-6. Off Peak Hour Speed Comparison Before and After the Ramp Extension

Table 4-3. Average Off-Peak Hour Speed, mph

Period	I-24E/Bell Road Exit	I-24W/Bell Road Entrance	I-24E/Harding Pl Exit	I-24W/Briley Pkwy Exit
Before	64.29	64.14	60.91	62.68
During	63.80	64.09	61.54	63.33
After	64.08	65.54	60.85	64.63
Change	-0.3%	2.2%	-0.01%	3.1%

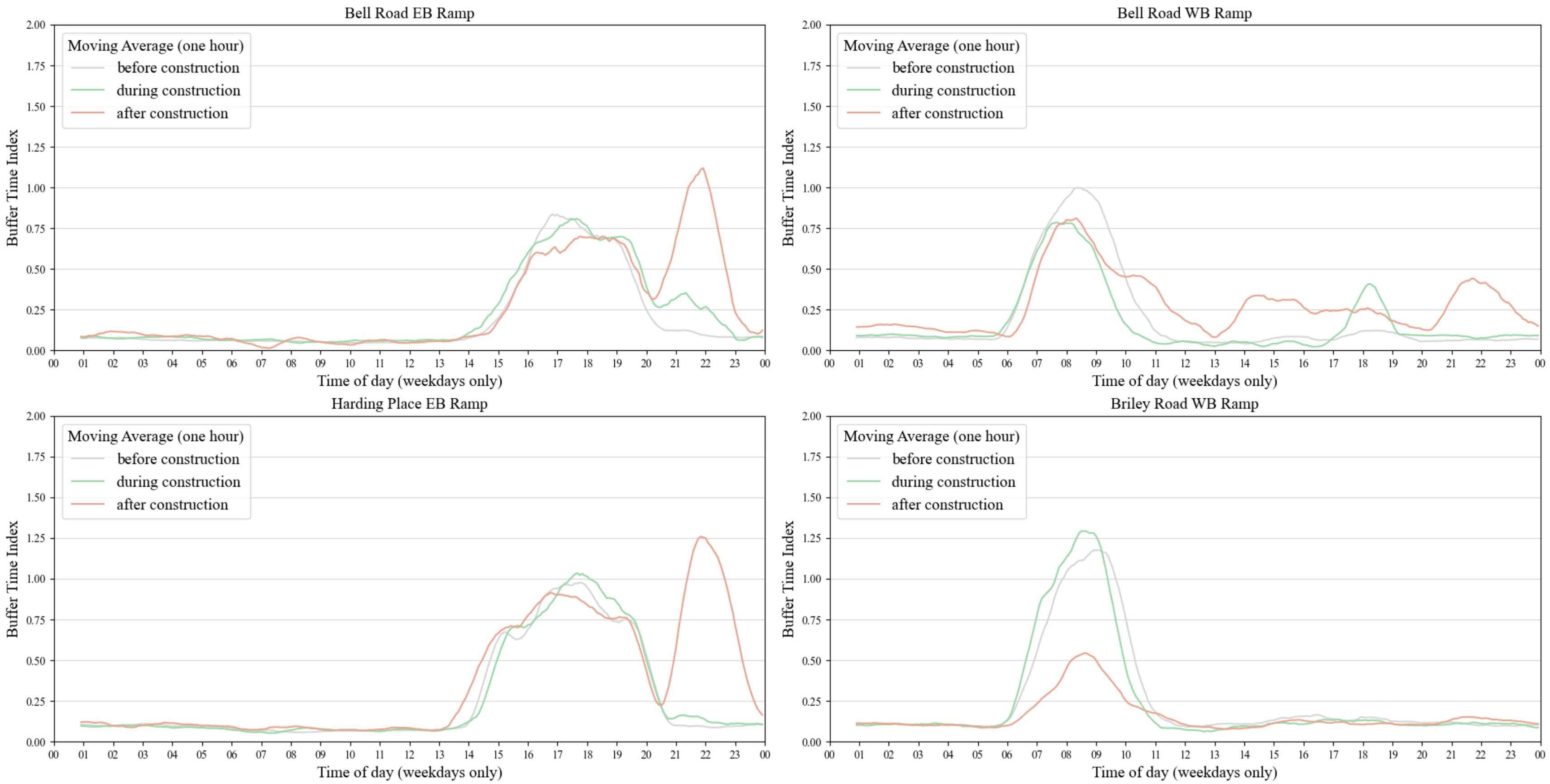


Figure 4-7. Buffer Time Index by Hour of Day

Table 4-4. Average Peak Hour Buffer Time Index

Period	I-24E/Bell Road Exit	I-24W/Bell Road Entrance	I-24E/Harding Pl Exit	I-24W/Briley Pkwy Exit
Before	0.70	0.72	0.74	0.90
During	0.62	0.59	0.77	0.89
After	0.70	0.61	0.69	0.37
Change	+0.2%	-15.3%	-6.3%	-58.9%

4.4 Emergency Pull-offs

The pull-off stations are shown in **Figure 4-8**. As indicated by red diamonds, there are seven pull-off stations in each direction, spanning from mile marker 52 to mile marker 74. The length of the pull-off area is approximately 300ft. The emergency pull-off stations are installed for vehicles who encountered emergency issues such as mechanical issues, flat tire or patrol vehicles (e.g., HELP truck, police).

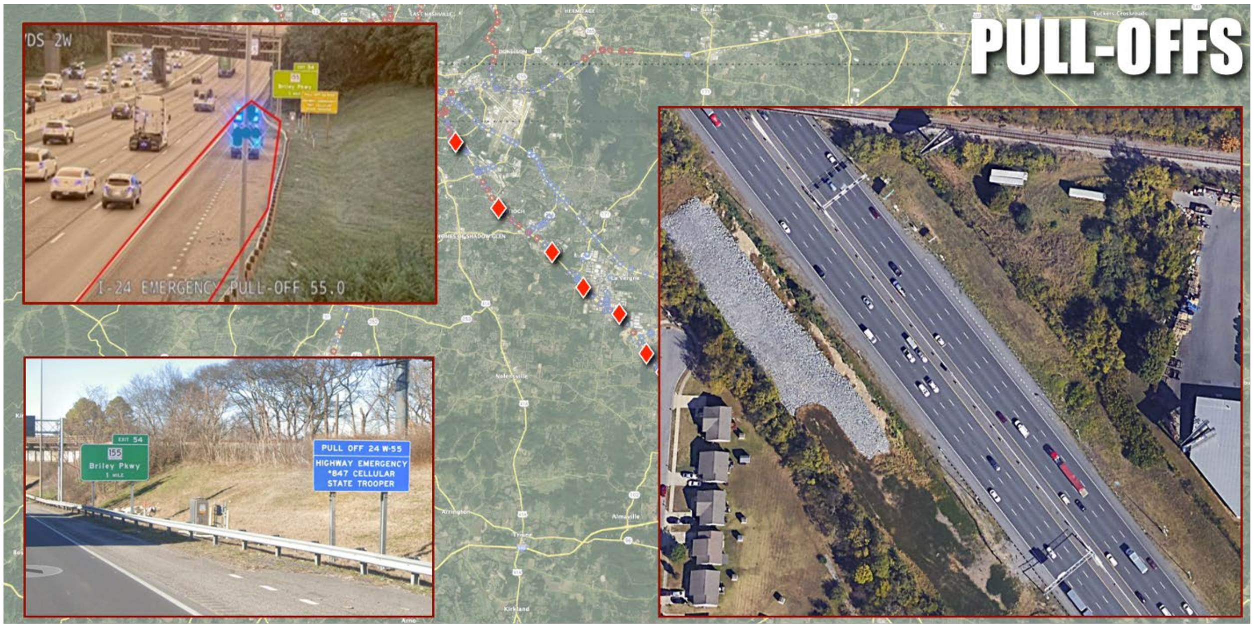


Figure 4-8. Location of Pull-Off Stations on I-24 Smart Corridor, an Example of I-24 Mile Marker 55 Westbound is Showed.

To evaluate the effectiveness of pull-off stations, we compared the change of mainline traffic speed and volume when vehicle stops on shoulder and pull-offs under the similar traffic conditions. Using the Yolo-v8 image processing algorithm, we detected the moments when a vehicle stopped at the pull-off sections. The data spans the last three months of 2023, yielding a total of 1,504 samples for the pull-off stations based on the algorithm's output. For the shoulder sections, we used the incident data from RITIS instead of video footage, as the shouldered vehicles were outside the range of the cameras. RITIS is a comprehensive data platform that aggregates transportation and traffic data from various sources to support traffic management, incident response, and transportation planning (*22*). It provides detailed incident data with reference to space and time, allowing us to distinguish the vehicles on shoulders from pull-offs. The data collection for shoulder sections is identical to that for pull-off sections, particularly with respect to time stamps and geographic coordinates. This includes the same length as I-24 and covers the last three months of 2023. From the RITIS database, we identified 439 instances of vehicles stopped on the shoulder. Then, we used data from the nearest downstream TDOT RDS detector to obtain traffic flow characteristics such as speed and volume. Since RDS detectors and gantries are spaced at intervals of less than 0.2 miles, the distance between them is quite short, ensuring that the observed traffic data accurately reflects conditions near the gantries. We aligned the timestamps and locations of the detected stops with the corresponding traffic speed and volume data from RDS. RDS detectors provide real-time traffic data, including speed and volume, at intervals of less than 0.5 miles along highways.

For our analysis, we selected a 10-minute window before and after the start of vehicle occupation in both pull-off sections and shoulder areas. For each incident, we analyzed 20 data points before and 20 data points after the start of the occupation. Following that, we attempted to identify the sharp changes of speed and volume time series, which is used to explain the traffic fluctuations resultant from the stopped vehicles. **Table 4-5** summarizes the outcomes of the analysis, comparing the impact of incidents at pull-off stations versus shoulder stops on traffic flow characteristics. It is found that:

- In the pull-off station scenario, 17% of incidents resulted in significant speed changes in adjacent lanes. When both speed and volume are included in the analysis, only 0.1% of the incidents led to significant changes in both metrics. This indicates that while pull-off stations certainly affect traffic flow, the overall impact is relatively minor.
- On the other hand, in the shoulder stop scenario, 40% of incidents resulted in significant speed changes, with 3% affecting both speed and volume. This demonstrates a much higher impact on traffic flow than pull-off stations, highlighting the disruptive nature of shoulder stops. The higher percentage of significant changes in speed and volume for shoulder stops compared to pull-off stations underscores the effectiveness of pull-off stations in mitigating traffic disruptions.
- Pull-off stations impact on traffic flow far less, as evidenced by the lower percentages of significant changes in both speed and volume. The deviations in traffic speed and volume were analyzed on a per-lane basis to ensure that changes in individual lanes were accurately captured rather than being masked by aggregation across all lanes. This approach allows us to account for lane-specific disruptions, including potential traffic shifts between lanes.

Table 4-5. Frequency and Types of Changes in Traffic Speed and Volume

Area	Num. of incidents	Num. of changes	Sharp change in	Change rate
Pull-off station	1504	265	Speed	17 %
		2	Speed + Volume	0.1%
Shoulder	439	179	Speed	40%
		17	Speed + Volume	3%

Further, we presented a case to better understand the impact of pull-offs on traffic flows. **Figure 4-9** presents traffic data for incident ID *TDOT_3_348356*, which occurred on December 15, 2023, at mile marker 58.3. The data covers a period from 07:02:40 AM to 07:22:11AM, showing traffic volume (left column) and speed (right column) across four lanes. For volume, in lane 1, a notable increase in traffic volume was found right before the shoulder occupation starts, followed by a significant decrease before the occupation begins, indicating potential lane change behavior or reduced vehicle entry. In lane 2, the volume remained relatively stable after occupied but presented a noticeable dip once before the shoulder was occupied, indicating its impact on traffic flow with fewer vehicles entering lane 2. Lane 3 initially exhibited volume fluctuations and then followed by a significant drop just before and after the shoulder occupation begins, highlighting the disruption caused by the incident. Similarly, in lane 4, the volume fluctuated before the occupation and then decreased markedly after the shoulder is occupied, reflecting a consistent response across all lanes. In addition, in lane 4, a drop in volume occurred shortly after the recorded start time, which may reflect the move-over effect as vehicles shift away from the affected lane. This behavior suggests that the actual vehicle stop might have occurred slightly earlier than recorded. For speed, in lane 1, speed was high initially but drops sharply before the shoulder occupation starts, stabilizing at a lower level, indicating a major disruption in traffic flow. Lane 2 experienced a steady decrease in speed before the occupation, with a sharp decline coinciding with the green line, marking a clear impact on traffic speed due to the incident. Lane 3 was observed a consistent decline in speed starting at the shoulder occupation, stabilizing at a much slower speed post-occupation, highlighting significant traffic disruption. In lane 4, speed decreased significantly around the shoulder occupation, stabilized at a lower speed afterward, mirroring the disruption seen in the other lanes.

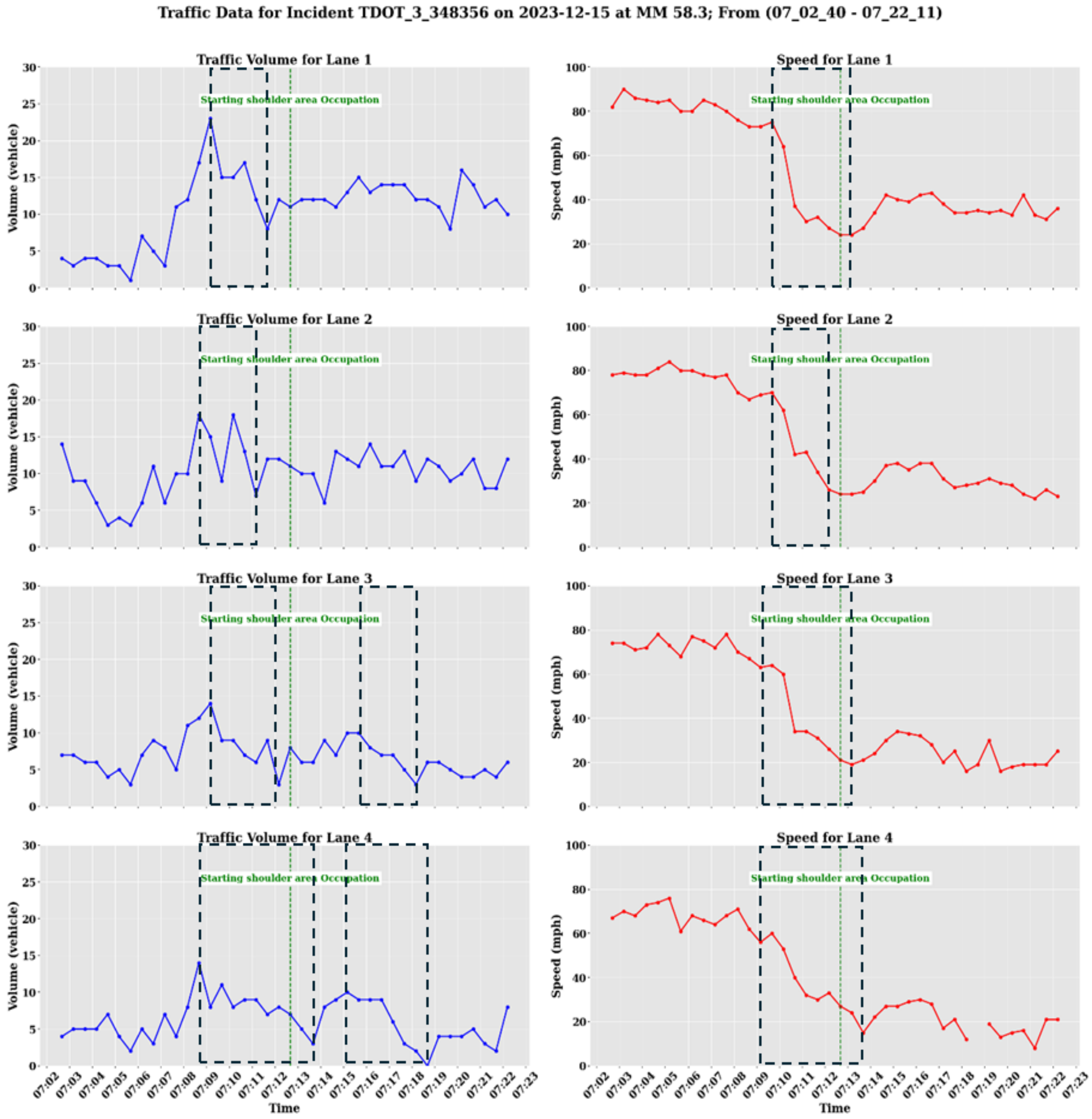


Figure 4-9. Volume and Speed for Incident *TDOT_3_348356* at the Shoulder.

4.5 Signal Intersection Upgrade

TDOT upgraded the intersection signal systems including infrastructure and optimizing signal timing along the arterial route SR-1 and connector routes between SR-1 and I-24 Smart Corridor during the Phase 1 from 2019 to 2020. As **Figure 4-10** shows, all signal intersections are separately managed by four cities, Nashville, La Vergne, Smyrna, and Murfreesboro. In this study, we evaluated the travel time reliability and safety change before and after the signal system upgrade. Correspondingly, we have built dashboards to visualize the longitudinal safety and travel time reliability at intersections. Please refer to the **Appendix 2: I-24 Signal Intersection Performance** Dashboard for dashboards information.

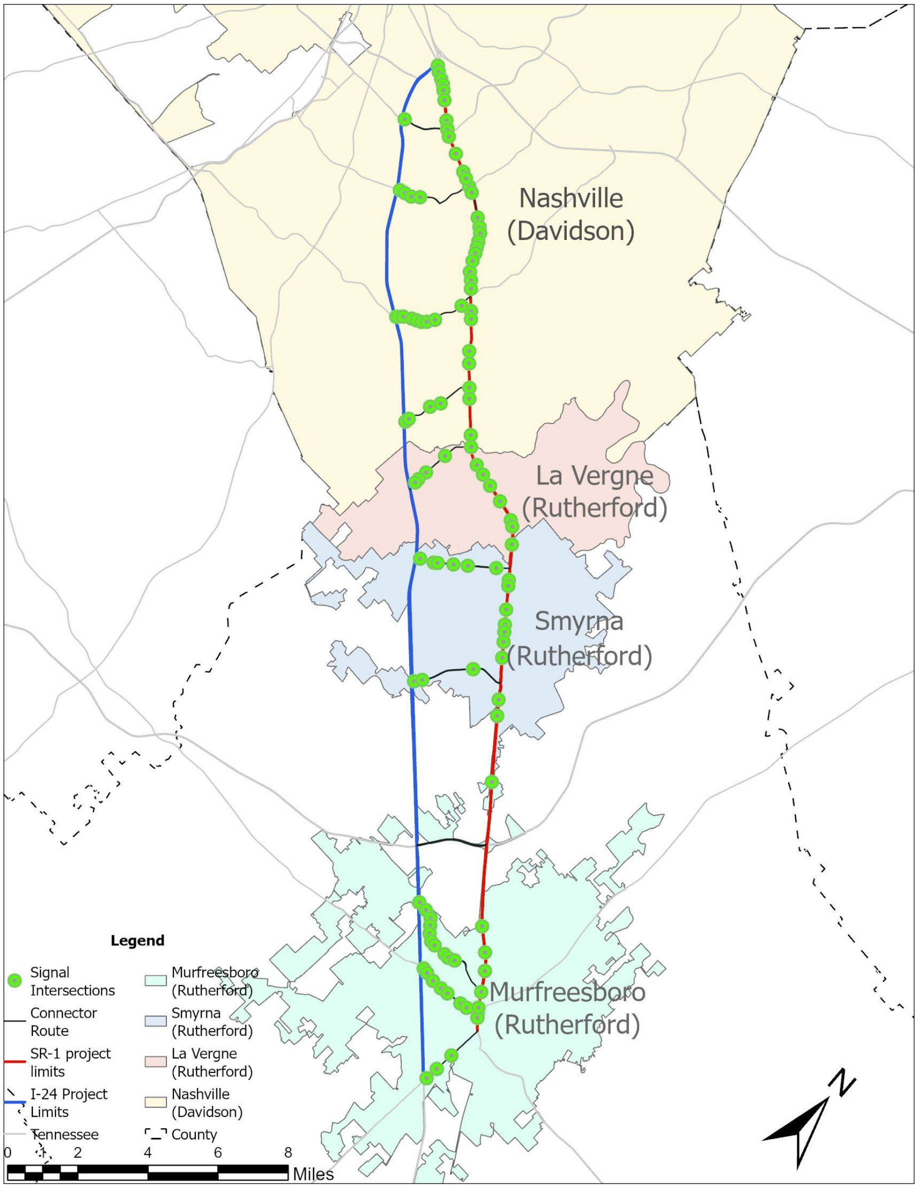
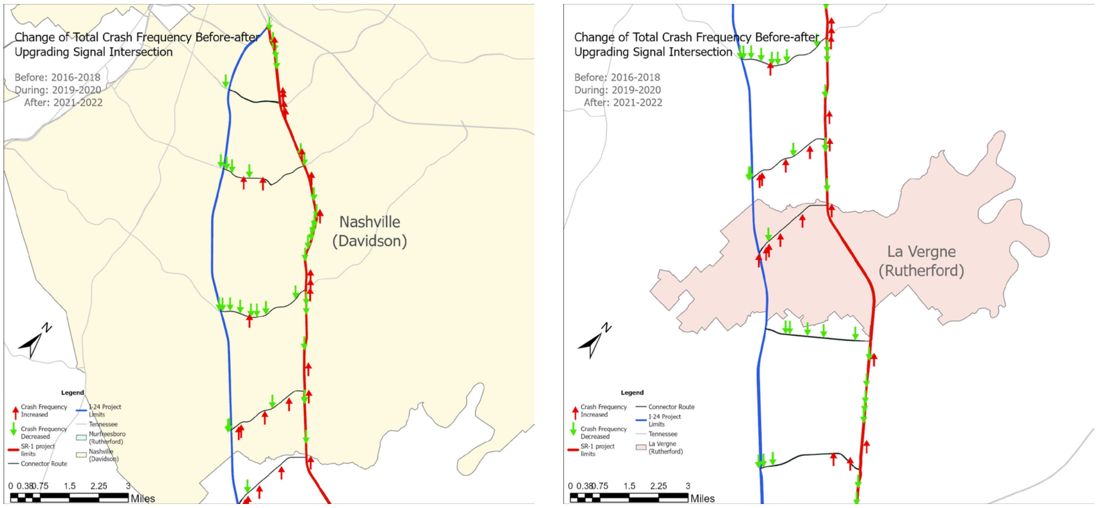


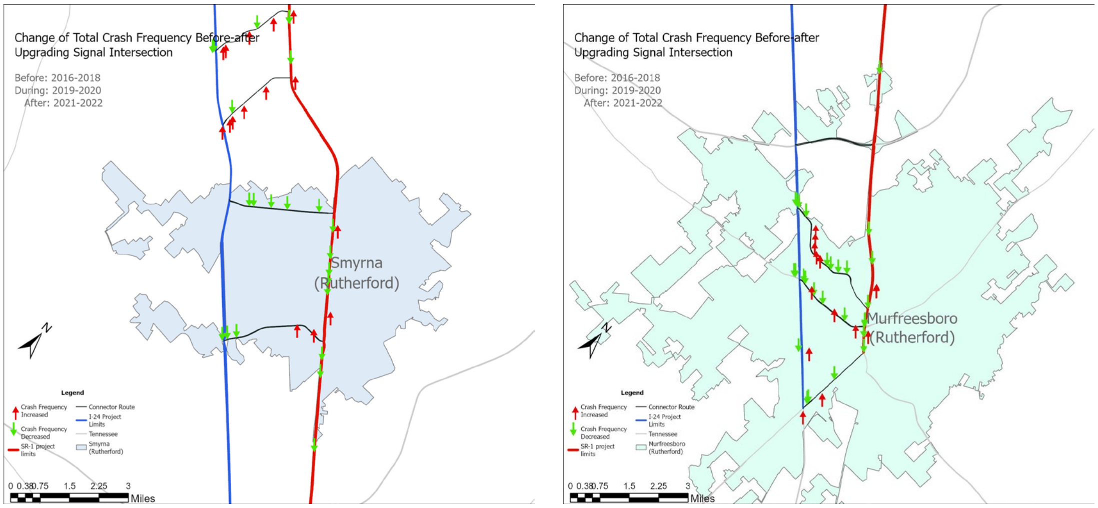
Figure 4-10. Signal Intersections in the I-24 Smart Corridor System

To avoid the impact of VSL system, the evaluation periods were divided into three phases: *Before (2016–2018)*, *During (2019–2020)*, and *After (2021–2022)*. shows the change of annual crash frequency before and after the signal system upgrade. Intersections are color-coded by crash frequency change, with green markers indicating a reduction in crashes and red markers showing an increase. It is found that:

- In Nashville, notable safety improvements were observed at 36 out of 58 signal intersections, particularly along major arterials such as Briley Parkway, Harding Pl, and Bell Road, where crash reductions were concentrated.
- Conversely, La Vergne experienced more mixed outcomes, with only 1 out of 7 intersections showing a crash reduction, indicating that the benefits of the upgrades were more localized.
- In Smyrna, the improvements were more widespread, with 15 out of 19 intersections exhibiting reductions, suggesting that the upgrades significantly enhanced safety in this area.
- Murfreesboro saw a half of improved intersections, with 20 out of 43 intersections experiencing fewer crashes, particularly along Medical Center Parkway and Old Fort Parkway corridors.



(a) Nashville (Davidson) **(b) La Vergne (Rutherford)**



(c) Smyrna (Rutherford) **(d) Murfreesboro (Rutherford)**

Figure 4-11. Safety Improvement over Signal Intersections

Further, the analysis of crash collision types across the four cities provides insight into how signal upgrades affected safety outcomes, with statistical significance evaluated using a t-test at the 90% confidence interval, indicated by an asterisk (*) in the table. Since the individual signal timing schemes are not available, the evaluation is conducted on an average basis. Therefore, the average values of all crash indicators, expressed per intersection and per year, were used for comparison.

