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Development of a New Tool for Evaluating Infrastructure and Planning Impacts Related to Changes in Truck Traffic and Truck Technologies: Final Report

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16. Abstract
Researchers developed a set of integrated infrastructure-based and economic models to evaluate the infrastructure and planning impacts of increased numbers of automated trucks and truck platoons operating on Texas highways. As automated and platooned truck technologies evolve and their use in Texas highway corridors continues to grow, it is critical that state transportation planners and engineers are able to quickly evaluate the potential impacts of, impediments to, and solutions for addressing the impacts of these vehicles upon Texas highway infrastructure. The project developed a geographic information system dashboard-based Fast Web Tool that uses user-input conditions to calculate physical infrastructure impacts on bridges, on different types of asphalt and concrete pavements, and under flooding or other soil conditions; and that allows economic analysis of the impacts of a given scenario over time. This project builds on the findings of TxDOT Project 0-6984, Evaluate Potential Impacts, Benefits, Impediments, and Solutions of Automated Trucks and Truck Platooning on Texas Highway Infrastructure, completed by the Texas A&M Transportation Institute in 2020.

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DEVELOPMENT OF A NEW TOOL FOR EVALUATING INFRASTRUCTURE AND PLANNING IMPACTS RELATED TO CHANGES IN TRUCK TRAFFIC AND TRUCK TECHNOLOGIES: FINAL REPORT

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DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

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PROJECT ABSTRACT

The Texas Department of Transportation (TxDOT) Project 0-7124: Develop a New Tool for Evaluating Infrastructure and Planning Impacts from Changes in Truck Traffic and Truck Technologies, developed a set of integrated infrastructure-based and economic models to evaluate the infrastructure and planning impacts of increased numbers of automated trucks and truck platoons operating on Texas highways. As automated and platooned truck technologies evolve and their use in Texas highway corridors continues to grow, it is critical that state transportation planners and engineers can quickly evaluate the potential impacts of, impediments to, and solutions for addressing the impacts of these vehicles upon Texas highway infrastructure. The project developed a geographic information system (GIS) dashboard-based Fast Web Tool that uses user-input conditions to calculate physical infrastructure impacts on bridges, on different types of asphalt and concrete pavements, and under flooding or other soil conditions; and that allows for performing an economic analysis of the impacts of a given scenario over time. This project builds on the findings of TxDOT Project 0-6984 Evaluate Potential Impacts, Benefits, Impediments, and Solutions of Automated Trucks and Truck Platooning on Texas Highway Infrastructure, completed by the Texas A&M Transportation Institute (TTI) in 2020.

PROJECT BACKGROUND

Although much of the conversation on automated vehicle technology surrounds automated/autonomous passenger vehicles, progress is also being made on automated/autonomous trucking and truck platooning technologies. Advancement in this type of technology has prompted governments at both the federal and state levels as well as several trucking/technology companies to launch and test both automated and platooned trucks. Truck platooning technology enables additional trucks to take up less space while on the road, improving traffic flow. Truck platooning technology also promises industries a cost savings because of lower fuel consumption, reduced likelihood of traffic accidents, and, when fully implemented, a reduced number of drivers/operators required. Similarly, automated or fully autonomous trucking promises to improve road safety and streamline the delivery of goods.

However, challenges exist for how to successfully integrate both new technology types into the existing freight transportation system and roadway network including identification of how infrastructure will be impacted by changed operations, what new or changed regulations will be needed, and how to address operational concerns such as jobs, liability, and cybersecurity.

REPORT OVERVIEW

This report includes chapters describing:

- The targeted literature review of changes in the platooned and automated/autonomous trucking industry in Texas and the United States that have occurred since the completion of TxDOT Project 0-6984 in 2020.
- A summary of the four integrated models supporting the function of the Fast Web Tool, which are the Pavement Condition Model, Bridge Susceptibility Model, Flood Susceptibility Model, and Economic Analysis Model.
- An overview of the Fast Web Tool and its features, user interface, and functionality.
- A review of conclusions and recommendations for further refinements and improvements to the Fast Web Tool.

More detailed information on the development and testing associated with development of the Fast Web Tool was included in the technical memoranda produced during the project. The appendices of this report include in-depth or additional information on modeling options for assessment of auxiliary lanes and more details on the Economic Analysis Model inputs and calculations for the major study corridors.

CHAPTER 2. TARGETED LITERATURE REVIEW OF CURRENT AUTOMATED AND PLATOONED TRUCKING ACTIVITIES IN TEXAS AND THE UNITED STATES

OVERVIEW

This chapter covers the targeted literature review and tool end-user workshop included in the work plan for TxDOT Project 0-7124. Combined, these activities were meant to better ensure usability, adoption, and use of the planned tool to be produced by the project by expanding the understanding of the autonomous and platooned trucking industry in Texas and the United States, discovering the operational needs and impacts of autonomous and platooned trucks, and collecting input from end users on desired features and requirements for the tool.

The targeted nature of the literature review for this project was designed to confirm, update, and add to the findings of a prior project, TxDOT Project 0-6984: Evaluate Potential Impacts, Benefits, Impediments, and Solutions of Automated Trucks and Truck Platooning on Texas Highway Infrastructure, to provide the most accurate and up-to-date information for tool development and to guide future project activities, such as the scenario creation and economic analysis. The intent of the TxDOT 0-7124 workshop was to gather stakeholder input about the desired tool features and requirements, including desired user interface and reporting features. The project panel meeting held on June 6, 2022, served largely as the workshop because all the primary TxDOT stakeholder groups were represented on the project oversight panel. Additional stakeholders within and outside TxDOT were consulted, as appropriate, based on specific tool development needs as the project progressed. The following sections describe several basic ways to describe and/or classify vehicle automation and platooning technologies and the reasons for implementing them.

Automated Vehicle Classification

Automated vehicles (AVs) are generally classified into the following five autonomy levels, which clearly communicate the type of projects being conducted, with each level becoming less reliant on human intervention:

- Level 1 vehicles contain stability control, automated braking, and lane recognition, which are features that are all typically seen in newer passenger vehicle models.
- Level 2 vehicles can adjust their own speeds and reposition themselves to the center of the lane.
- Level 3 vehicles are almost completely autonomous but require the aid of human supervisors at some point during the trip.
- Level 4 vehicles can complete entire trips without human intervention, but the option for a driver exists if needed.

- Level 5 vehicles are fully autonomous in function without requiring provision for an onboard human driver (*1*, *2*).

AV and Platooning Technology

AV technology applications can be summarized into three broad categories:

- Sensors.
- Communications.
- Software.

Sensors

Sensor types include light detection and ranging (LiDAR), geographic positioning system (GPS), radars, and cameras. LiDAR processes distances between the vehicle and its surroundings at a fast speed (about a million measurements per second) (*3*). However, its accuracy is severely affected by weather. Radar, in comparison, detects the speed, distance, or direction of objects through radio waves, but its performance in the AV context can vary depending on detection needs. Imaging cameras are useful for detecting lane markers or road signs. GPS is useful for general location and navigation however it is often not precise enough for use in AV applications. In addition to each vehicle sensing its own surroundings, it must also communicate with neighboring vehicles.

Communications

Communication devices include dedicated short-range communication (DSRC) and/or 5G network communications. DSRC enables vehicle-to-vehicle communication through the exchange of data relative to their location, which is important for maintaining constant distances when platooning (*3*, *4*). Use of 5G networks rather than DSRC for this purpose has been proposed and tested in the past few years because those networks have proliferated nationally in scope but with still limited 5G coverage in many areas.

Software

AV software processes information such as images and distances while additionally controlling the vehicle's movement. The software used for each company's AVs can vary greatly and is largely developed in-house for proprietary reasons at this early stage. While some sensors may be common across software programs, the number and configuration of sensors and how they communicate and update the underlying software have not yet solidified into a common standard. Competition, proprietary software, and advancements in processing speed/utility remain a key component within this industry sector.

There is progress in adopting general AV technologies originally developed for personal vehicles to the specific needs of automated and platooned trucking operations. As an example, in 2022 during the literature review for this project, the automated trucking company, TuSimple, focused on developing sensors better equipped to handle the longer required stopping distances of trucks. Whereas typical AV sensors used in personal vehicles may have a range of up to 200 meters, this company's technology was expanded to register a distance of up to 1,000 meters (*5*). Improved speed in data processing also contributes to better performance. For example, the use of faster 5G data networks enables near real-time feedback. This technology improvement enables more efficient platooning through the reduction of data traffic flow disturbances and extension to hours of operations (*6*). The required space between trucks in a platoon is expected to be reduced to 50 feet with the adoption of advanced autonomous trucking technologies (*7*).

Fuel Savings

As AV and connected vehicle technology continues to evolve, improvements in fuel savings are additionally expected. Truck fuel efficiency is significantly impacted by aerodynamic drag, which comprises about 40 percent of the truck's total energy consumption (*8*). Research has found that platooning can increase fuel savings and that the percentage of fuel saved is continuing to increase as improvements in platooning technologies are made. One study showed that truck platooning can reduce the fuel consumption of the first truck by 4 percent, while the truck behind saves 10 percent on fuel (*9*). In contrast, a recent study completed in 2021 found that a two-truck automated platoon can reduce fuel consumption by 3.8 to 8.9 percent (*8*). Adding an additional truck to the platoon can further increase overall fuel savings. For example, another study found that a three-truck platoon could reduce fuel consumption anywhere from 5 to 13 percent (*10*). Because fuel consumption is also dependent on other factors such as the truck's placement in the platoon, the speed, and the interval between trucks, AV technology presents a way for trucking companies to economize in that particular area.

PLATOONING AND AUTOMATED/AUTONOMOUS TRUCKING COMPANIES

The advancement in autonomous technology in transportation is prompting the federal government and states, including Texas, to seek ways to safely integrate its use into their roadway system. Released plans and statements highlight the current status of automation in the United States and in projects underway. The U.S. Department of Transportation (USDOT) released the *Automated Vehicles Comprehensive Plan*, highlighting the goals this agency will undertake to make automated transportation possible and safe (*11*). USDOT outlines its role in AV into three goals: be transparent and share information on autonomous technology, update the regulatory framework to ease adoption, and conduct the necessary research to ensure the safety and integration of autonomous vehicles.

Federal and state legislation is also accommodating AVs and technology needs. For instance, the Infrastructure Investment and Jobs Act was recently signed into law, which provides instruction regarding AVs. Some of the sections along this topic in the act include the following:

- Section 11129 of the bill directs USDOT to update the current *Manual on Uniform Traffic Control Devices* regarding the testing of AVs (*12*).
- Section 13005 appropriates funds for a pilot program to research ways to reduce the impact AVs will have on pavement and infrastructure.
- Section 25005 creates a grant program for city projects related to automation, connected vehicles, or smart infrastructure.

Individual states and groups of states have also released information announcing their role and achievements in this new field. Ohio, Michigan, and Pennsylvania, for example, recently conducted two-truck platoon testing in late 2020 by delivering groceries between several food banks along a 280-mile corridor in the three states (*13*). In Arizona, TuSimple successfully tested an autonomous semi-truck (a typical Class 8 truck defined as over 33,001 pounds) from Tucson to Phoenix, Arizona, and plans to use its own designated public highway system routes in the southwestern United States for future testing (*14*, *15*).

In addition to these states, several trucking and technology companies are partnering to bring autonomous trucks and/or platooning to Texas. Given that the state is home to some of the largest cities in the country, where billions of tons of cargo flow through its highway systems, this presents an opportunity to test new technologies (*16*). Companies such as Aurora, Waymo, and Embark have had recent projects located in the Texas region. Aurora is adapting artificial intelligence that will allow trucks to drive from Texas to California in just one day as opposed to the three-day trip normally completed by truck drivers. Aurora hopes to achieve completely autonomous trips by the end of 2023 (*17*). Aurora also partnered with Federal Express (FedEx) as part of a strategy to make delivery services autonomous (*18*). More recently in 2023, using its own autonomous driving system called Aurora Drive, Aurora has autonomous trucks making trips from Dallas to Houston, Texas, along I-45 with drivers behind the wheel (*19*). Table 1 lists several companies that were working on autonomous and platooning projects in Texas during the literature review period for this project, and Table 2 lists several other companies working on similar projects across the United States. Embark and Locomation are no longer existing companies—a testament to the ever-changing landscape within this industry sector. TuSimple and Waymo have made business decisions to no longer focus on automated/autonomous trucks and to focus on other AV projects in the U.S. market (*20*, *21*).

Table 1. AV and Platooned Trucking Companies Working in Texas.

Company	Type	Project
Aurora (*22*)	Autonomous tech	Conducting tests to achieve autonomous travel from California to Texas. Aurora Horizon is the name of its fleet and commercial service.
TuSimple (*23*)	Autonomous tech	Will establish a hub, located in the AllianceTexas Mobility Innovation Zone, and continue testing AV truck technology (*24*). **No longer participating in autonomous trucking development.**
Waymo (*25*)	Autonomous tech	Will conduct testing of autonomous truck on I-45 and establish a hub in Dallas. **No longer participating in autonomous trucking development.**
Kodiak Robotics (*26*)	Autonomous tech	Its technology is being used to conduct further testing in Texas, including adding a Dallas-to-San Antonio route. Pilot testing began in April 2023 (*27*).
JB Hunt (*28*)	Logistics/trucking	Partnered with Waymo.
FedEx	Package shipping	Partnered with Aurora.
Embark (*29*)	Autonomous tech	Conducting autonomous truck testing, establishing a trucking hub facility, and partnering with Texas A&M University. **Company dissolved.**
Ryder (*30*)	Logistics trucking	Partnered with Waymo to provide fleet management services.
Nuro	Autonomous delivery	Began testing in Houston in 2018.

Table 2. Other Autonomous and Platooned Trucking Companies in the United States.

Company	Type
Plus (*31*)	Autonomous tech
Einride	Autonomous electric truck
Volvo Trucks	Automobile and trucking
Paccar (*32*)	Trucking
Traton (*33*)	Trucking
Tesla	Platooning
Ford Otosan (*34*)	Platooning
Daimler (*35*)	Platooning
Robotic Research (*36*)	Autonomous tech
Locomation (*37*)	Autonomous trucks tech—**company dissolved**
Peloton (*38*)	Autonomous vehicle tech

FEDERAL AND STATE EFFORTS

Several platooning and autonomous initiatives by government agencies at both the federal and state level are also in place. The following sections discuss them.

Federal Highway Administration

The Federal Highway Administration's (FHWA's) Exploratory Advanced Research Program Projects is conducting several research projects related to truck platooning. The Truck Platooning Early Deployment Assessment analyzes how truck platooning on highways can be improved as well as its impact on roads. This project is currently in the data collection phase (*39*). Although this is a federal program, this project would not have been able to move forward without collaborating with states. Several states have also introduced legislation to promote and understand how this technology can be applied within their state. The following sections briefly describe notable state efforts including testing and pilot programs.

Arizona

Arizona has approved legislation instructing how autonomous vehicles can be operated in the state. Embark, Nuro, TuSimple, and Waymo are some of the companies that have submitted requests for permission to conduct tests in the state (*40*).

California

The University of California, Berkeley's Institute of Transportation Studies is conducting research on connected and automated technology, including truck platooning. In California, the California Department of Transportation (Caltrans) and FHWA have sponsored Partners for Advanced Transportation Technology projects such as cooperative adaptive cruise control demonstrations on public highways (*41*, *42*).

Florida

The Florida Department of Transportation is currently developing a pilot project to show how driver assistive truck platooning can be applied in the state. This pilot will help identify how truck platooning will affect traffic and infrastructure and help determine regulatory needs (*43*).

Minnesota

Minnesota approved legislation, the Truck Platooning Bill, instructing how truck platooning can be operated within the state. Truck platooning is only allowed on freeways and expressways, and the law additionally limits platooning according to size, weight, and height of the truck (*44*).

Smart Belt Coalition (Ohio, Pennsylvania, and Michigan)

The Smart Belt Coalition, comprised of Pennsylvania, Ohio, Michigan, the Pennsylvania Turnpike Commission, and the Ohio Turnpike and Infrastructure Commission, tested truck platooning technology across its member states. While driving on major highways and interstates, the lead truck was driven manually, and the following truck used platooning technology (*13*).

Virginia

The Virginia Department of Transportation (VDOT) developed the *2020 VDOT Connected and Automated Vehicle Program Plan* to prepare the state for the integration of AVs. As part of its plan, the state will update current regulations, laws, education, infrastructure, and data practices (*45*).

Other States

Additional information is available and updated regularly regarding state-level laws that have been enacted regarding autonomous/self-driving vehicles. The National Conference of State Legislatures provides this information on its website specifically focused on this topic (*46*).

IMPACTS OF TRUCK PLATOONING AND AUTOMATED/AUTONOMOUS TRUCKS

To accommodate both truck platooning and automated/autonomous trucks, the federal government and industry leaders have identified areas within infrastructure that will be affected by these new technologies. To address these concerns, FHWA, as part of its 2018 *Dialogue on Highway Automation*, released guidelines to help stakeholders understand and better prepare for AVs on the road. This document recommends that state and local governments cooperate to standardize emergency response and traffic law in the context of AVs. However, before full automation can be launched, testing of these vehicles must first occur on public highways. Testing of autonomous vehicles will require training, the collection and use of new data, and the revision of traffic laws (*47*). On the industry front, the establishment of facilities such as transfer hubs are already underway, which will need to be integrated into the highway system, further affecting infrastructure requirements and standards.

Infrastructure

Adopting AV transportation into existing roads will require retrofitting infrastructure to ensure that the proper exchange of information between the vehicle and its surroundings can occur. Several areas need to be addressed before launching this technology. In 2021, FHWA identified the following four primary areas where AVs will affect infrastructure:

- Physical infrastructure.
- Traffic control services.
- Transportation systems management and operations and intelligent transportation systems.
- Multimodal infrastructure.

Physical infrastructure refers to roads and bridges, which will be affected by the change in driving patterns caused by AVs; more trucks on the road can reduce highway capacity, inconvenience passenger vehicles, and increase the wear on bridges and pavement. Traffic control services will need to change how roads are planned. For example, road markings will need to be designed to make it easier for AVs to process their surroundings (*48*). Appendix A includes a decision tree describing modeling needs and considerations for several types of infrastructure upgrades that may impact automated and platooned trucks. Additionally, a standard for road signs and signals is needed to ensure consistent placement and meaning across the country. Infrastructure dedicated to managing road operations will also be impacted by AVs. These changes can include transitioning away from tolling and traffic management into a role involving information management and road pricing.

For the last area idea identified by FHWA, it is still uncertain how intermodal transportation will be affected by AV technology. Autonomous trucks can potentially compete and disrupt the railroad industry if they prove to be the more reliable, cheaper alternative (*49*). However, the potential for intermodal collaboration exists.

There are also alternatives for easing the transition to platooning and autonomous trucks. One option is to designate a truck-only lane for platooning or autonomous truck use, as recommended by the Mineta Transportation Institute and already employed by a few states. Caltrans already uses commercial-only lanes to help improve safety and relieve congestion flow (*50*). The Georgia Department of Transportation is also starting a commercial vehicle lane project to improve driving conditions on I-75 (*51*). Although the lanes are designed for standard commercial vehicles, these truck-only lanes can be retrofitted for platooning and autonomous trucking purposes as well. For example, USDOT awarded DriveOhio with $4.4 million for the I-70 Truck Automation Corridor project, allowing for autonomous truck testing on public roads (*52*).

Transfer Hubs

In addition to retrofitting existing infrastructure, the establishment of transfer hub facilities will serve to promote autonomous trucking and platooning. A transfer hub facility allows for cargo to be transported from a manually driven truck to a driverless automated truck and vice versa. The manually driven route is the first and last mile, which are typically comprised of a more complicated street network. Once the driver reaches the hub, planned to be located near an interstate highway, an autonomous truck can take over for the entirety of the route until the next transfer hub is reached, where the last mile will be manually driven. Additionally, transfer hubs can be used for other purposes such as refueling, inspection sites, and unloading or reloading stations (*53*). These hubs are also incorporating smart technology to inform drivers of space availability in real time, reducing the need to work extended hours due to lack of parking.

Phasing in autonomous trucks through the hub-to-hub model is seen as a cost-effective option in the long term. According to UberFreight, this model can be divided into three major cost components: truck operation costs, hub-to-hub costs, and technology costs. Although costs initially will be high, they estimate that operating an autonomous truck will cost about $1.06 per mile, \$0.72 per mile less than standard trucks, as labor and fuel conditions change (*54*). Costs included in the hub-to-hub model are primarily accrued from land, leases, and operations within the hub as well as the first and last mile traveled. Technology costs are more difficult to quantify given the recent development in automated testing, but nonetheless it is expected prices will decrease in the years to come.

An example of this parking technology is the Trucks Park Here program, funded by the USDOT Better Utilizing Investments to Leverage Development Transportation grants, which helps drivers locate parking sites and provides information on space availability (*55*). Figure 1 shows an example of a transfer hub model, where the truck driven by a person leaves the distribution center (step 1), the trailer is then switched to an autonomous truck (step 2), the truck drives onto the highway until it reaches the next transfer hub (step 3), and the trailer switches to a truck operated manually to reach its destination (steps 4 and 5) (*56*).

Figure 1. Transfer Hub Model.

Several companies are already launching transfer hubs, with some even projecting how they will expand across the country. Although Embark ceased operations, it did provide some insight into the expansion of autonomous trucking operations. As part of Embark's initial partnership with Ryder, the latter company would have helped locate and create up to 100 transfer points in the United States and provide fleet management and logistical services. Embark was set to launch this expansion in early 2022 beginning with states where freight movement is prominent and weather is more favorable, such as California and Texas (*57*, *58*). Figure 2 shows key states shaded in blue as areas where Embark was to first establish transfer hubs.

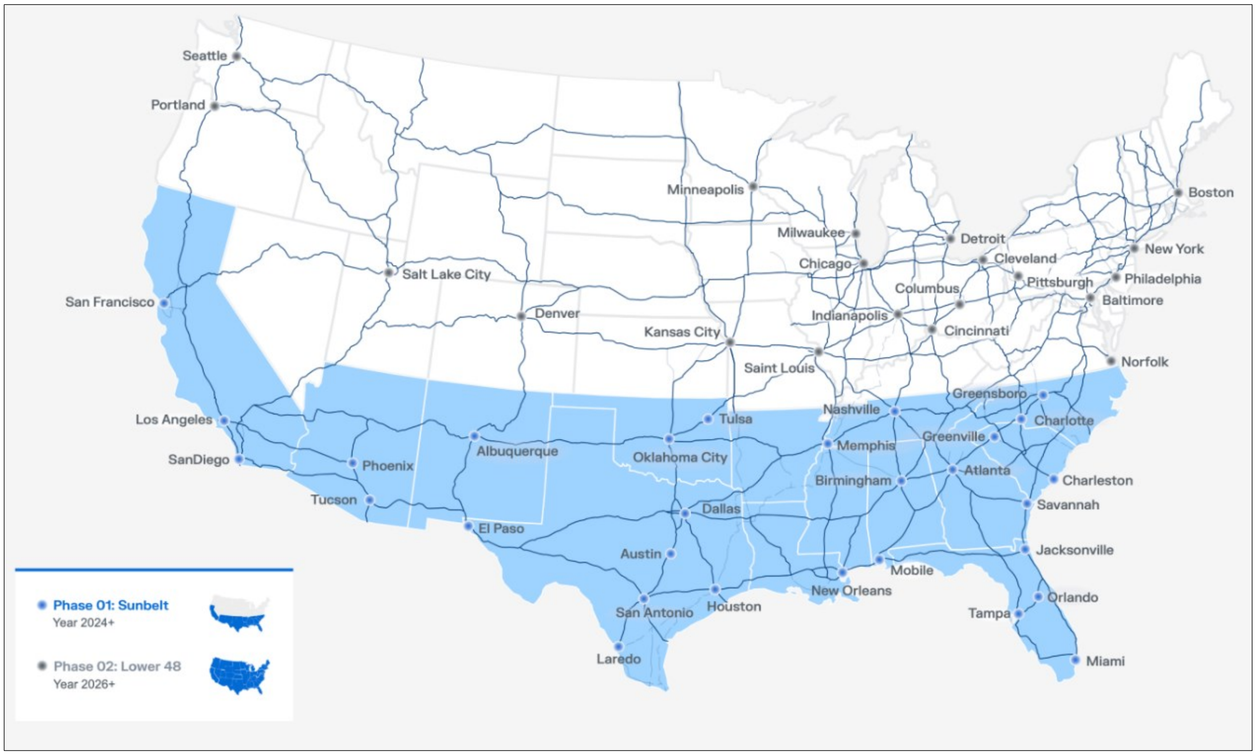


Figure 2. Embark's Planned Transfer Hub Adoption.