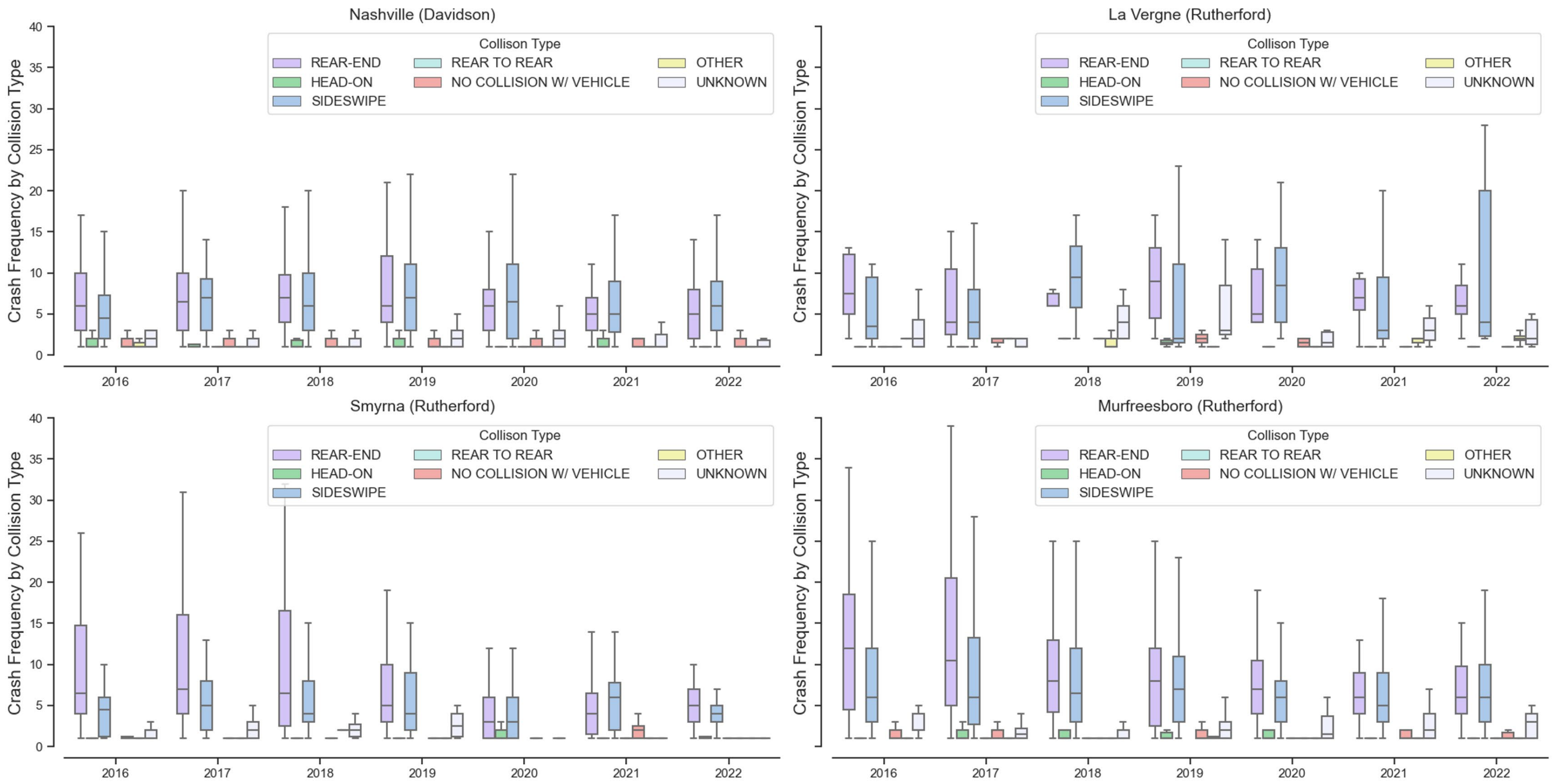
- **Nashville experienced a significant reduction in terms of rear-end crashes, decreasing from an average of 8.01 to 6.28 crashes per intersection per year.** This result suggests that the signal coordination effectively reduced sudden braking and stop-and-go traffic, leading to smoother flow through intersections. However, sideswipe crashes slightly increased from 6.89 to 7.12 per intersection per year, and head-on crashes remained stable (1.41 to 1.39 per intersection per year), with neither change reaching statistical significance.
- For La Vergne, which included only seven signal intersections, crash frequencies fluctuated but none of the changes were statistically significant. Rear-end crashes decreased slightly from 12.0 to 10.54 per intersection per year, while sideswipe crashes increased from 6.73 to 8.62 per intersection per year, showing that benefits of the signal upgrades were limited and localized.
- **In Smyrna, notable safety gains were observed in rear-end crashes**, which dropped significantly from 9.66 to 4.97 crashes per intersection per year. This reduction demonstrates the strong positive effect of the upgrades in improving traffic flow and reducing sudden braking. Head-on and sideswipe crashes showed marginal, non-significant changes, indicating these collision types were less influenced by the upgrades.
- **Murfreesboro showed the most substantial improvements. Both rear-end crashes (11.94 to 7.74** per intersection per year**) and sideswipe crashes (8.89 to 6.95** per intersection per year**) experienced statistically significant decreases, indicating meaningful improvement in safety.** Additionally, head-on crashes declined from 1.50 to 1.08 per intersection per year, suggesting that the upgrades also enhanced safety for more severe collision types, likely by improving signal timing and reducing high-speed conflicts at intersections. Overall, rear-end collisions were the most common crash type across all cities and showed the most consistent reductions, with significant improvements in Nashville, Smyrna, and Murfreesboro. Murfreesboro also achieved reductions in both sideswipe and head-on crashes, indicating a comprehensive safety benefit.

The **Table 4-6** and boxplots **Figure 4-13** present the Property Damage Only (PDO, including both property damage over and property damage under) crashes, Minor Injury crashes (including both suspected minor injury and possible injury), and Serious Injury (i.e., suspected serious injury) crashes. The fatal crash is not considered as it is the corner case. It is found that:

- **In Nashville, the most notable change was a significant reduction in PDO crashes,** which dropped from an average of 11.96 crashes per intersection per year before the upgrades to 9.39 after (*). This suggests that the upgraded signals were effective at reducing lower-severity crashes, likely due to smoother traffic flow and fewer stop-and-go conditions. Minor injury crashes increased slightly (5.17 to 5.55 per intersection per year), and serious injury crashes also rose slightly (1.09 to 1.29 per intersection per year), though these changes were not statistically significant. The boxplot for Nashville reflects this trend, with a visible decline in PDO crash variability over time, especially after 2020.

- In La Vergne, none of the crash severity categories showed a statistically significant change. PDO crashes slightly increased from 15.80 to 17.71 per intersection per year, while minor and serious injury crashes fluctuated but remained relatively stable. The boxplots show high variability, indicating that traffic patterns in La Vergne may require additional interventions beyond signal upgrades to achieve meaningful safety improvements.
- For Smyrna**,** there was a visible decrease in PDO crashes, dropping from 12.89 to 7.13 per intersection per year; however, this change did not meet the statistical significance threshold. Minor injury and serious injury crashes also showed slight decreases, from 4.00 to 3.33 per intersection per year and 1.14 to 1.20 per intersection per year, respectively, though neither was significant. The boxplot reflects this steady downward trend, especially in PDO crashes, suggesting that while the signal upgrades improved safety, the effects were modest given the city's smaller intersection network.
- **Murfreesboro demonstrated the most comprehensive safety improvements. Statistically significant reductions were observed across all crash severity levels**: **PDO crashes fell from 18.14 to 13.68** per intersection per year**, minor injury crashes dropped from 4.77 to 3.15** per intersection per year**, and serious injury crashes declined from 1.34 to 1.00** per intersection per year**.** These results indicate that the signal upgrade program had a strong and broad safety benefit in this area, reducing both the frequency of less severe crashes and the likelihood of more serious outcomes. Overall, the results reveal that PDO crashes are the most sensitive to signal upgrades**,** showing notable reductions in Nashville and Murfreesboro. The boxplot for Murfreesboro shows clear downward trends after 2020, with consistently lower medians and reduced variability.

Although significant decreases were observed in both the total number of crashes and crash frequency by collision type and severity, it should be noted that the evaluation is based on macro-level observations. It is still uncertain how drivers respond to the upgraded signal timing from a micro perspective. In future studies, intersection turning movements and signal plans could be analyzed to further explore how signal timing affects individual driving behavior.



Nashville (Davidson)

La Vergne (Rutherford)

Smyrna (Rutherford)

Murfreesboro (Rutherford)

Figure 4-12. Intersection Crash Frequency by Collision Type.

Table 4-6. Average Yearly Crash Per Intersection by Collision Type Before and After the Signal Upgrade

Period	Nashville	La Vergne	Smyrna	Murfreesboro
Head-on	1.41/1.39	1.5/1	1.17/1.17	1.50/1.08*
Rear-end	8.01/6.28*	12/10.54	9.66/4.97*	11.94/7.74*
Sideswipe	6.89/7.12	6.73/8.62	5.49/5.00	8.89/6.95*
Note * denotes that after period crash frequency is statistically significantly lower than before period, under 90% confidence interval				

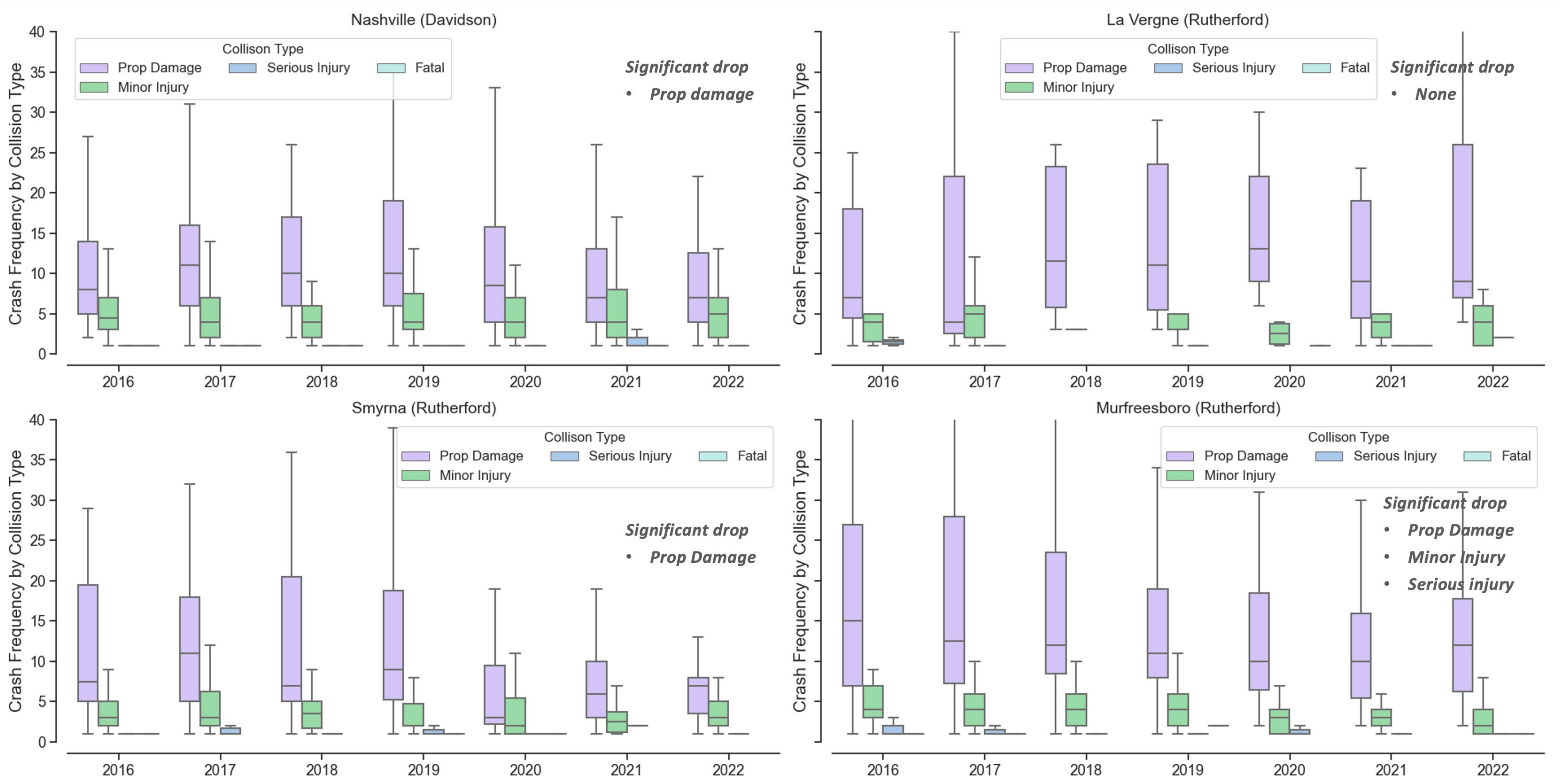


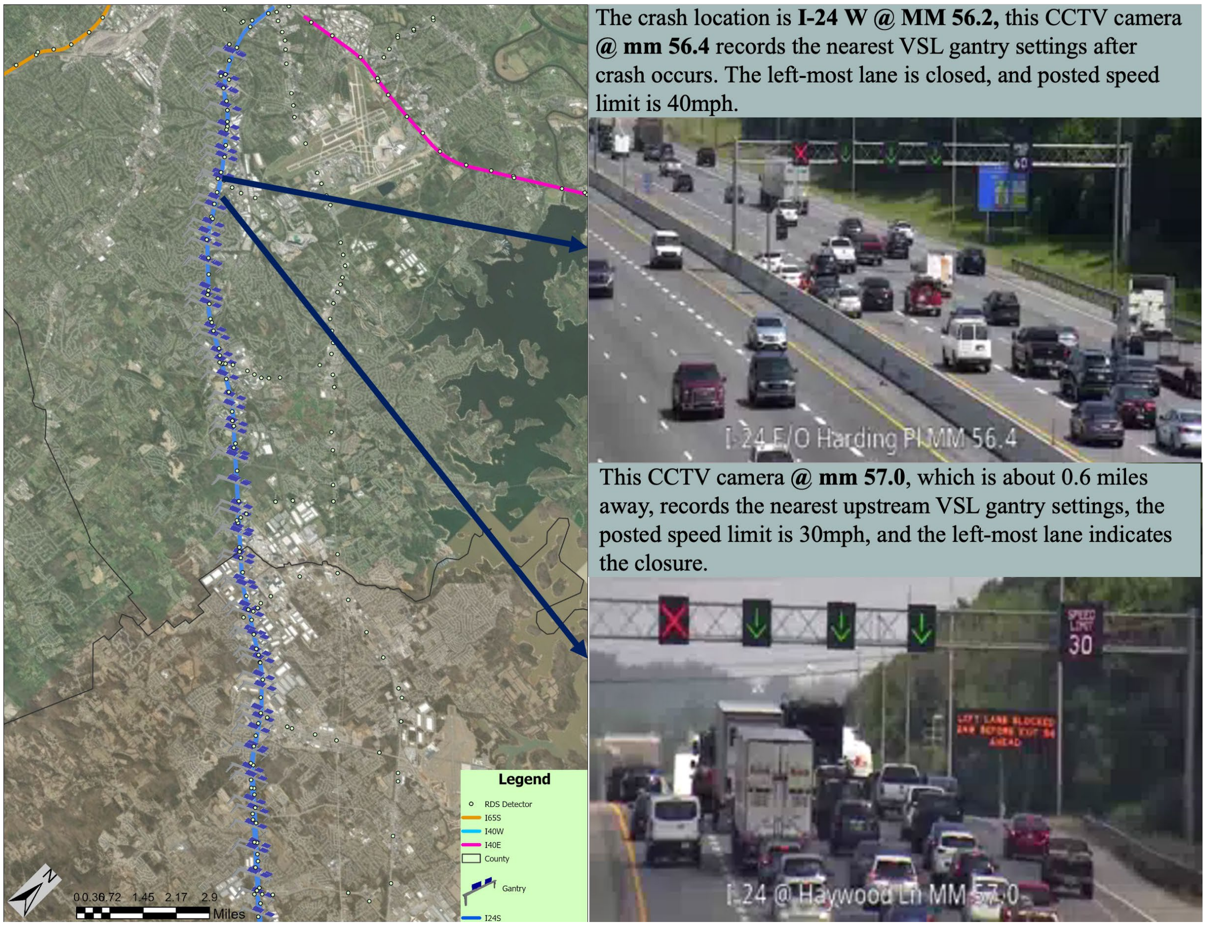
Figure 4-13. Crash Severity Before and After Signal Upgrade.

Table 4-7. Average Yearly Crash by Collision Type Before and After the Signal Upgrade

Period	Nashville	La Vergne	Smyrna	Murfreesboro
PDO	11.96/9.39*	15.80/17.71	12.89/7.13	18.14/13.68*
Minor Injury	5.17/5.55	5.25/4.8	4/3.33	4.77/3.15*
Serious Injury	1.09/1.29	1.2/1.5	1.14/1.2	1.34/1.0*
Note * denotes that after period crash frequency is statistically significantly lower than before period, under 90% confidence interval				

4.6 Variable Speed Limit and Lane Control Signs

The variable speed limits and lane control signs are core elements of the ICM system. As the left side of **Figure 4-14** shows, a total of 67 overhead VSL gantries are installed along a 17-mile stretch of I-24, spaced at intervals of approximately 0.4 to 0.5 miles. The VSL/LCS system went online on June 20, 2023. The overhead gantries generally display the speed limits, lane closures, and other warning information. The right side of **Figure 4-14** demonstrates an example of activated VSL at mile markers 56.4 and 57.0 in response to the crash that occurred at mile marker 56.2 Westbound. As we can see, the left-most lane was closed (i.e., *X* symbol) due to the crash, and green arrows indicate the open lanes, the right-most board shows the posted speed limit. Further, looking at the nearest upstream gantry, which is about 0.6 miles away, the traffic gets congested, and the left-most lane also indicates the closure despite the vehicles on that lane, suggesting drivers change their lane and slow down proactively to avoid delay and collision. The speed limit is lowered to 30mph. Although different VSL/LCS control strategies may lead to varying levels of safety benefits, this study focuses on evaluating the overall safety effectiveness of VSL/LCS systems. Therefore, the specific algorithms used to determine VSL settings are not discussed in detail. Interested readers can refer to the work by Zhang et al. (*23)* for backend algorithms.



The crash location is **I-24 W @ MM 56.2,** this CCTV camera **@ mm 56.4** records the nearest VSL gantry settings after crash occurs. The left-most lane is closed, and posted speed limit is 40mph.

This CCTV camera **@ mm 57.0**, which is about 0.6 miles away, records the nearest upstream VSL gantry settings, the posted speed limit is 30mph, and the left-most lane indicates the closure.

Figure 4-14. Layout of Variable Speed Limit System on I-24 Smart Corridor, Tennessee

4.6.1 Compliance rate

Compliance rate is critical to the overall performance of the VSL system. Using VSL and RDS data collected between September 2023 and April 2024, we estimated compliance rates during peak hours, when VSL primarily addresses both recurring congestion (e.g., peak-hour traffic) and non-recurring congestion (e.g., accidents). Since RDS data is aggregated in 30-second intervals, we define compliance rate as the percentage of intervals during peak hours in which the observed traffic speed is lower than the posted variable speed limit by less than 5 mph. The compliance rate is calculated for each lane and for each VSL gantry. The nearest RDS station of each gantry was used for comparison. **Figure 4-15** visualizes an example of one week comparison between VSL speed limits labeled by red points and RDS speeds represented by the black dots. It should be noted that speed limits are applied uniformly across all lanes; however, drivers in the fast lanes are more likely to disregard them, whereas those in the slow lanes tend to show higher compliance.

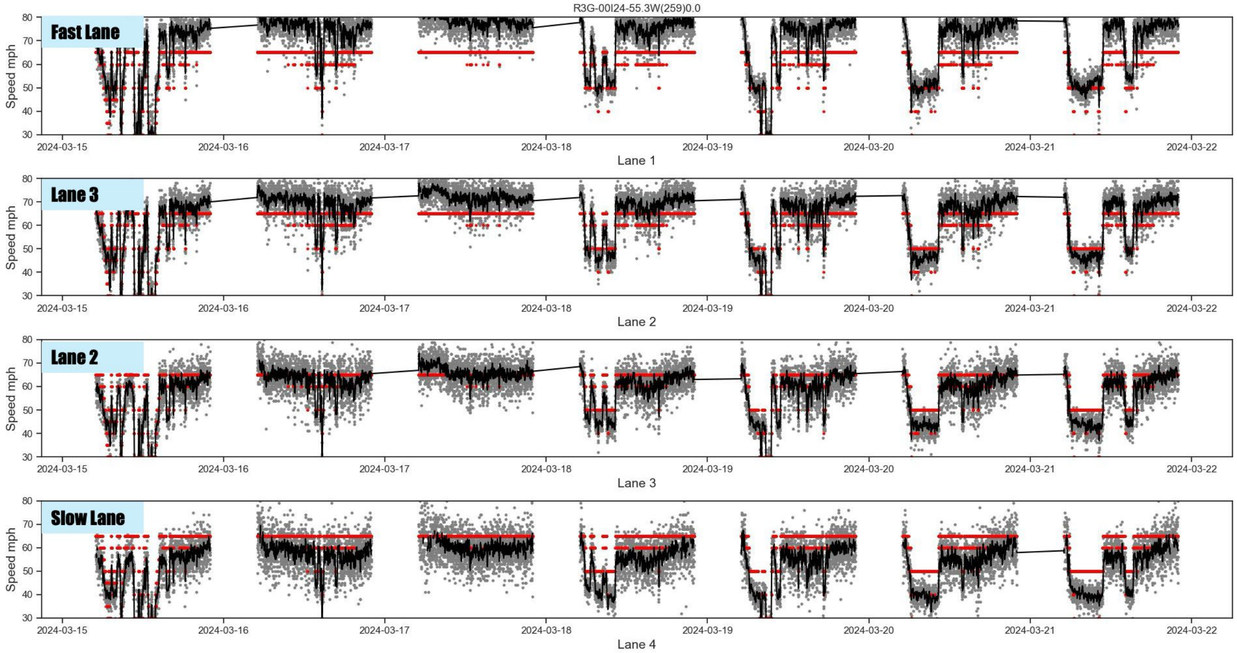


Figure 4-15. Example of VSL Speed Limits and RDS Speed at I-24 Mile Marker 55.3 Westbound

Following that, **Figure 4-16** illustrates the distribution of compliance rate for two directions over multiple lanes for the study period. As shown,

- In the fast lane, westbound compliance rates show a wider spread and lower median compared to eastbound, **meaning westbound drivers in the leftmost lane were much less consistent in following VSL settings, with many intervals of low compliance.** Eastbound traffic in the fast lane, by contrast, maintained relatively higher compliance, though still with some variability.
- For the middle lanes (Lane 3 and Lane 2), eastbound traffic again demonstrates higher compliance overall, with medians near the upper portion of the boxplots, while westbound lanes display lower median values and broader variability. **This suggests that drivers heading eastbound were more responsive to VSL in these lanes, whereas**

westbound compliance was weaker and less stable. In the slow lane, compliance rates are the highest for both directions, reflecting more cautious driving behavior.

- Eastbound again outperforms westbound, with a higher median and tighter distribution. Westbound slow-lane compliance shows more variability and includes some very low outliers, indicating that even in the slow lane, adherence was less reliable in the westbound direction. However, it is also possible slow lanes are connected to ramps which physically limit their speed for leaving or entering the mainline.
- **Taken together, the results suggest that drivers heading into Nashville in the morning are less compliant with VSL than those traveling toward Murfreesboro in the afternoon, especially in the fast and middle lanes.** This pattern is expected, **as commuters heading westbound toward Nashville in the morning are often in a hurry to get to work, whereas in the afternoon, when returning eastbound to their homes, drivers may not face the same time pressure and thus exhibit higher compliance.**

The **Figure 4-17** shows that VSL compliance varies notably by lane and time of day. In the fast lane, compliance is the lowest and most inconsistent, with wide variability and many low outliers, particularly during off-peak hours when drivers face less congestion pressure and are more inclined to speed. Lane 3 demonstrates moderate compliance, with slightly higher adherence during off-peak periods, suggesting that when traffic is lighter, drivers in this lane are somewhat more responsive to VSL. Lane 2 exhibits consistently strong compliance, with medians above 80% and less variability, while the slow lane shows near-perfect compliance in both peak and off-peak periods.

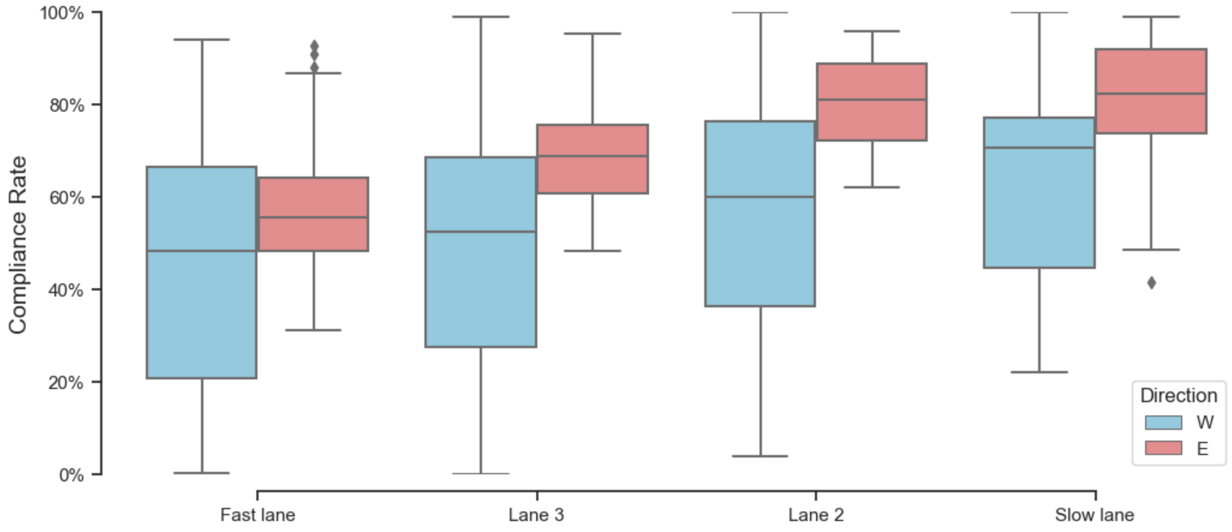


Figure 4-16. Peak Hour Compliance Rate.