As with the Embark planning experience, the Deloitte Autonomous Truck Adoption Tool helps predict how the adoption of autonomous trucks will look across the country (*56*). This tool separates adoption scenarios into three stages. Stage one in Figure 3 predicts integration will first occur in the southwest region of the United States given the area's combination of technology-friendly regulations, high freight movement, and favorable weather. Stages two and three are not as certain, but it is possibly autonomous trucking will steadily spread northward and eventually become nationwide as shown in Figure 4.

Funding for these projects is obtained from different public and private sources. Authorized by the Fixing America's Surface Transportation Act, some autonomous technology projects are supported through the Advanced Transportation and Congestion Management Technologies Development Program grants made available for large projects intended for the improvement of the overall driving experience (*59*). DriveOhio received a grant to help fund the I-70 Truck Automation Corridor Project, receiving $4.4 million from the program and $4.5 million in matching funds (*52*). The private sector, in addition to participating in public-sector projects, is financing its own projects through investor contributions, such as Plus, which has seen funding grow to $200 million (*60*). Similarly, Kodiak Robotics, Inc., has secured $165 million, hoping to add 15 new trucks to its fleet (*61*).

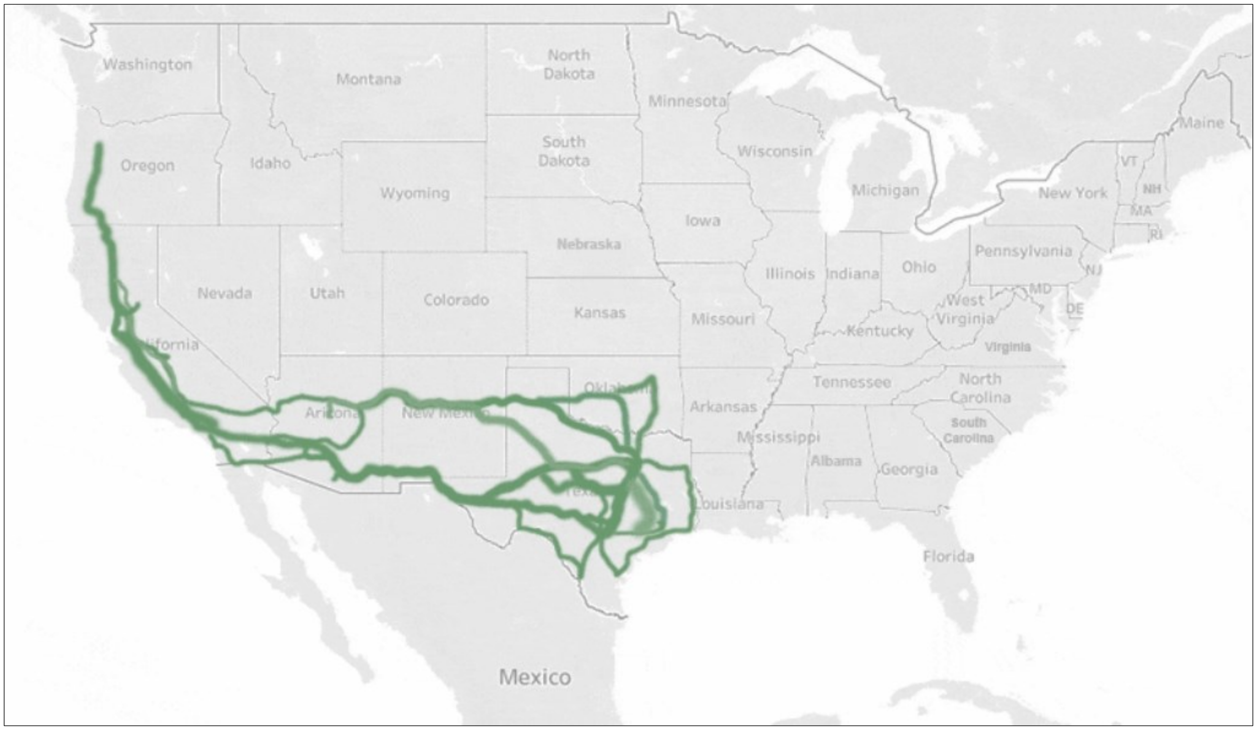


Figure 3. Stage One Autonomous Truck Adoption Projected Map in Deloitte's Autonomous Truck Adoption Tool.

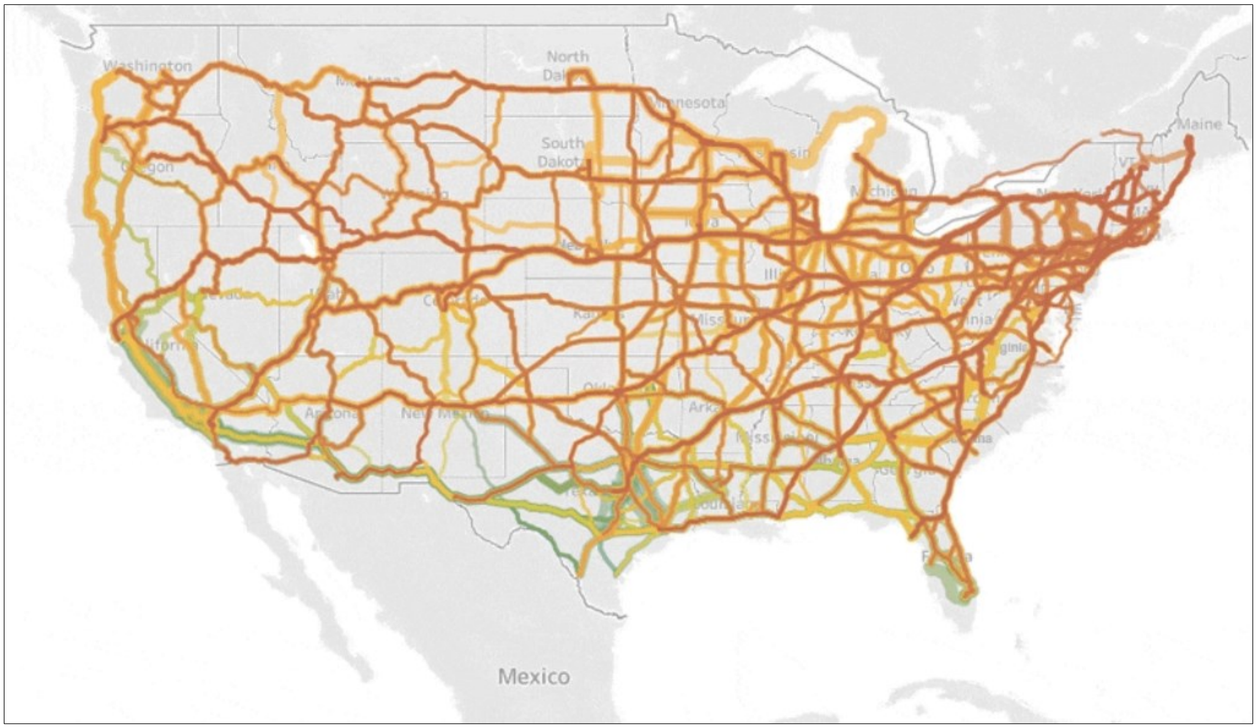


Figure 4. Stage Three Autonomous Truck Adoption Projected Map in Deloitte's Autonomous Truck Adoption Tool.

LITERATURE ON THE ECONOMICS OF AUTOMATED AND PLATOONED TRUCKING

The data and methodology surrounding platooning and automated/autonomous trucks can vary by the scope of the economic analysis. Although an analysis can cover anything from the impact on corridors to the lifetime cost of operating an autonomous truck, analyses often use similar variables and include market penetration scenarios to calculate the overall impact. Some of the most common variables in these types of analyses include fuel consumption, emissions, safety, labor, and equipment. Data depicting the road network, route distance and milage, and where the truck stops can help gauge the truck's route and be used to construct different scenarios (*62*). Models additionally generate the necessary data or conduct the analyses themselves if required. In terms of methodology, the analysis can be performed by comparing a combination of passenger and trucking lanes and by introducing different platooning and automation scenarios. This section highlights the data, methodology, and results of several truck platooning and autonomous economic reports.

Since the completion of the TxDOT Project 0-6984 report in 2020, more has become known about the anticipated economic impact of autonomous trucking. A 2021 report completed by USDOT calculated the macroeconomic impact for different AV trucking adoption scenarios. The USAGE-Hwy model is used to compare this technology against traditional trucks through an industry lens. Three different technology adoption scenarios of 19, 48, and 75 percent over

10 years were applied to control for the unknown adoption rate. This report found that Level 4 and Level 5 autonomous trucking will increase the gross domestic product by 0.3 percent, employment by about 10,000 jobs, and wages from $203 to $267 per year, depending on the adoption scenario (*63*). The report additionally says that layoffs are more likely to occur in the high-adoption scenario, while the low and medium scenarios are not impacted much by AV technology.

Another report investigated the impact of congestion and traffic flow on infrastructure using spatial average annual daily traffic (AADT) data obtained from the National Performance Management Research Data Set. Specifically, this dataset contains speed, average speeds, travel time, and density information (*64*). This study concluded that as autonomous vehicles become more prominent, a smaller, stable platoon size can result in smoother travel conditions (*64*).The benefits of autonomous trucking can also be calculated through the changes in speed when compared to trucks piloted by drivers (*65*). The idea behind this study is that through the reduction of peak speeds and removal of hours-of-operation limits, the use of autonomous vehicles will result in greater cost savings.

To determine this, a methodology consisting of four parts was developed:

1. The first part involves creating a fuel consumption model to account for fuel savings when variables such as vehicle speed, loading capacities, and highway driving patterns are considered.
2. The second part examines the differences between trucks piloted by a driver versus an autonomous truck. This part developed 42 scenarios comprised of a combination of traffic conditions, different vehicle types, and cargo volume for two different speed reduction approaches.
3. The third part of the study involves analyzing a case study using distribution data from a United Kingdom supermarket.
4. The fourth part compares the United Kingdom to the United States. The results indicate that by reducing speeds by 20 km/h, assuming a medium cargo time value, costs for autonomous trucks decrease by 4 percent, while costs for trucks driven by humans see a rise in costs by 3 percent.

A study completed in 2021 by the Georgia Institute of Technology and in collaboration with Ryder took a different approach to determining the impact of autonomous trucking. As opposed to quantifying the impacts of autonomous vehicles in general, this project focused on the impacts centered around a trucking hub model and the Autonomous Transfer Hub Network (ATHN) for the southeast region of the United States, where Ryder conducts the majority of its operations (*62*). The ATHN was created by reviewing Ryder order data, which contain information on stop locations and arrival and departure times, to map the highways and most-used access points. Proposed transfer hubs were then placed in these areas and connected to other hubs to form the

ATHN. An optimization model was then presented to demonstrate how autonomous truck operations could be scheduled. The model connects the hubs with corresponding tasks and accounts for empty cargo, loading, unloading, and driving times. Essentially, this model schedules cargo transport to prevent truck times from overlapping. This study found that most of the benefits are derived from the lower cost of labor, but optimal operations also play a significant role in the overall benefit. Depending on the complexity and size of orders, savings could range from 30 percent to 40 percent, which totals anywhere from $5.5 million to $8.4 million per year.

A similar study evaluated the impact of a transfer hub approach on long-haul trucking operation hours. The purpose of this study was to better understand how, and if, long-haul automated trucking will make up for the labor shortage in the trucking industry and whether short-haul jobs will be created (*66*). To determine this, data from the 2017 Commodity Flow Survey (CFS) were filtered to narrow down shipments classified as long haul and manipulated to obtain truck routing and hours in operation. Google Maps API and GGMAP, along with CFS data, were used in determining truck routing. Once routing was determined, operation hours for urban and highway routes were calculated based on the 11-hour regulation and weighting factor. Lastly, interviews were held to supplement the analysis, focusing primarily on driver input given their firsthand on-road experience. The study concluded that about 94 percent of long-haul trucking operation hours will be affected in the long run when automated trucking expands across the country. In contrast, 10 percent of operation hours will be affected if automated trucking remains in the southern part of the country.

Phasing of AV and Platooned Truck Adoption

Scenarios depicting the adoption of AV trucks as a portion of the overall truck population typically represent these levels through multiple levels ranging from little adoption to total adoption. In 2020, for TxDOT Report 0-6984-R1, the research team considered adoption rates in these terms but also considered the phasing of automation between current operations to tandem autonomous truck platoons (*67*). For that analysis, the base case represented trucks operating independently (not platooning) from dock to dock, while three time frame horizons were developed that represented increased levels of platooning and autonomous operations, as depicted in Figure 5 and Figure 6.

These time frame horizons were:

- **Near term, beginning in 2021:** two truck platooning for the long-haul portion with rest breaks for the two drivers.
- **Mid-term, beginning 2026:** two truck platooning, with a driver only in the front truck and a drone (autonomous) following truck, for the long-haul portion with rest breaks for the one driver.

- **Long term, beginning 2036:** two truck platooning, with two autonomous trucks, for the long-haul portion.

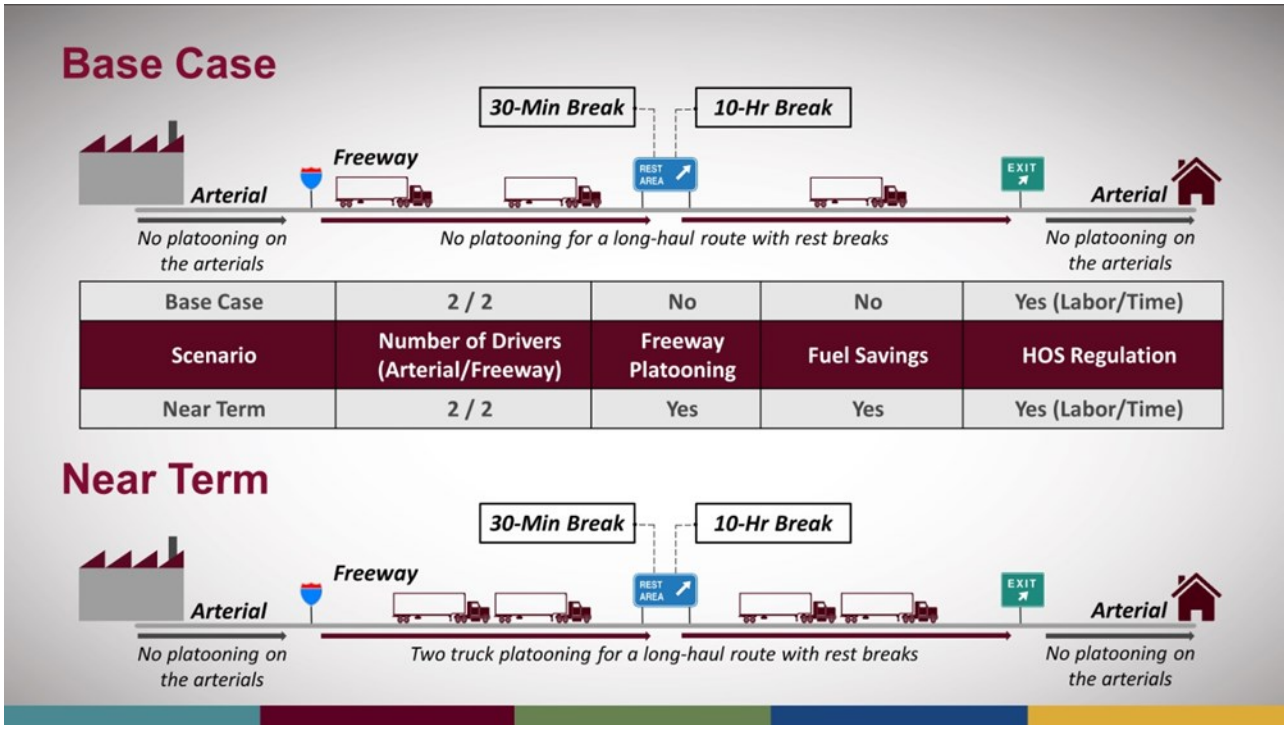


Figure 5. Base Case and Near-Term Scenarios Represented in TxDOT Report 0-6984-R1.

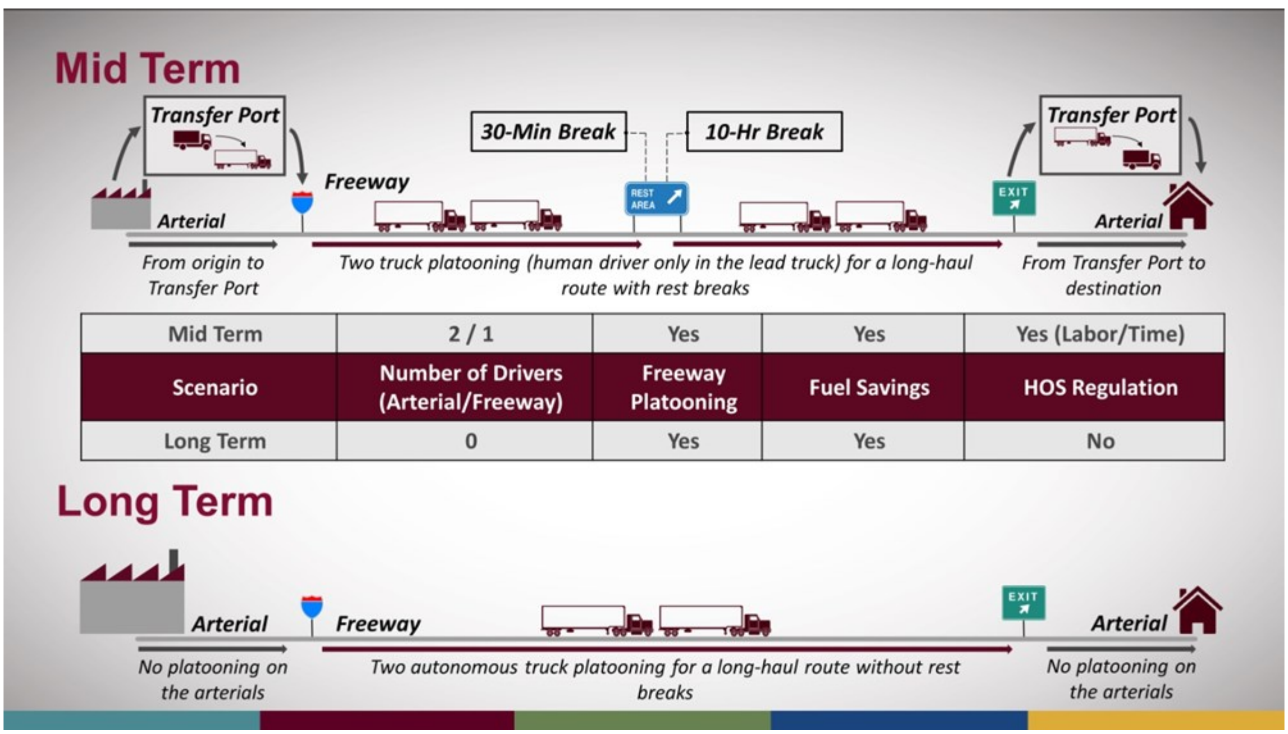


Figure 6. Mid-Term and Long-Term Scenarios Represented in TxDOT Report 0-6984-R1.

The outcome of the economic analysis using these phasing periods showed increased benefits because of the reduction of driver-related costs as the levels of autonomy increased, as Figure 7 shows.

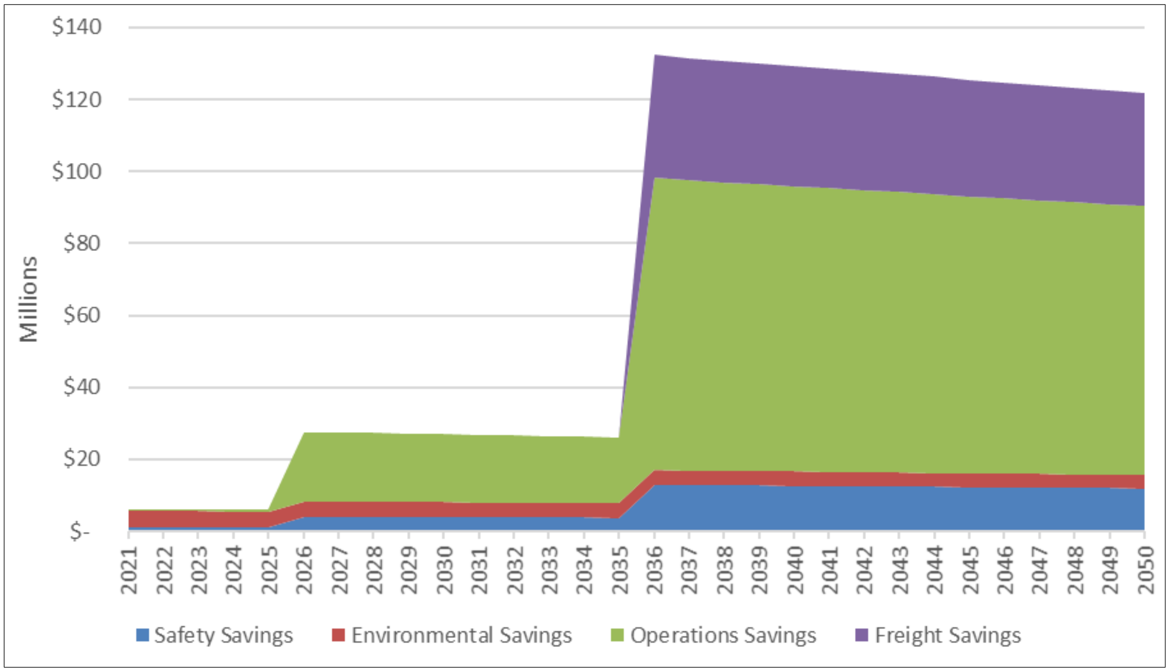


Figure 7. Low-Growth Scenario Discounted Benefits over Time.

In a December 2021 webinar, Locomation, the now-dissolved private trucking company focused on a specific platooned trucking operations model, discussed its economic analysis framework and results (*68*). The framework closely resembled the TTI framework with phasing over time representing advances in automation levels. Figure 8 graphically exhibits Locomation's planned strategy and timeline. Shown in terms of cost savings in Figure 9, the Locomation analysis, similar to the TTI analysis, shows greater savings (or benefits) with the reduced driver costs associated with more advanced automation.

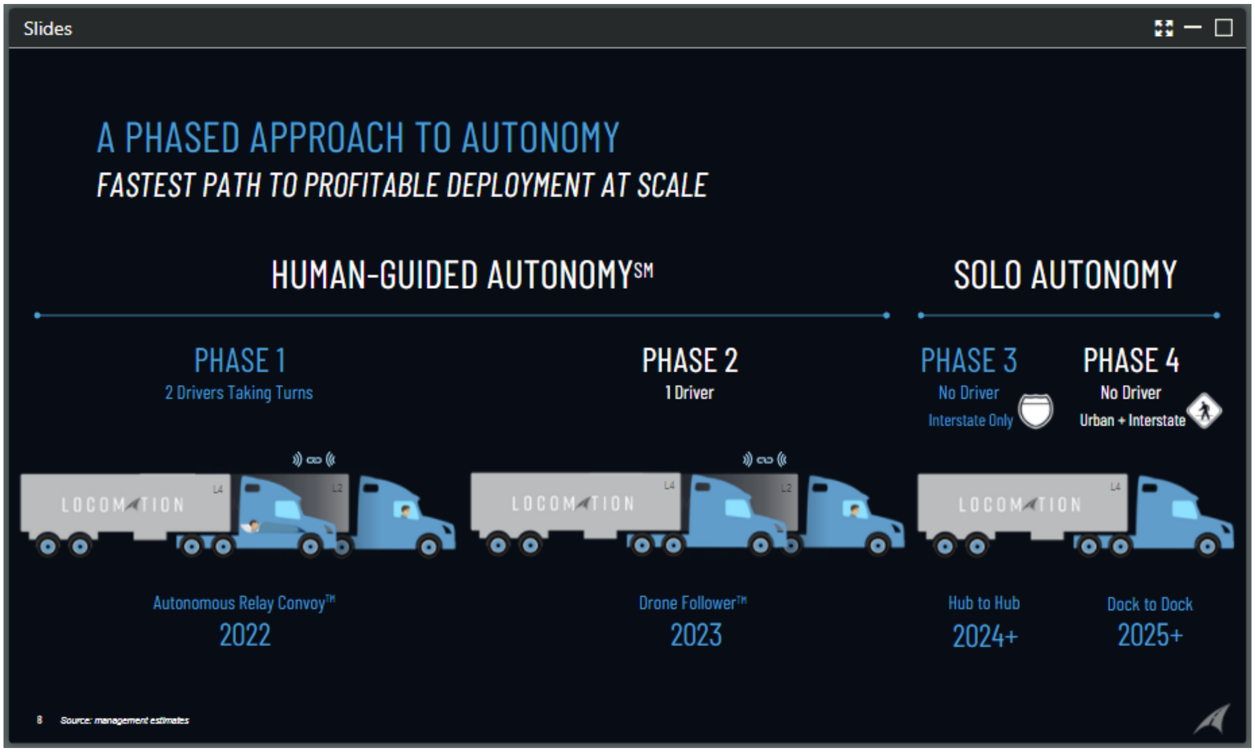


Figure 8. Locomation Phased Approach to Autonomy.