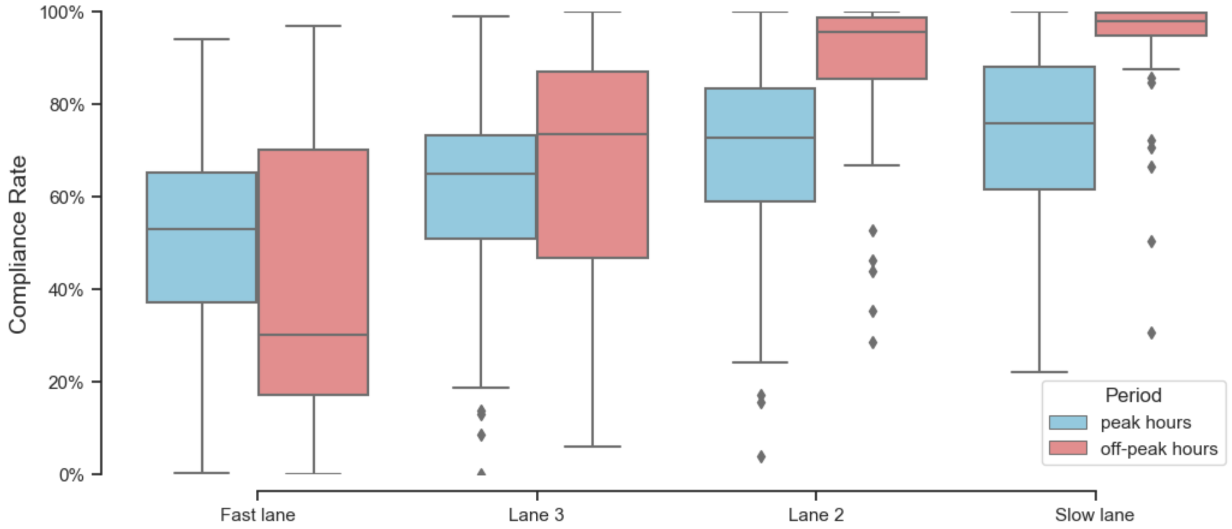


Figure 4-17. Compliance Comparison when VSL on and Off for Both Directions.

4.6.2 Travel time and reliability

VSL slows down traffic and reduces the speed to prevent the crashes. Hence, it is important to look at whether travel time reliability improves before and after the VSL implementation. To do so, NPMRDS speed data was used to calculate the travel time and reliability measures for VSL implementation for the consistence of speed data. As VSL was implemented in June 2023, to make a fair comparison, we use the fiscal year from July to June to calculate the yearly performance. We calculated the average speed, buffer time, and extremely bad travel time (i.e., 95th of travel time) for the peak hours for the fiscal year starting 2016 till 2024. All summary statistics are provided in **Table 4-8**, and the historical trends are shown in **Figure 4-18 and Figure 4-19**.

- Prior to 2020, westbound travel times declined steadily, with both average and 95th percentile travel times dropping significantly until the onset of the pandemic. After 2020, however, westbound conditions worsened year by year, and by 2023, average travel times exceeded pre-pandemic levels.
- Following the VSL implementation, there was a modest improvement: the average westbound travel time in FY 24–25 decreased by about 1.15 minutes compared with FY 23–24, although travel times remained historically high.
- **Overall, westbound reliability worsened in recent years, with average travel times rising from 26 minutes in FY 21–22 to a peak of 32.5 minutes in FY 23–24 before moderating slightly to 31.4 minutes in FY 24–25.** The rate of increase in average travel time has noticeably slowed following the VSL/LCS implementation, compared to the approximately three-minute rise in travel time every year observed prior to deployment.
- A similar pattern is observed for the 95th percentile travel time, which climbed from 35.8 to 44.6 minutes, while buffer time increased from about 9.6 to 13.2 minutes and the buffer time index rose from 37–38% to above 40%, indicating less predictable conditions.

By contrast, the eastbound direction has been more stable.

- **Average travel times rose modestly from 23.9 minutes in FY 21–22 to 25.3 minutes by FY 23–24 and held steady in FY 24–25.** The 95th percentile travel time fluctuated slightly between 29 and 32 minutes without the escalation seen westbound, while buffer time and buffer time index remained comparatively low, averaging around 6 minutes and 25% with only minor year-to-year changes. The historical trend also indicates that eastbound travel times have stabilized in the range of 20–30 minutes, reflecting greater reliability compared to the westbound commute toward Nashville.

For both directions, the implementation of the VSL/LCS systems has helped cool down the previously rising average travel time, even as westbound and eastbound VMT increased by 10.3% (approximately 0.08 million miles per day), and 3% (0.04 million miles per day) after the VSL/LCS implementation. Although average travel time and reliability initially declined during the first fiscal year of VSL/LCS deployment, notable improvements were observed in the second fiscal year (2024–2025). This trend suggests that VSL/LCS work well, and drivers became more familiar with the overhead gantry system and adapted to its operational patterns over time.

Table 4-8. Travel Time Reliability Before and After VSL Implementation

	Fiscal Year*	Average Travel Time (minutes)		95th Travel Time (minutes)		Buffer Time (minutes)		Buffer Time Index	
I840-SR155 (Westbound)	21-22	26.1	Avg. 27.9	35.8	Avg. 38.5	9.6	Avg. 10.6	37%	Avg. 38%
	22-23	29.7		41.2		11.5		39%	
	23-24	32.5	Avg. 31.9	44.6	Avg. 44.6	12.1	Avg. 12.6	37%	Avg. 40%
	24-25	31.4		44.6		13.2		42%	
SR155-I840 (Eastbound)	21-22	23.9	Avg. 24.3	29.3	Avg. 30.6	5.3	Avg. 6.3	22%	Avg. 26%
	22-23	24.7		32.0		7.2		29%	
	23-24	25.3	Avg. 25.3	31.1	Avg. 31.5	5.8	Avg. 6.3	23%	Avg. 25%
	24-25	25.3		32.0		6.7		26%	

*The fiscal year starts in July and ends in June because VSL went online in June 2023. The 21-22, 22-23 are before period, and the 23-24, 24-25 are after period.

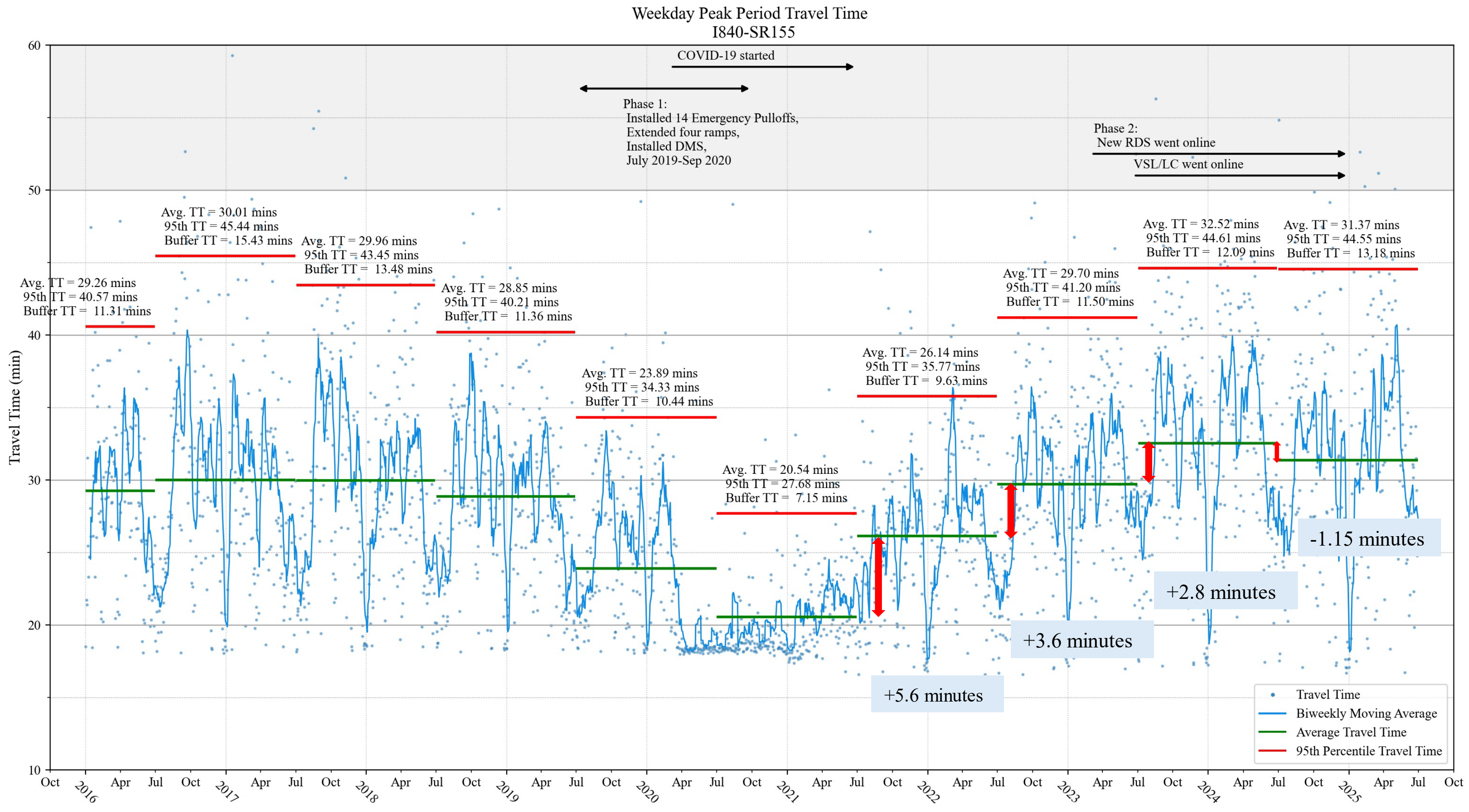


Figure 4-18. Peak Hour Travel Time from I-840 to SR-155

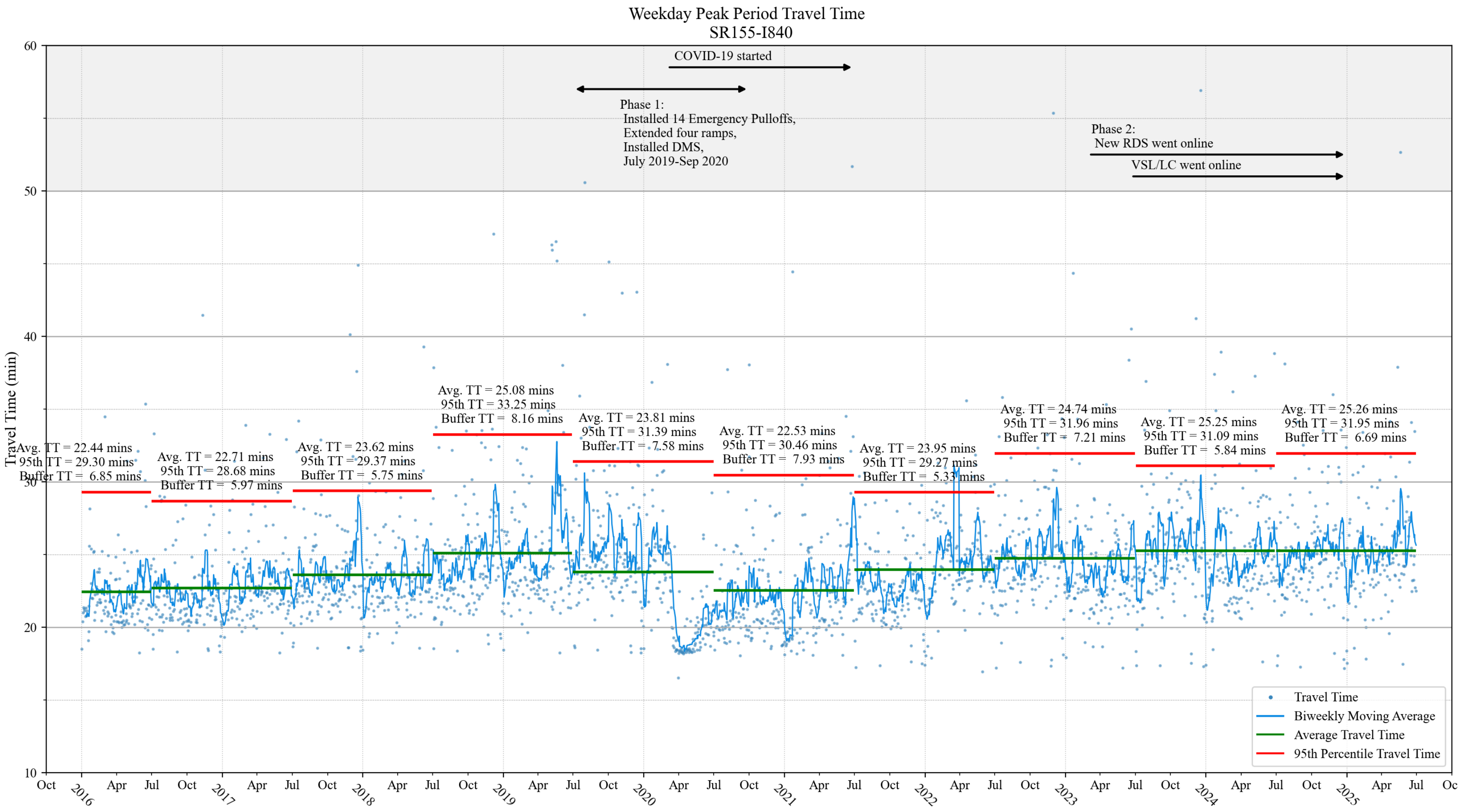


Figure 4-19. Peak Hour Travel Time from SR-155 to I-840

4.6.3 Spatiotemporal congestion pattern

Traffic congestions are dynamic which typically propagates along the corridor over the time. Thus, understanding the spatiotemporal congestion patterns would help us manage the demand and protect the queue. We used one-year RDS speed data before and after the VSL implementation to reveal the congestion pattern on I-24 Smart Corridor. The probability of excessive congestion is calculated at 0.1-mile spatial intervals and 30-second time intervals. It is defined as the proportion of days within the study period (i.e., one year) when excessive congestion occurred. A higher probability indicates a greater likelihood of recurring congestion. The left side of **Figure 4-20** demonstrates the congestion pattern of eastbound before and after the VSL implementation. The redder color area indicates the congestion impacted time (x-axis) and area (y-axis, mile markers). The right side of **Figure 4-20** highlights the areas and times where the probability of congestion exceeds 30%. The dashed line represents the before condition, while the solid line indicates the after condition. For each contour level, the same color is used to highlight both periods, with line style distinguishing between before and after. It is found that:

- **For the eastbound direction, the most affected period occurs between approximately 15:30 and 18:20, spanning mile markers 53 to 56 (from I-24 at Briley Parkway to Harding Place).** During this timeframe, weekday afternoon travelers face over a 70% probability of encountering severe congestion. While looking at the 50% and 30% probability contours reveals that, after the VSL implementation, congestion begins roughly 30 minutes earlier and persists about 30 minutes longer compared to the year prior to VSL implementation.
- However, looking at the corridor level, **the congestion impacted area does NOT significantly expand towards Murfreesboro.**
- **Another finding is that the congestion begins slightly earlier and ends slightly later between mile marker 56 and mile marker 59, which is from Harding Pl to Bell Road.** The apparent expansion of congestion probability after VSL implementation might be due to the proactive operation of VSL, as it is activated before peak hours begin and remains in effect for a more conservative duration.

Figure 4-21 shows the spatiotemporal congestion pattern for Westbound (from Murfreesboro to Nashville). Compared to the eastbound side, the westbound traffic congestion lasts longer and impacts longer stretch of the route. There are several findings through this spatiotemporal diagram.

- First, between approximately 6:30 AM and 9:00 AM, and along mile markers 54 to 65, there is more than a 50% probability of encountering congestion.
- **Second, the queue length near Murfreesboro between 6:30 and 6:50 AM has shortened following the VSL implementation.**
- Third, like the eastbound direction, **congestion now begins earlier, about 20 minutes earlier than before, though the timing varies across segments of the corridor**. At the same time, congestion persists significantly longer than in the prior situation, particularly **between mile markers 55 and 59 (from Harding Place to Bell Road), where queues last about one hour longer than previously observed.**

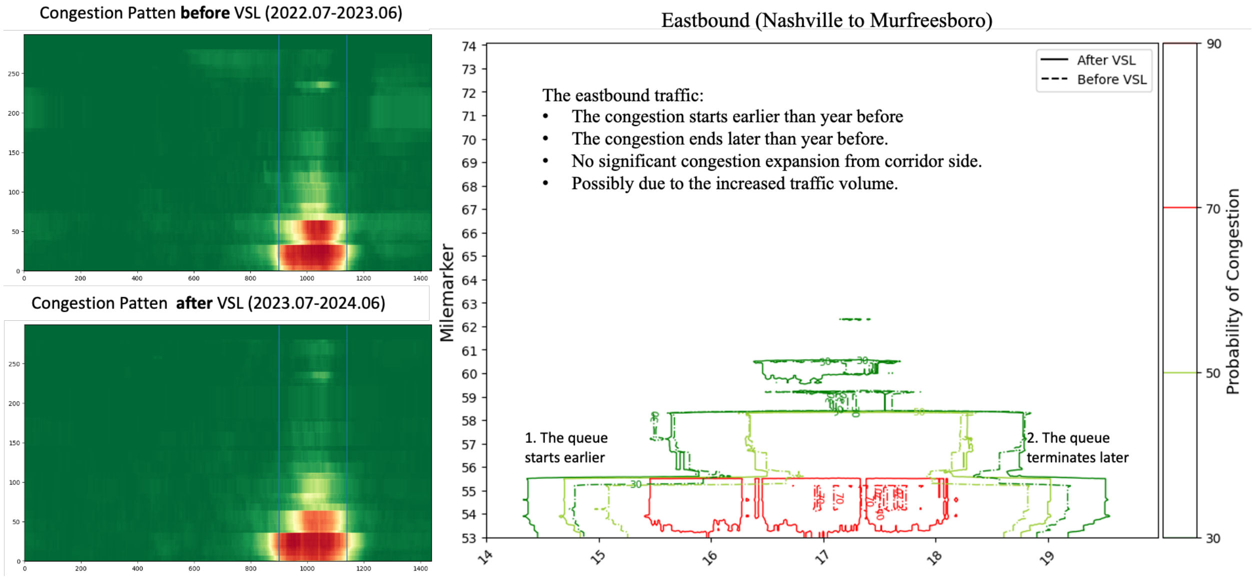


Figure 4-20. Spatial Temporal Traffic Congestion Contour for Eastbound

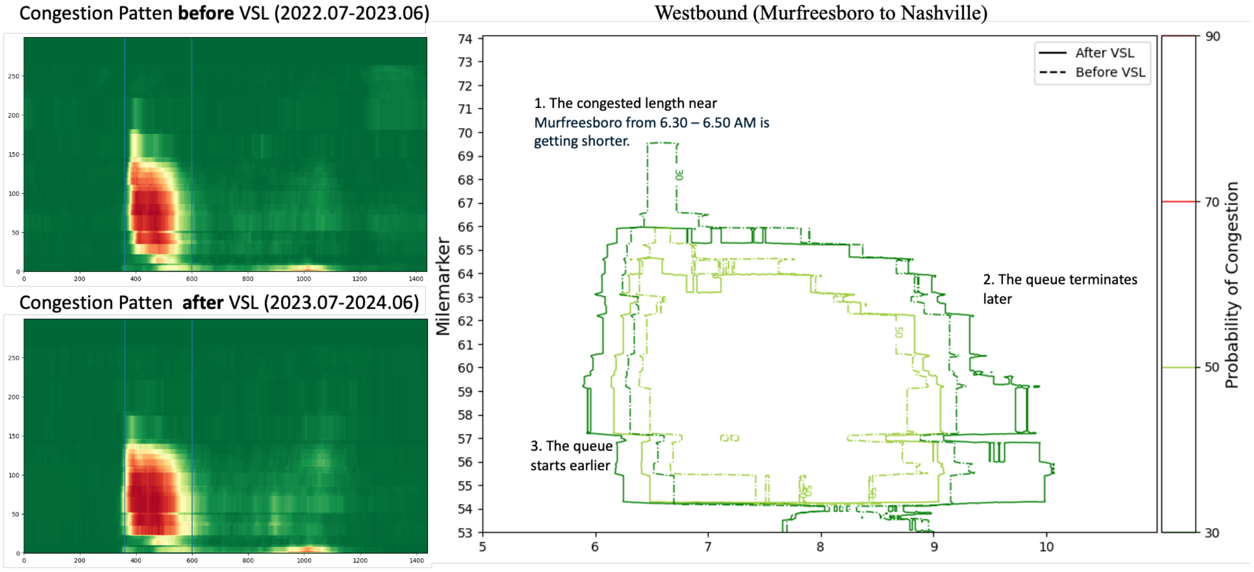


Figure 4-21. Spatial Temporal Traffic Congestion Contour for Westbound

Figure 4-22 compares peak-hour delay before and after VSL implementation. The left panel shows the eastbound direction, while the right panel shows the westbound. The y-axis corresponds to mile markers, with the top representing the Nashville area and the bottom representing the Murfreesboro area. The gray solid line indicates delay before VSL, and the red solid line indicates delay after VSL. The area between the two lines reflects the change in delay: green shading represents delay savings, whereas red shading indicates delay deterioration. Please note that the delay calculated here does not take the volume into account. Each point on the line represents the total delay during peak hours. For example, a value of 0.6 at mile marker 53 indicates that 0.6 out of the 4 peak hours at mile marker 53 were affected by excessive delay. The red and green bar on the left side of each panel indicate the percent increase or decrease of AADT following the VSL implementation.

- Looking at the eastbound, **it is found that excessive delay typically takes place between mm 52 and 63, which corresponds to I440 and county line, the closer to I440, the larger delay during peak hours.** Delay increased after the VSL implementation across most of this section, even though AADT decreased on several segments, including those between Briley Parkway and Bell Road.
- However, there is an exception for the segment from mile marker 58.2 to 59.2 near Bell Road, where conditions improved substantially. This improvement may also be likely due to the ramp extension at I-24 and Bell Road (i.e., the addition of ramp lanes), in addition to the benefits of the VSL system.
- For the **westbound traffic, the excessive delay during the morning peak usually propagates to I-24 at Sam Ridley Pkwy.**
- **Traffic delay worsened significantly between Briley Parkway and Waldron Road; however, at the end of the queue, that is, between Waldron Road and Sam Ridley Parkway, traffic conditions improved compared to the pre-VSL period.**
- In contrast to the eastbound direction, most segments in Davidson County exhibited traffic growth in the westbound direction.

Table 4-9 summarizes the delay per mile for the entire corridor.

- Eastbound undergoes 9.8% increase of delay per mile, while westbound undergoes over 40% of increase of delay per mile. The VSL aims to slow down and smooth traffic flow and therefore sometimes the travel time increase is unavoidable, but what we observed is that the impact is significantly different between two directions.
- The observed differences in delay growth may be attributed to several factors. First, the increase in westbound delay is positively associated with rising traffic volumes. Second, the effects of VSL may vary by trip purpose. Westbound traffic is predominantly inbound and work-related, with commuters traveling under time pressure to reach their workplaces, the chaotic driving behavior in the morning peak hours may negatively influence the VSLs operations, leading to the increased delay. By contrast, eastbound traffic is more likely to be associated with home-based or shopping-related trips, which may be less time-sensitive. In such scenarios, drivers may be more willing to follow the VSL signs. This could be a future study to investigate the impact of I-24 Smart Corridor project on the travelers' trip patterns, local business, and even the increasing immigration from other counties or states.