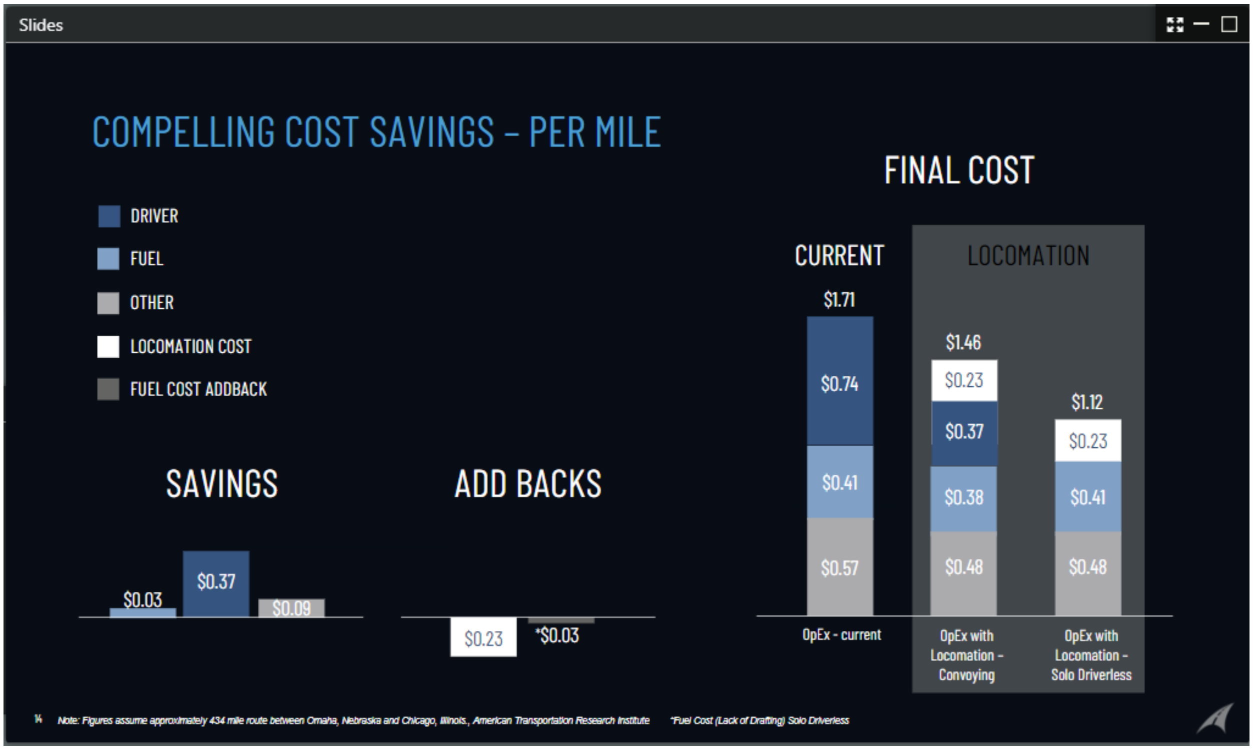


Figure 9. Locomation Economic Analysis Results.

Challenges to Truck Technology Adoption

The regulatory framework surrounding truck platooning and autonomous travel will require renovating or updating current guidelines, including standardization across states. Although states are already launching their autonomous vehicle efforts, regulations surrounding these are not consistent throughout. Additionally, states must ensure that these new regulations do not inhibit future efforts, as discussed during the Truckload Carriers Association's Truckload 2022 (*69*). Existing regulations are also being researched to understand the regulatory landscape and how truck platooning can be accommodated in highway system operations. This includes finding legislation related to safety, technology innovation, data storage and protection, and permits. Approximately 44 states have introduced or adopted AV policies (*70*). Although platooning laws already exist in some states, it could be in the form restrictions such as bridge weight limits or distance between vehicles when driving (i.e., laws about following too closely).

Typically, research on this subject is performed by searching the current regulatory framework, as in the case with studies completed in New Mexico and California (*71*,*72*). The New Mexico study explored the benefits of truck platooning while determining how parties, including the government, drivers, and employers, would be affected in the case of an accident. The report on California is a comprehensive review summarizing actions taken by other states or regions related to AVs that can be applied to this state. The report includes topics such as safety, infrastructure, data, economic benefits, and stakeholders involved. Overall, much of the research surrounding regulation is attempting to understand what new problems will arise and what laws and current practices will need to be changed for a successful adoption of autonomous and AV trucks.

Other challenges include the perception of AV trucking in the form of costs, safety, and privacy. On the costs front, companies are less likely to immediately adopt AV practices into their business. This slow uptake is due to the initial high costs of AV technology adoption, training, insurance and liability uncertainties, and loss of benefits in case of accidents. Safety issues can potentially affect industry, drivers, and the general public. Some of these concerns are present simply by operating a platooning vehicle, such as the obstruction of views and lower situational awareness. The drivers themselves could also be impacted by platooning practices. The driver may experience boredom and higher stress or be expected to work longer hours (*4*). Areas where merging vehicles might interact with trucks in a platoon are also concerning. The physical infrastructure needs in these areas may be more complex. Appendix A discusses the additional modeling needs for auxiliary lane areas, as well as the design and operations considerations related changes in truck and traffic technologies. It includes decision trees that guide where complementary or supplementary analysis may be needed. Lastly, privacy and cybersecurity can impact trust in platooning. Companies and drivers can potentially be tracked, and trucks run the risk of hijacking. Therefore, addressing these concerns through regulations will be essential.

TXDOT PROJECT 0-7124 TOOL END-USER WORKSHOP

The end-user workshop, scheduled early in the project after the literature review was well underway, was designed to gather input on desired impact analysis tool features and requirements, including the preferred user interface and reporting formats. Input from the end users up front in the timeline was meant to dramatically improve the final tool under development and maximize its utility. An overview and preliminary interface for the planned tool were discussed with the project oversight panel during the TxDOT panel update meeting in June 2022 to meet the requirements of the end-user workshop outlined in the research plan. The panel represented a wide range of potential TxDOT end users including the following areas of expertise:

- Statewide planning.
- Design.
- Freight planning.
- Safety.
- Bridge.
- Pavement.

The research team presented the preliminary tool, which consists of a user interface designed to resemble several other tools developed for TxDOT by TTI, such as the Truck Congestion Analysis Tool. The panel did not suggest any specific changes to the interface appearance or functionality. The research team discussed bridge and pavement data and modeling extensively during the meeting. Panel members raised concern over the bridge scour calculations, suggesting the need for a follow-up meeting. The panel recognized the importance of resiliency and redundancy in the freight network and the ability to incorporate some of the modeling suggested by the research team. However, the panel directed the research team to only consider aspects critical to completion of this project with the focus more on planning-related impacts. The research team subsequently used the input and thoughts portrayed during the workshop to address data, modeling, and output features for the tool moving forward. After further enhancing planning for the tool features and functions, the research team contacted additional TxDOT areas, such as the Maintenance and Strategic Planning Divisions, as individual components were under development for input into the tool operations and capabilities during the remaining months of the project.

CHAPTER 3. FAST WEB TOOL INTEGRATED MODELS

The Fast Web Tool integrates four major independent models that cohesively operate within the tool. These are the:

- Pavement Condition Model.
- Bridge Susceptibility Model.
- Flood Susceptibility Model.
- Economic Analysis Model.

Users may select or change parameters for each of the models or select one or more to run independently or with the others. The following sections describe each of the models.

PAVEMENT CONDITION MODEL

The Pavement Condition Model is used to predict the fatigue cracking initiation time and rutting in flexible pavements and faulting in jointed concrete pavements (JCPs). The procedures for predicting the fatigue cracking initiation time and rutting in flexible pavements are similar. Figure 10 illustrates the process for predicting fatigue cracking initiation and rutting. To predict cracking and rutting in flexible pavements, the first step is to input information regarding the climate, material properties, and mechanical properties of materials in each layer. For example, to predict the mechanical properties of asphalt concrete based on climate information, the temperature variation over time in the asphalt concrete layer is first obtained using a climate model. Then, using an asphalt aging model, the change in mechanical properties of the asphalt over time is obtained based on the temperature and microstructure of the asphalt concrete. Next, the mechanical properties of the asphalt concrete (e.g., dynamic modulus and scalar modulus) are obtained using a micromechanics model based on the mechanical properties and volumetric fractions of each component in the asphalt concrete. The material module also includes an equilibrium soil suction model and artificial neural networks (ANNs) to support determination of the resilient moduli and the soil–water characteristic curve (SWCC). The traffic load spectra are then obtained based on the traffic information. Based on the pavement structure information, the driving energy of distresses is next obtained through finite-element analysis. Finally, using the cracking model and rutting model, the estimated fatigue cracking initiation time and rutting in pavements are obtained.

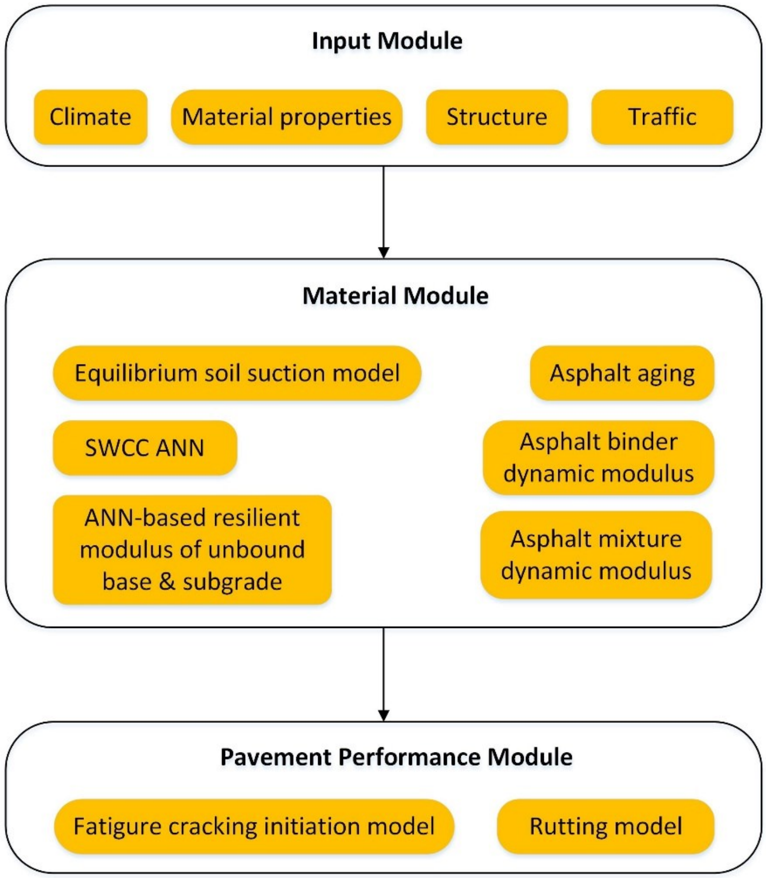


Figure 10. Prediction Process for Fatigue Cracking Initiation Time and Rutting in Flexible Pavements.

In the cracking and rutting models, field data from the long-term pavement performance (LTPP) database and WesTrack project (*73*) were used for model calibration and verification, and the relationships between the model parameters and the mechanical properties of materials were obtained. Figure 11 shows these relationships for the rutting model. Thus, once the mechanical properties of the materials are obtained in the first step, the model parameters can be derived directly from the relationships. Figure 12 compares the model predictions with the test data from one section in the WesTrack project.

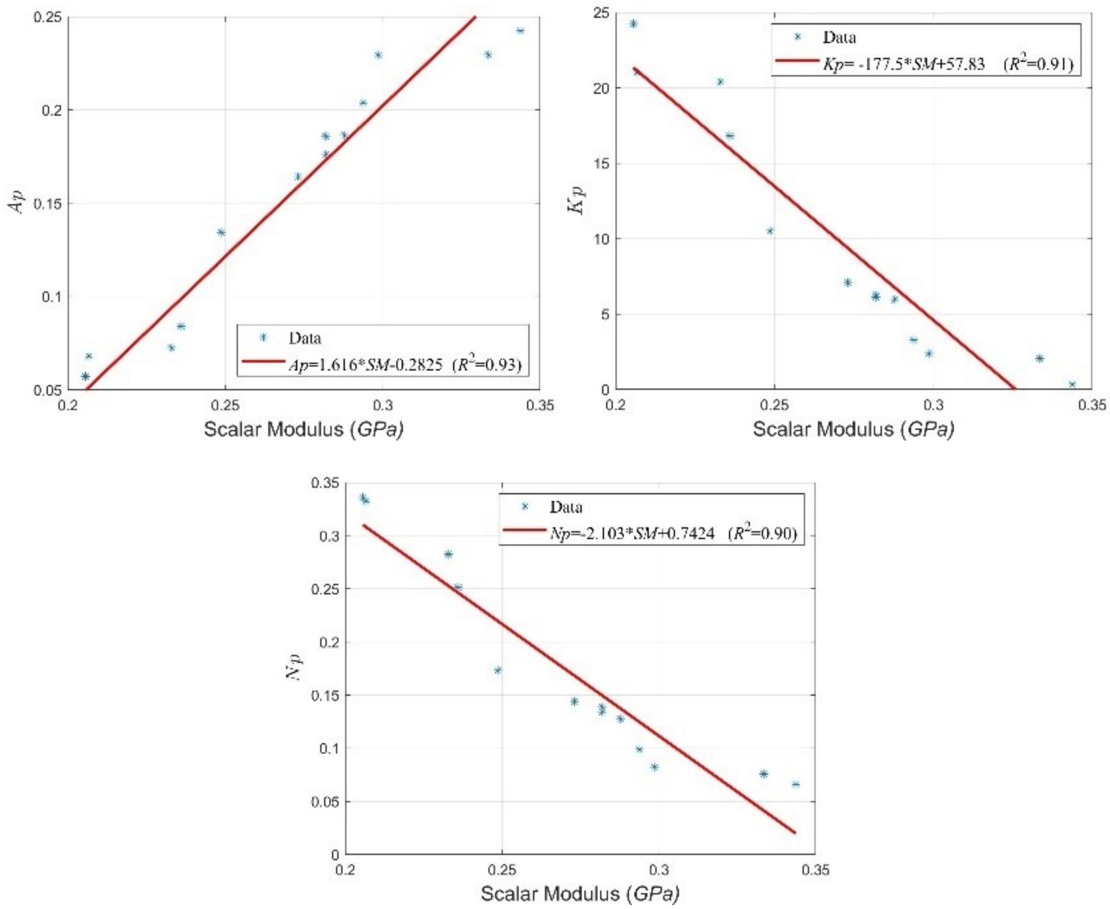


Figure 11. Relationships between Model Parameters and the Reference Scalar Modulus in the Rutting Model.

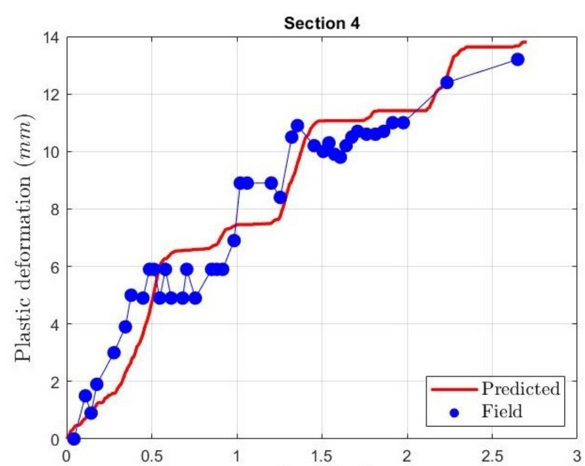


Figure 12. Comparison of Model Predictions and Test Data from Section 4 in the WesTrack Project.

A mechanical-empirical faulting model (*74*) is used to predict the faulting depth at joints in the wheel path in JCPs. For better implementation, the effects of pavement performance-related factors on the determination of model parameters in the model were investigated using LTPP data. Thus, the model is capable of meeting the requirements of simplicity and acceptable accuracy.

BRIDGE SUSCEPTIBILITY MODEL

To understand the full extent of bridge infrastructure susceptibility, both the spatial context of the infrastructure and the source of susceptibility need careful and thorough assessment. Two main sources of susceptibility exist: structural sources and landscape-induced sources. Bridges have unique structural characteristics that contribute to their susceptibility to flooding. Additionally, bridges are part of a larger landscape that is exposed to susceptibilities induced by the physical and hydroclimatic characteristics of the landscape. These combined structural and landscape-induced susceptibilities constitute the overall susceptibility rating or assessment of a bridge. Thus, to assess relative bridge susceptibilities within the Texas transportation infrastructure system, researchers proposed a framework that can integrate both types of susceptibilities (see Figure 13).

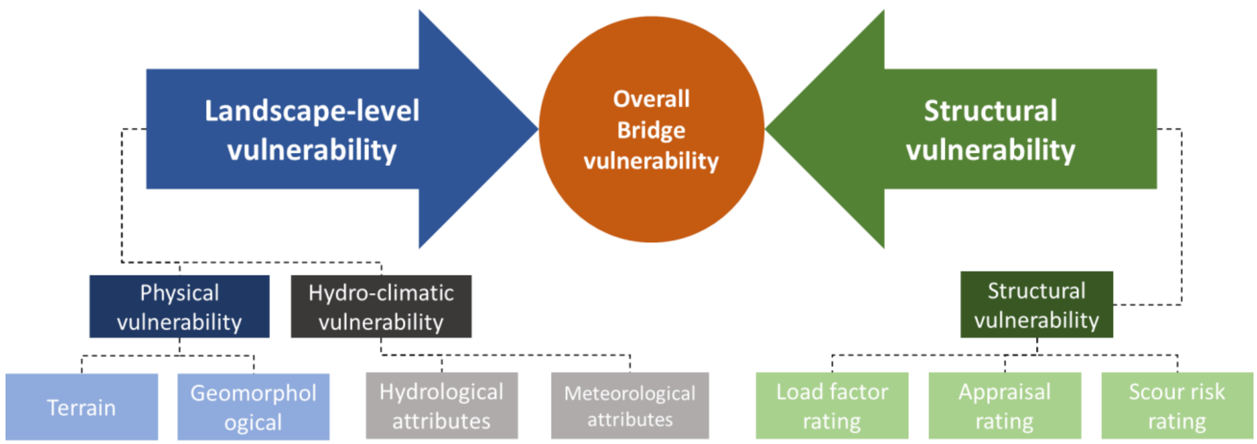


Figure 13. Framework to Assess Bridge Susceptibility in Texas.

Structural Susceptibility Assessment

While bridges are exposed to the same level of landscape-induced susceptibility as the roads they are connected to, bridges also have a structural susceptibility component related to their attributes such as load-bearing capacity, substructure and superstructure length and width, bridge condition, and scouring. Researchers selected attributes from the publicly available data in TxDOT's Open Data Portal and Bridges dataset (*75*, *76*). Specifically, researchers selected load factor ratings calculated using annual AADT and structure type, scour risk ratings calculated using reported scour risk factors, and appraisal ratings from the database. Combining these three ratings, researchers developed a composite index of structural susceptibility using a scale from one to five, with one being the least susceptible and five being the most susceptible.

Overall Bridge Susceptibility

By combining structural susceptibility and landscape-level/flood susceptibility assessments (described in the following section), the research team generated a measure of overall bridge susceptibility (see Figure 13).

FLOOD SUSCEPTIBILITY MODEL

To create the Flood Susceptibility Model, which becomes a factor in bridge susceptibility assessments, researchers combined a multicriteria decision analysis (MCDA) and an analytic hierarchy process (AHP). Using an MCDA and AHP together combines the strengths of both methods, providing a systematic approach to decision making by combining multiple criteria through the MCDA (*77*, *78*, *79*, and *80*) and evaluating their relative importance through the AHP (*78, 79*). Once researchers determined the relative importance of the multicriteria elements, researchers overlaid the spatial layers in a GIS. Figure 14 shows the workflow diagram for modeling flood susceptibility in Texas.

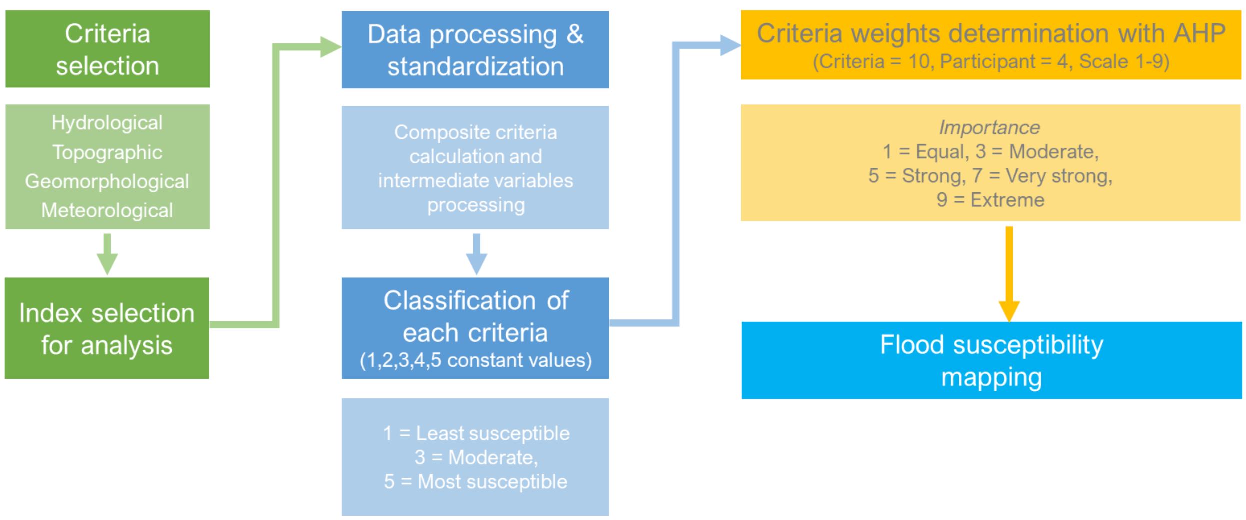


Figure 14. Workflow Diagram for Modeling Flood Susceptibility in Texas.

With respect to explanatory variables, researchers identified two major components of landscape susceptibility based on the literature—form-based susceptibility and process-based susceptibility. Table 3 lists specific variables used in this study. Using both form-based and process-based factors, researchers defined a composite index of flood susceptibility using a scale from one to five, with one being the least vulnerable and five being the most vulnerable. The data used in this study were collected from various sources, including the Soil Survey Geographic Database (SSURGO) from the U.S. Department of Agriculture (*81*), the National Land Cover Database (NLCD) and the National Elevation Dataset (NED) 3D Elevation Program (3DEP) from the U.S. Geological Survey (*82*), and TxDOT's Open Data Portal (*75*). The data were preprocessed to ensure consistency and completeness, and any missing or inconsistent data were either removed or corrected as appropriate.

Table 3. Explanatory Variables Used for Landscape-Level Flood Susceptibility Modeling.

Name	Description
Slope (NED-3DEP)	The slope was calculated as the rate of change of elevation for each pixel, expressed as a percentage.
Precipitation	Average annual total precipitation, 30-year normal (1991–2020).
Temperature	Average annual daily mean temperature, 30-year normal (1991–2020).
Geomorphic description (SSURGO)	A geomorphic description helps identify a discrete land surface feature or assemblage of features in an area.
Flood frequency (SSURGO)	Flood frequency classes represent different ranges of the return period of floods. Flood frequency data give the dominant flood frequency class for a map unit based on its major soil components.
Taxonomic suborder (SSURGO)	To identify flood-prone areas, the *taxsubgrp* data can be used to determine the taxonomy information for the major soil component of each map unit. Flood-prone areas can be delineated by selecting map units that contain *fluv* characters in the taxonomic suborder.
Imperviousness (NLCD)	Imperviousness describes the proportion of the land surface covered by impermeable materials that prevent water from infiltrating into the soil, increasing the amount of runoff and reducing the natural capacity of the landscape to absorb and store water. Researchers classified the level of imperviousness based on the categories of developed lands based on density.
Flow accumulation (NED-3DEP)	Flow accumulation is the process of calculating the amount of upstream drainage area that contributes to the flow at a given point in a river network.
Topographic wetness index (NED-3DEP)	The topographic wetness index is used to identify areas of the landscape that are likely to be wet or dry based on their position in relation to other areas.
Topographic position index (NED-3DEP)	The topographic position index is a terrain-based index that is used to identify the position of a location in the landscape relative to its surroundings. The index is used to measure the local terrain variability and the position of a location with respect to its surrounding area.
Horizontal distance to nearest stream	The horizontal distance to the nearest stream is used in flood susceptibility modeling to describe the distance between a given point in the landscape and the nearest stream or river. This distance is typically measured in meters or feet and is used as an explanatory variable in flood susceptibility modeling to estimate the likelihood of flooding in a given area.

With respect to model evaluation and consistency assessment, researchers used a consistency index and consistency ratio (CR)—two metrics commonly used to evaluate the consistency of the results—to calibrate and optimize the model and to check its validity. Typically, AHP results are considered consistent when the CR value is less than 0.1. The analysis showed a CR of 0.043, which was well within the consistent range of less than 0.1. Researchers calibrated multiple times to regenerate different scenarios and reach a consistent outcome based on pairwise comparisons of the explanatory variables.

Flood Susceptibility Map

Based on the pairwise comparisons and the consistency ratio evaluation, researchers produced weights for each explanatory variable that indicate how they contribute to overall flood susceptibility. Researchers used these weights to generate the overall flood susceptibility map for Texas (see Figure 15). The final flood susceptibility map indicates the level of flood susceptibility with a 30-meter resolution. All pixels of flood susceptibility were classified into five classifications:

- Very low (less than 1.001).
- Low (1.001–1.886).
- Moderate (1.886–2.669).
- High (2.669–3.346).
- Very high (3.346–5).

The output from the Flood Susceptibility Model indicates that more than 85 percent of the pixels in Texas are situated in moderate to very high flood-susceptible areas (moderate is 72.38 percent, high is 9.58 percent, and very high is 3.36 percent). Most of the high susceptibility regions are in the coastal regions of southeast Texas. In contrast, most of the low susceptibility regions (14.68 percent) are in the central Texas region (see Figure 15).

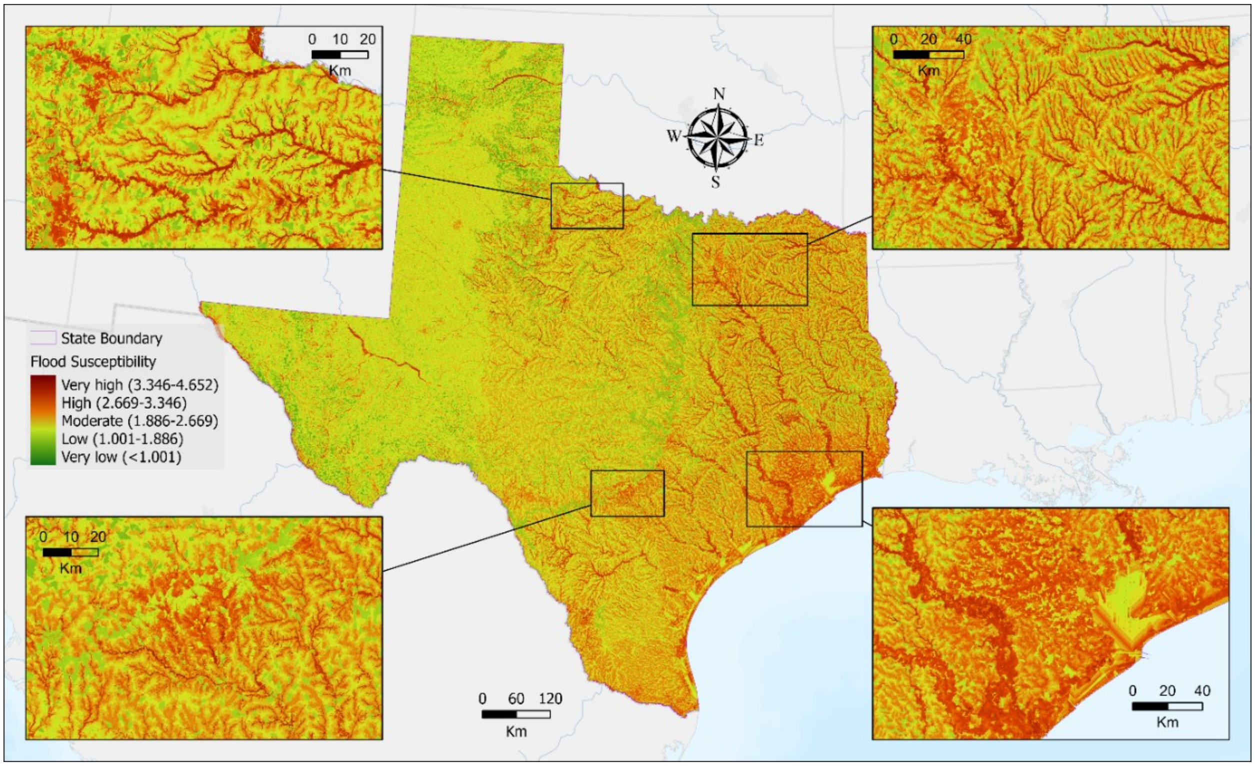


Figure 15. Flood Susceptibility Map for Texas Derived Using MCDA.

ECONOMIC ANALYSIS MODEL

The Economic Analysis Model calculates the benefits, costs, and economic impacts of truck platooning and automation. The benefit-cost analysis (BCA) determines the impacts of truck platooning and autonomous trucks on selected corridors. This first step in the economic analysis considers infrastructure costs to TxDOT, safety and environmental benefits to society, operational benefits to truck companies, and freight benefits to businesses. Thus, the results of the analysis are presented as costs to TxDOT compared to benefits to businesses, consumers, and society. The cost and benefit components in the analysis include the following:

- Costs:
  - Increased pavement costs.
  - Increased bridge costs.
- Safety benefits:
  - Decreased crashes.
- Environmental benefits:
  - Decreased emissions.
- Operational benefits:
  - Decreased driver costs.
  - Decreased fuel costs.
  - Decreased break costs.

    - Increased automation cost (negative impact).
- Freight benefits:
    - Decreased commodity time costs.
    - Decreased just-in-time costs.
    - Decreased perishability costs.

The second step of the economic analysis estimates the economic impacts using multipliers from the input-output model in the IMPLAN software. The operational cost savings calculated in the BCA represent the out-of-pocket savings to the trucking industry. These savings will be reinvested in the industry, distributed to shareholders and employees, and/or passed on to the customers and consumers. The economic impact analysis shows the effects of these additional dollars on the Texas economy. The estimated results include economic output, employment, and labor income (wages). The economic impacts are calculated using a combination of operations benefits and freight cost savings.

The economic analysis compares a baseline scenario representing the status quo to a project scenario with truck platooning and autonomous trucks. Each component cost in the truck platooning/autonomous truck scenario is subtracted from the baseline scenario to generate the project costs and benefits. The selected scenarios account for changes in the number of human drivers required, technologies, and roadway conditions and volumes over the analysis period. The baseline scenario assumes two individual drivers for the truck pair, no platooning, minimal fuel savings, and drivers subjected to current hours-of-service (HOS) regulations. The truck platooning/autonomous truck scenario reduces the number of human drivers, which decreases HOS and driver costs but may increase costs associated with other components, such as pavement and bridge costs.

Results will show that more benefits accrue with added driver HOS break requirements, which extend the amount of time required to travel the corridor. Therefore, shorter corridors will accrue fewer benefits. A more thorough explanation of the Economic Analysis Model is included in Appendix B of this report.

EXAMPLE TYPES OF SCENARIOS ADDRESSED BY USE OF THE TOOL

The research team has crafted several scenarios to assess and demonstrate the benefits of the proposed/partially developed framework and tool. These scenarios are intended to exhibit the potential benefits and applications of the modeling framework to specific planning problems being faced by TxDOT currently and in the coming years. These scenarios range from considering new infrastructure development and technological innovations to hazard response and consequences on mobility and accessibility after a hazardous event. Social and economic scenarios are additionally emphasized that will help demonstrate how the susceptibility assessment through this framework would benefit the ongoing and forecasted growth potential of Texas.

Scenario 1: New Technological Innovations Impacts

Transportation modes have seen substantial technological innovations in the past decade. Although the freight industry and relevant innovations are not always highlighted in the popular media, researchers have seen numerous innovations and significant automation of many processes within the freight industry. With platooning and other technological innovations, the capacity of freight traffic and other freight-related activities on existing roadways are expected to increase significantly. The bridges, roadways, and other transportation infrastructure features of the current transportation system in Texas are not necessarily designed or maintained at a level to accommodate such an increased daily and annual traffic load. Additionally, approximately 40 percent of the bridges in Texas were built more than 50 years ago. Therefore, one of the outcomes of this tool and framework is examining whether the existing infrastructure can accommodate the growing freight traffic levels stemming from technological innovations. Because newer technologies need service facilities beyond the traditional support centers, this analysis will allow for examination of that issue. For example, additional load-bearing calculations, charging stations, strengthening or replacing certain pavements, and/or addition of freight transfer hubs at strategic locations will be required in addition to standard improvements to the network. The research team included those types of calculations in this scenario type in order to examine the outcomes and future demands induced by new technologies.

Scenario 2: Impact on Future Growth Potential

As more businesses move to Texas and continue the economic development trend and potential, it is crucial to provide uninterrupted access and connection to the market from industry sites. The most recent (2023) Texas Freight Mobility Plan, Texas Delivers 2050, points out the magnitude of this challenge. It states the following:

> In 2019, Texas contributed about $1.9 trillion or 8.8 percent of the U.S. total gross domestic product. Texas continues to lead the nation in economic growth and remains one of the strongest and most diverse economies in the nation. In 2019, the state of Texas had a population of 29 million and an annual population growth of 1.5 percent from 2014 to 2019. Along with a growing population comes a growing demand for goods and an increased need for a clear freight mobility vision and plan.
>
> Freight tonnage moving to or from Texas has grown nearly 29 percent between 2014 and 2019 from 2.8 billion tons to about 3.7 billion tons. This amounts to 130 tons per resident and 274 tons per job. The average freight tonnage per person coming to or from Texas has grown from 109 tons per person to 130 tons per person, with a five-year average of 117 tons per person. (*83*)

Economic and industrial activities and population growth will require more and more infrastructure to support continued growth. The outcome of the framework and modeling will be able to identify susceptibilities in existing infrastructure along with the location and level of susceptibility and to examine how added infrastructure will impact what currently exists. This, in turn, will contribute to system expansion by enabling TxDOT to prioritize target areas indicated by the analysis for improvements to ensure higher capacity and continuous freight movement.

Scenario 3: New Distribution Centers and Transfer Hubs

With the growing freight (truck) traffic and newer technologies, demand for new distribution centers and transfer hubs will also increase. Additional service facilities will also be required for newer trucks and freights. As a result, both truck average daily traffic (ADT) and overall AADT would increase. Tool users will be able to evaluate whether the existing infrastructure can accommodate expected growth. The outcome will also include the areas and infrastructure most (or least) likely to experience high expected growth levels and thus need immediate (or long-term) attention, such as those areas around/near existing or new freight generators. This need is especially acute given the growth numbers in general freight cited in the Texas Freight Mobility Plan and referenced above under Scenario 2.

Scenario 4: Overweight Loads Analysis

The analysis tool will be able to evaluate the impacts of additional overweight loads on corridor pavements and bridges and their network effects. Freight loadings of various excess weight levels and their impacts can be examined by segment and at specified points along identified oversize and overweight routes or within specified areas such as TxDOT districts or other spatial regions. Pavement types and bridge ratings within the tool can be used in the early stages of route planning to choose or recommend routes with less potential damage or routes that would balance damage to infrastructure over a longer period. Additionally, use of prepared data from other sources, such as recent Texas Department of Motor Vehicles oversize and overweight permits that TTI has recently compiled for TxDOT's Transportation Planning and Programming Division under the freight planning interagency contract, can be used to inform future decision-making and other planning activities. TTI's analysis shows medium- and longer-term summations of where oversize and overweight loads are traveling.

Scenario 5: Disaster Preparedness and Response

It is often reported that following a disaster event or hazard, the response team faces obstacles in reaching the affected area. Preparation, evacuation, and recovery phases are more chaotic when considering the associated problems of accommodating personal travel and reaching affected areas with supplies before, during, and after an event. Roads and bridges are often exposed to flooding in natural disasters. Without a predetermined, least-vulnerable, and optimized route, evacuation in the pre-disaster period and response during and after the disaster become problematic. As researchers examine the susceptibility level of the physical infrastructure, the tool could also be used to select and recommend routes for optimized response/recovery operations based on possible scenarios and observation data. An examination of infrastructure susceptibilities is also recommended if any specific road segment or bridge is under water or unusable for a prolonged period. Selection of priority routes will include alternative freight routes by optimizing the load-bearing capacity of the probable road segments and bridges while minimizing the traveling distance (and associated cost) for the operators. The use of elements of this tool could be incorporated into roadway and infrastructure resilience planning efforts by the FHWA and other national-level agencies. The tool could also be used to inform future updates of the TxDOT Statewide Resiliency Plan (SRP), the first of which was under development while this project was underway. The TxDOT SRP is expected to be completed in late 2024 (*84*).

Scenario 6: Alternative Routes

If any road segments or bridges are affected and unusable for a prolonged period, it is important to have an alternative route selected that can carry the additional freight traffic. Alternative freight routes can be selected in the tool by optimizing the load-bearing capacity of the potential road segments and bridges while minimizing the traveling distance (and cost) for the operators.

Scenario 7: Social Impacts

It is important to identify the hotspots where vulnerable and exposed road segments and bridges are located. Geospatial modeling and analysis can identify those locations. Socioeconomic data from American Community Survey (ACS) five-year estimates will be incorporated to examine whether any clusters of specific communities are more exposed to disasters or infrastructure failure compared to their peers and other areas statewide. This will enable TxDOT planners to prioritize project locations based on social aspects in addition to the structural and spatial demands. It is also beneficial for local government administrators because they can sort out their priorities in allocating future budgets.

Scenario 8: Indirect Effects

Identification of locations of bridge and roadway susceptibility by the tool is also important because there can be potential cascading effects on building footprints in and around the physical infrastructure elements of the transportation system. While adjacent lands are not directly part of the transportation system, transportation infrastructure interacts with adjoining land, affecting its use, value, and development capability. The changes required to accommodate new trucking technologies may change roadway design features and secondarily have indirect effects upon land values both near and a distance from the roadway. For example, understanding the location and design needs of transfer hubs and/or charging stations for trucks will have effects that should be incorporated into long-term transportation planning.

Scenario 9: Economic Impacts

The economic benefits resulting from changes in operation will also be assessed. This analysis will include a BCA that extends the cost for infrastructure improvement or construction as well as maintenance projects. The economic analysis functions will also account for the benefits of the improvements in terms of enhanced safety, environmental protection, optimized operations, improved mobility, connectivity, and accessibility. Additionally, the economic assessment can consider the number of new employment opportunities generated by changed designs, new operations, and new challenges associated with future projects.

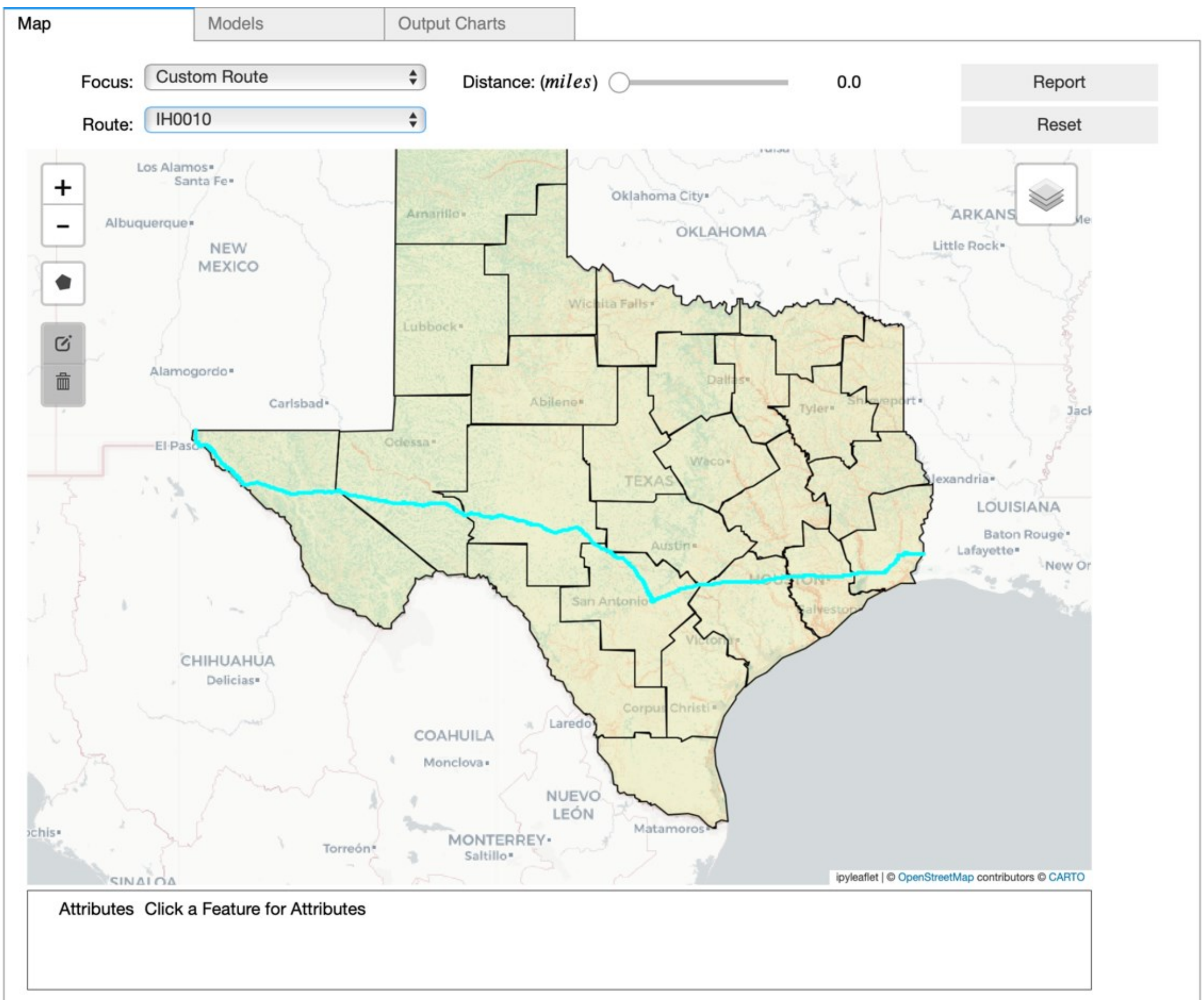
CHAPTER 4. FAST WEB TOOL INTERFACE AND FEATURES

This chapter discusses the interface, data used, and coupling and optimizing of components within the Fast Web Tool.

FAST WEB TOOL INTERFACE

Map Tab

Several controls on the Map tab were streamlined to facilitate scenario development. After the response to feedback that the research team received in a previous meeting with TxDOT officials, users can now select just a freight route/corridor as a study area rather than having to select all roads on the Texas Highway Freight Network within a given distance of the route. Figure 16 shows changes in the user interface and functionality.



Note: The background image represents the *Current Climate* scenario in the flood susceptibility submodel. Functionality to select only a route/corridor for study area is highlighted.

Figure 16. Map Tab User Interface in the Fast Web Tool.

Models Tab

Decisions regarding parameters in the Pavement Condition Model are largely dependent on database values within each segment, but the user can select whether the scenario has *Human-Controlled Traffic* with a standard wheel wander of approximately 10 inches or *Automated Traffic*, where precision-guided or automated trucks along freight routes are modeled with no wheel wander. This choice will appear under the *Traffic Composition* drop-down menu (see Figure 17).

The output of the Flood Susceptibility Model is a continuous layer throughout Texas with values spaced at 30 meters (see Figure 15 and Figure 17). The user has the choice between flood susceptibility with current precipitation and temperature values or forecasted precipitation and temperature values from two shared socioeconomic paths (SSPs) from the 2021 *Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report* (*85*), specifically SSP1 Sustainability and SSP3 Regional Rivalry for the years 2041–2060.

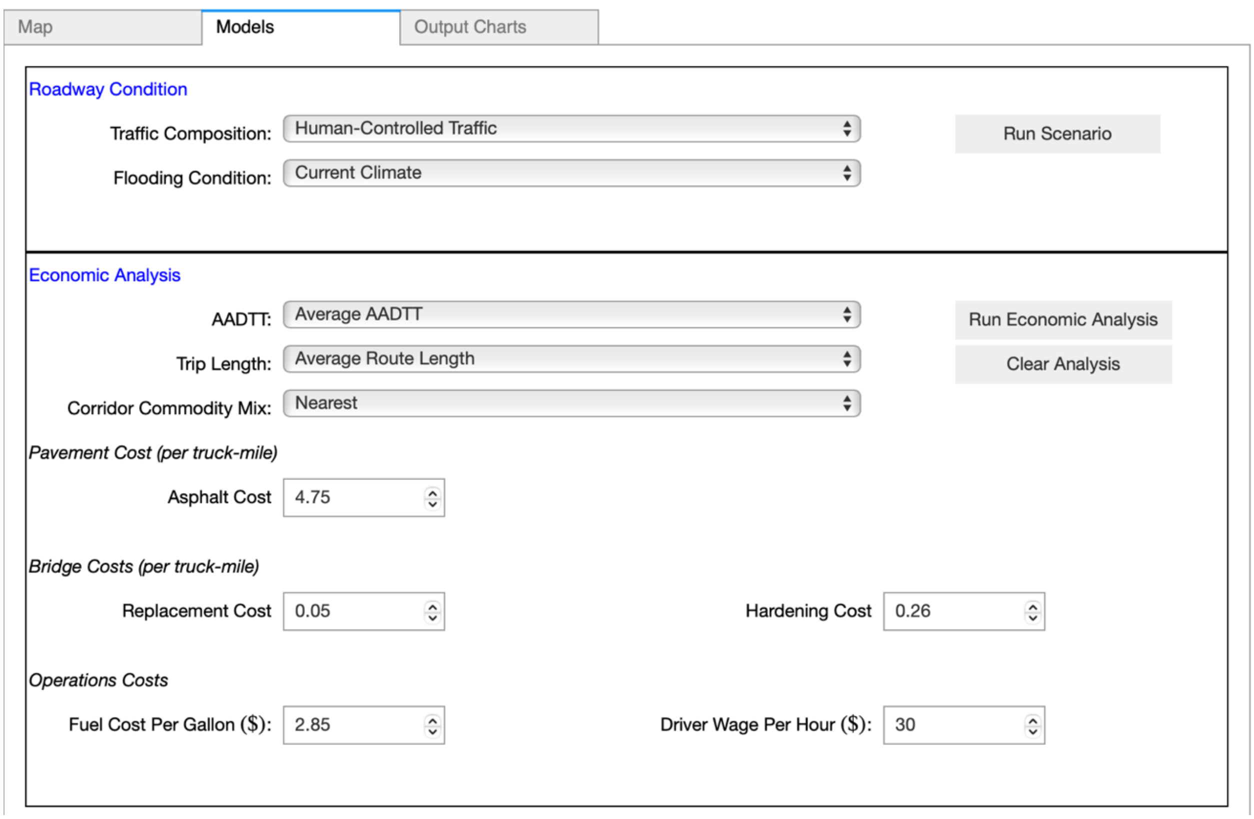


Figure 17. Models Tab User Interface in the Fast Web Tool.