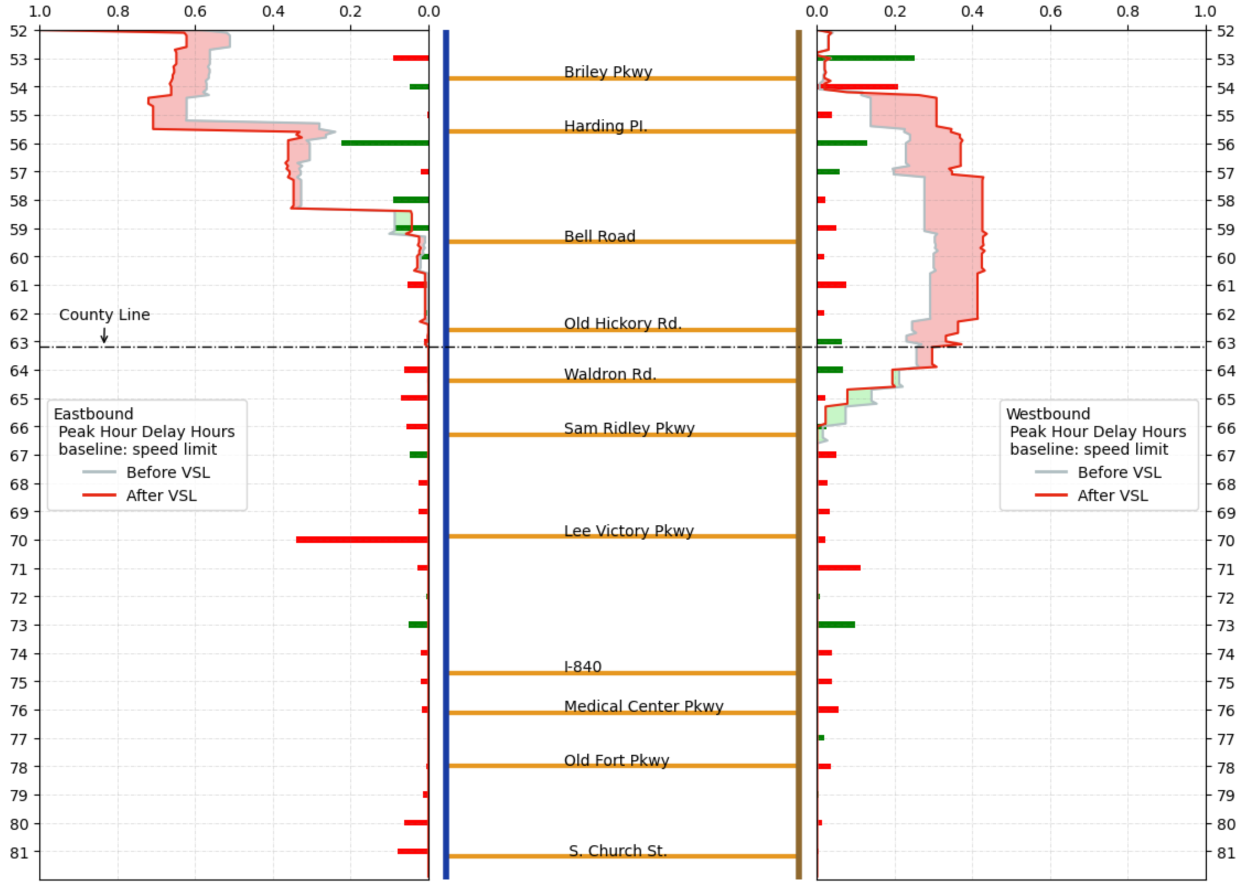


Figure 4-22. Comparison of Delay over the Corridor

Table 4-9. Average Median Delay Per Mile During Peak Hours (Minutes)

Direction	Before	After	Change
Eastbound	1.02	1.11	+9.8%
Westbound	0.96	1.36	+41.4%

4.6.4 Vehicle miles traveled

Vehicle Miles Traveled (VMT) is a key metric for quantifying the amount of vehicular travel along the I-24 Smart Corridor. In this project, VMT was derived from RDS traffic volume data, which has been shown to closely approximate ground-truth conditions. Unlike AADT which is estimated at yearly level, the VMT generated by RDS data offers flexibility to view the change between fiscal years, as **Figure 4-23** shows. We calculated the average daily VMT for one year before the VSL implementation, and two years after the VSL implementation, separately. As **Table 4-10** shows,

- **Overall, both directions show growth in VMT after VSL was deployed, but the magnitude differs.** In the eastbound direction, VMT increased modestly, rising from 1.33M to 1.37M miles, a 3.0% gain. This suggests that eastbound travel demand remained relatively stable, with only slight growth over the two-year period.

- By contrast, **the westbound direction, which enters Nashville, saw a more substantial increase, from 1.37M to 1.45M miles, reflecting a 10.3% gain (0.08M).** This larger growth likely reflects stronger commuter demand and regional economic activity tied to Nashville as a major employment hub.
- The VMT pattern aligns with travel time trends, as the westbound direction records an average peak-hour travel time roughly six minutes longer than the eastbound.

Table 4-10. Summary Statistics of Daily VMT Change Before and After VSL/LCS Implementation

Direction	Before (2022-2023)	After (2023-2025)	Change
Eastbound	1.33M	1.37M	+3.0% (0.04M)
Westbound	1.37M	1.45M	+10.3% (0.08M)

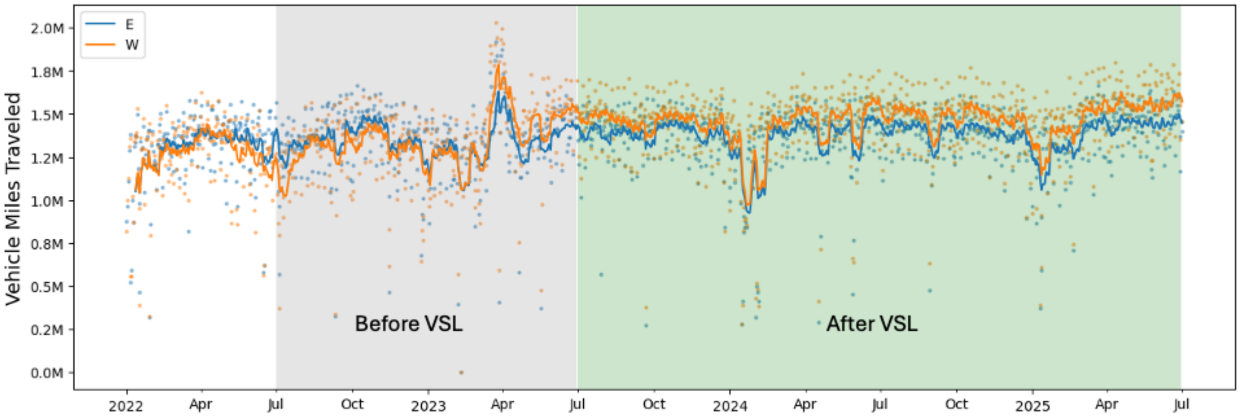


Figure 4-23. Longitudinal VMT Tracking Using RDS Volume Data

4.6.5 Delay and cost

Delay captures the extra time spent on the road due to the traffic congestions. Delay is calculated using the volume data from RDS and speed data from NPMRDS. Travel time is compared against the historical average speed and fixed speed limits. We compared the delay two years before and one year after VSL implementation. The historical average speed accounts for the recurring traffic congestions yet fixed speed limits do not. In other words, the delay calculated by historical average speed tends to reveal the delay caused by the incidents, while delay calculated against post speed limits reveal the extra time compared to almost free flow time. Therefore, the delay and cost estimated by fixed speed limit are generally larger than the one based on the historical average speed, yet they can be used for different purpose.

The delay and delay cost are summarized in the following **Table 4-11**. Analysis of delay based on historical average speeds shows that westbound travel consistently experiences heavier delays than eastbound, reflecting stronger congestion toward Nashville.

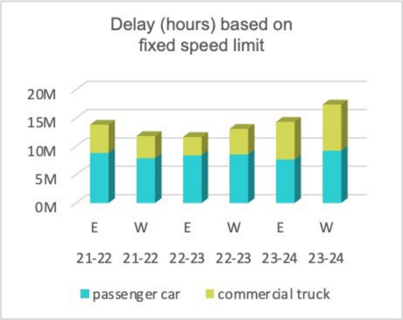
- Westbound delays rose from 5.64M hours in FY 21–22 to 9.25M in FY 23–24, with costs increasing from $11.76M to $18.49M.
- Eastbound delays were somewhat lower, fluctuating between 4.40M and 5.44M hours, but costs grew from $22.35M to $29.99M due to the higher share of commercial vehicle delay. This indicates that while westbound traffic bears the bulk of absolute congestion,

eastbound delay is more costly because of its greater economic impact on commercial vehicles.

- When measured against posted speed limits, both directions show much larger delays and costs, underscoring the magnitude of non-compliance with VSL targets. Eastbound delays rose to 14.31M hours in FY 23–24 with costs reaching $71.76M, while westbound delays climbed to 17.37M hours with $39.18M in costs.
- The total delay of both directions estimated by historical average speed and fixed speed limits increased by 36.2%, and 27.8% respectively.

Table 4-11. Travel Delay and Cost Before and After VSL/LCS Implementation

Fiscal Year	Direction	Pass. car delay	Com. delay	Total delay		Delay cost		Delay/VMT (mins)	Delay Cost/VMT ($)
Delay based on historical average speed									
21-22	E	2.99M	2.22M	5.21M	10.85M	10.59M	22.35 M	0.64	0.022
21-22	W	3.36M	2.28M	5.64M		11.76M		0.68	0.023
22-23	E	3.00M	1.41M	4.40M	10.79M	10.79M	24.64M	0.54	0.023
22-23	W	3.77M	2.62M	6.38M		13.85M		0.77	0.028
23-24	E	2.81M	2.63M	5.44M	14.69M	11.51M	29.99M	0.65	0.023
23-24	W	4.44M	4.81M	9.25M		18.49M		1.05	0.035
Delay based on fixed speed limit									
21-22	E	8.82M	4.99M	13.81M	25.63M	30.53M	57.62M	1.71	0.063
21-22	W	7.90M	3.93M	11.82M		27.08M		1.42	0.054
22-23	E	8.42M	3.24M	11.66M	24.74M	30.94M	62.62M	1.44	0.064
22-23	W	8.58M	4.50M	13.08M		31.68M		1.57	0.063
23-24	E	7.68M	6.63M	14.31M	31.6M	32.58M	71.76M	1.72	0.065
23-24	W	9.23M	8.14M	17.37M		39.18M		1.96	0.074



(a) Delay - historical speed **(b) Delay – fixed speed limit** **(c) Delay cost – historical speed** **(d) Delay cost – fixed speed limit**

Figure 4-24. Delay and Cost by Vehicle Types.

4.6.6 Safety effects of VSL/LCS

Observational results

To evaluate the safety effects of VSL/LCS systems, we first examined observational safety outcomes one year before and after the VSL/LCS implementation, focusing on total crash frequency (**Figure 4-25)** as well as specific crash types of interest, including sideswipe and rear-end collisions **(Figure 4-26).** The crash frequency was aggregated into segments between connecting routes in order to reveal the spatial heterogeneity caused by the various traffic exposure, land use and geometry profiles along the corridor. The blue bar and green horizontal bars represent the crash frequency (left to the blue vertical line) and crash rate (right to the blue vertical line) for the before and after period. The triangles at the ends of the bars indicate the increase or decrease in crash outcomes. The right panel of the figure summarizes crash frequency by time of day, with daytime defined as 8:00 AM to 10:00 PM and the remaining hours classified as nighttime. It is found that:

- **Figure 4-25** shows that the segments between Briley Pkwy and Old Hickory Rd experience much more crashes than other areas of I-24 Smart Corridor. After VSL/LCS system implementation, **the safety of segment from Briley Pkwy to Bell Road has been improved**, yet the safety of segment from Bell Road to Old Hickory Road tends to get worse after the VSL implementation, indicated by both raw and normalized crash frequency.
- **It should also be noted that the crash frequency of segments that are outside of VSL/LCS operation areas (i.e., down the road of I-840) are increasing after the VSL/LC implementation,** this may explicitly indicate the benefits of VSL/LCS in safety improvement as a comparison. While comparing the crash frequency by the time of day (except the segment between I-840 and Medical Center Pkwy), it is found that total number of daytime crashes increased with different rates, which may indicate that the daytime safety is still a concern given the increasing traffic volume**. Figure 4-26** shows the total rear-end and sideswipe crashes before and after the VSL implementation. It can be found that the pattern is quite like the total crash frequency. However, while comparing the crash frequency by the time of day, **the frequency of rear-end and sideswipe crashes that happened during the daytime decrease significantly for most of segments within the VSL/LCS control area except for the stretch from I-440 to the Harding Pl and from Bell Road to Old Hickory Road**. This is a positive signal of VSL as VSL is mostly activated during the daytime when traffic congestion take place.
- **It should be noted that total, rear-end, and sideswipe crashes continued to increase after the VSL/LCS implementation.** This trend is very likely attributable to the substantially increasing traffic demand near downtown Nashville and the complex ramp and interchange systems among I-440, I-40, and I-24, where frequent lane-changing occurs. Drivers entering I-24 from Nashville may not be well prepared for the VSL/LCS settings, while those exiting I-24 toward the city may rush to leave the congested area. Such travel behaviors are likely to reduce the overall effectiveness of the VSL/LCS system.

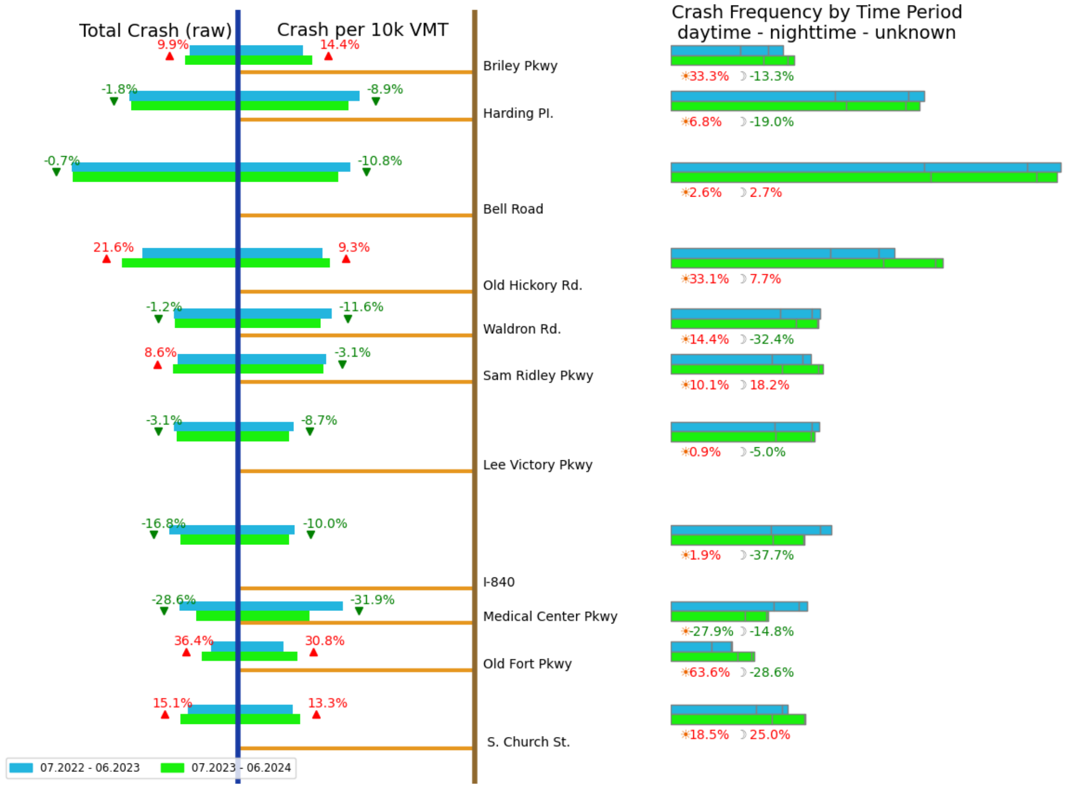


Figure 4-25. Total crash frequency by segments and time of day

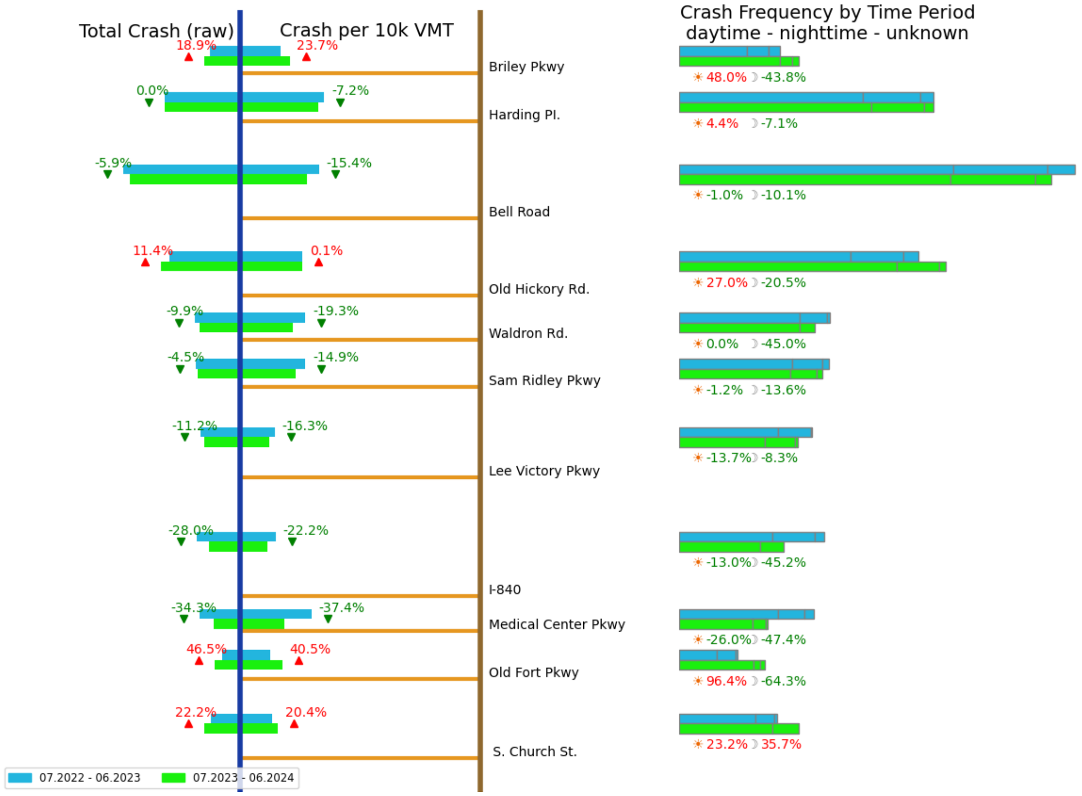


Figure 4-26. Rear-end and Sideswipe Crash Frequency by Segments and Time of Day.

Full Bayesian Before-after Evaluation

The above results are based on observed crash counts, with crash rates normalized by AADT. However, numerous confounding factors may influence changes in crash frequency, including seasonal variations in traffic demand, and latent factors such as shifts in driving behavior (people may get more familiar with the VSL/LCS as time goes). In addition, regression-to-the-mean effects may arise, as average crash frequency often declines over time despite year-to-year fluctuations. Without careful consideration, these trends may be misattributed to the benefits of enhancements. Therefore, we applied a sophistical causal inference framework by designating I-24 Smart Corridor as the treatment group and East of I-40, West of I-40, and South of I-65 in Nashville as comparison groups. Crash frequency by type were then estimated using a negative binomial model within a full Bayesian framework. This framework aims to predict the crash frequency for the treated sites if the VSL/LCS had not been implemented. Then the net between prediction and observed crash frequency denotes the safety effectiveness of VSL/LCS. **Table 4-12** summarizes the prediction of crash frequency by severity type and collision type. It is found that:

- Only a few fatal crashes (K), less than 10, were identified over a four-year study period. The prediction results are not statistically significant as the training size is extremely small.
- For injury-related crashes, the model reveals a certain of safety improvement. **The Crash Reduction Rate (CRR) indicates that the suspect serious injury, suspect minor injury, and possible injury crashes declined by 18.1%, 10.4%, and 17.5% respectively**. This indicates that VSL has produced positive impacts on reducing the injury severity of crashes on the I-24 Smart Corridor. This finding is consistent with previous VSL/LCS evaluations, which reported crash reductions of approximately 8.9% to 31.6% for injury-related crashes (*18*).
- By contrast, the PDO crashes exhibit the smallest decline, which is about 3.8% compared to the prior VSL/LCS implementation.
- The drop in injury and PDO crashes suggests the safety benefits of VSL systems as VSL/LCS slowed down the traffic to prevent the potential damage and threats to vehicle and drivers or passengers.
- With respect to collision types, rear-end and sideswipe crashes decreased by 14.0% and 3.2%, respectively. These reductions can be interpreted as a direct effect of VSL implementation, which reduces speed differentials between upstream and downstream traffic. The decline in sideswipe crashes may be attributed to the use of LCS signs, which notify upstream drivers in advance to change lanes before reaching a closure point.

Table 4-12. Full Bayesian Before-after Crash Estimation

Crash	Before	After	Prediction	Reduction	CRR
K (Fatal)	6	7	2.92	-4.08	-408.0%
A (Suspect Serious Injury)	32	34	29.32	5.32	18.1%
B (Suspect minor Injury)	487	405	451.79	46.79	10.4%
C (Possible Injury)	290	215	260.65	45.65	17.5%
O (Property Damage Only)	1935	1669	1734.30	65.30	3.8%
Rear-end	1341	1130	1314.32	184.32	14.0%
Sideswipe	674	552	570.53	18.53	3.2%

Secondary crash

Since the VSL aims to reduce the speed difference between upstream and downstream traffic, it may also mitigate the occurrence of secondary crashes, which are commonly caused by incidents, traffic queues, and speeding behaviors. The approach of identifying the secondary crash is presented in the methodology section. **Figure 4-27** illustrates an example of a secondary crash that occurred during the morning peak hours. The gray lines indicate VSL/LCS locations, with blue segments showing periods when VSL/LCS was active. Red points denote areas of traffic congestion, represented by low speeds. The blue star denotes the rear-end crash, and the blue square represents other crash collisions. This example depicts traffic heading toward Nashville, with congestion propagating backward in the direction of Murfreesboro. The primary crash occurred at 5:45 AM at mile marker 54.5 because of improper lane changing. Following that, a rear-end crash happened at 6:20 AM at mile marker 56 because of slowing down in the traffic lane. At the time of the primary crash, before significant congestion had formed, the VSL was not yet activated. After the crash happened, the upstream VSL gantries were activated, and the secondary crash (rear-end) happened after 35 minutes in the traffic queue. This case explains the secondary crash, and it also suggests that VSL/LCS may not be able to eliminate every single secondary crash, but instead, it helps mitigate the secondary crash, which is proven by using multiple years of crash data.

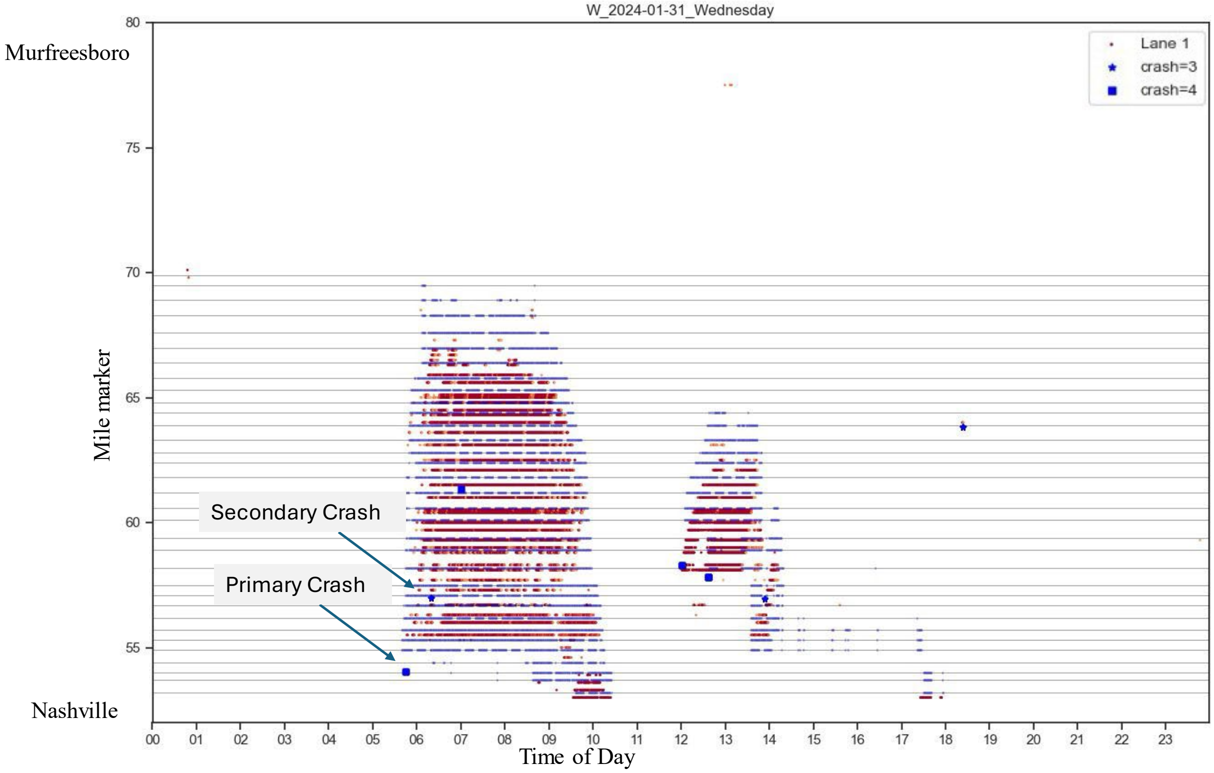


Figure 4-27. An Example of A Secondary Crash Happened on 01.31.2024, Westbound.

Table 4-13 presents the identified primary and secondary crashes on I-24 smart corridor. The rate of secondary to total crashes, secondary crash per primary crash, total number of secondary crashes, and the change of secondary crash before and after the VSL implementation are estimated. To avoid the impact from the 2020 pandemic and earlier deployed strategies, we used two years before and two years after the VSL implementation for comparison. Note that the primary crash in the **Table 4-13** represents the first crash that led to the secondary crashes; if there are no secondary crashes, the crash is called a normal crash. It is found that:

- First, the net primary and secondary crashes decreased significantly after the VSL implementation. **The rate of secondary crash also declines from 7.72% in the fiscal year of 21/22 and 6.61% in the fiscal year of 22/23 to 5.19% and 6.22% in 23/24 and 24/25, respectively.** This means that secondary crashes are less likely to happen after the VSL implementation.
- The secondary crash per primary crash also slightly reduced, from about 1.11 to 1.02, in other words, previously, a primary crash could cause 1.11 secondary crashes, **but now it led to fewer secondary crashes.** This is meaningful because a primary crash may cause one or more secondary crashes.
- An examination of the total number of secondary crashes over the two years shows a 13.8% reduction, decreasing from 213 to 174. This represents a positive indicator of the safety benefits associated with VSL/LCS implementation.

Table 4-13. Historical Primary and Secondary Crashes on I-24 Smart Corridor

Year	Primary	Secondary	Normal	Total	Rate of Sec.	Sec./Pri.*	Total	Change
17/18	111	120	1363	1594	7.53%	1.08		
18/19	111	123	1496	1730	7.11%	1.10		
19/20	204	308	1309	1821	16.91%	1.51		
20/21	122	158	1125	1405	11.25%	1.30		
21/22	104	116	1282	1502	7.72%	1.11	213	-18.3%
22/23	88	97	1283	1468	6.61%	1.10		
23/24	76	78	1349	1503	5.19%	1.02	174	
24/25	91	96	1356	1543	6.22%	1.05		

*Note: Sec./Pri. is the rate of secondary crash per primary crash.

4.6.7 Benefit cost analysis

This research project compared the benefits from the ICM activations against costs for the deployment, administration, and operation of the ICM program. To minimize the influence of the pandemic, the baseline period was defined as July 1, 2021, to June 30, 2023 (2 years), and the post period was defined as July 1, 2023, to June 30, 2025 (2 years). Correspondingly, the project limit is from MM 53 to MM 70, where the VSL/LCS gantries are deployed.

The benefits of the I-24 smart project are estimated through the delay savings and crashes prevented. Note that delay savings could bring secondary savings such as fuel savings and emission reductions. However, sections **4.6.2 Travel time and reliability and 4.6.5 Delay** show that both travel time, delay and delay cost increased slightly compared to the baseline conditions. Hence, the delay savings, as well as the savings in emission and fuel consumption are not considered in the benefit side. Therefore, we mainly monetized the safety improvement. The crash unit costs by injury types are provided in **Table 4-14** which refers to the FHWA guidance. Note that the available crash unit costs were estimated in 2016 for the entire US. We first converted the 2016 dollars to 2023 dollars for Tennessee by applying the regional discount factor and inflation factors. The specific method refers to the methodology section. The 2023 dollars are used because the major enhancement LCS/VSL was implemented this year.

Table 4-14. Adjusted Tennessee Comprehensive Crash Unit Costs

FHWA Comprehensive Crash Unit Costs			
Crash Severity	*2016 US average Dollars*	*2016 TN dollars*	2023 TN dollars
(O) Property-Damage Only	$ 11,900.00	$ 10,414.00	$ 13,266.20
(B) Suspected Minor Injury	$ 198,500.00	$ 173,709.00	$ 221,284.66
(C) Possible Injury	$ 125,600.00	$ 109,914.00	$ 140,017.40
(A) Suspected Serious Injury	$ 655,000.00	$ 573,197.00	$ 730,184.97
(K) Fatal Injury	$ 11,295,400.00	$ 9,884,717.00	$ 12,591,956.67

Table 4-15 presents the crash savings by each injury type, note that the fatal crash is not considered as there is no sufficient evidence to claim the benefits in saving fatal crashes. Hence, the total non-fatal crash savings are $21,497,762.59 after considering the TN price values in 2023.

Table 4-15. Crash Savings

Dollar Amount Saved Per Year, Tennessee Comprehensive	
Crash Severity	**Amount Saved**
(O) Property-Damage Only	$ 866,240.14
(B) Suspected Minor Injury	$ 10,354,794.20
(C) Possible Injury	$ 6,391,576.28
(A) Suspected Serious Injury	$ 3,885,151.96
(K) Fatal Injury	Not Applicable
Non-fatal Total	$ **21,497,762.59**

Table 4-16 summarizes the cost of the I-24 Smart Corridor project. So far, there have been two phases implemented, and the third phase like ramp metering is still under design, which is not in the range of this project. The total equivalent cost measured by 2023 dollars is $59,813,794.94.

Table 4-16. I-24 Smart Corridor Cost Summary

Description	**Year of Cost**	**Cost**	**2023 Cost**
I-24 ITS Improvements Phase 1	2018	$ 10,311,383.05	$ 12,591,903.11
I-24 ITS Improvements Phase 2	2019	$ 36,780,783.22	$ 44,271,956.32
AI-DSS	2021	$ 2,600,000.00	$ 2,949,935.50
	Total cost		**$ 59,813,794.94**

Based on the above benefit and cost information, the Benefit Cost Analysis was conducted by considering the lifespan of 10 years, annual discount factor (7%) of the project. As such, the discounted annual investment is $8,516,138.75. Suppose the cost of annual operation and management is $1,000,000, then the Equivalent Annual Cost (EAC) is $9,516,138.75. Based on these information and assumptions, the statistics of benefit cost analysis are summarized in **Table 4-17**:

- The estimated savings per year is $1,232,742.54, the cost per savings per year is $48.52, and the **Benefit Cost Ratio considering a typical lifespan of 10 years is 1.13.** This implies that for every dollar invested in the I-24 Smart Corridor, an average return of **$1.13** can be expected over the next ten years, considering only the benefits from crash prevention.
- Note that this should serve as the bottom line. As commuters become more familiar with VSL/LCS operations, the AS-DSS system continues to mature, and enforcement measures are introduced, the delay savings are expected to persist. Consequently, the associated safety benefits are likely to increase, and the benefit–cost ratio (BCR) may further improve in the near future as additional years of data become available.

Table 4-17. Summary Of Benefit/Cost Analysis

Item	Value
Crash Savings per year	$10,748,881.29
Lifespan (years)	10
Savings per year	$1,232,742.54
Cost/savings per year	$48.52
BCR using EAC	**1.13**

In the project, 10 years lifespan is selected as recommended by FHWA 2022 Benefit Cost Analysis Guidance. The expected service lives for intelligent transportation systems and similar investments are generally somewhat less than 20 years and may be as short as 7-10 years for some types of technologies (*21*).Nonetheless, we also provided the BCR value for different service years, which is shown in **Figure 4-28**. The BCR generally increases with service years; however, the comparison could be made against other projects with similar expected service years.

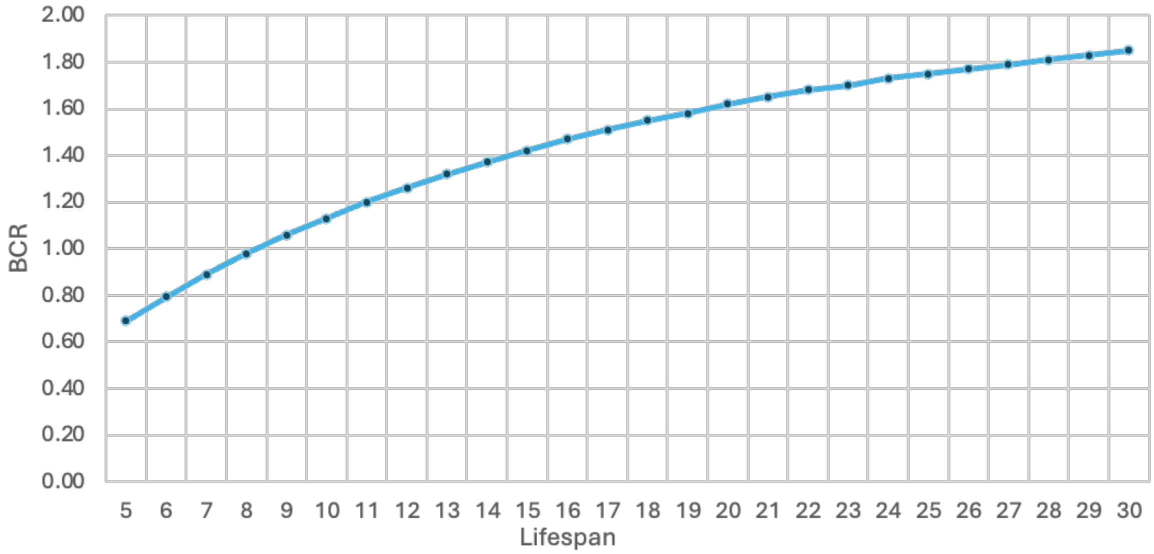


Figure 4-28. BCR With Respect to the Lifespan of I-24 Smart Corridor Enhancements.

4.7 Candidate Smart Corridor Evaluation

Through the comprehensive review of existing Smart Corridor projects in the US, several distinct characteristics of a Smart Corridor have been identified as follows:

- First, the Smart Corridor is a combination of discrete, adjacent surface transportation networks (e.g., freeway, arterial transit networks) that link the same major origin and destinations. It is defined operationally rather than geographically or organizationally.
- Second, the coordination and communication among different transportation networks, agencies, and modes to manage the corridor as a single unified system. The integration of technical, institutional, and operational linkage of systems, data, and processes enables coordinated management.
- Third, they are often driven by intelligent transportation systems, including both infrastructure (e.g., traffic detectors, VSL/LCS signs, DMS, Bluetooth) and technique (e.g., DSS, ATM, incident management) investments.
- Lastly, the priority is often given to the corridors that exhibit increasing traffic congestion, high concentrations of crashes, especially the secondary and rear-end crashes, excessive delays, and strong opportunities for multimodal integration.

Based on those characteristics, we specifically investigated the three candidate corridors in Tennessee, which are Knoxville I-40, Chattanooga I-24, and Nashville I-65. Please also note that those corridors are also in the TDOT 10-year project plan (*24*), which should be given priority for the Smart Corridor deployment.

4.7.1 Knoxville I-40

As Figure 4-29 shows, the first candidate corridor is the section of I-40 concurrent with I-75, extending from the I-40/I-75 split to the I-640/I-40 split west of Knoxville. It has a parallel arterial route, Kingston Pike, with several connecting roads linking the two corridors. The distance of the I-40 corridor is about 17 miles. The busiest stretch of the entire I-40 is in Knoxville, which has an AADT volume of more than 210,000 vehicles according to TN-Times. This network architecture offers a great opportunity for integrated management. Kingston Pike operates two transit routes (Route 11 and Route 17) running from west to east Knoxville, which could be incorporated into the ICM strategy to support multimodal diversion and reduce corridor congestion. There have been many traffic detector systems installed on I-40, which can continue to collect the real-time traffic data for integrated corridor management and incident management systems.

Safety

Figure 4-30 and **Figure 4-31** present the crash frequency by collision type and collision severity. By looking at historical data from 2016-2024, it is found that:

- Rear-end crashes are the dominant crash type across all years, which account for about 45%-55% among all crashes. This suggests that frequent stop-and-go conditions occur on I-40 in Knoxville.
- Sideswipe crashes are the second most frequent type of collision, accounting for 20%-30% of total crashes. This suggests frequent lane changes and weaving behaviors happen on I-40 in Knoxville.
- No-collision-with-vehicle crashes, also referred to as single-vehicle crashes, account for approximately 15–20% of total crashes. These incidents are often caused by roadway debris, roadside infrastructure, or environmental obstacles, and may also result from driver distraction, overcorrection, or other human factors.
- In terms of crash severity, PDO is the outcome of about 80% of crashes, followed by suspected minor injury, possible injury and serious injury crashes.
- Looking at the intersection of crash collision and severity in **Figure 4-32**, the rear-end crashes caused 42.4% PDO and 10.4% injury crashes, respectively. The sideswipe collisions led to 18.3% PDO and 1.8% injury crashes.

In total, the rear-end and sideswipe crashes on I-40 account for more than 65% of total crashes every year. It is suggested to deploy Variable Speed Limits, Lane Control Signs, Dynamic Message Signs, and ramp metering systems to help mitigate rear-end and sideswipe crashes, as well as to reduce the severity of crashes resulting from these types.

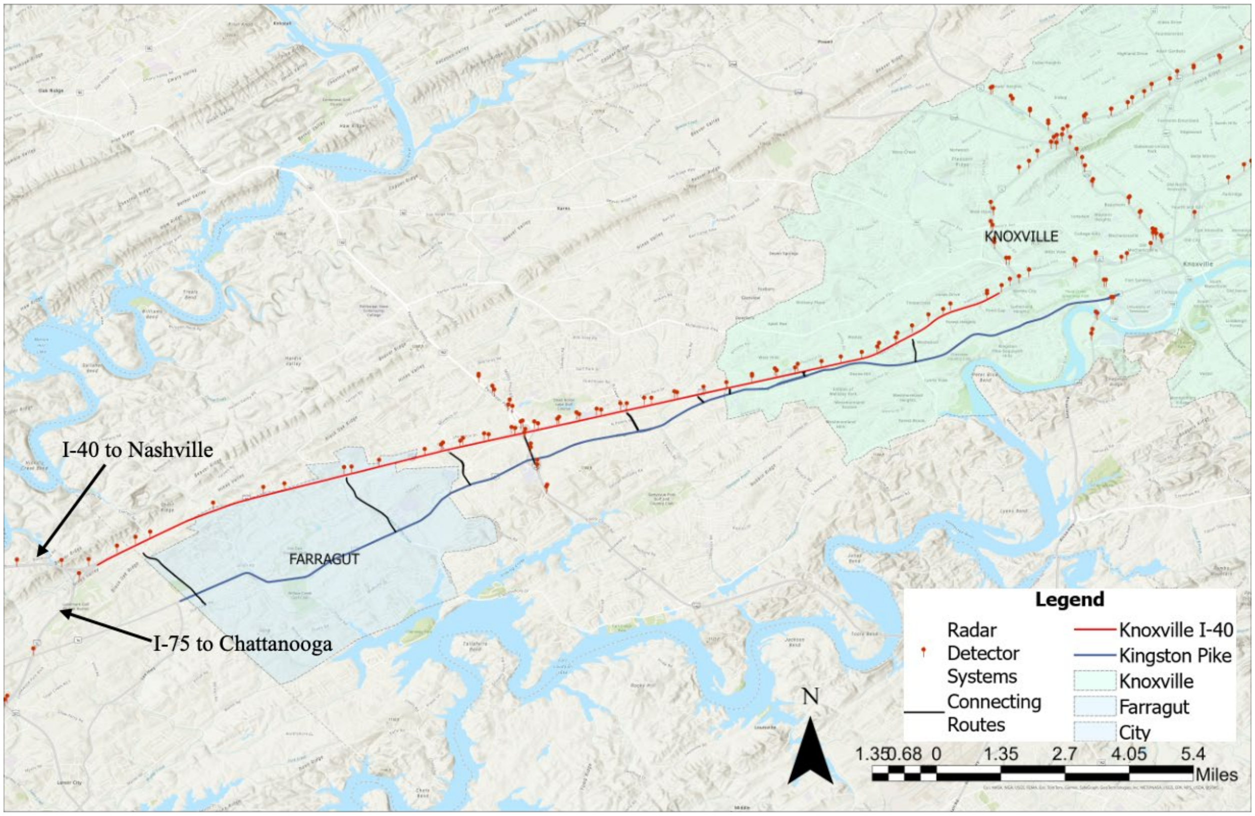
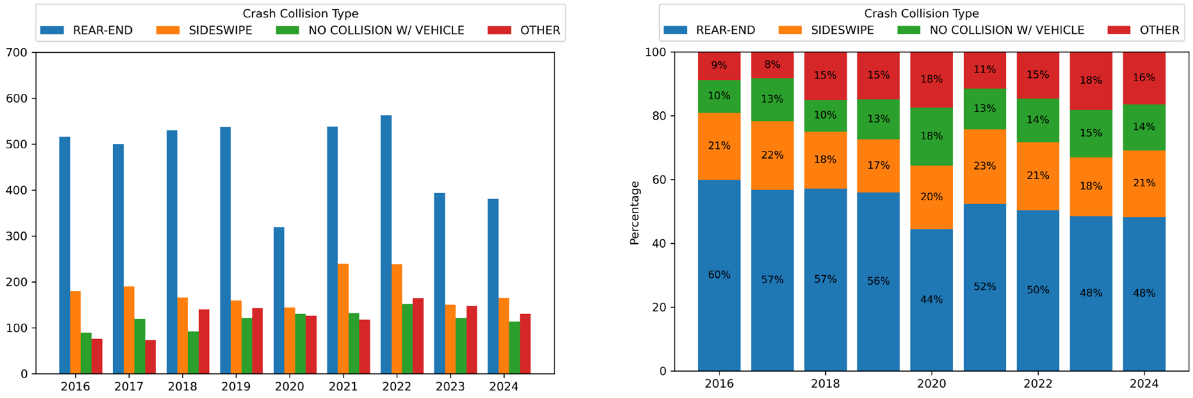


Figure 4-29. Candidate Corridor: Knoxville I-40



(a) Crash Frequency by Collision Type

(b) Crash Frequency Contribution

Figure 4-30. Knoxville I-40 Historical Crash Frequency by Collision Type

(a) **Crash Frequency by Collision Severity** (b) **Crash Severity Contribution**

Figure 4-31. Knoxville I-40 Historical Crash Frequency by Collision Severity

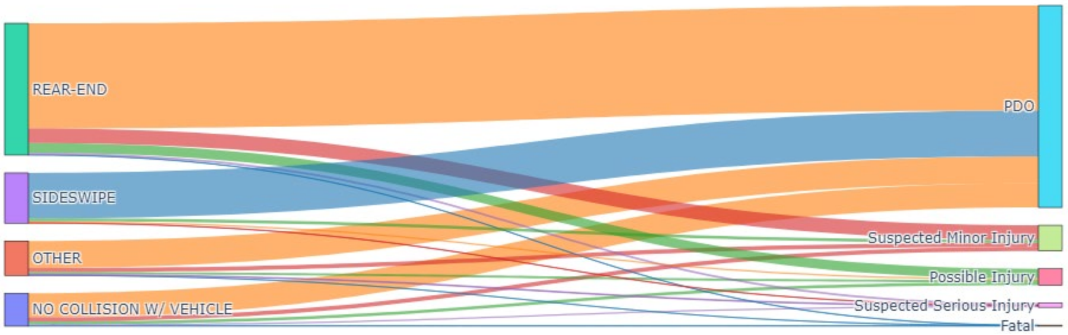


Figure 4-32. Knoxville I-40 Crash Severity Caused by Collision Types

Disabled Vehicles

Among the various incident types, disabled vehicles were specifically examined because: (1) they help justify the need for emergency pull-off areas, (2) their occurrence patterns support the evaluation and potential implementation of the HSR. And (3) their occurrence patterns support the allocation of incident response such as HELP patrol truck. **Figure 4-33** illustrates the spatial distribution of disabled vehicles. The left panel is the cumulative frequency with respect to the mile markers (the bottom is city of Knoxville). The right panel shows the heatmap of disabled vehicles over the year. The data show that disabled vehicles are **highly concentrated from mileposts 374 to 385**. This stretch accounts for approximately 80% of all disabled vehicle incidents along I-40, although the frequency has shown reduction after the 2020 within the city area, as indicated by the lighter red colors on the heatmap. **The emergency pull-off should be particularly considered in this stretch if hard shoulder running needs to be deployed to increase the capacity.**

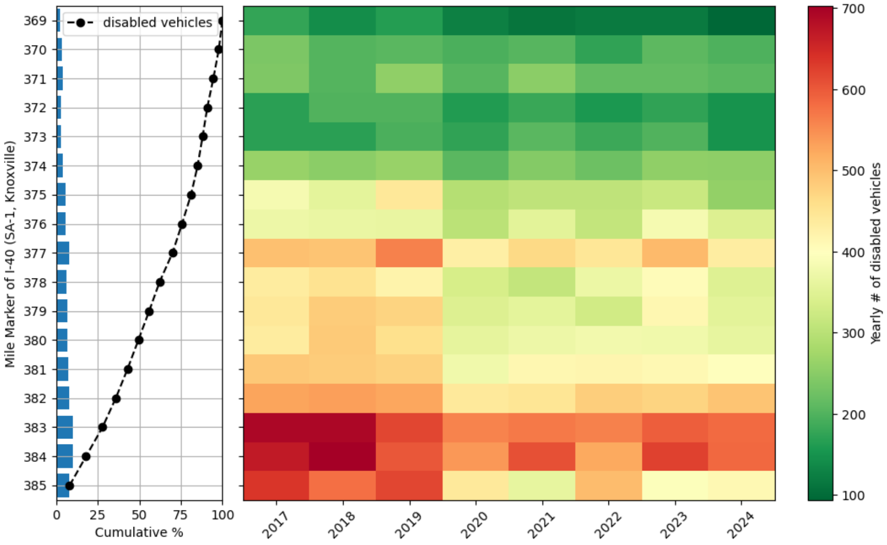


Figure 4-33. Knoxville I-40 Disabled Vehicle Spatial Distribution

Travel time and reliability

Figure 4-34 illustrates the travel time for peak hours for each direction. The bottom and top of each box represent the first and third quartiles of travel time, respectively, while the horizontal line inside the box indicates the median travel time. It can be found that:

- Afternoon peak hour travel time is almost 1.5 times of travel time during the morning peak hours. Meanwhile, the afternoon peak hour travel time presents larger variance than the morning peak hours, indicated by the height of box.
- The travel time variance and average travel time increased year to year after 2020. This indicates heavier traffic congestion and larger trip uncertainty during the peak hours.
- The westbound morning travel time is quite steady after 2020, by contrast, the eastbound traffic towards the city of Knoxville is getting worse in the morning.
- The eastbound traffic in the afternoon peak hours is the most congested compared to the westbound and other periods.

The growing travel time and unreliability strongly suggests the implementation of integrated corridor management to divert the freeway traffic to arterial routes and smooth traffic flow to reduce the travel time volatility on the freeways.

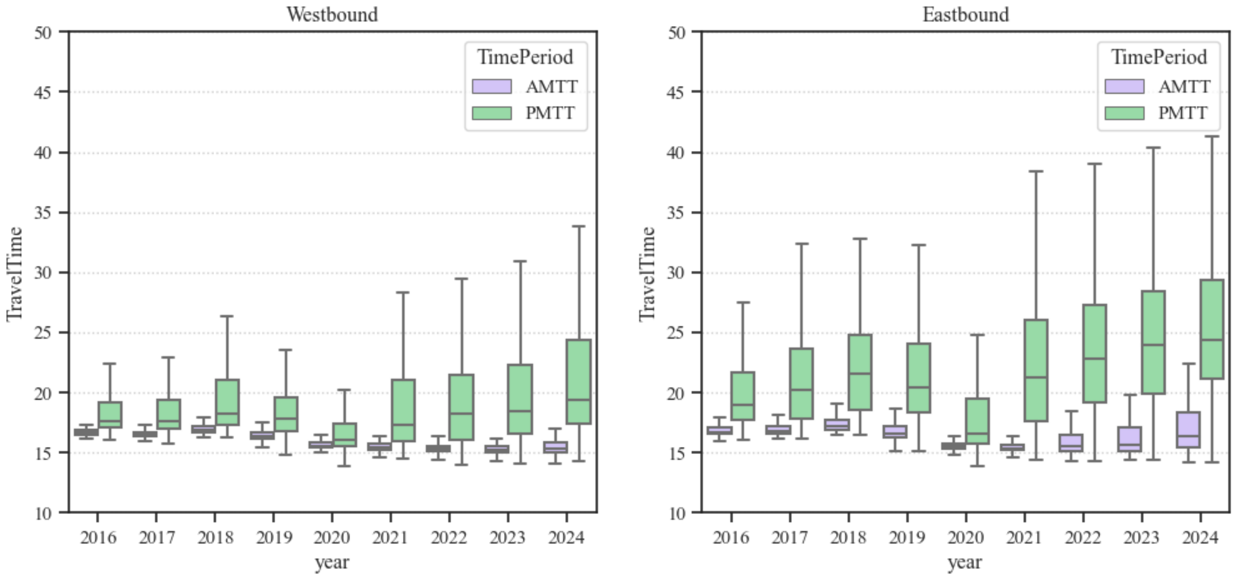


Figure 4-34. Knoxville I-40 Peak Hour Travel Time Variation.

Further, the spatiotemporal excessively congested area is highlighted by **Figure 4-35** and **Figure 4-36**. The westbound direction experiences excessive delays primarily **between mile markers 373 and 376, most notably during the 17:00–18:00** period, with this congestion pattern persisting and expanding across both spatial and temporal dimensions. In the eastbound direction, excessive delays occur mainly **between mile markers 377 and 382, spanning from 16:00 to 19:00**. Over time, the extent of these delays has expanded significantly in both space and duration, indicating growing congestion and reduced operational efficiency along the corridor.

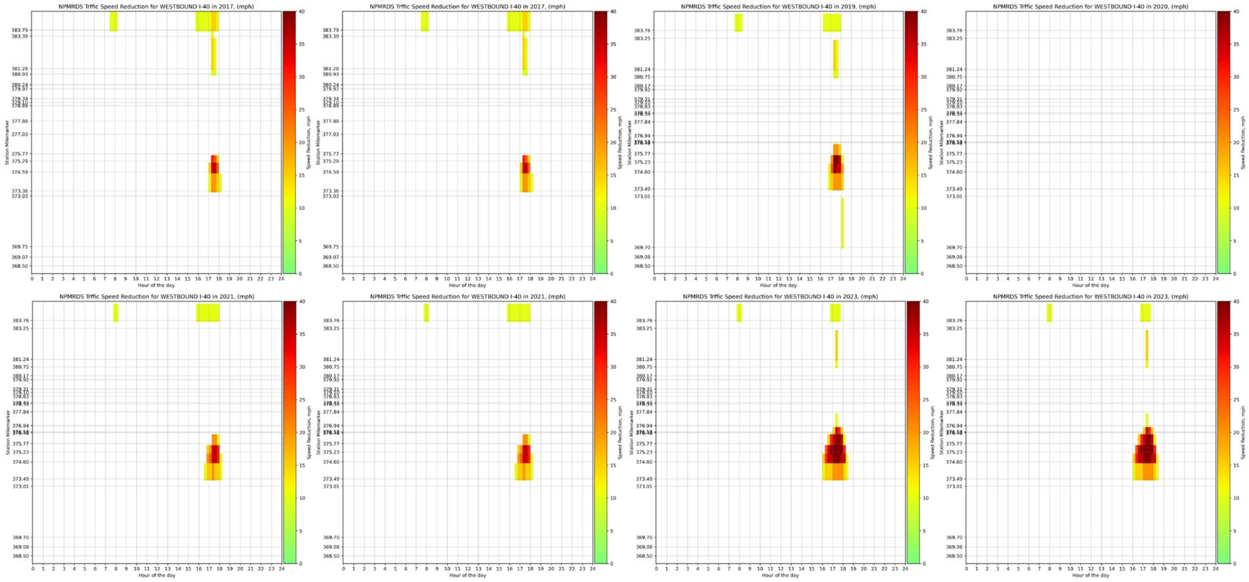


Figure 4-35. Excessively Congested Areas of I-40 Westbound.