DATA IN THE FAST WEB TOOL

Creation of a Data-Rich Texas Highway Freight Network Dataset

The Texas Highway Freight Network (THFN) dataset, which is publicly available on the TxDOT Open Data Portal (*75*), does not include many descriptive columns of information per segment (less than 10); among the columns included, several are used for identifying the highway and route name. Efforts were made to match the route names (RT_NAME) in the abbreviated THFN dataset to the route names (RIA_RTE_ID) in the Texas Roadway Inventory dataset (*86*)which has many descriptive columns of information per individual pavement segment. Once matches were identified, they were saved as a separate dataset. Then, all roadways within the larger Texas Roadway Inventory dataset were screened based on a functional classification reflecting all roads smaller than principal arterials. These two datasets were next merged in a geometric union. Programmers then visually added local roads to the dataset and eliminated road segments that were added inadvertently and not present in the THFN dataset.

Graph-Based Corrections in Major Metropolitan Areas

The data-rich THFN dataset contains shapefile information for the appropriate roadways for freight analysis but currently has some data-formatting features that are not conducive to accurate graph-based theoretical representation. In many cases, intersections are represented within the THFN files only as two lines that simply cross without a specific node or vertex location included at the intersection. To give appropriate background information, within a graph-based model, a vertex is simply a point on a digital line feature (i.e., a road) that divides two or more significant pieces of a digital line feature. By evaluating the degrees of freedom of all nodes in the dataset, an analyst can quickly identify intersections where there should be nodes with high degrees of freedom (a rating of three or four) instead of low (a rating of two) degrees of freedom or no node at all. Efforts to completely automate this approach are further challenged by grade-separated roadway intersections that are not meant to connect at that single location and therefore should, in fact, be represented as two individual line segments that cross with no node present.

The other formatting feature that must be addressed within a graph-based theoretical model is when ramps join a larger road, and the ramp and road do not join at a distinct intersection node/vertex. A keen analyst that uses the degrees of freedom of the nodes in the network can spot this anomaly and correct it—just as they can catch the intersection errors. Manually correcting the entire dataset would require an inordinate amount of work. Researchers have endeavored to correct these data features in districts that correspond to the five largest metropolitan areas of Houston, San Antonio, Dallas, Austin, and Fort Worth (*87*). To date, the districts that contain Houston, Dallas, and Austin are corrected and optimized for graphical theoretical analysis.

COUPLING AND OPTIMIZING COMPONENTS IN THE FAST WEB TOOL

Coupling the Pavement Condition Model with the Fast Web Tool

Pavement condition models were originally developed in the Microsoft Windows® operating system using software programs and utilities (WinJULEA, Calculix, and GMSH) that were either only developed for Windows or were outdated versions that were unavailable for other operating systems. These tools/utilities are highly specialized, and no easy alternatives are available. This introduces obstacles to using the Fast Web Tool in a web server/cloud environment, which is often based on Linux/Unix. With adaptation, these obstacles were overcome, and the software is now able to operate in the MacOS®/Linux/Unix operating systems and Microsoft Windows®. With these obstacles overcome, researchers have now implemented the pavement condition models to run seamlessly within the Fast Web Tool.

Coupling the Flood Susceptibility Model with the Fast Web Tool

In Technical Memorandum 3, researchers produced flood susceptibility mapping products using MCDA to standardize relevant parameters and the AHP to assign weights from multiple experts. These outcomes were then integrated to create a composite score of flood susceptibility (one through five). Researchers derived layers that correspond to precipitation and temperature for three different scenarios: baseline (present temperature and precipitation), and two forecast SSPs that are featured in the *Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report* (*85*): SSP1 Sustainability and SSP3 Regional Rivalry (*85*). This analysis was conducted for the entire state of Texas where values are spaced every 30 meters. The baseline scenario has been included in the interface as a background image in the Fast Web Tool (see Figure 17). Values have been fused to the THFN, informing of the overall flood susceptibility of bridges and pavements within the network. This is accomplished by creating a buffer area 30 meters from the road, evaluating all flooding susceptibilities within that buffer, and associating the flood susceptibility that is closest to a given segment's midpoint.

Coupling the Bridge Susceptibility Model with the Fast Web Tool

Structural bridge susceptibility and scour criteria were implemented as part of the data retrieval procedure. In this procedure, the bridge segments—retrieved as points—were given the same geometries as roads (see Figure 18) based on structural information from TxDOT's Bridges dataset (*76*).Then, operations were made to create bridge prioritization metrics based on previous findings from (*67*) and (*88*).These metrics were weighted and used to implement structural bridge susceptibility into each bridge record.

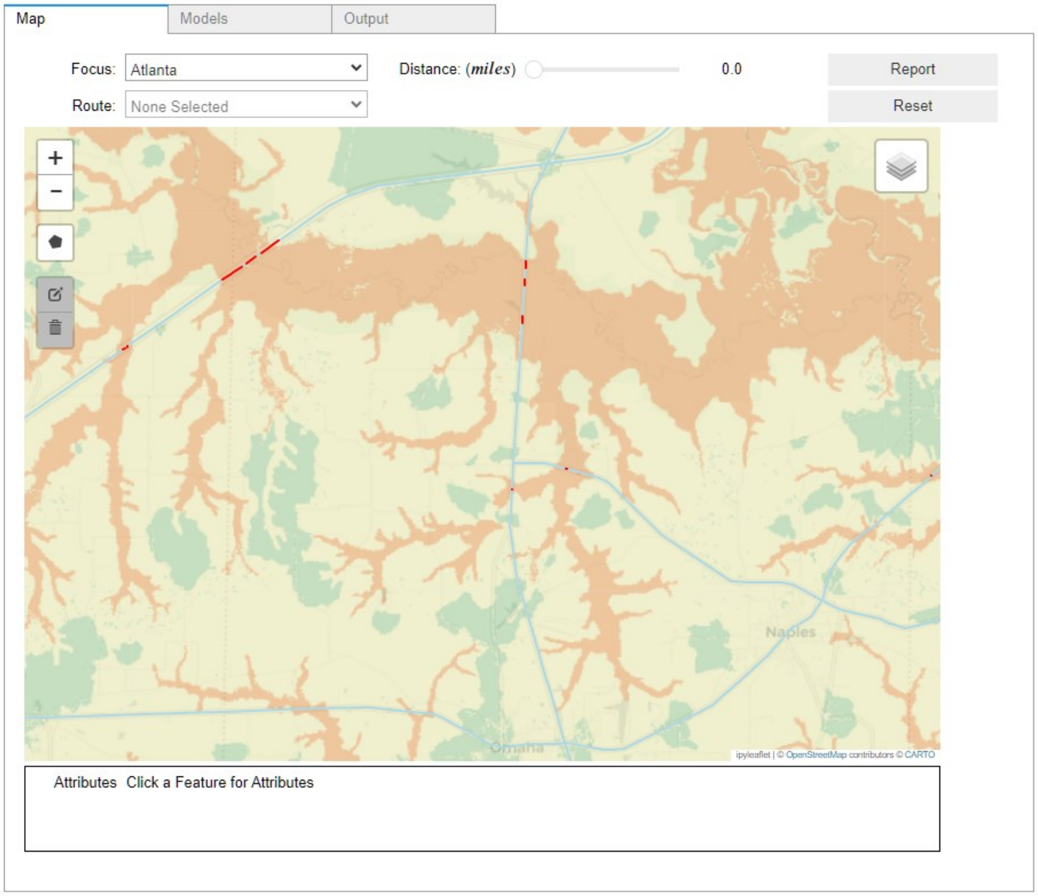
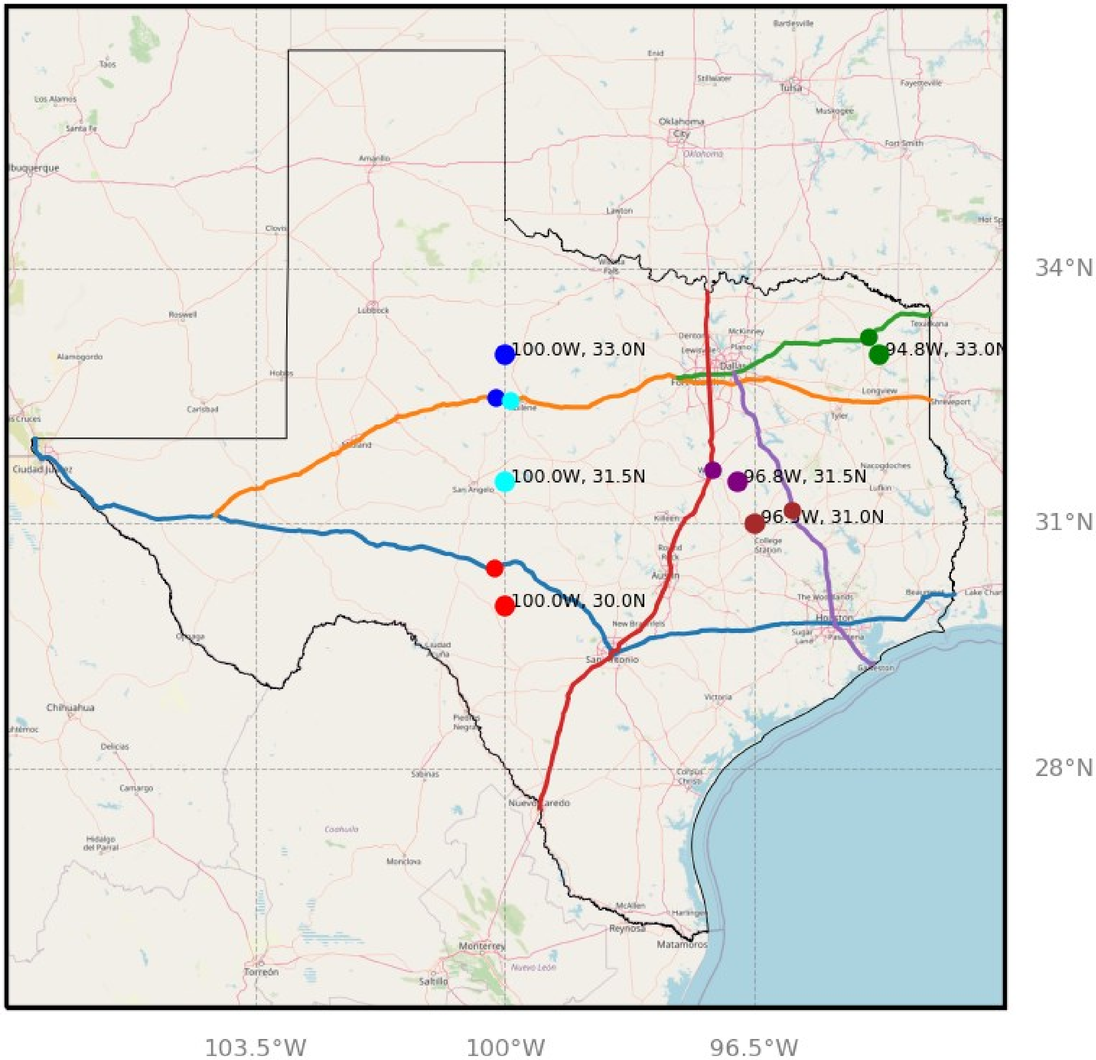


Figure 18. Bridge Segments Incorporated into the Texas Highway Freight Network near Mount Pleasant in the TxDOT Atlanta District.

Coupling the Economic Analysis Model with the Fast Web Tool

Unlike the Pavement Condition Model, the Economic Analysis Model depends on several input parameters from the user although default values initially populate the user interface (see Figure 17). Multiple additional parameters are derived directly from the data within the tool. In particular, the commodity mix is imported from the corridor nearest the centroid of the study area by default. Figure 19 shows an example of the corridor–study area relationships. To describe the process, the centroid of the study area is found and then matched with the closest corridor using a method similar to the Environmental Systems Research Institute, Inc. (Esri), Query Point and Distance tool described at https://pro.arcgis.com/en/pro-app/latest/sdk/api-reference/topic75804.html.



Note: Locations are theoretical centroids for a given study area. Colors are used only to differentiate between example locations on this statewide map.

Figure 19. Example Corridor–Study Area Relationships.

Optimizing Weather Data Retrieval for the Fast Web Tool

Weather data are essential for accurate Pavement Condition Models. These data are currently retrieved from the Open-Meteo.com weather application programming interface (*89*)—a free service (for nonprofit ventures) that provides 80 years of historical weather variables for any location in the world. Although this service is free for light usage, the service does reserve the right to start charging for access in heavy-data-use scenarios. Researchers opted to make this data retrieval less intensive by constraining both the space where the data are located and the time span.

Originally, daily temperature and precipitation data were retrieved from this service for each pavement segment for up to 20 years. Researchers created a system in which weather data are retrieved for each half degree of coverage within the user's study area and the state of Texas (see Figure 20).

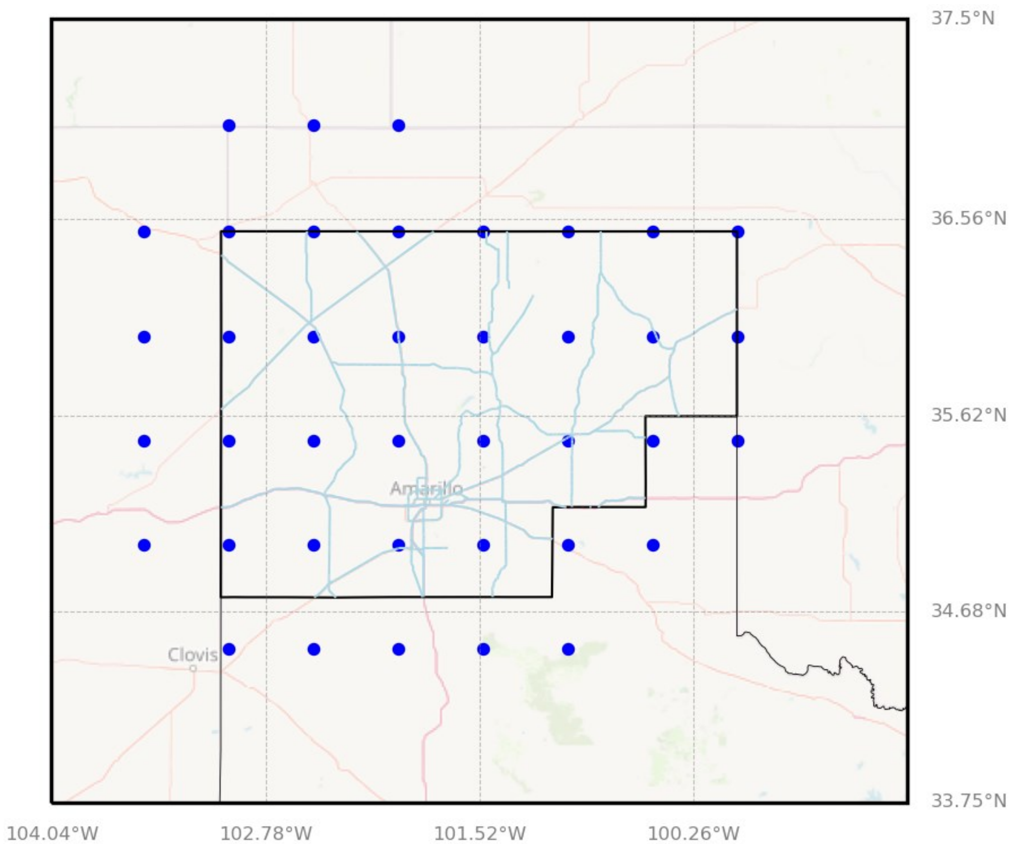


Figure 20. Example Weather Data Retrieval Locations in the TxDOT Amarillo District.

Once the centroid of a pavement segment is located, then data are retrieved for the four nearest points, and an inverse distance weighted interpolation is performed so that each segment has a temperature and precipitation value that is representative of that unique location. Furthermore, daily temperature and precipitation data for multiple years at each location are stored in the data folder for the Fast Web Tool. This allows temperature and precipitation data to be obtained locally for queries that have a time span up to the number of years stored. When a query is made at a location for more years than is available locally, then those data are obtained from the service and concatenated within the local data folder for the Fast Web Tool. Therefore, each scenario further optimizes the weather data retrieval for speed and efficiency.

In initial tool development attempts, the time domain over which the Pavement Condition Models were run was the time between the date open to traffic (DOTT) field in the Texas Roadway Inventory dataset (*86*) and the current date, as a surrogate for the latest pavement maintenance date information. After conferring with the TxDOT panel and data team, researchers discovered that this field is not accurate and that alternative strategies should be pursued. Therefore, researchers opted to use the current date for the dataset during development

(2021) as the maintenance date and to give the user the ability to hindcast and forecast traffic some number of years before and after that date. This allows for the standardization of data stored in each half degree and makes it possible for researchers to constrain data usage in time and space.

Analyzing the Network within the Fast Web Tool

Network analysis of the system was conducted using methods such as those proposed by TxDOT Research Project Report 0-6984 (*67*) in which connectivity is assessed by *removing* bridges or certain classifications of bridges from the network according to their condition (from worst to best). Connectivity is measured as a ratio of the *giant component*—the largest network hub after a series of bridge removals—to the original network size. This enhanced analysis capability allows researchers to now assess the flooding susceptibility of the bridges as well as their condition. The network analysis submodel is run for the study area after the pavement condition and flood susceptibility submodels have produced results.

CHAPTER 5. END-USER TOOL DEVELOPMENT

The research team determined, based on input from the stakeholder end-user workshop, that the web-based fast analysis tool for planning and strategy scenario evaluations should be in the form of an interactive dashboard where users can both create scenarios and view the consequences of implementing those scenarios through connectivity/performance/scaled metrics on transportation infrastructure. This interactive dashboard is organized as a framework that has three major components: platform, user interface, and stakeholders. Additional information on the use of the Fast Web Tool and its various functions is available in TxDOT Report 0-7124-P1, *Development of and User Manual for the Fast Web Tool to Evaluate Infrastructure and Planning Impacts of Changes in Truck Traffic and Technologies*, as described near the end of this chapter.

The platform component is comprised of the server operating system, programming language(s), and application programming interfaces used in delivering the user interface to stakeholders. The user interface is composed of visuals in the form of maps, charts, plots, and widgets in the form of slide bars, check boxes, labels, drop-down boxes, and buttons that the user will use to interact with submodels and mapping components. The stakeholder component is an ever-present concern when designing the other two components and therefore has no section explicitly devoted to it.

TOOL PLATFORM SELECTION

The first step toward making this interactive dashboard was to focus on the selection of a platform. The research team conducted a search for similar platforms used by other projects, evaluated their strengths and weaknesses, and chose one that best fit the stakeholders' needs. Four potential existing platform options were considered:

- JupyterHub (*90*).
- ArcGIS Dashboard (*91*).
- Pyodide (*92*).
- Flask (*93*).

Each of these was evaluated considering the following attributes:

- Ease of use.
- Ease of design.
- Ease of implementation.
- Operating system.
- Security (code not editable).
- Ease of maintenance.
- Level of interactivity.
- Ease of access by mobile device.

- Third-party code.
- Licensing requirements.

From all these considerations, the research team considered JupyterHub the most viable solution and used it in the tool. JupyterHub can accommodate two tiers (presentation and server-side logic) of the three-tier web application. Given that Python, one of the languages that powers JupyterHub, can make calls to database servers, it is easy to implement the third tier (storage) as a database that the logic layer can call and present. Furthermore, the use of Python introduces many modules that can accommodate the presentation of charts, plots, graphs, and maps. The most critical factor in this decision was the ability to import third-party libraries and transparency. For these two final concerns, JupyterHub excels and has established methods. Furthermore, JupyterHub is open source, and therefore costs are just with deployment and development rather than requiring any licensing going forward.

PLATFORM DATA

To consider the geomorphic impacts on infrastructure, data are needed that represent infrastructure, natural processes, and demographic data. For all datasets, researchers prefer to source them from government agencies (*94*, *95*, *96*, *97*, *98*, *99*) or academic institutions (*100*) (in cooperation with government agencies).

Data Types

For infrastructure, vector datasets representing freight routes, roadways (*94*), and point geometries representing bridges on the highway system are needed (*95*). Bridges are associated by proximity to linear segments within roadways/freight traveling over each one. Each linear segment in the roadways/freight features contains scores assessed from the three contexts of infrastructure susceptibility.

For natural processes, data are discussed in the following order:

1. Hydrologic.
2. Meteorologic.
3. Topography.
4. Soil types/composition.

The hydrologic data are U.S. Geological Survey (USGS) stream gage heights (*96*), which are largely obtained from bridge locations. For meteorology, PRISM (*100*) data are ideal for examining intensity and location of rainfall throughout Texas. For topography, USGS 3D Elevation Program (3DEP) digital elevation models (*97*) (DEMs) and National Hydrography Dataset (NHD) watershed boundaries (*98*) are necessary. Finally, soil types/composition is obtained from the SSURGO database (*99*), where hydraulic conductivity/infiltration risk is assessed from soil type. For demographic data, various demographic factors obtained from the

ACS (*101*) are used and aggregated at the tract level to assess social susceptibility in populated areas.

Data Usage and Logistics

The datasets used in the model have different sizes with respect to required storage capacity and downloading logistics (from megabytes to gigabytes) and are updated at different time frequencies. These two attributes of data introduce compromise when developers seek to maximize the speed and responsiveness of the interface and keep up with changes in the data. Figure 21 illustrates this compromise.

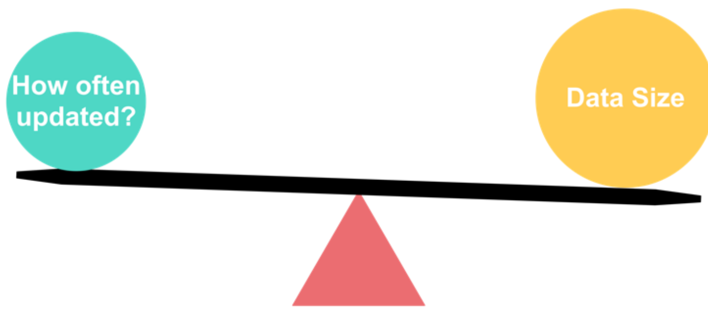


Figure 21. Illustration of Compromise Related to Data Size versus Update Frequency.

Data size and update frequency determine which approach should be used to update the data. For datasets that are typically small in size and constantly updated, the best approach would be to not keep the data locally and download the data from the source upon each use of the software—to keep up with the latest data. Typically, most geospatial data are stored locally in open-source formats, such as shapefiles (*102*) and geopackages (*103*), or proprietary formats, such as Esri Geodatabase (*104*).

In terms of data update periods, the research team found the following:

- The TxDOT Roadways dataset is updated annually (*94*) and has been shown to take a long time to load.
- The TxDOT Bridges dataset is updated often (*95*) and has been shown to take a short amount of time to load.
- The USGS stream gages data (*96*) are updated every 15 minutes and have statistics recorded for longer time periods. The USGS stream gages data are projected to have similar properties to the TxDOT Bridges dataset, and preliminary work has shown this to be the case.
- The USGS 3DEP DEMs (*97*) are not updated often and, given that the data are raster data, would take longer to load.
- The NHD Watershed Boundaries dataset is linked to topography and modeled precipitation to establish flowlines and drainage divides, but it is ambiguous how often the data are updated. Some sources (*105*) indicate that this national dataset is updated

four times a year, but the California website description of this dataset questions this update rate.
- The USDA Soil Survey Geographic Database is updated once per year on October 1 (*99*), but the data are often in raster format or in the form of complicated polygons—which implies a large dataset size.
- PRISM climate data are in the form of raster precipitation, which implies that the data are large. However, statistics for longer time periods can be obtained as well, such as 1 month, 6 months, annual, and annual normal for a period of 30 years (*100*).

Given the compromise described between update temporality and data size/loading times, the research team made decisions along two potential choices: live data and local data. Live data are retrieved in real time from other data sources in the form of a data interchange language, such as JavaScript Object Notation (JSON) (*106*). Specifically, GeoJSON (*107*) is used to download geospatial data, such as TxDOT bridge information, and to select roadways in Fast Web Tool interface maps. The other choice is locally stored data, where the spatial data are often put into a local database server, such as Structured Query Language, and the interface would make spatial and attribute queries of that periodically updated and stored data on demand as needed. This database server could be local and easily accessible to the server that hosts the tool interface.