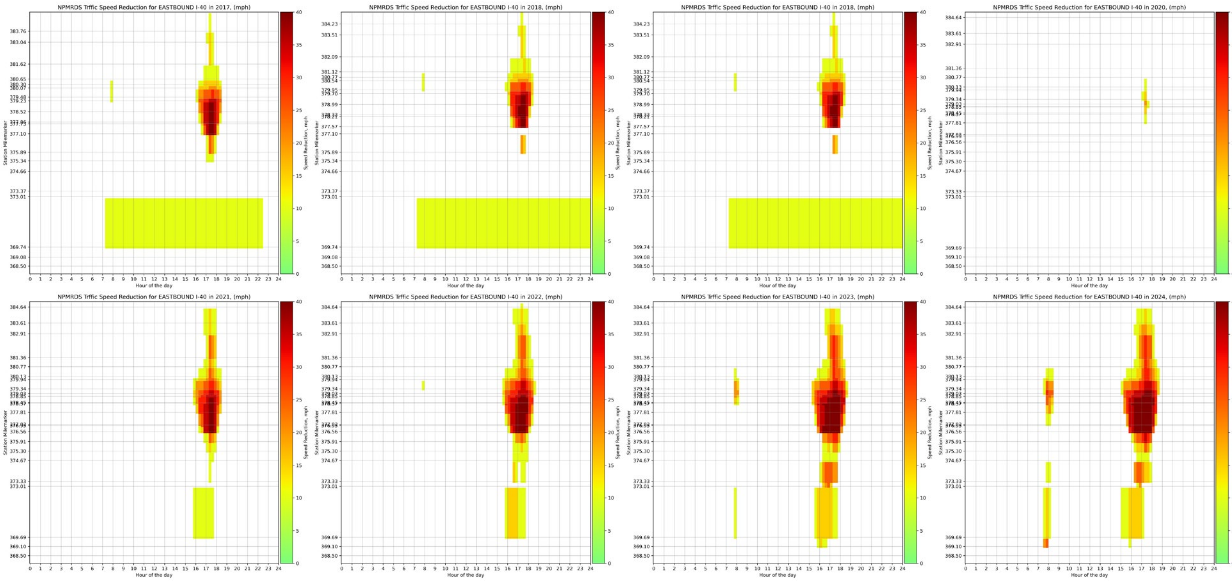


Figure 4-36. Excessively Congested Areas of I-40 Eastbound.

4.7.2 Nashville I-65

In this project, the stretch of I-65 from Nashville to the Spring Hill is examined due to the high traffic exposures every year. The total length is about 18 miles. It can be paired with US-31, as well as the connecting routes between them to establish integrated corridor management. The corridor traverses multiple major cities in the Nashville metropolitan area, namely Berry Hill, Franklin, Brentwood, and Spring Hill. Given the growing regional travel demand, investment in a smart corridor initiative would be a strategic step toward improving traffic efficiency and intercity mobility.

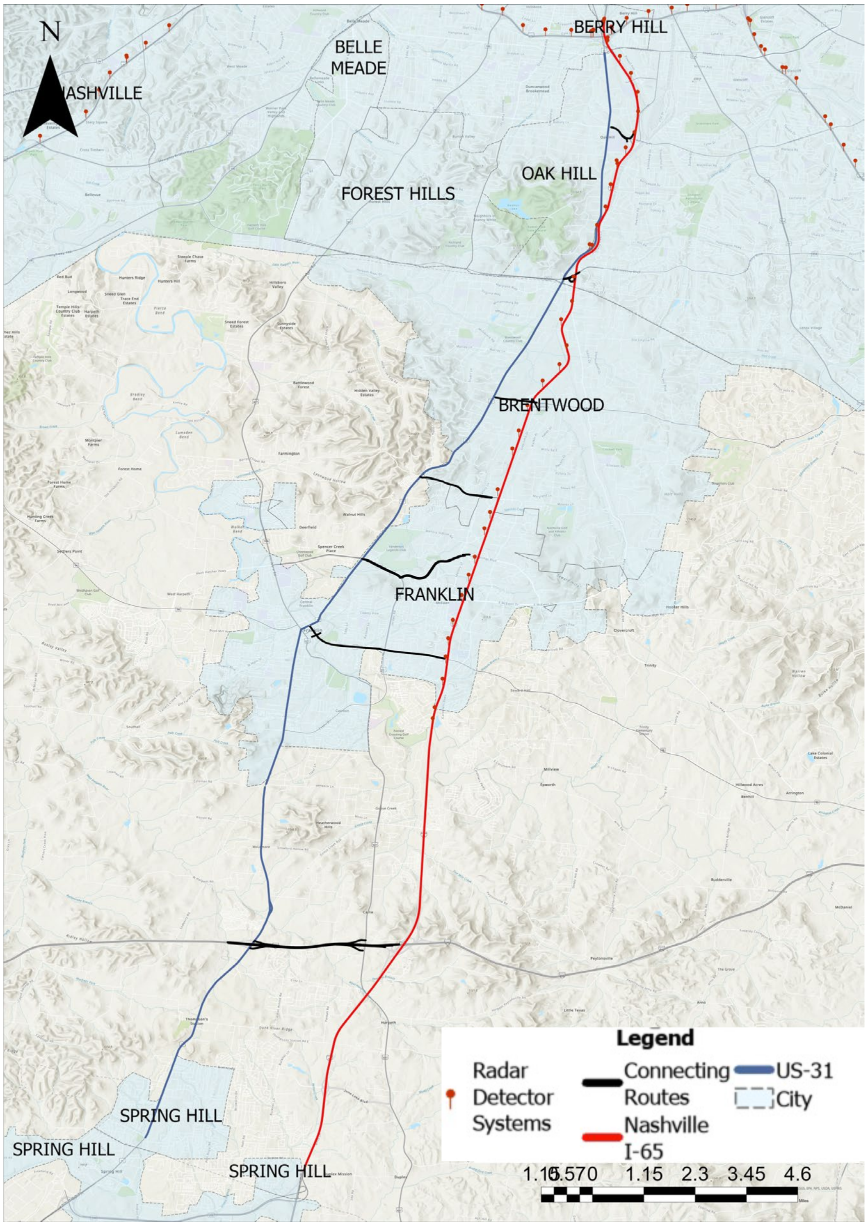


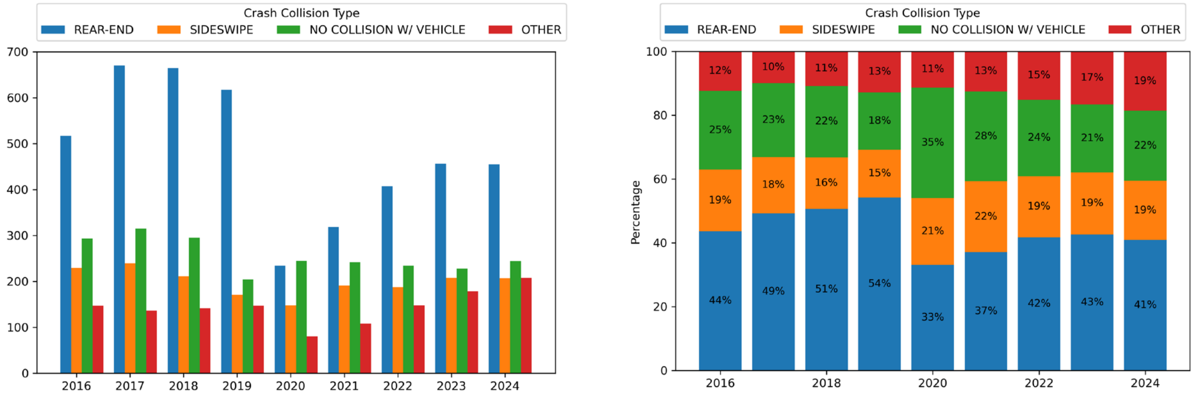
Figure 4-37. Candidate Corridor 1: Nashville I-65.

Safety

Figure 4-38, Figure 4-39 and Figure 4-40 present the crash frequency by collision type and collision severity. By looking at eight years historical data, it is found that:

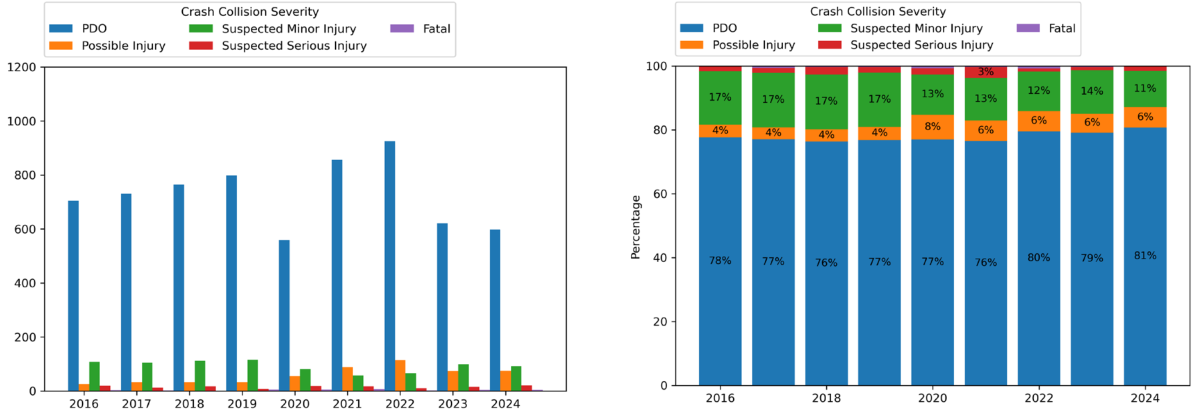
- Since 2020, I-65 has experienced a growing number of crashes, although overall crash severity appears to have improved compared to the pre-2020 period.
- Rear-end and sideswipe collisions are the two most frequent crash types, together accounting for approximately 50–60% of all crashes.
- PDO leads the crash severity, accounting for over 75% of all crashes, followed by suspected minor injury, possible injury and serious injury.
- Rear-end crashes caused 34% of PDO crashes, and 10.6% of injury crashes. Sideswipe crashes led to 16% of PDO crashes, and 2.5% of injury crashes.

Based on above crash distributions, it is also suggested to deploy Variable Speed Limits, Lane Control Signs, Dynamic Message Signs, and ramp metering systems to help mitigate rear-end and sideswipe crashes, as well as to reduce the severity of crashes resulting from these types.



(a) Crash Frequency by Collision Type **(b) Crash Frequency Contribution**

Figure 4-38. Nashville I-65 Historical Crash Frequency by Collision Type.



(a) Crash Frequency by Collision Type **(b) Crash Frequency Contribution**

Figure 4-39. Nashville I-65 Historical Crash Frequency by Collision Severity.

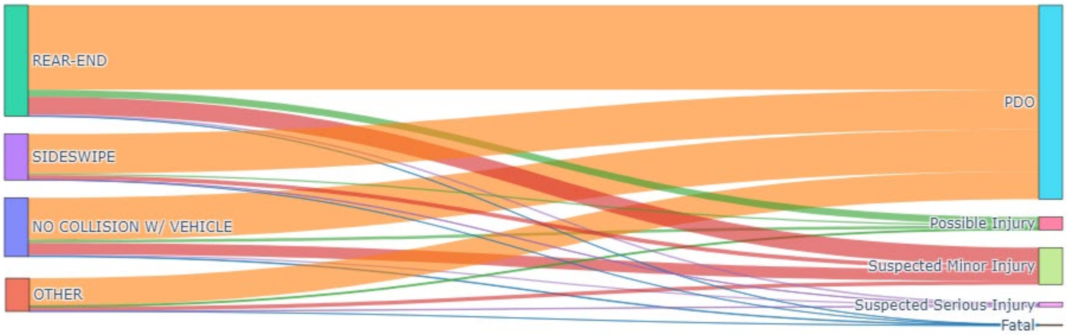


Figure 4-40. Nashville I-65 Crash Severity Caused by Collision Types.

Disabled Vehicles

Figure 4-41 illustrates the spatial distribution of disabled vehicles on I-65. The data show that disabled vehicles are **highly concentrated from mile markers 67 to 80 (approximately from McEwen Dr. to I440)**. This stretch accounts for approximately 80% of all disabled vehicle incidents along I-65, although the frequency has shown reduction after 2017 within the city area, as indicated by the lighter red colors on the heatmap. **The emergency pull-off should be particularly considered in this stretch if hard shoulder running needs to be deployed to increase capacity.**

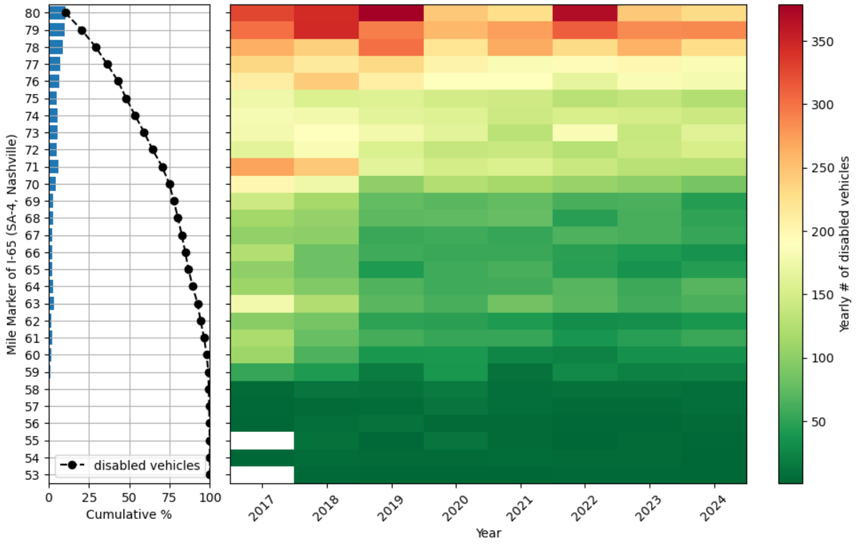


Figure 4-41. Nashville I-65 Disabled Vehicle Spatial Distribution.

Travel time and reliability

Figure 4-42 illustrates the travel time for peak hours for each direction. The bottom and top of each box represent the first and third quartiles of travel time, respectively, while the horizontal line inside the box indicates the median travel time. It can be found that:

- Northbound traffic heading toward Nashville shows considerable variability in travel times across both directions. The morning peak period experiences notably higher travel times than the afternoon peak. Following the post-2020 pandemic recovery, both the median and volatilities of travel times during peak hours have risen markedly, indicating growing congestion and unreliable traffic conditions.
- By contrast, Southbound traffic leaving Nashville in the morning peak hours appears to be improving compared the years before 2020. However, the travel time and reliability during afternoon peak hours are getting worse, indicated by the higher median travel time and consistent large variations.

Hence, it is needed to deploy ICM strategies to curb traffic congestion and improve the travel time reliability.

Further, the spatiotemporal excessively congested area is highlighted by **Figure 4-43** and **Figure 4-44**. Since I-65 passes through multiple cities, areas of excessive congestion are not continuous in either space or time. For example, in the Nashville metropolitan area, congestion typically occurs between mile markers 80 and 67, from around 7:00 to 9:00 a.m. In contrast, in the Spring Hill area, morning peak-hour traffic conditions have worsened since 2020. The duration of excessive delays has increased noticeably, and by 2024, severe congestion persists from approximately 6:00 to 10:00 a.m. Likewise, the southbound congestion is more likely to happen in the afternoon. The congestion expansion is also observed at the two ends of the corridor. Hence, deploying the strategies should focus on addressing the congestion near the two ends of the corridor.

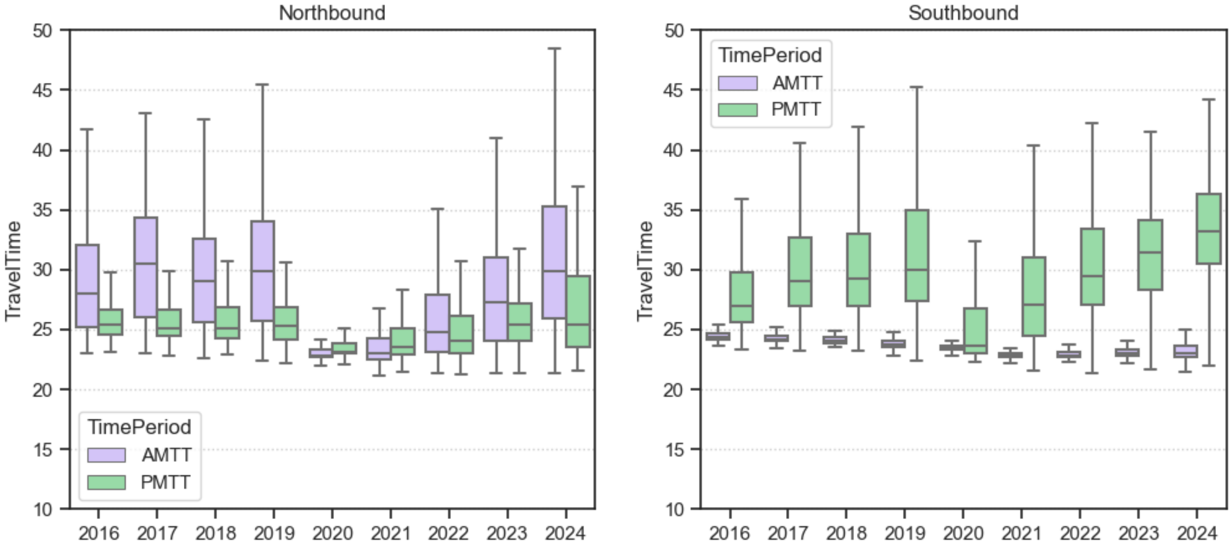


Figure 4-42. Nashville I-65 Peak Hour Travel Time Variation.

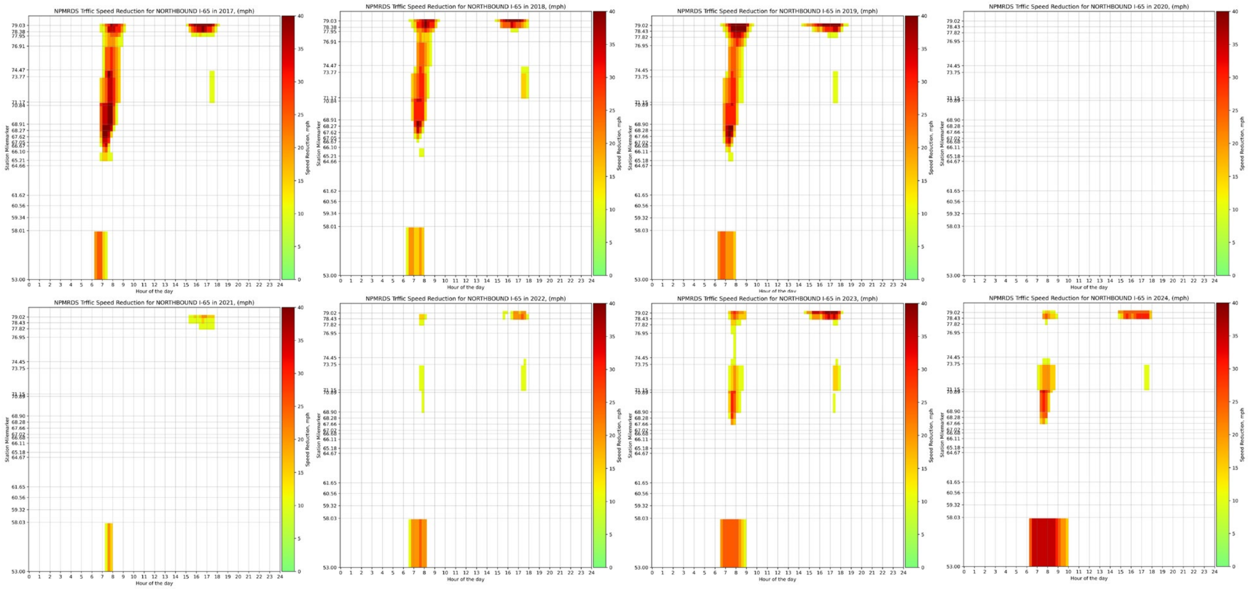


Figure 4-43. Excessively Congested Areas of Nashville I-65 Northbound.

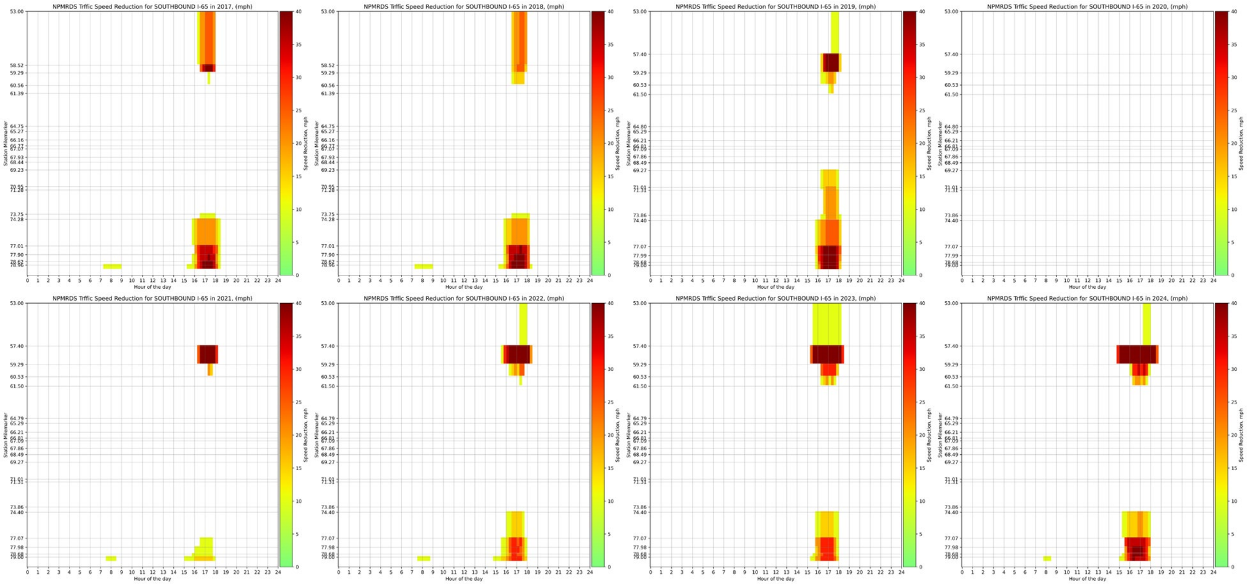


Figure 4-44. Excessively Congested Areas of Nashville I-65 Southbound.

4.7.3 Chattanooga I-24

Existing I-24 is a heavily traveled corridor that serves Tennessee and Georgia. I-24 provides a direction connection to downtown Chattanooga, Lookout Mountain and other area attractions. Unlike other candidate corridors, there is no proper arterial corridor paired with I-24. Nonetheless, the ITS strategies such as VSL/LCS, HSR, and ARM could be deployed on I-24 to curb traffic congestion and safety issues.

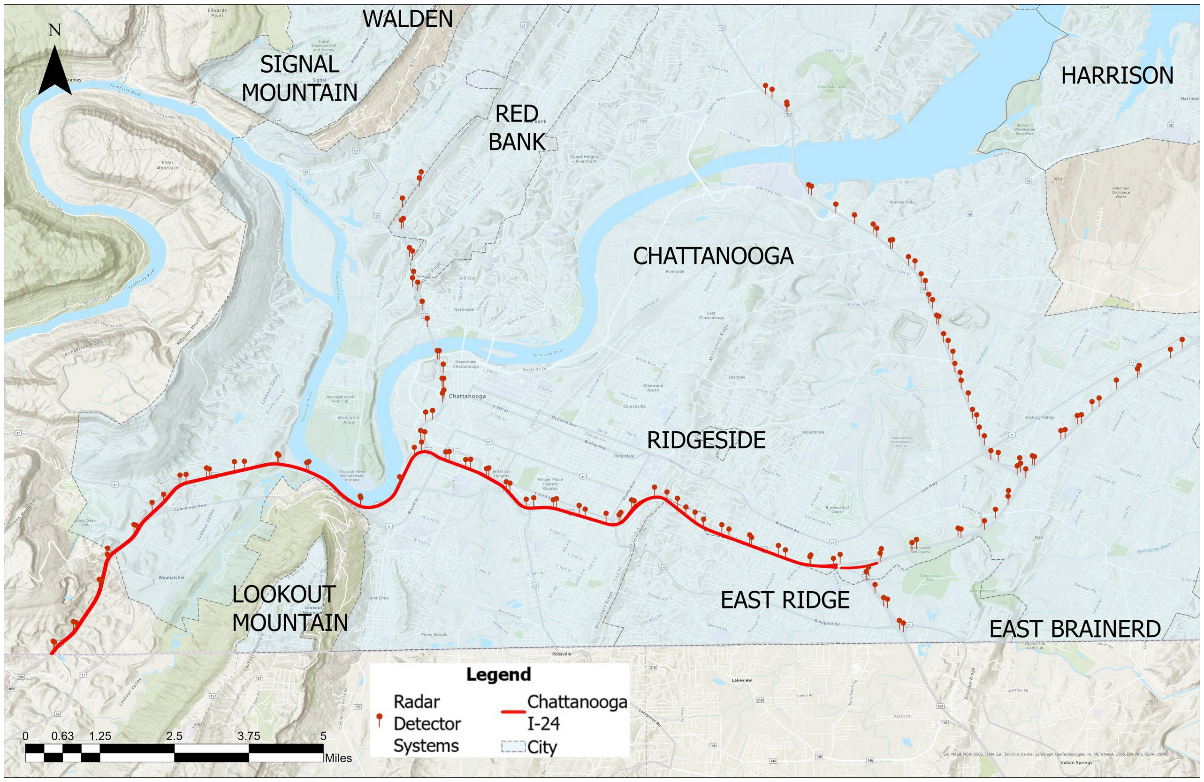
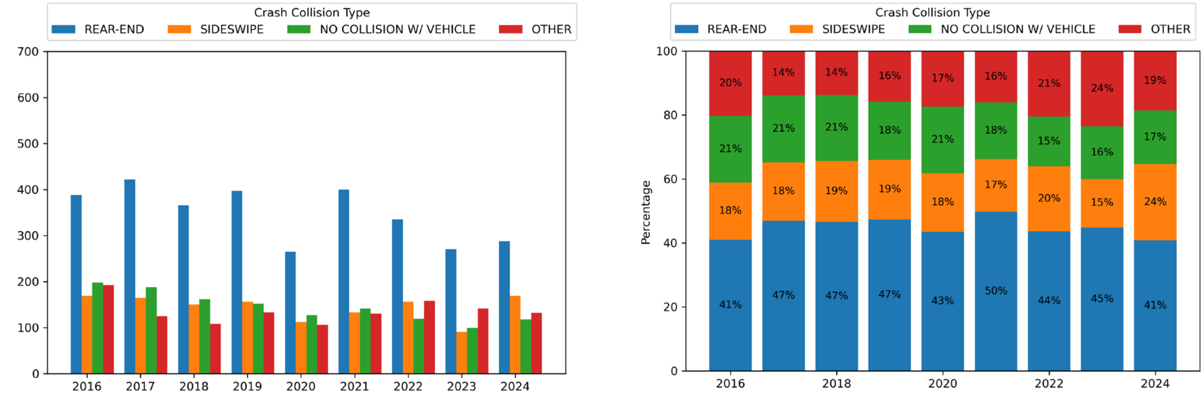


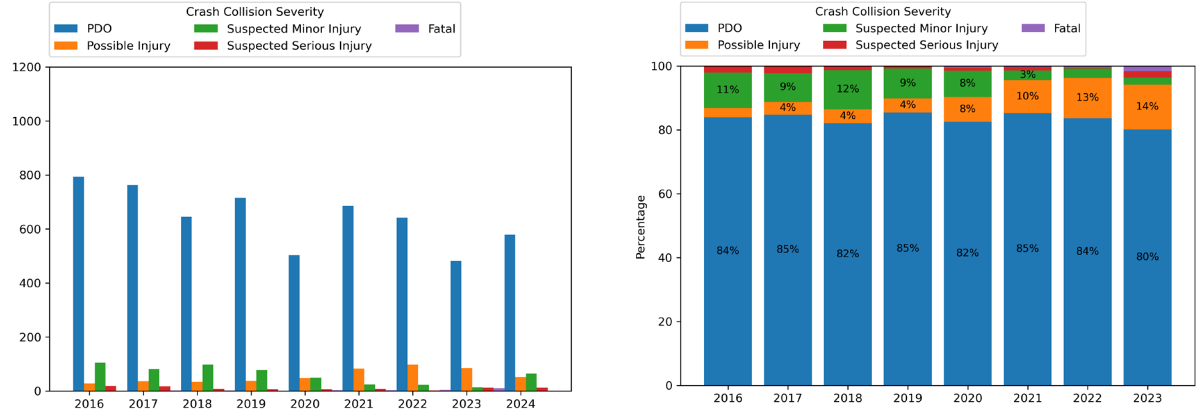
Figure 4-45. Candidate Corridor: Chattanooga I-24.

Figure 4-46 and **Figure 4-47** present the crash frequency by collision type and severity. Like other corridors, rear-end and sideswipe crashes account for approximately 50%–70% of all crashes. It is worth noting that this proportion remains steady over the years. Deploying VSL/LCS systems may be a good choice to mitigate relevant crashes. PDO crashes dominate the severity distribution, representing over 80% of total crashes. Since 2020, the number of possible injury crashes has increased slightly, while suspected minor and serious injury crashes have shown a declining trend. This indicates that the vehicle crash outcome generally become less severe in recent years.



(a) Crash Frequency by Collision Type **(b) Crash Collision Contribution**

Figure 4-46. Chattanooga I-24 Historical Crash Frequency by Collision Type.



(a) Crash Frequency by Collision Severity **(b) Crash Severity Contribution**

Figure 4-47. Chattanooga I-24 Historical Crash Frequency by Collision Severity.

Figure 4-48 highlights the outcomes of crash collisions. It is estimated that rear-end crashes caused 36.1% of PDO, and 8.7% injury crashes, sideswipe crashes caused 17% of PDO and 1.5% of injury crashes, respectively.

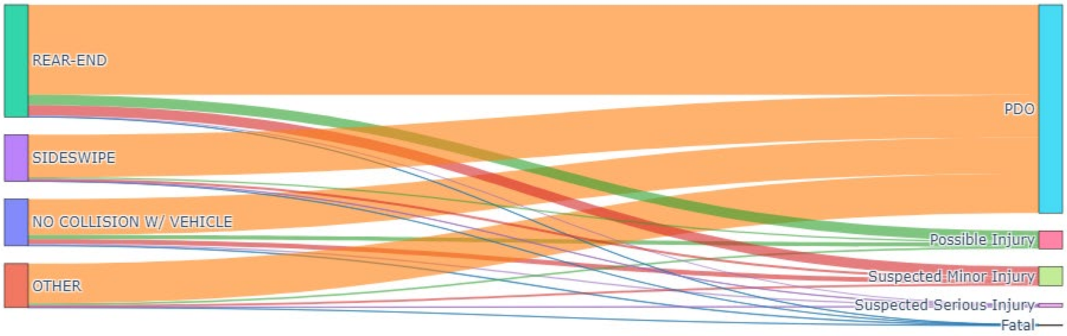


Figure 4-48. Chattanooga I-24 Crash Severity by Collision Types.

Disabled Vehicles

Figure 4-49 illustrates the distribution of disabled vehicles along I-24 in Chattanooga. It is evident that the segment between mile markers 185 and 182 experiences the highest frequency of vehicles stopping on the shoulder. Overall, approximately 80% of disabled vehicle incidents occur between mile markers 185 and 177, spanning from the I-75/I-24 interchange to the I-24/US-27 interchange. If emergency pull-offs are to be installed, placing them within this segment would be a reasonable and strategic choice.

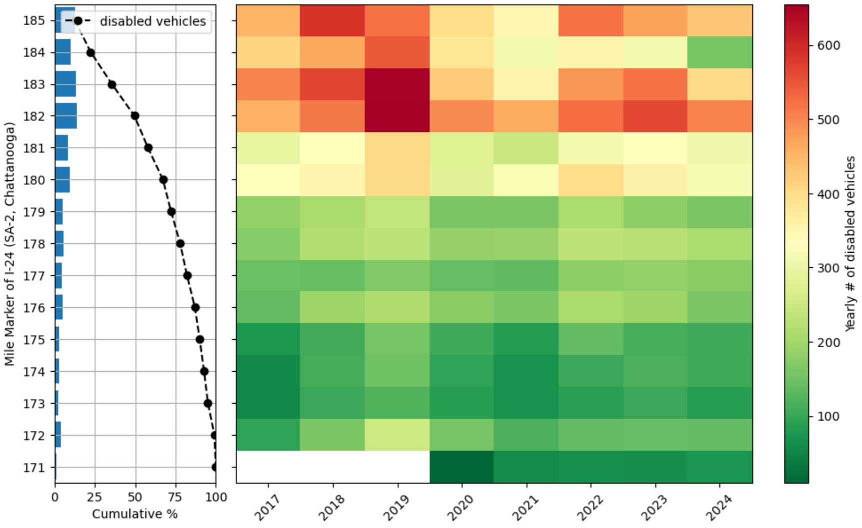


Figure 4-49. Chattanooga I-24 Spatial Distribution of Disabled Vehicles.

Travel Time and Reliability

Figure 4-50 illustrates the travel time for peak hours for each direction. It is found that:

- Median and volatility of travel time during afternoon peak hours are significantly higher than the morning peak. The afternoon congestion appears to be a serious issue.
- The westbound direction exhibits greater travel time volatility during afternoon peak hours than the eastbound direction. This indicates the traffic leaving Chattanooga (to Georgia) typically encounters significant delay and uncertainty.

Figure 4-51 and **Figure 4-52** show when and where the excessive delay occurs for Westbound and Eastbound, respectively. It is found that:

- Westbound excessive delay area does not expand significantly in recent years, but compared to the years before 2020, it has expanded a lot.

- The typical congestion period for westbound traffic occurs between 3:30 p.m. and 6:00 p.m., primarily within mile markers 175 to 181, extending from the I-24/US-27 interchange toward the Lookout Valley direction.
- For eastbound traffic, both the duration and extent of congestion are greater than those observed westbound. Excessive delays typically begin around 1:00 p.m. and persist until 6:00 p.m., affecting the segment between mile markers 184 and 178.

The large travel time volatility and delay expansion suggest the installation of VSL/LCS signs to smooth traffic flow, thereby improving the travel time reliability.

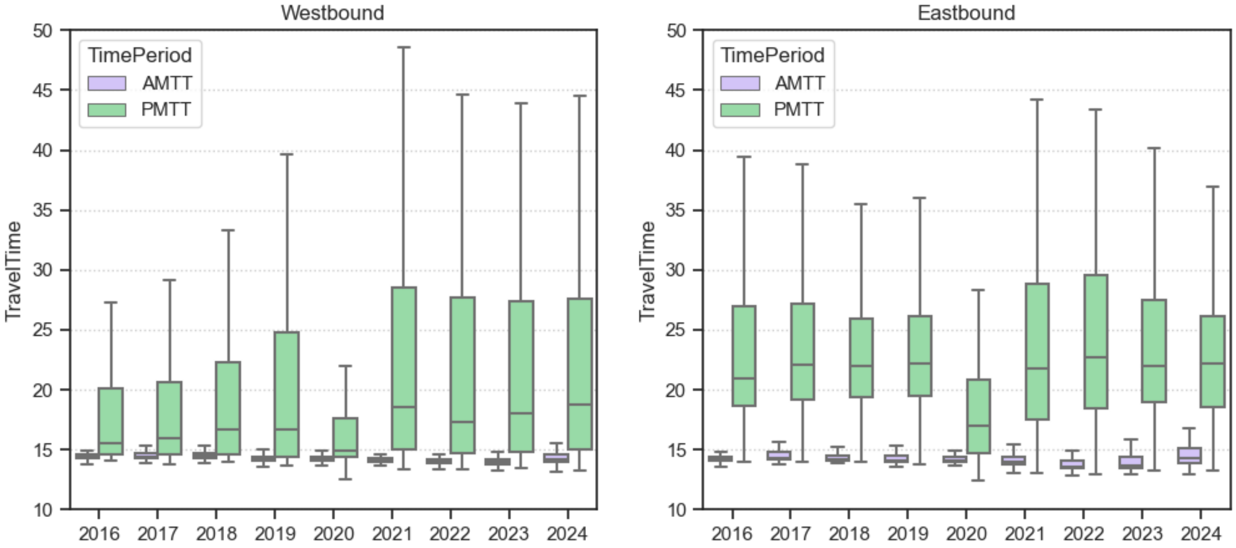


Figure 4-50. Chattanooga I-24 Peak Hour Travel Time Variation.

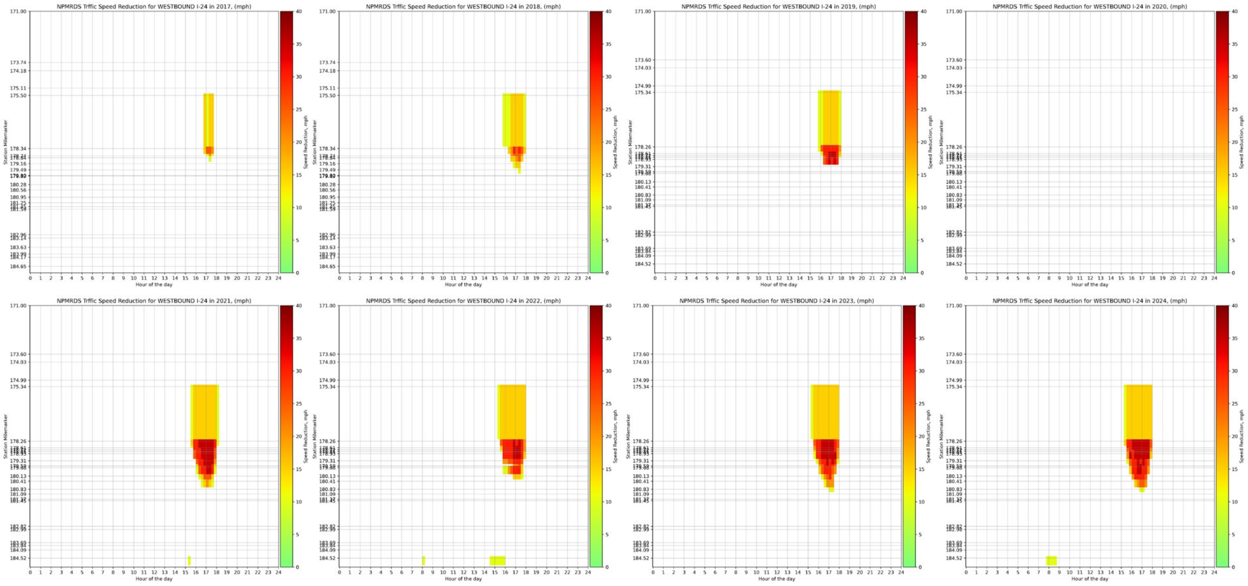


Figure 4-51. Excessively Congested Areas of Chattanooga I-24 Westbound.

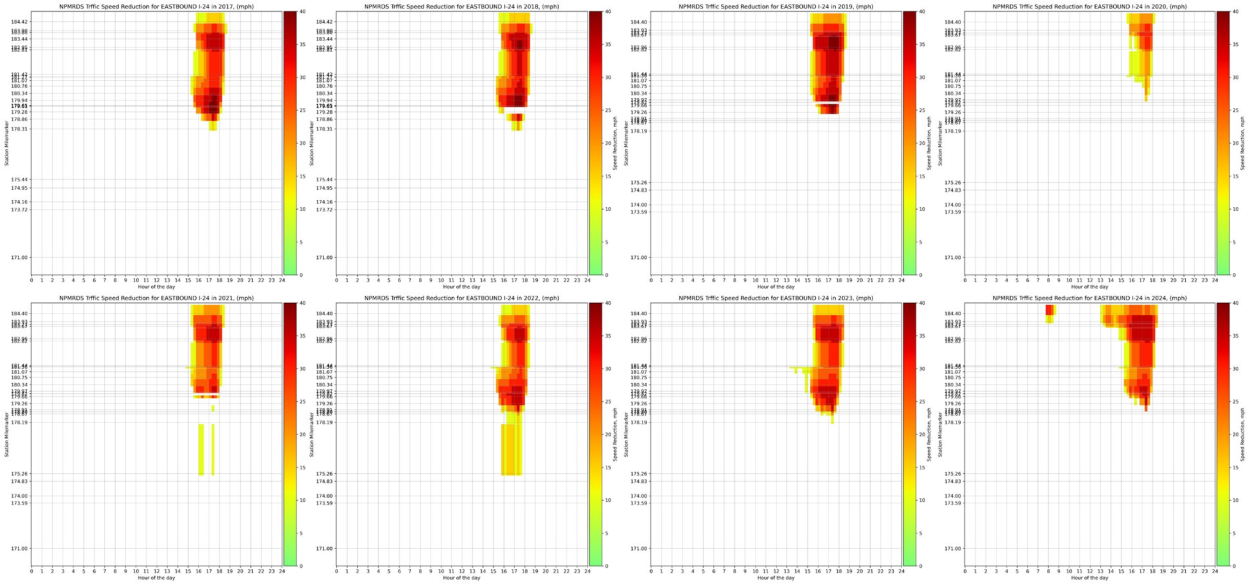
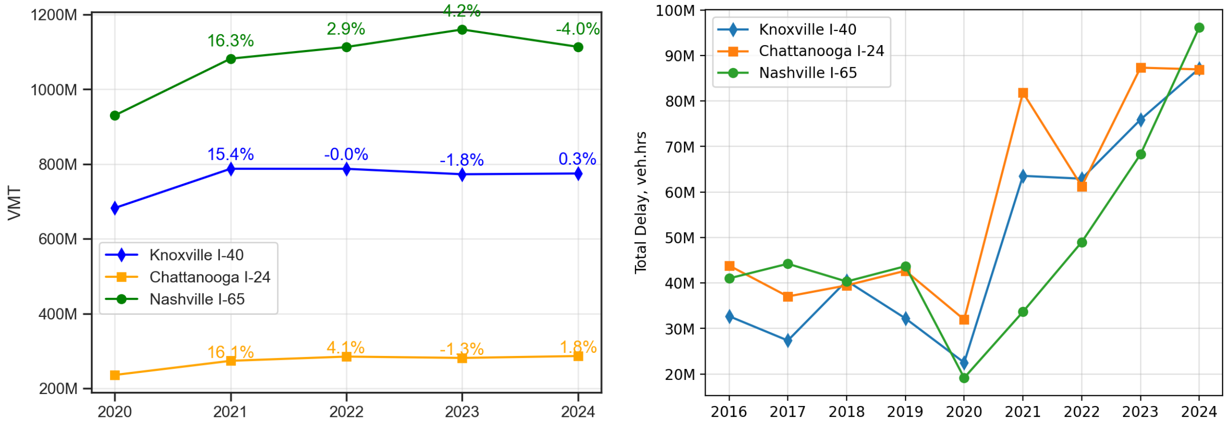


Figure 4-52. Excessively Congested Areas of Chattanooga I-24 Eastbound.

4.7.4 VMT and delay

Due to the RDS availability, we calculated the year VMT for three candidate corridors, however for delay, we used the NPMRDS data for the approximate estimation so that we can trace back to the year of 2016 to see the historical change of delay. **Figure 4-53** shows that the Nashville I-65 corridor has experienced significant growing travel demand, while Knoxville I-40 and Chattanooga I-24 have remained relatively steady since 2020. However, when comparing travel delays, it is evident that all candidate corridors have experienced a significant increase since 2020. The steep growth in delay strongly indicates the need to implement ICM strategies.



(a) **Yearly VMT and growth rate** (b) **Travel Delay**

Figure 4-53. VMT And Delay Of Candidate Corridor.

4.7.5 Other considerations

Beyond conventional performance metrics, the prioritization of smart corridor candidates should integrate economic resilience**,** environmental sustainability, and social equity perspectives. Economically, corridors linking industrial zones, logistics hubs, and commuter concentrations can yield high benefit–cost ratios, as reduced delay translates directly into productivity gains and lower freight operating costs. From an environmental perspective, deploying integrated traffic management, transit signal priority, and variable speed limits can mitigate stop-and-go emissions, supporting local air-quality goals and state carbon-reduction initiatives. Equitably, corridors that connect low-income or transit-dependent communities can leverage ICM to provide safer, cleaner, and more reliable travel options. Considering these cross-cutting benefits ensures that smart corridor implementation contributes not only to improved traffic performance but also to broader regional sustainability and livability outcomes.

4.7.6 Summary of candidate corridor selection

All three candidate corridors demonstrated above show the need for improvement in terms of safety, mobility and travel time reliability. But comparatively speaking, Knoxville I-40 can be given priority for next investment because of 1): The network integrates I-40 and the parallel arterial street, Kingston Pike. A series of connector routes between them facilitate traffic diversion. Kingston Pike also serves multiple transit routes, offering opportunities to implement transit signal priority and promote multimodal transportation. 2) The spatiotemporal excessive congestion is growing after 2020, with a great momentum, especially for the eastbound traffic moving towards the city of Knoxville. The growing congestion needs to be curbed with the intelligent transportation systems. 3) The rear-end and sideswipe crashes that happened on Knoxville I-40 account for about 80% of total crashes, and this contribution is higher than other two candidate corridors. The high rear-end and sideswipe crashes could be mitigated by installing the VSL/LCS control system.

On the other hand, if the Chattanooga I-24 and Nashville I-65 corridors are not yet well suited for implementing full ICM strategies, selected technologies such as the VSL/LCS system can still be deployed along congested segments to address safety and mobility concerns. Evidence from the I-24 Smart Corridor project indicates that such deployments can yield notable safety improvements, ultimately translating into substantial economic benefits.

4.8 Benefits to TDOT and Implementations

This project has helped TDOT systematically evaluate the operational, safety, and reliability impacts of the I-24 Smart Corridor. Beyond the results and discussions, the benefits and implementations of this project are multifaceted.

- Through a comprehensive before after analysis, the benefits of each key component of the I-24 Smart Corridor have been clearly demonstrated. This helps justify the return on the Smart Corridor investment.
- The findings of this project could also provide TDOT with valuable insights into the effectiveness of ICM strategies and offer a practical foundation for guiding future Smart Corridor investments across Tennessee.
- The lessons learned, and potential issues found in this project could help TDOT continue to improve their operations and management.
- The examination of three candidate corridors could help identify and justify the most appropriate strategies for future improvements. This analysis serves as a technical and planning reference for future ICM project selection and investment justification.
- The established Power BI dashboards (refer to **Appendices**) could help TDOT continue to monitor the performance of I-24 Smart Corridor and Intersections, allowing TDOT to

make data-driven adjustments and performance-based decisions for ongoing I-24 Smart Corridor management.

Chapter 5 Conclusion

The I-24 Smart Corridor project, launched by TDOT since 2018, is a first-ever ICM endeavor in Tennessee. This project integrates I-24 and SR-1, along with physical, technological, and operational improvements, to provide drivers with accurate, real-time information and actively manage traffic. The whole project is conducted via three phases. At the time of this report, phases 1 and 2 are complete, while Phase 3, targeted at long-term development, is still under design.

As part of the I-24 Smart Corridor project team, our work closely aligns with the project's overarching goals, to assess the impacts of multiple strategies implemented during Phases 1 and 2, with particular emphasis on travel time reliability, safety, and mobility. Through comprehensive before-and-after evaluations and benefit–cost analyses, this effort also aims to provide a data-driven foundation for future investments in Smart Corridor initiatives across Tennessee**.**

5.1 Findings

The findings of this project are summarized by the strategies.

- The upgrade of RDS detection system significantly improved the speed accuracy, as well as spatial granularity, which provides the reliable input for the VSL/LCS controls.
- The ramp extension is particularly effective in alleviating congestion and improving mainline traffic flow toward Nashville (Westbound). The average speed increased by 19.2% near the I-24W/Briley Pkwy exit ramp, followed by the I-24W/Bell Road entrance ramp, with a 12.3% improvement during peak hours. Correspondingly, the BTI was reduced by 58.9% at the I-24W/Briley Pkwy exit ramp, and by 15.3% at I-24W/Bell Road entrance. It has been verified as an effective strategy for mitigating westbound congestion under growing travel demand. The benefits of the two-ramp extension on eastbound side are comparably less notable, which might be due to less traffic exposure.
- The emergency pull-offs mitigate the impact of stopped vehicles on the mainline traffic. Only 17% of stopped vehicles in pull-offs resulted in significant speed changes in mainlines; however, 40% of vehicles stopped on shoulders led to significant turbulence to mainline traffic flow.
- Following the traffic signal upgrades,
    - Notable safety improvements were observed at 36 of 58 intersections in Nashville, 1 of 7 in La Vergne, 15 of 19 in Smyrna, and 20 of 43 in Murfreesboro. In other words, more than 50% of upgraded signalized intersections demonstrated measurable safety improvements in Nashville and Smyrna.
    - In Nashville, rear-end crashes decreased by 21.6% (from 8.01 to 6.28 per intersection per year). In Smyrna, rear-end crashes dropped by 48.6% (from 9.66 to 4.97 per intersection per year). Murfreesboro showed the most substantial improvements, with rear-end crashes reduced by 35.2% (from 11.94 to 7.74 per intersection per year) and sideswipe crashes reduced by 22.7% (from 8.99 to 6.95 per intersection per year), both demonstrating statistically significant reductions.
    - In Nashville, PDO crashes is significantly reduced by 27% (from 11.96 to 9.39 per intersection per year). In Murfreesboro, significant reductions were observed across all crash severity levels. PDO crashes decreased by 24.6% (from 18.14 to

    13.68 per intersection per year), minor injury crashes dropped by 34.0% (from 4.77 to 3.15 per intersection per year), and serious injury crashes declined by 25.4% (from 1.34 to 1 per year per intersection per year).

- Regarding the VSL/LCS signs:
    - Drivers heading into Nashville in the morning are less compliant with VSL than those traveling toward Murfreesboro in the afternoon, especially in the fast and middle lanes. This is not only related to the travel demand, but also the travel sentiment.
    - Westbound reliability worsened in recent years, with average travel times rising from 26 minutes in FY 21–22 to a peak of 32.5 minutes in FY 23–24 before moderating slightly to 31.4 minutes in FY 24–25.
    - For eastbound, after the VSL/LCS implementation, average travel times rose modestly from 23.9 minutes in FY 21–22 to 25.3 minutes by FY 23–24 and held steady in FY 24–25.
    - For the eastbound direction, the most affected period occurs between approximately 15:30 and 18:20, spanning mile markers 53 to 56 (from I-24 at Briley Parkway to Harding Place). Moreover, the congestion begins slightly earlier and ends slightly later between mile markers 56 and 59, which is from Harding PI to Bell Road.
    - For the westbound direction, the queue length near Murfreesboro between 6:30 and 6:50 AM has shortened following the VSL implementation. Congestion begins about 20 minutes earlier than before the VSL/LCS implementation, particularly between mile markers 55 and 59 (from Harding Place to Bell Road), where queues last about one hour longer than previously observed.
    - VMT increased by 3% and 10.3% in the Eastbound and Westbound directions, respectively, after the VSL/LCS implementation.
    - When combining two directions, the delay estimated by historical average speed and post speed limits increased by 36.2% and 27.8% respectively.
    - The suspect serious injury, suspect minor injury, possible injury, and PDO crash frequency declined by 18.1%, 10.4%, 17.5% and 3.2% respectively. Rear-end and sideswipe crashes decreased by 14.0% and 3.2%, respectively.
    - The rate of secondary crash also declined from 7.72% in the fiscal year of 21/22 and 6.61% in the fiscal year of 22/23 to 5.19% and 6.22% in 23/24 and 24/25 respectively. The primary crash leads to fewer secondary crashes now. The total number of secondary crashes reduced by 13.8% after the VSL/LCS implementation.
    - Although overall delay savings were not evident, individual trips may still experience benefits from the ICM and AI-DSS systems when drivers follow recommended detour routes or adhere to posted variable speed limits.
- The return is **$1.13** for every dollar invested in the I-24 Smart Corridor project, assuming a 10-year service period and a 7% annual discount rate. This value is expected to increase as the service years extend and additional travel time savings materialize in the future.
- The annual crash savings is estimated at **$10.1 million**, while the net annual return after operations and management costs is approximately **$1.2 million**.