Between these two choices is a hybrid data update strategy where data would be stored locally and use an operating system command on the server, such as the cron command-line utility (*108*), that can execute a shell script to update the data on a regular basis over a period of months or years, to match the update frequency of the data. All data updated with the hybrid approach also have the time period of the planned update mentioned afterward. With these considerations, the recommended data sources/update cycles used in the tool were determined to be:

- TxDOT Roadways, updated hybrid annually.
- TxDOT Bridges, updated live.
- USGS stream gages, updated live.
- USGS 3DEP DEMs, updated locally.
- National Hydrography Dataset (NHD) Watershed Boundary dataset, updated hybrid annually.
- USDA Soil Survey Geographic Database (SSURGO Soil Database), updated hybrid annually.
- PRISM climate data—6 months normally but updated hybrid semi-annually.
- Census data attributes, updated live.

MODEL INTEGRATION

Pavement condition models are conducted based on the user's selection of routes on the THFN. The Web Tool implements the models that simulate top-down pavement crack initiation and pavement plastic deformation (rutting) for a range of factors including traffic composition, pavement material properties, traffic growth, climate, and a model for landscape-level flood susceptibility. Also implemented are different scenarios for each of the factors impacting pavement conditions and flood susceptibility.

Scenario Input Modes

Traffic Composition

Traffic composition modes vary by the proportion of traffic from vehicles belonging to certain FHWA vehicle classes. The 13 standard classes of vehicles vary by the number of tires. Axles with lower classes refer to simpler vehicles with two axles, and higher classes refer to large freight vehicles with three or more axles generally used by FHWA (*109*). An additional class (Class 14) representing platooned and/or automated trucks was used to estimate various levels of new technology trucks with differing parameters within the model. Varying proportions of traffic from these classes, researchers plan to have three general traffic composition scenarios:

1. Normal traffic.
2. Freight-dominated traffic (more traffic from FHWA Classes 5–13).
3. Automated freight-dominated traffic, which is traffic where freight is dominated by automated traffic (less traffic from Classes 5–13 and more traffic from the new truck technology Class 14).

Parameter Values Used in the Pavement Models

Values for the other parameters used in pavement models can be determined based on the three different scenarios:

- **As is:** The values will largely be driven by values within the TxDOT Roadways dataset. (https://www.txdot.gov/data-maps/roadway-inventory.html) and by values that are aggregated at a local or regional scale and taken from other database sources—such as average daily temperature aggregated per annum. The values are not allowed to be adjusted by the user.
- **Expert determined:** The parameter values will consist of ensemble values that are determined by experts to fit a given condition.
- **User defined:** The parameter values in expert-determined scenarios can be modified by the user. For example, there are inputs for additional temperature (± degrees Fahrenheit per day averaged per annum) and traffic growth rate (± percentage of traffic per day).

Flooding Susceptibility

Flood susceptibility is realized as a layer that reflects the rated level of susceptibility—in a scale from one to five (one is very low, and five is very high)—at a 30-meter spatial resolution with coverage for the entire state of Texas. Table 4 shows the explanatory variables.

Table 4. Explanatory Variables Used for Landscape-Level Flood Susceptibility Modeling.

Name	Description	Spatial Resolution
Slope	The slope was calculated as the rate of change of elevation for each pixel, expressed as a percentage. Researchers used NED DEM data to calculate the slope for Texas.	30 m
Precipitation	Average annual total precipitation, 30-year normal (1991–2020)	800 m (resampled to 30 m)
Temperature	Average annual daily mean temperature, 30-year normal (1991–2020)	800 m (resampled to 30 m)
Geomorphic description	The geomorphic description of a map unit helps identify a discrete land surface feature or assemblage of features in an area.	30 m
Flood frequency	Flood frequency classes represent different ranges of the return period of floods. The SSURGO flood frequency data give the dominant flood frequency class for a map unit based on its major soil components.	30 m
Taxonomic suborder	To identify flood-prone areas, the *taxsubgrp* column in the component table of SSURGO can be used to determine the taxonomy information for the major soil component of each map unit. Most flood-prone areas can be delineated by selecting map units that contain the *fluv* character in their *taxsubgrp* attribute field.	30 m
Imperviousness	Imperviousness describes the proportion of the land surface covered by impermeable materials that prevent water from infiltrating into the soil, increasing the amount of runoff and reducing the natural capacity of the landscape to absorb and store water. Areas with high levels of imperviousness are more susceptible to flooding because the increased runoff can overwhelm drainage systems and cause water to accumulate on the surface. Researchers used the NLCD dataset from 2020 and classified the level of imperviousness based on the categories of developed lands based on density.	30 m
Flow accumulation	Flow accumulation is the process of calculating the amount of upstream drainage area that contributes to the flow at a given point in a river network. Researchers used NED-3DEP DEM data to calculate flow accumulation in Texas.	30 m
Topographic wetness index (TWI)	The TWI is used to identify areas of the landscape that are likely to be wet or dry based on their position in relation to other areas. Researchers used NED-3DEP DEM data to calculate the TWI in Texas.	30 m

Name	Description	Spatial Resolution
Topographic position index (TPI)	The TPI is a terrain-based index that is used to identify the position of a location in the landscape relative to its surroundings. The TPI was calculated from NED-3DEP DEM data and is used to measure the local terrain variability and the position of a location with respect to its surrounding area.	30 m
Horizontal distance to nearest stream	The horizontal distance to the nearest stream is used in flood susceptibility modeling to describe the distance between a given point in the landscape and the nearest stream or river. This distance is typically measured in meters or feet and is used as an explanatory variable in flood susceptibility modeling to estimate the likelihood of flooding in a given area.	30 m

Web Tool Input Modes

Data input for the models take place in *three different modes*:

- **Database driven:** This mode considers only the as-is parameter value scenario and the normal traffic composition scenario and allows the user to select one from two scenarios of flood susceptibility (no flooding and business as usual [BAU]).
- **Scenario driven:** This mode considers the expert-determined parameter values and allows the user to select one from three traffic composition scenarios (normal, freight dominated, and automated freight dominated) and one from five scenarios of flood susceptibility (no flooding, BAU, SSP1, SSP2, and SSP5).
- **User driven (customized scenarios):** This mode allows the user to select the pavement model parameter values (e.g., parameter 1, parameter 2, …, parameter n, traffic growth, and temperature), one from three traffic composition scenarios (normal, freight dominated, and automated freight dominated), and one from scenarios of flood susceptibility.

Figure 22 shows an example interface.

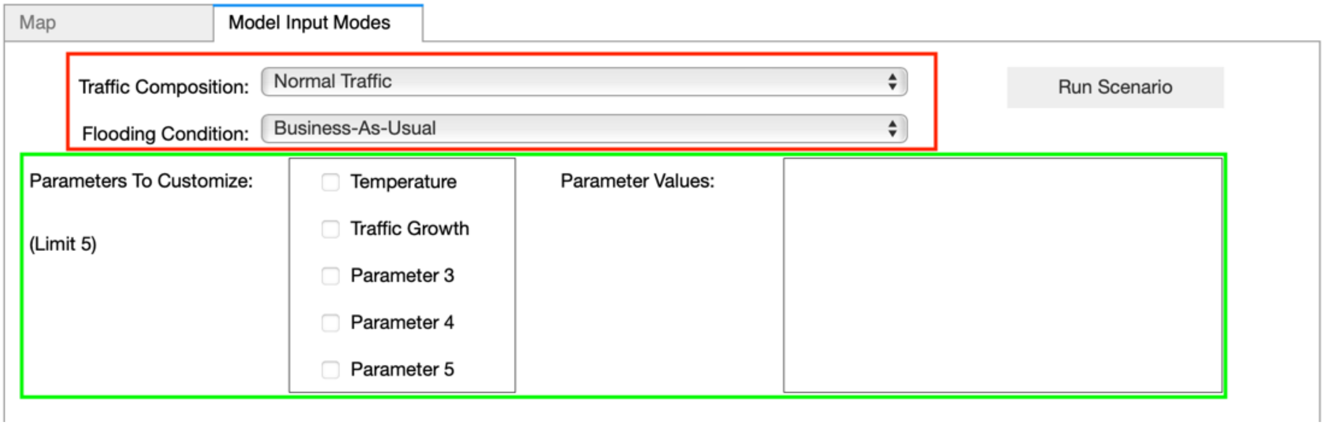


Figure 22. Example Interface That Allows for the Specification of Different Scenarios for the User-Defined Mode.

FAST WEB TOOL USER MANUAL

As stated at the beginning of this chapter, a user manual for the Fast Web Tool is published separately from this final report as TxDOT Product 0-7124-P1. The document gives the full details of the tool, its functions, and the input variables used in generating information from the tool. The following are some details on basic functions and general steps covered within that report.

Usage of the Fast Web Tool includes three major tasks:

1. Selecting a study area.
2. Specifying the models.
3. Auditing the model output.

These tasks are performed primarily in the Map, Models, and Output tabs of the Fast Web Tool interface, respectively, as follows:

1. Selecting a study area. The study area is selected in one of two ways:
    a. By selecting a major highway. All routes within a given distance (from 0 to 100 miles) from that major highway are selected.
    b. By selecting a TxDOT district. All routes within that TxDOT district are selected. *Optional:* The user also can use selection tools within the Fast Web Tool to further refine the selection (see Figure 23).
2. Specifying models. Models within the Fast Web Tool include the following:
    a. Pavement Condition.
    b. Bridge Susceptibility.
    c. Flood Susceptibility.
    d. Economic Analysis.

The user can choose to run models from all (or a subset) of these categories. Once the user has selected the appropriate parameters that describe their scenario, they can then run the model(s) they selected in the Fast Web Tool. If the model successfully executes, the Run button for the model will turn green (see Figure 24). If the button turns red, an error condition is present.

To audit the model output, the following steps can be taken:

1. Once models are successfully run, the user can output results from these models using the Report button in the Map tab (see Figure 25).
2. The report is displayed in the Output tab. Figure 26 shows an example report for the Flood Susceptibility Model. The report shows the susceptibility of bridges at various locations throughout the selected study area. In this example, almost all the bridges have a low susceptibility rating.

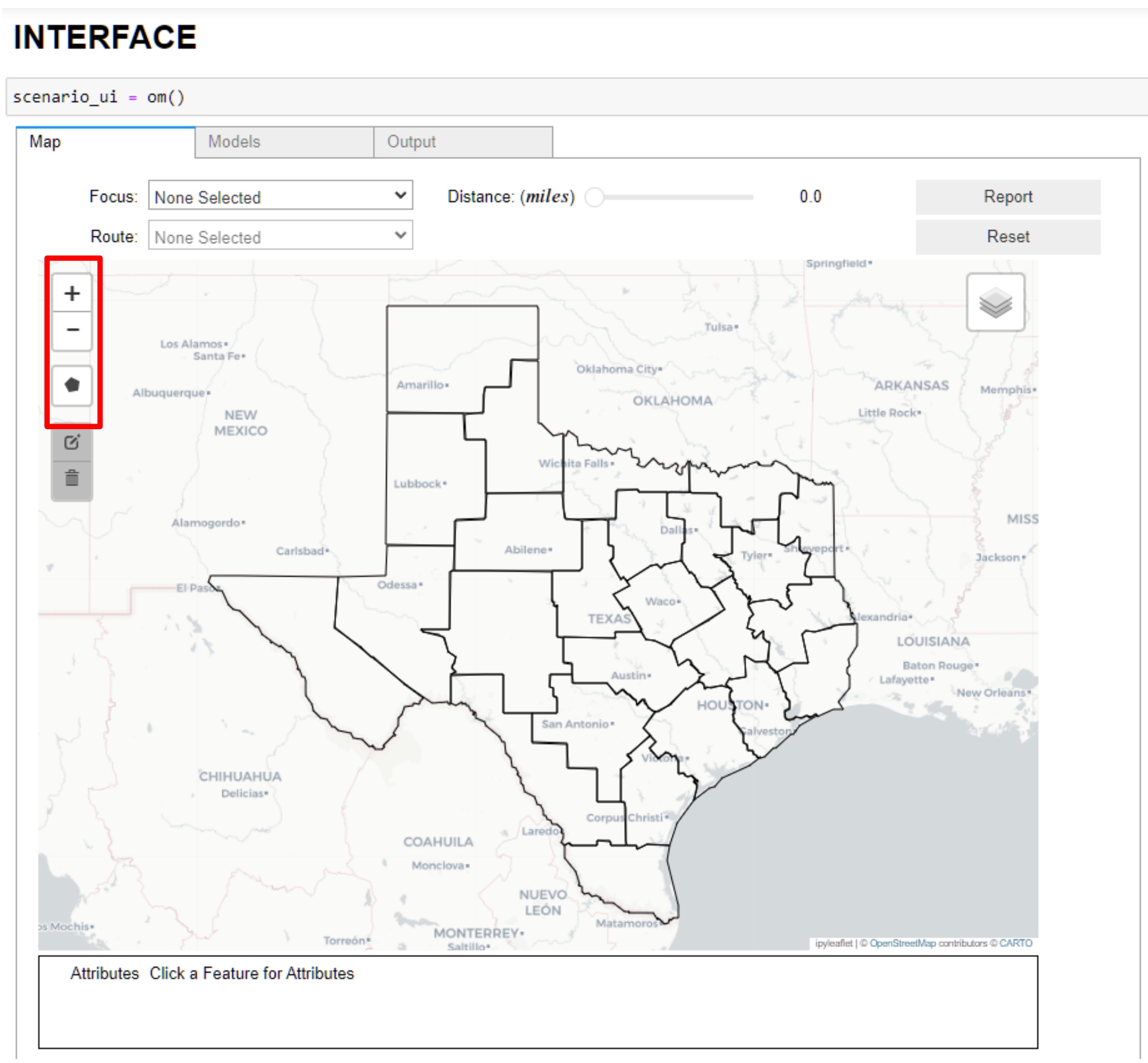


Figure 23. Main Interface Map Showing Selection Tools to Refine the Study Area.

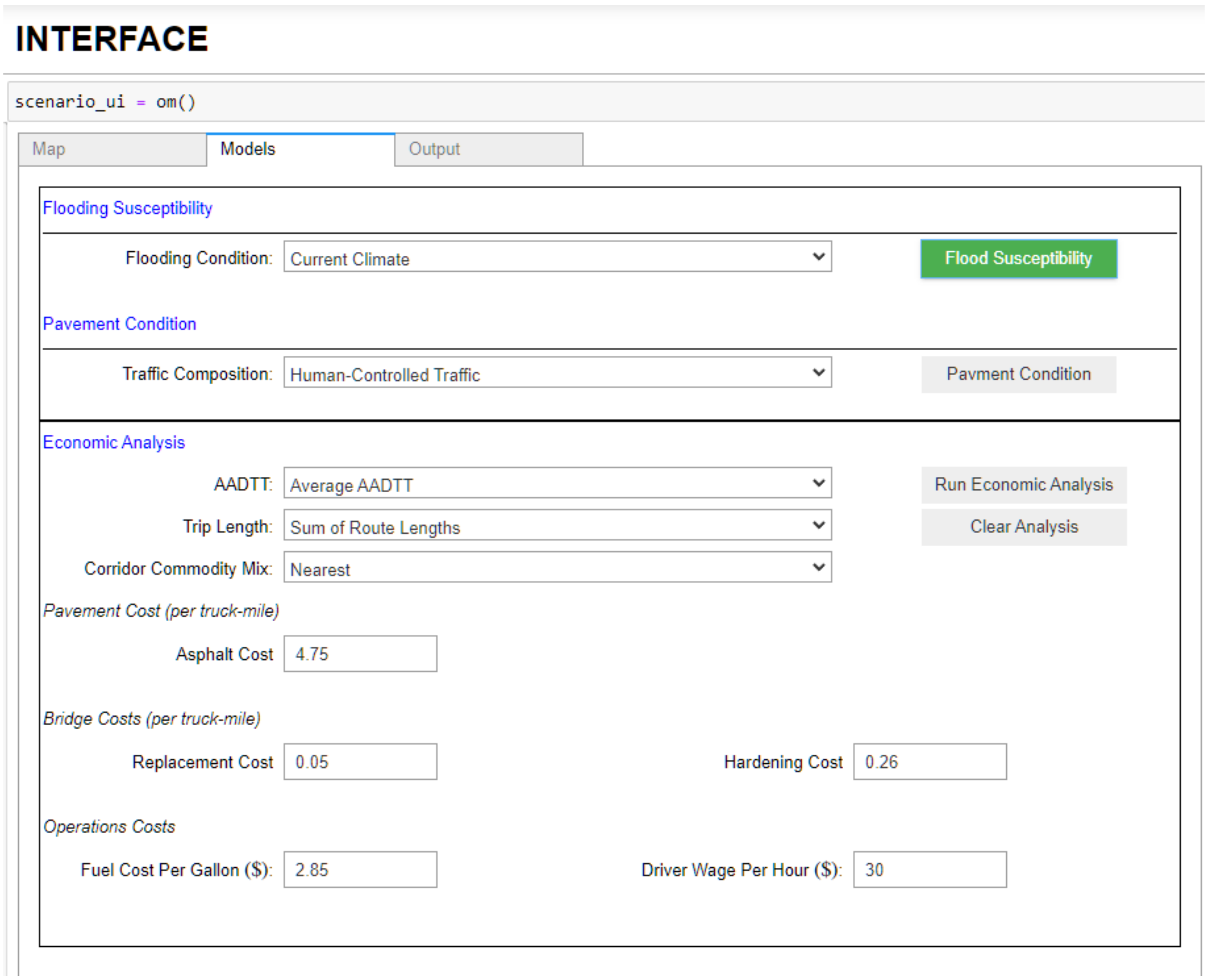


Figure 24. Example of Successful Flood Susceptibility Model Execution.

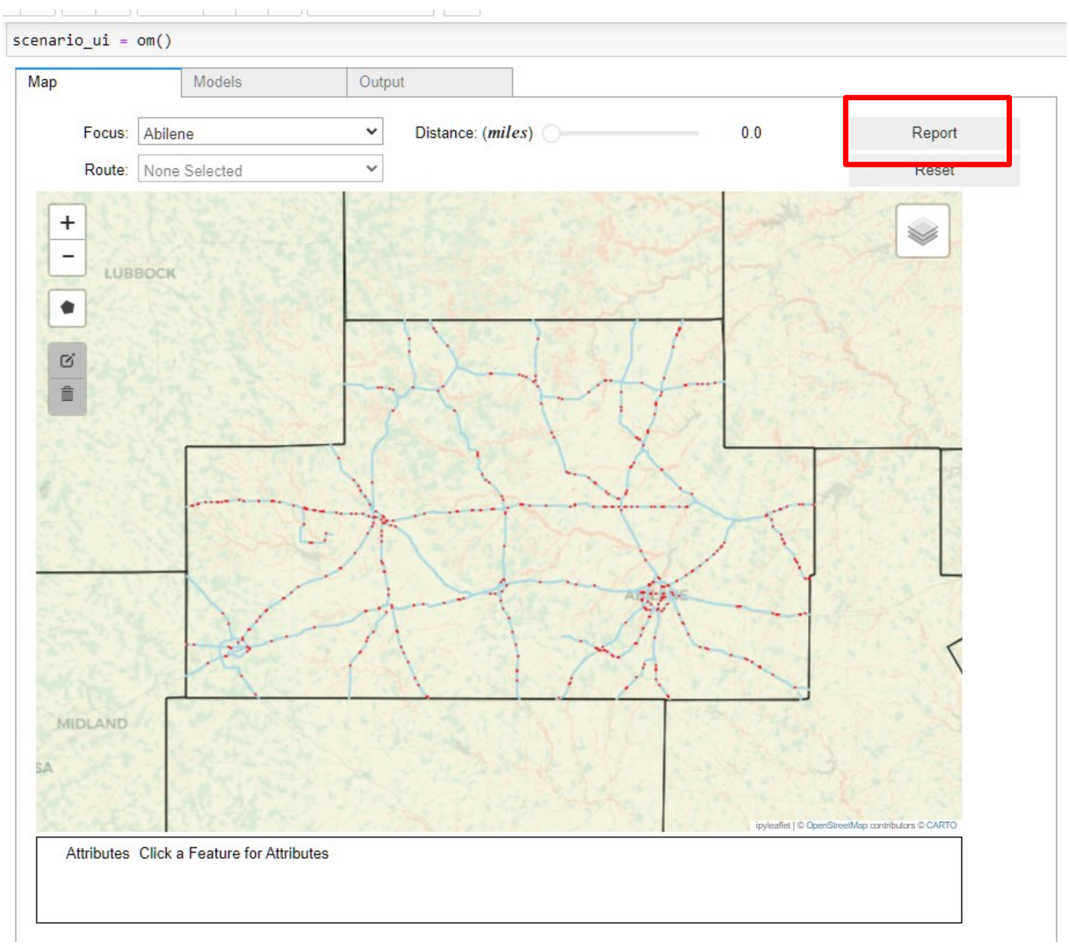


Figure 25. User Interface with the Report Button.

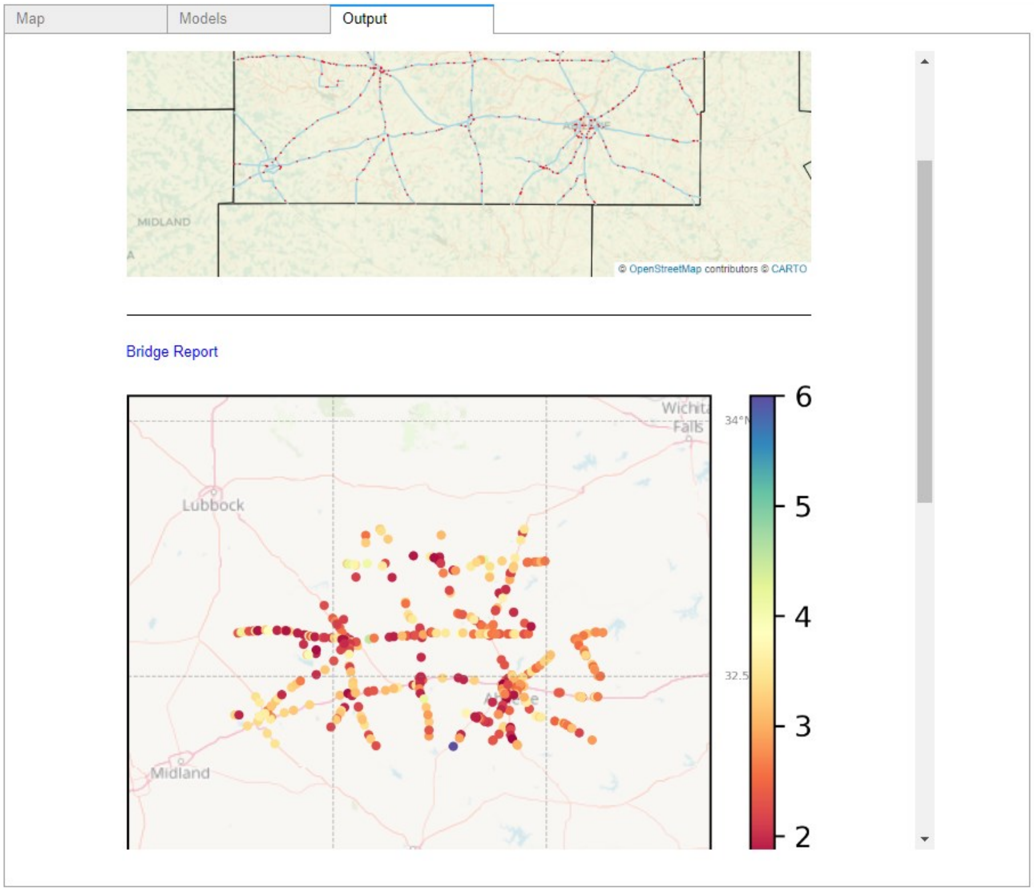


Figure 26. Example Output Report for the Flood Susceptibility Model.

As stated previously, additional information on the use of the Fast Web Tool and its various functions is available in TxDOT Product 0-7124-P1, *Development of and User Manual for the Fast Web Tool to Evaluate Infrastructure and Planning Impacts of Changes in Truck Traffic and Technologies*, published separately.

EXAMPLE FAST WEB TOOL MODEL RUNS/OUTPUT REPORTS ON MAJOR STUDY CORRIDORS

Appendix C shows example project runs and output reports for I-10, I-35, and I-45. Appendix C also includes several graphics on various pavement analyses and describes the potential hardening options that could be applied to these corridors.