- Three candidate corridors were evaluated for future investment in ICM strategies. Among them, the Knoxville I-40 could be given priority in terms of parallel interstate and arterial network, multimodal integration, expanding traffic congestion and large number of rear-end, sideswipe crashes.

After a comprehensive review of Smart Corridor initiatives across the United States and an in-depth analysis conducted in this study, several recommendations are presented to enhance corridor performance and support future Smart Corridor implementation in Tennessee.

5.2 Recommendations

The success of an ICM corridor relies on more than advanced technologies—it depends on strong data foundations, coordinated partnerships, consistent performance monitoring, and active public engagement. Each recommendation targets one of these core aspects to enhance corridor efficiency, transparency, and user compliance, ensuring that ICM investments achieve long-term operational and safety benefits.

- **Data quality assurance and system-wide data integration** are critical to the successful development and operation of the Smart Corridor. During the before-and-after analysis, the limitations of the legacy RDS data prevented a full representation of pre-implementation traffic conditions for the VSL/LCS system. Therefore, third-party probe data were utilized to ensure consistency and continuity in the analysis. The crash data are saved by different databases such as ETRIMS, TITAN, AASHTO and RITIS or SWCS. The differences between these are not fully known or reconciled. It is recommended to integrate all the key data sources and conduct a data quality assessment to ensure the quality of future performance monitoring efforts.
- **Data sharing across TDOT divisions and partner agencies** is highly recommended to enhance coordination and support performance evaluations. At present, much of the operational data is managed by external consultants or contracted data collectors, which makes access to crucial and already-collected data circuitous for the purposes of academic assessments and impartial evaluations. Establishing a centralized data-sharing framework would improve transparency, facilitate interagency collaboration, and strengthen data-driven decision-making.
- It is recommended that **targeted law enforcement or automated speed enforcement strategies be coordinated** during congestion periods to enhance compliance and improve overall corridor performance. Driver compliance with VSL/LCS is critical to achieving the intended safety and mobility benefits. If commuters adapt to “violating the VSL” due to a lack of enforcement, the effectiveness of the ICM system is likely to diminish.
- TDOT could benefit from **continuously monitoring the performance and adjusting the operation strategies,** as road users might get more familiar with the VSL/LCS, and travel time reliability might improve as a result. The previous trends of rapid rise in average travel time and decrease in travel time reliability appear to have been effectively curbed following the implementation of the VSL/LCS systems.
- **Public attitudes and sentiment matter**. TDOT can continue to conduct periodic surveys to assess traveler sentiment regarding perceived changes in travel time, delay, safety, and support for future investments**,** using these insights to guide outreach and operational

refinements. Additionally, artificial intelligent based social media sentiment assessment could provide unsolicited insights.

- **Conduct proper public outreach and education**, especially highlighting the corridor as an interdependent system. Educating road users to comply with the VSL/LCS system can positively influence their driving behavior and thereby improve the performance of ICM strategies.

5.3 Limitations and Future Studies

There are also some limitations identified due to the data availability, project limits, and others, followed by future studies.

- For the signal system evaluation, detailed signal timing and turning movement data were not accessible to the research team. As a result, the evaluation was conducted at a macroscopic level, limiting the ability to assess intersection-level performance. Future studies could be performed if signal timing and turning movement data from the *Miovision* system become available. The current macro-level evaluation may not fully capture the benefits of signal coordination or freeway-arterial integration.
- The AI-DSS system was not evaluated in this study, as it was deployed in late Summer 2025, and the research team had limited access to the system during the study period.
- Westbound travel demand toward Nashville has increased significantly in recent years; however, the underlying causes remain unclear. Future studies are encouraged to investigate the factors driving this growth in travel demand, potentially utilizing origin–destination (OD) datasets such as *SafeGraph* to gain deeper insights into traveler behavior and trip patterns.
- HSR has proven effective in increasing roadway capacity during crash events on other Smart Corridors, while the effectiveness of HSR on I-24 Smart Corridor remains unknown. It can be examined once the HSR data is available.

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Appendices

To keep monitoring the performance of the I-24 Smart Corridor project, the research team developed two dashboards, including I-24 Smart Corridor Performance Dashboard and Signal Intersection Performance Dashboard. The dashboards were built on Microsoft Power BI platform, which is often used by TDOT for performance measurement. Currently, they are hosted and updated by the research team at University of Tennessee. Nonetheless, they can be shared via a link upon request or transferred to the TDOT Power BI cloud.

Appendix 1: I-24 Smart Corridor Performance Dashboard

Appendix 2: I-24 Signal Intersection Performance Dashboard

Appendix 1: I-24 Smart Corridor Performance Dashboard

This dashboard monitors crashes and incidents occurring along the I-24 Smart Corridor. The dataset spans from 2016 to the present, providing a comprehensive historical view of safety trends on the corridor. Safety data is obtained from the ETRIMS, and incident data is obtained from RITIS. Key performance indicators, such as fatalities, normalized crash rates, crash severity, collision types, and incident counts, are visualized to support ongoing safety evaluation (**see Figures 1-5 in the appendices**). The data are aggregated by corridor segments defined between major connecting routes. The first page, as **Figure 1** shows**,** allows user to select the segment on the I-24 Smart Corridor. The following pages will then present the outcomes with respect to the selected segment.

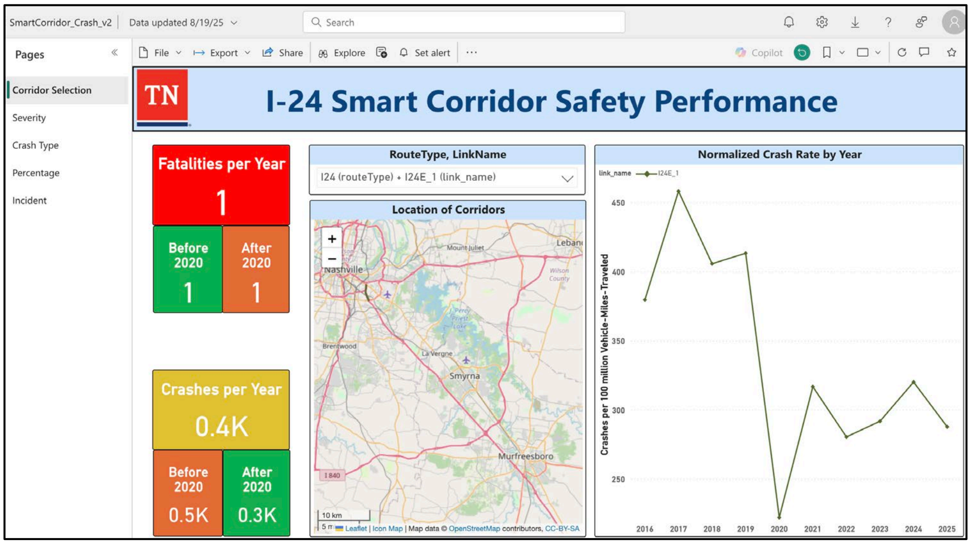

Figure 1. I-24 Smart Corridor Safety Performance Page 1: Segment Selection and Crash Rate.

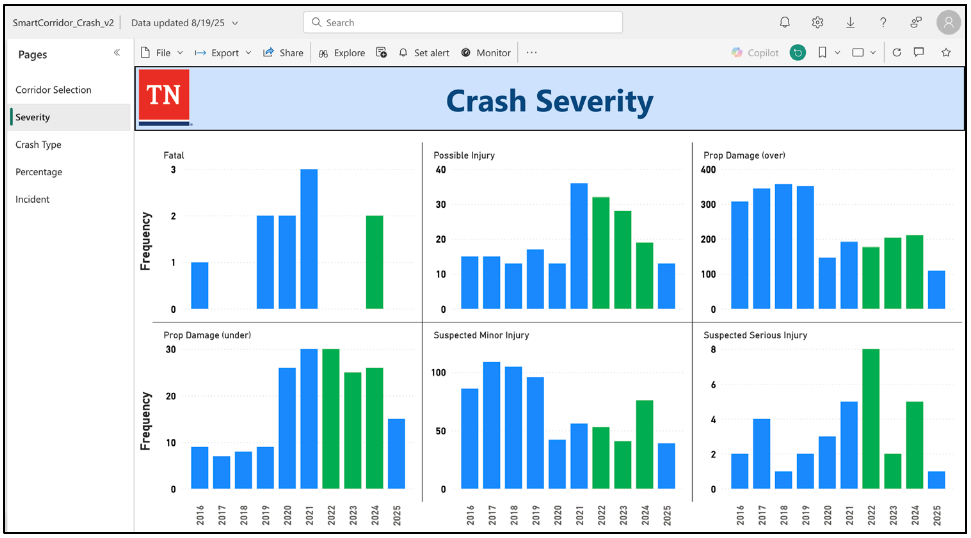

Figure 2. I-24 Smart Corridor Safety Performance Page 2: Crash Severity.

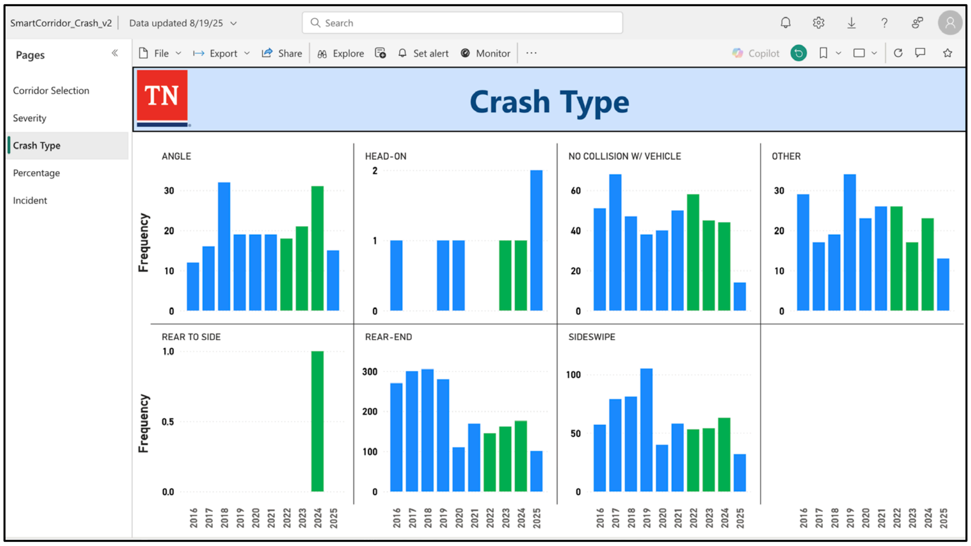

Figure 3. I-24 Smart Corridor Safety Performance Page 3: Crash Type.

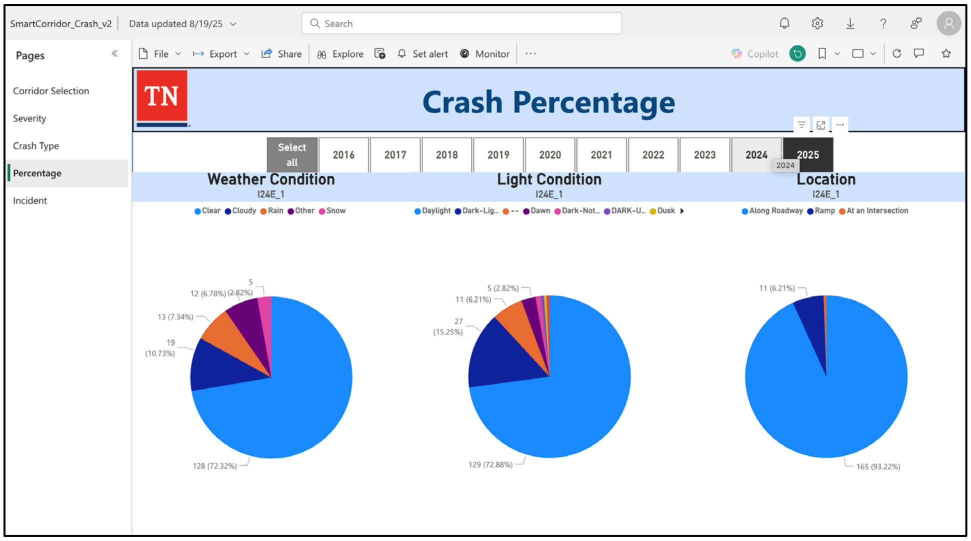

Figure 4. I-24 Smart Corridor Safety Performance Page 4: Crash Scenarios.

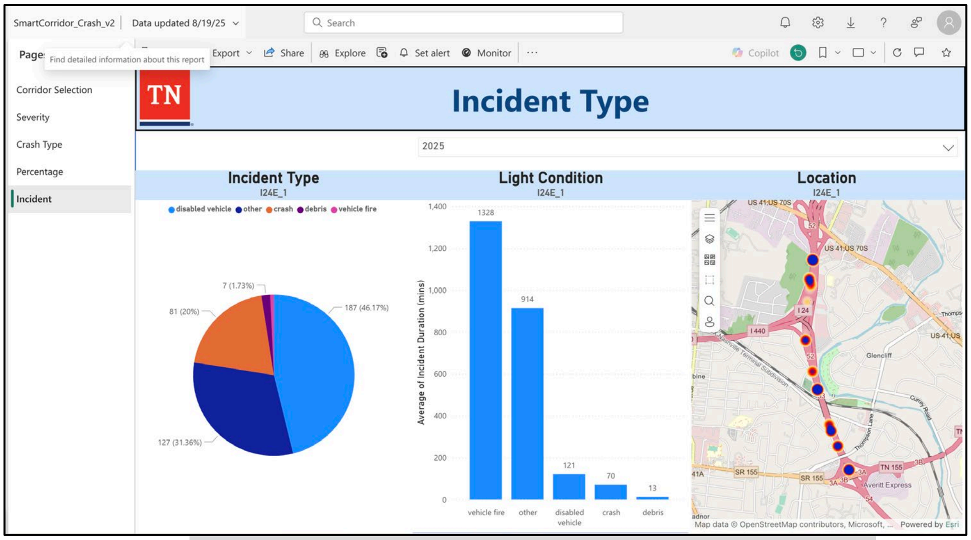

Figure 5. I-24 Smart Corridor Safety Performance Page 5: Incident.

Appendix 2: I-24 Signal Intersection Performance Dashboard

This dashboard monitors the safety and travel time reliability of signal intersections at I-24 Smart Corridor because of the signal system upgrade in Phase 1. Likewise, the crash frequency by collision type, severity, and context, and travel time reliability are calculated and visualized through pages shown by **Figures 6-11**. The first page, as **Figure 6 shows,** allows the user to select the segment on the I-24 Smart Corridor. The rest of the pages will then present the outcomes with respect to the selected segment.

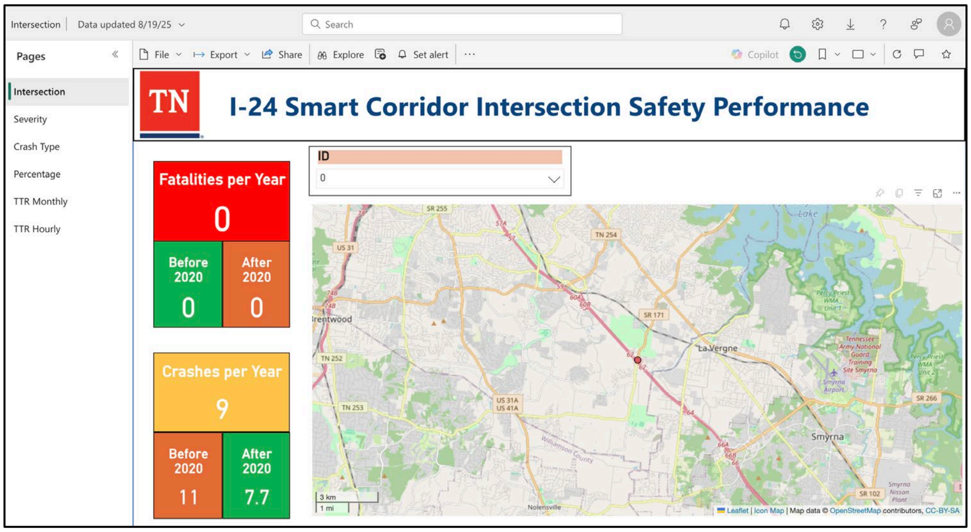

Figure 6. I-24 Smart Corridor Intersection Safety Performance Page 1: Intersection Selection.

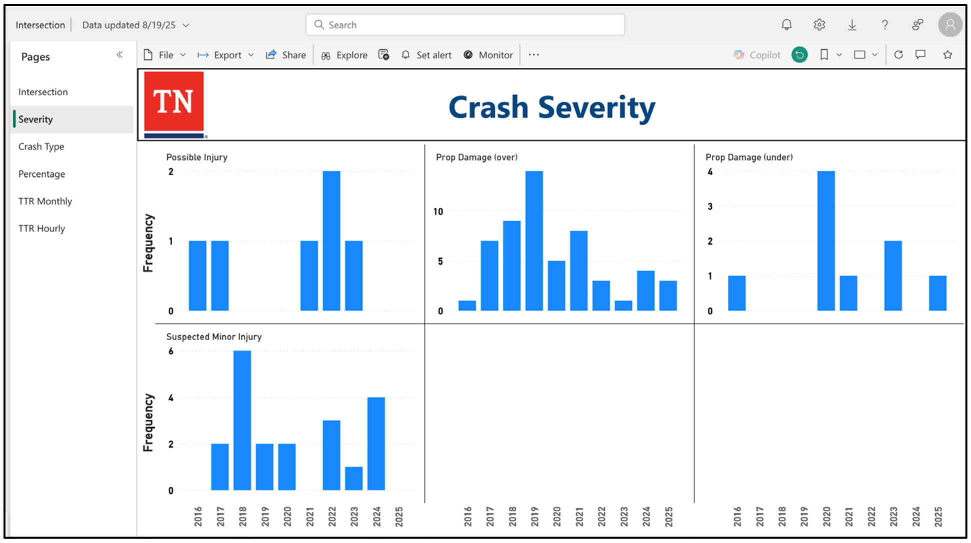

Figure 7. I-24 Smart Corridor Intersection Safety Performance Page 2: Crash Severity.

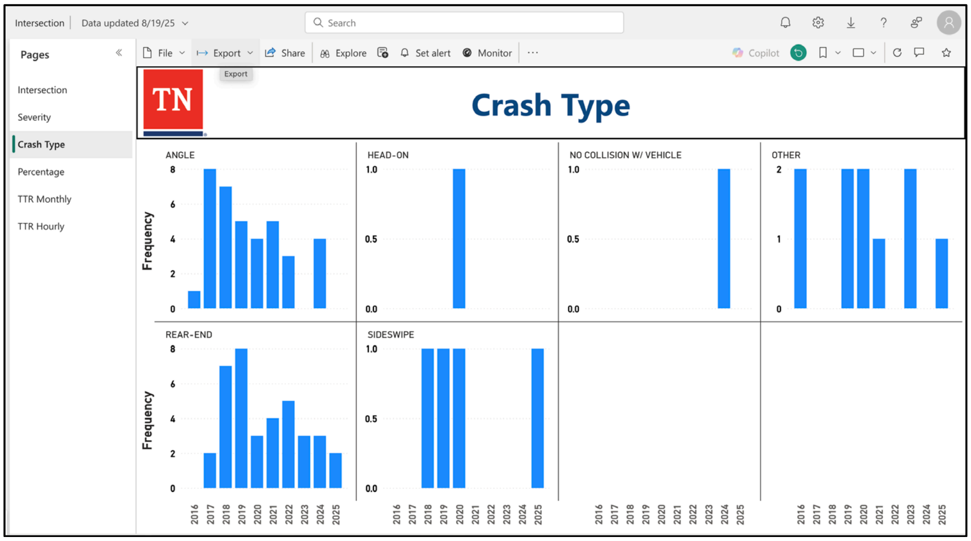

Figure 8. I-24 Smart Corridor Intersection Safety Performance Page 3: Crash Type.

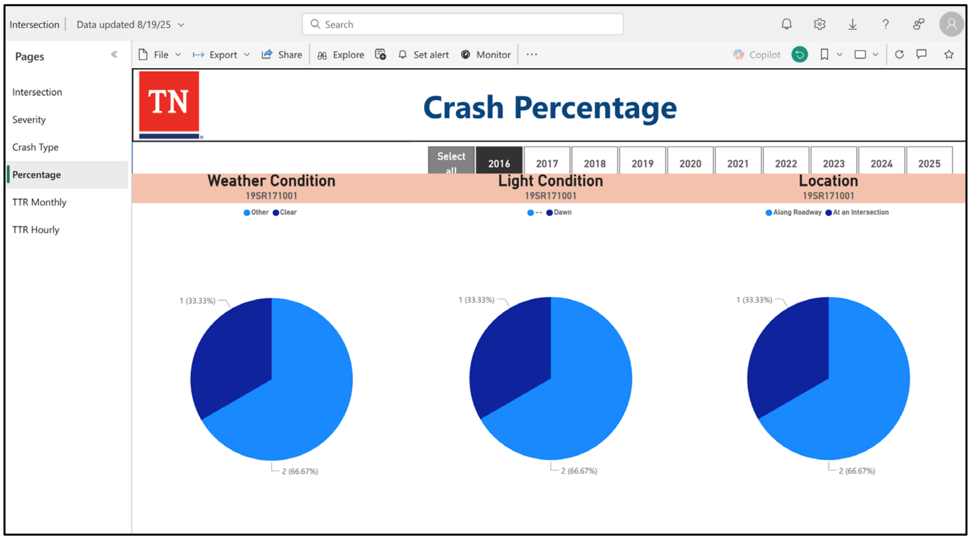

Figure 9. I-24 Smart Corridor Intersection Safety Performance Page 4: Crash Context.

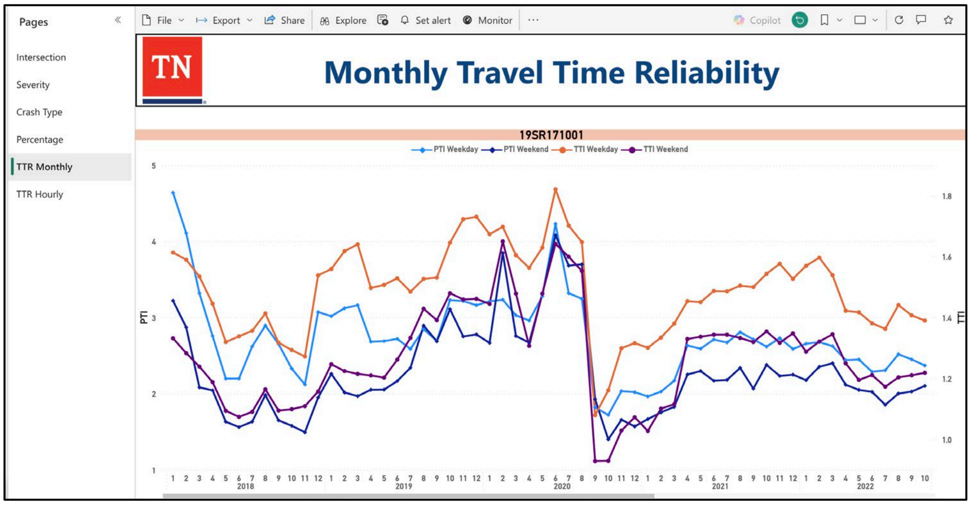

Figure 10. I-24 Smart Corridor Intersection Safety Performance Page 5: Monthly TRR.

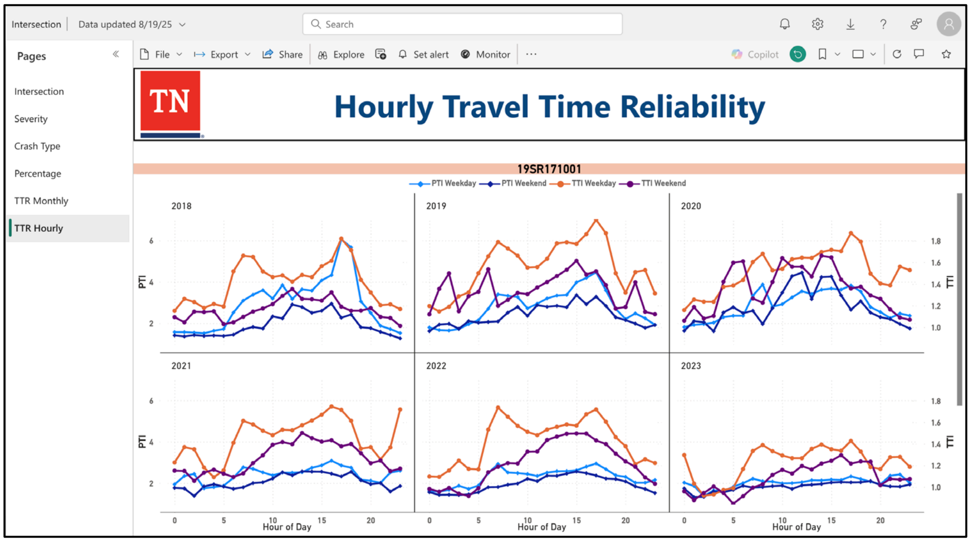

Figure 11. I-24 Smart Corridor Intersection Safety Performance Page 5: Hourly TTR.