CHAPTER 6. CONCLUSIONS

This report summarizes the development and application of a new Fast Web Tool to assist TxDOT and other planners in assessing the impacts of changes in truck traffic levels and new truck technologies by using user input and standard scenarios for the THFN corridors. This report does so by considering the output of four separate models, which it integrates to provide a report on bridge and pavement conditions. Those models are the Pavement Condition, Bridge Susceptibility, Flood Susceptibility, and Economic Analysis Models.

The interface of the web-based dashboard of the tool was developed to be similar in format to other tools TxDOT uses to assess roadway congestion and other features. The appendices of this report describe example tool scenario runs and roadway hardening options.

Planners in several TxDOT divisions and districts can use this tool to quickly assess the impacts that changes in truck traffic or truck technologies may have on existing roadways, to plan for maintenance needs proactively, or to assess the economic impacts of various input scenarios.

APPENDIX A. ADDITIONAL MODELING NEEDS FOR AUXILIARY LANES, DESIGN AND OPERATIONS, AND CHANGES IN TRUCK AND TRAFFIC TECHNOLOGIES

The implementation of truck technologies (e.g., truck platooning) also requires roadway design changes such as an increase in the number of lanes, lane restrictions for dedicated truck/autonomous truck lanes, introduction of auxiliary lanes (ALs)[1], etc. These changes to roadway design and their impact on traffic operations need to be studied using various modeling and simulation tools before being implemented. Currently, there is limited guidance on what type of analysis needs to be performed and when.

As part of this study, TTI researchers embedded user flags in the graph-based tool that signal the user when more detailed local traffic modeling and/or simulations are required. In particular, the user flags signal the need for further local traffic flow modeling or simulations to determine design considerations for the selection of dedicated truck lanes, dedicated autonomous truck lanes, and ALs.

ALs are typically built to provide additional roadway capacity and help facilitate safe traffic movements such as speed changes and weaving, merging and diverging, entering and exiting, and turning. ALs help balance the traffic load and provide transitions, vehicle storage, acceleration/deceleration to and from driveways/cross streets, turnaround lanes, and interchange approaches and departures.

Acceleration and deceleration lanes, climbing lanes, and right- and left-turn lanes are typical examples of different AL types that can be used for truck platooning. The TxDOT *Roadway Design Manual* addresses AL design by focusing on freeway main lanes and intersections/interchanges of frontage roads with cross streets, side streets, and driveways.

Figure A-1, adapted from Chapter 13 of the *Highway Capacity Manual*, shows the AL merge and diverge influence areas (*110*).

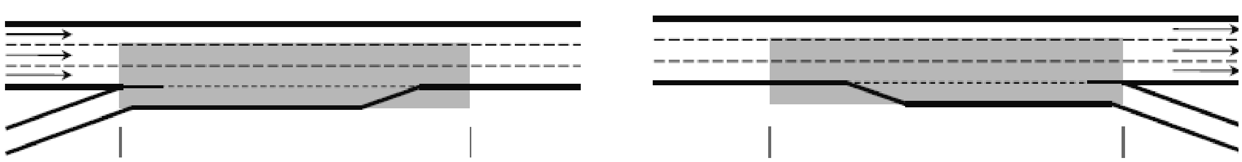


Figure A-1. Merge Influence Area (Left) and Diverge Influence Area (Right).

In the context of this study, the goal of the traffic modeling or simulation process is two-fold:

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[1] An auxiliary lane is a type of roadway lane that is built alongside and typically adjoining a roadway's primary lanes for a limited distance that varies depending on site needs and conditions.

- To understand the operation impact on traffic by restricting platooning to lanes (e.g., left or right lanes).
- To identify if and/or when a certain type and length of the AL may be more beneficial from a traffic operations perspective.

These design strategies can be modeled at a macro level (large scale) using dynamic traffic assignment (DTA) or multi-resolution modeling (MRM). DTA models can be used to model strategies such as dedicated truck lanes, off-peak use of high-occupancy toll or high-occupancy vehicle lanes or lane restrictions, reliable truck route information, land use planning, and zoning. Strategies such as incentivized off-peak delivery, land use planning, and zoning can be modeled either by sketch planning or DTA models. Specific types of lane restrictions and lengths of ALs for truck platooning should be studied in a microsimulation platform such as VISSIM or AIMSUN.

This assessment is primarily based on TTI researchers' knowledge, experience, and understanding of the abovementioned factors in each respective location and may need further local TxDOT expert input prior to final adoption in practice.

Figure A-2 is a decision tree that will help analysts flag the correct tools for modeling or simulation for studying various design-related changes that may need to be implemented for studying truck platooning and other technologies. The decision tree has four tiers that relate to decision points.

1. The first tier begins with the most recommended design strategy for dedicated truck lanes.
2. The second tier considers the presence of lane barrier separation and ALs.
3. The third tier provides options for granularity, quick response, and truck route designations.
4. The fourth tier lists all the available modeling and simulation tools that can be used.

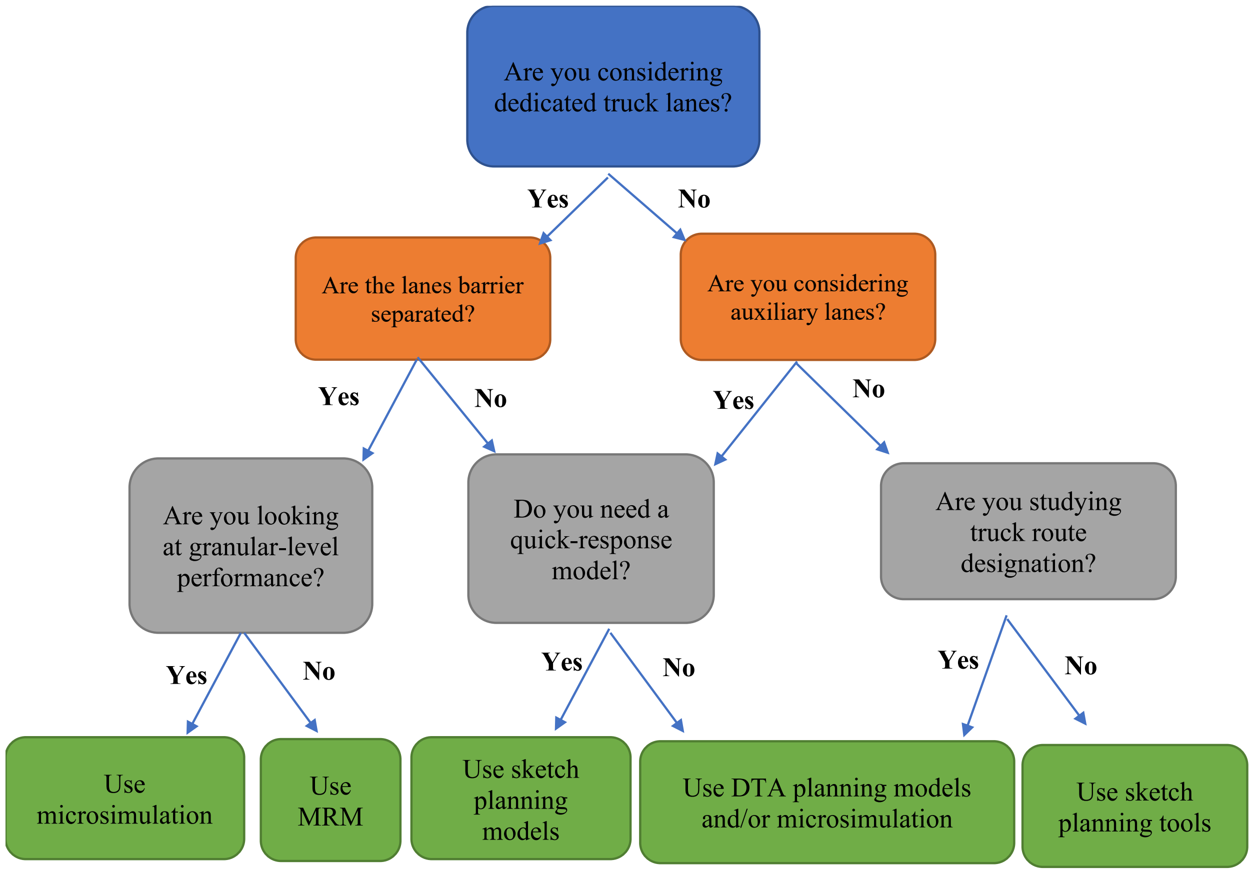


Figure A-2. Decision Tree for Selecting Modeling and Simulation Tools for Evaluating Traffic Planning or Operational Issues.

APPENDIX B. ECONOMIC IMPACTS CALCULATIONS

The objective of Task 4 of TxDOT Project 0-7124 was to develop the framework to identify benefits and costs, as well as the economic impacts, of different truck configurations across Texas. This framework is an extension of the economic model developed as part of TxDOT Project 0-6984. In that project, a scenario spanning 30 years and divided into near, mid, and future periods was developed to capture the forecast advancement in truck platooning and autonomous technologies. An Economic Analysis Model calculates the total benefit and cost and economic impact of truck platooning and automation. This appendix summarizes the model and describes in more detail the further scenario development for Project 0-7124 and results for the BCA and economic impact analysis.

SCENARIO DEVELOPMENT

To conduct the analysis, a scenario was developed to account for changes in driving conditions and technologies in years to come. The scenario time period ranges from the year 2024 until 2053 and is split into near-, medium-, and long-range periods, which define applied changes in rates, costs, and percentages in the model calculations. The periods range as follows:

- Near is from 2024 to 2028.
- Medium is from 2029 to 2038.
- Long is from 2039 to 2053.

Additionally, the scenario period determines the truck driver configuration, or pairs, if platooning and autonomous trucking technology were to be adopted. As shown in Figure B-1, the base case uses two individual drivers for the truck pair, no platooning, minimal fuel savings, and drivers subject to current HOS regulations. In the near-term scenario, drivers are platooning, resulting in fuel savings. As technology continues to improve, the mid-term scenario will have the truck pair comprised of a single driver in the lead truck and an automated driverless truck following right behind in the platoon. Fuel savings and HOS regulations still apply, but there is one less driver. Lastly, the long-term scenario employs a fully autonomous approach, removing the need for drivers and eliminating HOS costs/impacts. Figure B-2 displays the mid- and long-term truck configuration.

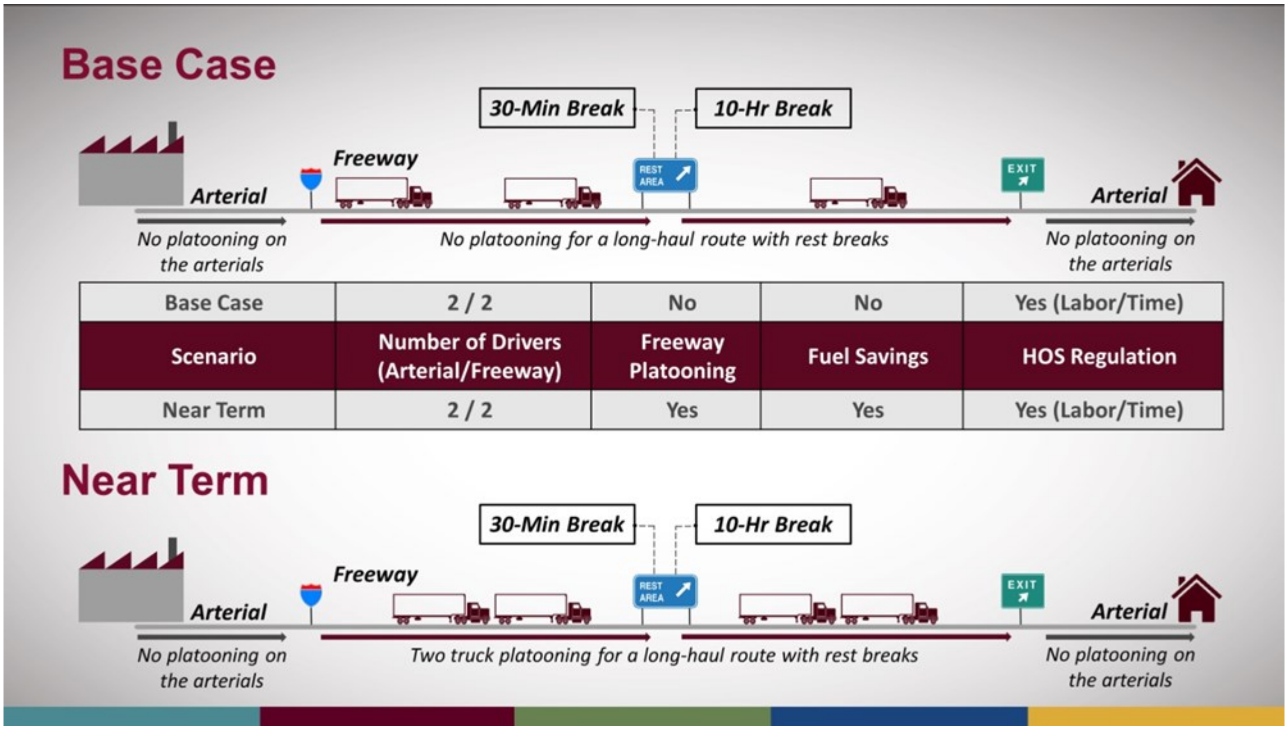


Figure B-1. Driver Base and Near-Term Scenario.

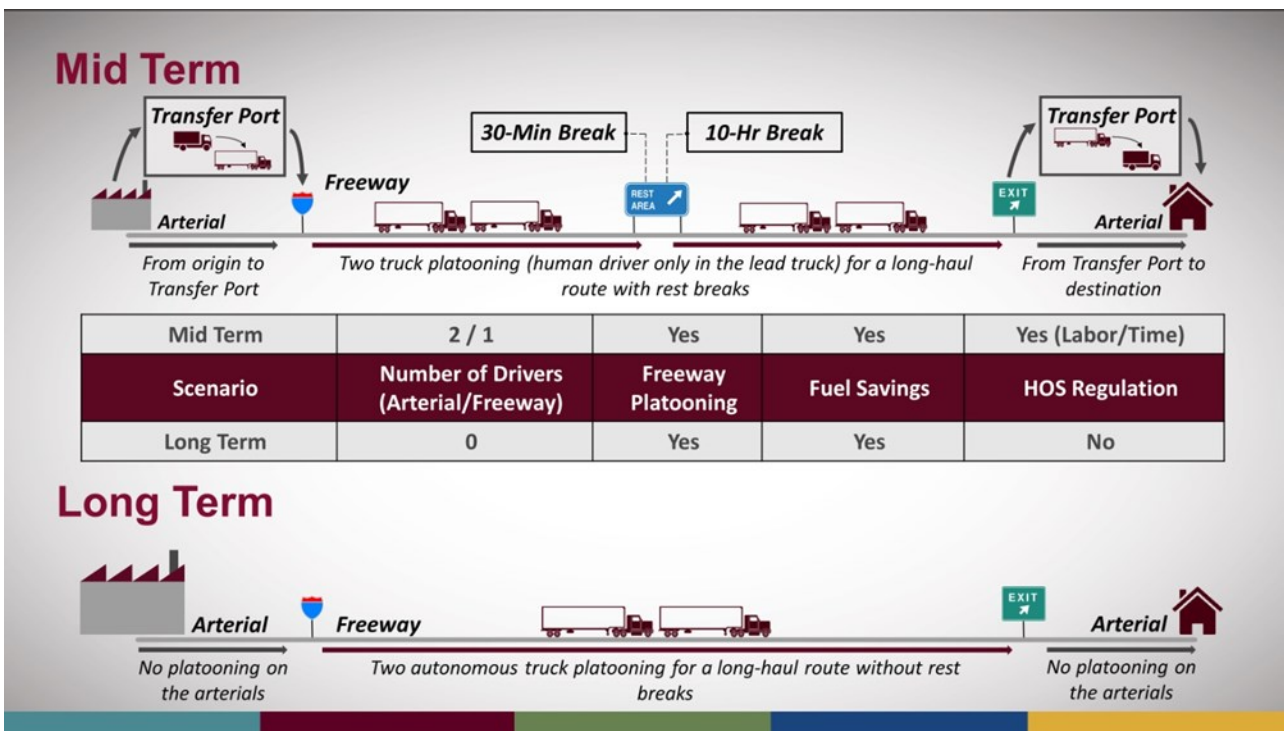


Figure B-2. Driver Mid- and Long-Term Scenario.

CASE STUDY CORRIDORS

Three Texas main corridors were selected as case studies for the Project 0-7124 analysis: I-35, I-45, and I-10. These selected corridors, identified within the contract, reflect several factors including importance for freight movement, high traffic volume, corridor length, and a variety of pavement types and bridges of concern. The I-10 study corridor was chosen to extend from El Paso to Orange, Texas, to ensure that HOS rest requirements are considered in the calculations. Two additional alternate I-10 corridors splitting into I-20 and I-30 were also incorporated into the tool. Together, these three major corridors cover the Texas Triangle, which sees a high movement of trucks between the major urbanized areas of San Antonio, Dallas-Fort Worth, and Houston. Figure B-3 shows the corridors chosen for this analysis and the additional corridors. After incorporation into the network tool, the goal is for users to select specific corridors and/or corridor segments in which to calculate the impacts on the Texas infrastructure.

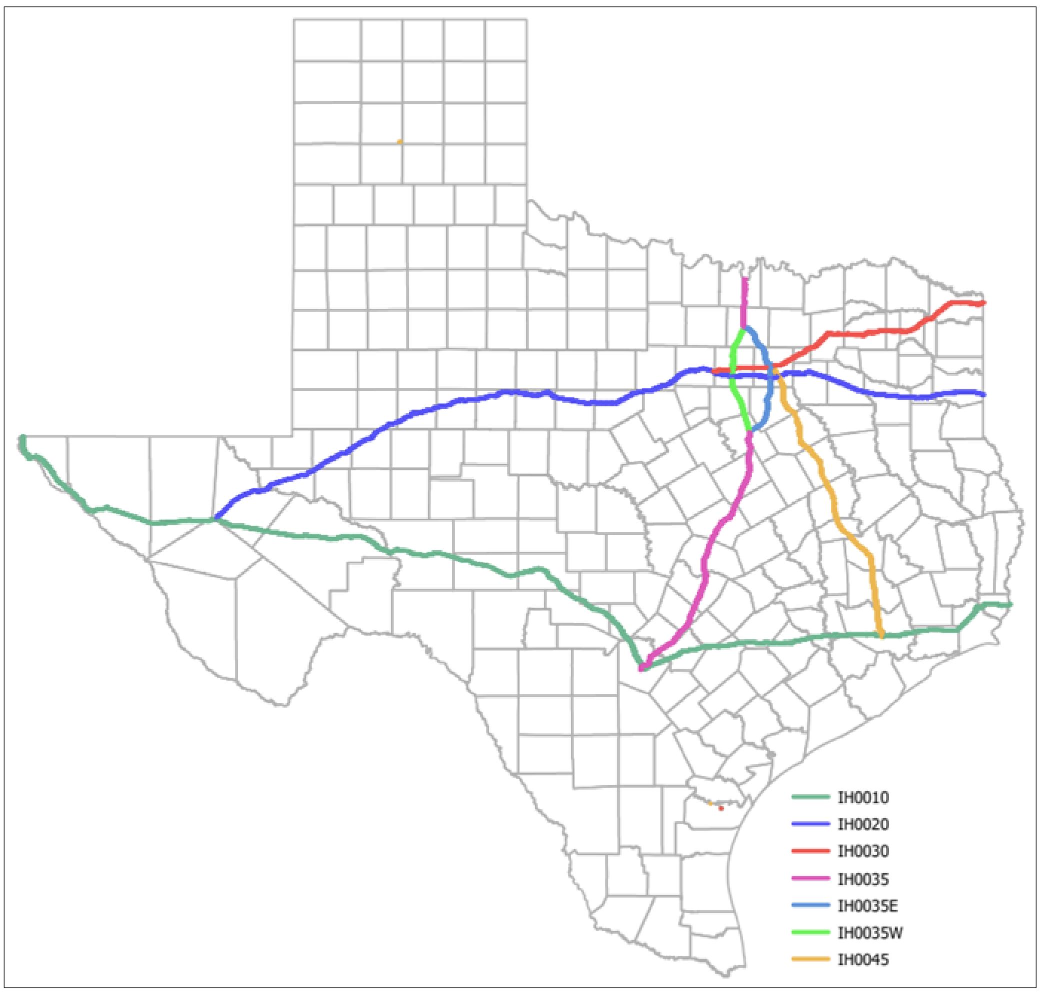


Figure B-3. Analysis Scenario Corridors.

The study truck corridors' characteristics were obtained and segmented according to Texas safety rest areas, referred to hereafter as simply *rest areas*, located across Texas. Rest areas along the corridors were selected to represent transfer hubs where trucks could initiate platooning or where autonomous operations could begin. The list was taken from TxDOT's "Safety Rest Area List," which contains information on each of the 76 rest areas in the state (*111*). The dots in Figure B-4 represent rest areas located along the corridors or major nodes in which future transfer hubs could exist for the purposes of this scenario. Northbound (NB) and southbound (SB) distances and travel time were obtained from Google Maps. The Google Maps time may differ based on the time of day that the travel time was recorded. The travel time was also recorded for a corridor average speed of 65 mph and 70 mph. Table B-1 and Table B-2 summarize the shorter of the corridors, and

Table B-3 extends from one end of the state to the other through I-10 from El Paso to Orange, Texas. Table B-4 and Table B-5 contain different variations of the I-10 corridor. (Rest areas in the latter three tables are italicized and dashes inserted in empty cells to represent HOS breaks.)

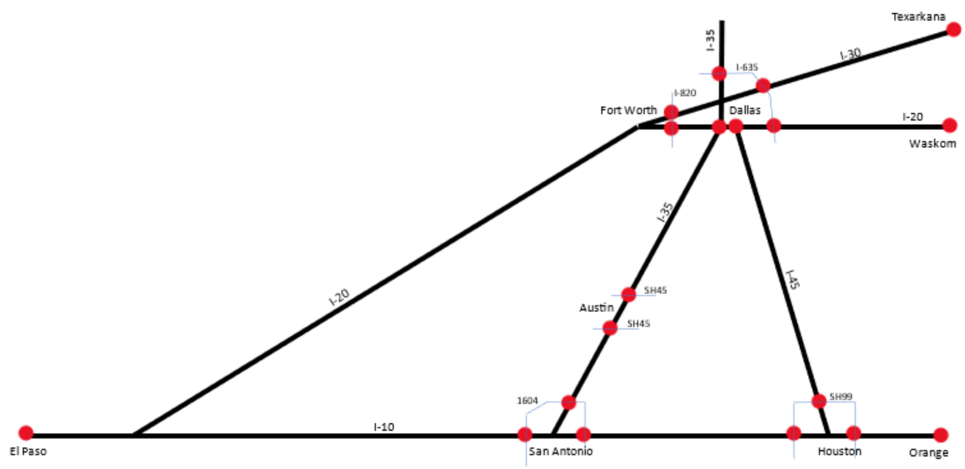


Figure B-4. Schematic of Potential Transfer Hub Locations.

Table B-1. I-35 Corridor: San Antonio–Dallas.

Direction	Location	Reference City	Roadway	Miles	Google Maps Time	65 mph	70 mph
NB	*Travel Center*	*San Antonio*	*I-35*	-	-	-	-
NB	Austin	Austin	I-35	135	2.18	2.08	1.93
NB	Bell County	Salado	I-35	188	0.54	2.89	2.69
NB	Hill County	Hillsboro	I-35	271.9	1.1	4.18	3.88
NB	Travel Center	Gainesville	I-35	403.9	2.5	6.21	5.77
SB	*Travel Center*	*Gainesville*	*I-35*	-	-	-	-
SB	Hill County	Hillsboro	I-35	123	2.6	1.89	1.76
SB	Bell County	Salado	I-35	206.3	1.13	3.17	2.95
SB	Austin	Austin	I-35	256.8	0.56	3.95	3.67
SB	Travel Center	San Antonio	I-35	336.8	1.2	5.18	4.81

Table B-2. I-45 Corridor: Houston–Dallas.

Direction	Location	Reference City	Roadway	Miles	Google Maps Time	65 mph	70 mph
NB	*Travel Center*	*Houston*	*I-45*	-	-	-	-
NB	Walker County	Huntsville	I-45	70.5	1.04	1.08	1.01
NB	Navarro County	Corsicana	I-45	163.2	1.14	2.51	2.33
NB	Travel Center	Gainesville	I-35	312.2	2.32	4.80	4.46
SB	*Travel Center*	*Gainesville*	*I-35*	-	-	-	-
SB	Navarro County	Corsicana	I-45	130	2.42	2.00	1.86
SB	Walker County	Huntsville	I-45	246	1.45	3.78	3.51
SB	Travel Center	Houston	I-45	315.8	1.7	4.86	4.51

Table B-3. I-10 Corridor: El Paso–Orange.

Direction	Location	Reference City	Roadway	Miles	Google Maps Time	65 mph	70 mph
Eastbound (EB)	Travel Center	Anthony	I-10	-	-	-	-
EB	Sutton County	Sonora	I-10	392	5.5	6.0	5.6
EB	Kerr County	Kerrville	I-10	525	7.3	8.1	7.5
EB	Colorado County	Columbus	I-10	687	9.7	10.6	9.8
EB	Chambers County	Hankamer	I-10	810	11.6	12.5	11.6
EB	Travel Center	Orange	I-10	876	12.6	13.5	12.5
Westbound (WB)	Travel Center	Orange	I-10	-	-	-	-
WB	Kerr County	Kerrville	I-10	362	5.9	5.6	5.2
WB	Sutton County	Sonora	I-10	482	7.6	7.4	6.9
WB	Pecos East County	Sheffield	I-10	567	8.8	8.7	8.1
WB	Pecos West County	Fort Stockton	I-10	642	9.8	9.9	9.2
WB	Culberson County	Van Horn	I-10	731	11.1	11.2	10.4
WB	El Paso County	Fabens	I-10	825	12.4	12.7	11.8
WB	Travel Center	Anthony	I-10	877	13.2	13.5	12.5

Table B-4. I-10 and I-20 Corridor: El Paso–Waskom.

Direction	Location	Reference City	Roadway	Miles	Google Maps Time	65 mph	70 mph
EB	*Travel Center*	*Anthony*	*I-10*	-	-	-	-
EB	Callahan County	Abilene	I-20	481	6.9	7.4	6.9
EB	Eastland County	Ranger	I-20	538	7.7	8.3	7.7
EB	Van Zandt	Van	I-20	722	10.3	11.1	10.3
EB	Travel Center	Waskom	I-20	828	11.9	12.7	11.8
WB	*Travel Center*	*Waskom*	*I-20*	-	-	-	-
WB	Mitchell County	Colorado City	I-20	431	6.4	6.6	6.2
WB	Ward County	Monahans	I-20	565	8.4	8.7	8.1
WB	Culberson County	Van Horn	I-10	676	9.8	10.4	9.7
WB	El Paso County	Fabens	I-10	770	11.2	11.8	11.0
WB	Travel Center	Anthony	I-10	822	12.0	12.6	11.7

Table B-5. I-10, I-20, and I-30 Corridor: El Paso–Texarkana.

Direction	Location	Reference City	Roadway	Miles	Google Maps Time	65 mph	70 mph
EB	Travel Center	Anthony	I-10	-	-	-	-
EB	Callahan County	Abilene	I-20	481	6.9	7.4	6.9
EB	Eastland County	Ranger	I-20	538	7.7	8.3	7.7
EB	Hopkins County	Dallas	I-30	718	10.3	11.0	10.3
EB	Travel Center	Texarkana	I-30	831	12.0	12.8	11.9
WB	*Travel Center*	*Texarkana*	*I-30*	-	-	-	-
WB	Mitchell County	Colorado City	I-20	440	6.8	6.8	6.3
WB	Ward County	Monahans	I-20	575	8.8	8.8	8.2
WB	Culberson County	Van Horn	I-10	686	10.2	10.6	9.8
WB	El Paso County	Fabens	I-10	779	11.6	12.0	11.1
WB	Travel Center	Anthony	I-10	831	12.4	12.8	11.9

Once the corridors were identified, truck movement occurring within the corridors was more clearly defined. Commodity data were obtained from TxDOT Texas Freight Mobility Plan datasets. Table B-6 shows the commodity breakdown for each of the corridors. The commodity profile of the case study corridors is needed to calculate changes in value.

Table B-6. Corridor Commodity Profile.

Commodity Group	Commodity Group Name	I-10	I-20	I-30	I-35	I-45	Grand Total
CG1	Agriculture	2.0%	4.7%	1.6%	2.0%	1.9%	2.2%
CG2	Other Mining	0.0%	0.0%	0.0%	0.1%	0.3%	0.1%
CG3	Coal	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CG4	Nonmetallic Minerals	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CG5	Food	5.8%	7.1%	6.2%	6.3%	7.6%	6.4%
CG6	Consumer Mfg.	7.2%	7.3%	3.2%	3.1%	1.6%	4.5%
CG7	Non-Durable Mfg.	3.3%	2.8%	5.1%	4.8%	5.4%	4.3%
CG8	Lumber	0.4%	1.2%	0.6%	0.3%	0.3%	0.4%
CG9	Durable Mfg.	53.0%	52.0%	55.4%	58.5%	49.2%	55.1%
CG10	Paper	0.9%	1.1%	1.4%	1.1%	0.9%	1.0%
CG11	Chemicals	8.1%	2.9%	3.2%	2.3%	4.8%	4.3%
CG12	Petroleum	2.0%	1.9%	1.4%	1.3%	1.0%	1.5%
CG13	Clay, Concrete, and Glass	0.2%	0.4%	0.4%	0.4%	0.2%	0.3%
CG14	Primary Metal	6.9%	6.7%	4.9%	4.8%	8.6%	6.0%
CG15	Secondary and Misc. Mixed	10.2%	11.9%	16.6%	15.1%	18.2%	13.9%
All	All	100%	100%	100%	100%	100%	100%

The truck ADT was captured from TxDOT's Roadway-Highway Inventory. The datasets divide the truck volumes into single-unit trucks and combination trucks. This analysis focuses on the daily combination truck volumes because those are the truck configurations most closely related to current long-haul truck platoon and automation operations. Table B-7 shows the average and maximum daily combination trucks per corridor in the base year of 2021. Table B-8 shows the assumed platoon truck levels for each case study corridor.

Table B-7. Corridor Average Daily Traffic (2021).

Corridor	Average Combination Truck ADT	Maximum Combination Truck ADT
I-10	9,465	32,258
I-20	10,543	25,297
I-30	11,941	19,753
I-35	11,756	20,619
I-45	8,915	16,233
All	10,653	32,258

Table B-8. Corridor Assumed Platoon Truck Levels.

Corridor	Daily Combination Trucks	Daily Platoons
I-10	250	125
I-20	550	275
I-30	500	250
I-35	250	125
I-45	200	100
All	200	100

BENEFIT-COST ANALYSIS

The research team conducted a BCA to determine the impacts of truck platooning on the study corridors. This first step in the economic analysis consists of infrastructure costs to TxDOT, safety and environmental benefits to society, operational benefits to truck companies, and freight benefits to businesses. Thus, the results of the analysis are presented as costs to TxDOT compared to benefits to businesses, consumers, and society. The analysis cost and benefit components include:

- Costs:
  - Increased pavement costs.
  - Increased bridge costs.
- Safety benefits: reduced crashes.
- Environmental benefits: reduced emissions.
- Operational benefits:
  - Reduced driver costs.
  - Reduced fuel costs.
  - Reduced break costs.
  - Additional automation cost—negative impact.
- Freight benefits:
  - Commodity time cost savings.
  - Just-in-time savings.
  - Perishability savings.

The analysis uses a baseline scenario, representing the status quo, which is compared to a project scenario with truck platooning. The costs in the truck platooning scenario for each element are subtracted from the baseline scenario to generate the project costs and benefits. The analysis was conducted using a 3 percent discount rate, and all costs and benefits were discounted to 2022 dollars.

Truck Movements

All costs and benefits in the analysis are based on the number of trucks passing through the chosen study corridor. Therefore, the first step of the analysis was to determine the number of trucks, establish a truck growth rate, and calculate annual vehicle miles traveled (VMT), vehicle hours traveled (VHT), and HOS break hours. These were calculated for the baseline and project scenarios. In this case, these are the same for the base and project scenarios, except for break hours. Break hours are reduced by one-half in the mid-term because there is only one driver, and by 100 percent in the long term because there are no drivers.

Using the methodology discussed previously, the number of trucks per day for the selected corridor was used to determine the number of trucks per year in 2022. This was used as the initial truck count. Annual VMT, VHT, and break hours were calculated from this. The corridor break time was estimated based on the travel time for each segment. Depending on travel time, a segment could contain no breaks or up to one 10-hour break and two 30-minute breaks, and an extra 30 minutes of time per break associated with diverting to the break location, parking, etc. VHT, VMT, and break hours were then grown by the truck growth rate to provide a number for each analysis year. The following bullets describe how each is calculated:

- **Annual VHT** = (Corridor Travel Time) * (Annual Trucks).
- **Annual VMT** = (Corridor Distance) * (Annual Trucks).
- **Annual Break Hours** = (Annual Trucks) * (Corridor Break Time).
- **Corridor Break Time** = 0 to 12.5 hours based on segment.

Infrastructure Costs

Infrastructure costs represent the increase in pavement and bridge costs due to platooning. These costs would be borne by TxDOT and comprise the cost side of the BCA. The pavement and bridge models remain under formulation, so for this analysis the Economic Analysis Model uses generalized numbers. These calculations resulted in a total cost over the entire analysis period.

It was necessary to break the infrastructure costs into annual costs to apply the discount rate. This was accomplished by solving for an initial annual cost so that when the truck growth rate was applied to it, the sum of the years would equal the total cost previously calculated. This exponential growth method was used so that the growth in costs would track with the growth in truck traffic. Simply dividing the total cost by the number of analysis years would have overestimated the costs in the early years and underestimated the costs in the later years, substantially changing the results once they had been discounted.

Once annual infrastructure costs were estimated, the project costs were subtracted from the baseline costs to show an annual cost to TxDOT. The discount rate was then applied to these annual costs and summed to show a total project cost.

Safety Benefits

Safety benefits, generated by a reduction in crashes in the platooning scenario, are beneficial to road users. The analysis included fatality crashes, injury crashes, and property-damage-only (PDO) crashes. Researchers assumed that full automation would reduce these crashes by the rates shown in Table B-9. Furthermore, a percentage of this reduction was applied in the near term and mid-term of the analysis. The near term received 10 percent of this reduction, while the mid-term received 25 percent of this reduction. As stated previously in this section, the three periods of analysis are defined as *near* (2024 to 2028), *medium* (2029 to 2038), and *long* (2039 to 2053).

Table B-9. Crash Assumptions.

Crash Type	Base Crash Rate (per 100-m VMT) (*112*)	Near-Term Reduction	Mid-Term Reduction	Long-Term Reduction	Cost per Crash
Fatality	1.64	5.09%	12.73%	50.91%	$11,800,000
Injury	48.7	5.11%	12.77%	51.09%	$162,600
PDO	108.4	3.8%	9.49%	37.96%	$4,800

The crash rate reductions were applied to the base truck crash rates to determine a crash rate for each type of crash in the short, mid-, and long term of the analysis. These rates were then multiplied by the VMT for each year to determine the number of crashes of each type. The number of crashes was then multiplied by the cost of that type of crash to determine the annual costs for the baseline and project scenarios, which were then discounted. The difference in the lower project cost and the higher baseline cost is the safety benefit generated by platooning. The discount rate significantly affects this calculation because most of the safety benefits are generated in the long-term period of the analysis. This can be expressed as:

- **Number of Crashes** = (VMT/100,000,000) * (Crash Rate).
- **Crash Cost** = (Number of Crashes) * (Cost).

Environmental Benefits

Environmental benefits are a benefit to society, generated by a reduction in vehicle emissions. This analysis quantifies the benefits of reduced volatile organic compounds, nitrogen oxides, sulfuric oxides, and particulate matter. It was assumed that truck platooning would increase fuel efficiency in the project scenario by 7 percent, thus reducing emissions accordingly. Table B-10 contains the emissions rate assumptions used in calculating environmental impacts.

Table B-10. Emissions Assumptions.

Emission Type	Base Emissions Rate (Tons per VMT)	Project Emissions Rate (Tons per VMT)	Emissions Cost per Ton
Volatile organic compounds	0.0000004387	0. 0000004100	$2,421
Nitrogen oxides	0.0000039099	0.0000036541	$9,916
Sulfur oxides	0.0000000107	0.0000000100	$57,765
Particulate matter	0.0000002712	0.0000002535	$446,552

The emissions rate was multiplied by the VMT and then by the emissions cost per ton for the baseline and project scenarios. This generated a baseline and project emissions cost. These were discounted, and the resulting difference between the two was the total environmental benefit. This can be expressed as:

- **Environmental Cost** = (VMT) * (Emissions Rate) * (Emissions Cost).

Operations Benefits

Operations benefits are comprised of the savings generated by trucking companies in the project scenario. These savings include reduced driver costs, reduced fuel costs, reduced costs from idling during breaks, and reduced break costs. Additionally, automation costs were calculated in this section, creating a disbenefit to trucking companies. These benefits are captured by the trucking companies as reduced costs but additionally could translate into reduced costs for consumers because the trucking industry is highly competitive.

Driver Costs

Most of the benefit in this category was generated by reducing driver costs. Switching to one driver per truck pair in the mid-term portion and then zero drivers in the long-term portion of the analysis significantly reduces driver costs. Base scenario driver costs were calculated by multiplying the VHT by the driver cost per hour and then by the number of drivers per truck. The same was performed in the project scenario where the mid-term portion has one driver per two trucks and then zero in the long-term portion. In the mid-term portion, it is assumed that a portion of the trip uses one short-haul driver per truck with a lower wage. The remainder of the trip uses one driver per two trucks. This can be expressed as:

- **Driver Cost** = (VHT) * (Drivers per Truck) * (Driver Hourly Wage).

Fuel Costs

Fuel savings are generated by the difference in fuel consumption in the base and project scenarios. The project scenario assumes a 7 percent reduction in fuel consumption due to platooning, a value determined in the literature review. Fuel costs were calculated by multiplying the arterial and highway fuel consumption by arterial and highway VHT and then multiplying by the diesel price. Table B-11 shows the fuel cost assumptions used. This can be expressed as:

- **Fuel Cost** = ((Arterial VHT) * (Arterial Fuel Consumption)) + ((Highway VHT) * (Highway Fuel Consumption)) * (Diesel Cost).

Table B-11. Fuel Cost Assumptions.

Fuel Cost Assumptions	Base	Project
Arterial fuel consumption (gallons per hour)	6.25	5.84
Highway fuel consumption (gallons per hour)	10.16	9.49
Diesel cost ($2022)	$4.277	$4.277

Idling and Driver/Operator Break Costs

Idling savings are generated by reducing truck idling time during required driver/operator rest breaks. It was assumed that during these breaks, certain truck costs were incurred, including truck capital costs, maintenance costs, insurance, and permits. In total, these equal $16.61 per hour. This becomes a benefit in the long-term portion of the analysis because driver breaks are eliminated. Idling cost also includes idle fuel consumption. This is reduced by 50 percent in the mid-term portion because only one truck needs to idle and then is eliminated in the long-term portion.

Each 10-hour break and transfer terminal in the mid-term portion only was additionally assumed to have a cost associated with using the facility. This cost was simply multiplied by the number of breaks or transfers to generate a total. Table B-12 provides the idle truck assumptions. This can be expressed as:

- **Idle Truck Cost** = (Hourly Idle Cost) * (Break Hours).
- **Idle Fuel Cost =** (Hourly Idle Fuel Consumption) * (Break Hours) * (Diesel Price).
- **Break Cost =** (Number of Breaks) * (Break Cost).

Table B-12. Idle Truck Assumptions.

Idling Cost Assumptions	Value
Hourly idle truck cost	$16.61
Hourly idle fuel consumption (gallons per hour)	0.80
10-hour break cost	$20.00
Transfer port cost	$25.00

Automation Cost

Automation costs were included as a disbenefit in the "Operations Benefits" Section. This is the cost to trucking companies to equip their trucks with truck platooning and automation equipment. The serviceable life of a truck was assumed to be 600,000 miles, so the automation cost was divided by this to create a per-mile automation cost of $0.026 per mile in the short-term portion and $0.047 per mile in the mid- and long-term portions. This can be expressed as:

- **Automation Cost =** (Automation Cost per Mile) * (VMT).

Freight Cost Savings

Freight time costs represent the costs to industries that produce or consume the freight goods on the trucks moving through the project corridor. The freight time cost savings consist of commodity time costs, perishability costs, and just-in-time costs. These factors were calculated using a methodology developed by Fitzroy et al. with the EDR group (*113*). A freight profile was developed using FHWA's Freight Analysis Framework. This is statewide and, therefore, not specific to the corridor. The profile provided a cost per ton for each commodity on the road in Texas, as well as a percentage of trucks carrying each commodity.

First, the change in VHT was calculated by subtracting the project VHT from the base VHT. Then the commodity time cost for each commodity was calculated by multiplying the tons per vehicle by the commodity percent of freight, by the commodity cost per hour, and by the total change in VHT. This calculation repeats for each commodity moving through the project corridor. The commodity cost per hour for each commodity was calculated through EDR's methodology, which assumes an hourly return on capital of 10 percent, divided by 5,400, with 5,400 being the estimated number of productive hours in a year. This was then multiplied by the cost of the good as reported at the port of entry to determine the commodity cost per hour. This represents an hourly opportunity cost of the good not being at its destination.

The perishability cost was also estimated based on the change in VHT and using EDR's methodology. The perishability cost is the loss in value from goods spoiling during transport. This applies to goods that need to be fresh at their destination such as fruits and vegetables. A calculation similar to the commodity time cost calculation was used. The change in VHT was multiplied by the tons per vehicle and then by the commodity percent of freight. This was then multiplied by the perishability cost factor and then by the perishability commodity factor. A perishability cost factor of $0.001 per buffer hour was used, based on EDR's methodology. Perishability commodity factors were also assigned to goods based on the EDR methodology.

The just-in-time cost was calculated in the same way, using a just-in-time cost factor and a just-in-time commodity factor in place of the perishability factors. Just-in-time commodity factors were used based on the EDR methodology, with a just-in-time cost factor of $0.002. This can be expressed as:

- **Total Freight Time Cost** = (Commodity Time Cost) + (Just-in-Time Cost) + (Perishability Cost).

- **Commodity Time Cost** = (Change in VHT) * (Tons per Vehicle) * (Commodity Percent of Freight) * (Commodity Cost per Hour).
- **Commodity Cost per Hour** = (Commodity Price) * (0.1/5400).
- **Just-in-Time Cost** = (Change in VHT) * (Tons per Vehicle) * (Commodity Percent of Freight) * (Just-in-Time Cost Factor) * (Just-in-Time Commodity Factor).
- **Perishability Cost** = (Change in VHT) * (Tons per Vehicle) * (Commodity Percent of Freight) * (Perishability Cost Factor) * (Perishability Commodity Factor).

ECONOMIC IMPACT ANALYSIS FOR STUDY CORRIDORS

For the second component of the economic analysis, the project team estimated the economic impacts using multipliers from the input-output model IMPLAN. The operational cost savings calculated in the BCA represent the out-of-pocket savings to the trucking industry. These savings will be reinvested in the industry, distributed to shareholders and employees, and/or passed on to the customers and consumers. The economic impact analysis shows the effects of these additional dollars on the Texas economy. The estimated results include:

- Economic output.
- Employment.
- Labor income (wages).

The economic impacts were calculated using a combination of operations benefits and freight cost savings.

Economic Output

To determine the economic output, the operations and freight cost savings for short-, medium-, and long-term time frames were multiplied by the output multiplier determined using IMPLAN. IMPLAN is an economic impact assessment model that uses the standard input-out modeling technique with 546 different industry-sector multipliers. This model uses a diverse database of economic factors, established sector multipliers, and area demographics.

Output summary multipliers were applied to the near-, mid-, and long-term cost savings. IMPLAN defines multipliers as a measure of an industry's connection to the wider local economy by way of input purchases, payments of wages and taxes, and other transactions. The output multiplier describes the total output generated as a result of $1 of direct output in the impacted industry. For this analysis, researchers aggregated the industries associated with the commodities moved along the chosen corridors (see Table B-13). Aggregated output multipliers were collected for each of the metro regions associated with the corridors. These multipliers were then averaged to determine a single output multiplier for each corridor.

Table B-13. Economic Regions.

Corridor	Metropolitan Regions Used in Analysis
I-10	El Paso, Houston, and Beaumont
I-20	El Paso and Dallas-Fort Worth
I-30	Dallas-Fort Worth and Texarkana
I-35	Laredo, San Antonio, Austin, and Dallas-Fort Worth
I-45	Houston and Dallas-Fort Worth

Employment Impacts

IMPLAN was also used to determine the total aggregated employment and total aggregated output for each economic region within the selected industries. The total output was divided by the total employment to determine an output-per-worker factor for each region. These were then averaged by corridor to ascertain a single output-per-worker factor for each corridor to be analyzed. The corridor's short-, medium-, and long-term economic outputs calculated were then divided by the output-per-worker factor to establish the near-, mid-, and long-term employment impacts.

Wage Impacts

The calculated employment impacts were then multiplied by IMPLAN's average compensation for the selected industries. This resulted in corresponding wage impacts for the selected corridor.

ECONOMIC ANALYSIS RESULTS

Table B-14 displays the calculated net benefits for each corridor over the entire forecast analysis period from 2024 to 2053. Running the Economic Analysis Model produced the preliminary results presented in Table B-15 through Table B-29. The calculated costs and benefits are detailed in the following tables by corridor. These results use the generalized pavement and bridge costs.

Table B-14. Summary of Net Benefits for Each Major Study Corridor.

Corridors	Net Benefits
I-10	$1,115,128,406
I-20	$2,322,937,003
I-30	$2,144,572,082
I-35	$319,185,330
I-45	$205,401,919

I-10 Corridor Results

Table B-15. I-10: Summary of Benefits and Costs.

I-10	Total Costs	Total Savings	Net Benefits
Near term	$49,077,964	$30,440,211	−$18,637,753
Mid-term	$89,608,207	$229,980,880	$140,372,673
Long term	$115,475,820	$1,108,869,306	$993,393,486
Total	$254,161,992	$1,369,290,397	$1,115,128,406

Table B-16. I-10: Benefit Details.

I-10	Safety Savings	Environmental Savings	Operations Savings	Freight Savings
Near term	$5,484,194	$18,165,663	$6,790,353	$0
Mid-term	$33,775,396	$33,177,625	$163,027,859	$0
Long term	$150,463,275	$42,772,966	$718,184,099	$197,448,967
Total	$189,722,865	$94,116,254	$888,002,311	$197,448,967

Table B-17. I-10: Summary of Economic Impacts.

I-10	Economic Output	Employment Impacts	Wage Impacts
Near term	$9,879,276	10.1	$1,102,503
Mid-term	$237,189,015	242.6	$26,469,717
Long term	$1,332,153,326	1,362.4	$148,665,072
Total	$1,579,221,617	1,615.1	$176,237,292

I-20 Corridor Results

Table B-18. I-20: Summary of Benefits and Costs.

I-20	Total Costs	Total Savings	Net Benefits
Near term	$101,431,531	$63,073,089	−$38,358,442
Mid-term	$185,197,122	$474,606,419	$289,409,297
Long term	$238,658,827	$2,310,544,975	$2,071,886,148
Total	$525,287,481	$2,848,224,484	$2,322,937,003

Table B-19. I-20: Benefit Details.

I-20	Safety Savings	Environmental Savings	Operations Savings	Freight Savings
Near term	$11,354,668	$37,659,435	$14,058,985	$0
Mid-term	$69,929,471	$68,769,930	$335,907,018	$0
Long term	$311,524,600	$88,640,025	$1,520,981,219	$389,399,132
Total	$392,808,739	$195,069,391	$1,870,947,222	$389,399,132

Table B-20. I-20: Summary of Economic Impacts.

I-20	Economic Output	Employment Impacts	Wage Impacts
Near term	$22,618,981	51.8	$4,511,249
Mid-term	$540,428,373	1,236.7	$107,785,883
Long term	$3,073,540,262	7,033.6	$613,003,067
Total	$3,636,587,616	8,322.1	$725,300,198

I-30 Corridor Results

Table B-21. I-30: Summary of Benefits and Costs.

I-30	Total Costs	Total Savings	Net Benefits
Near term	$93,220,087	$57,944,771	−$35,275,316
Mid-term	$170,204,389	$436,306,969	$266,102,580
Long term	$219,338,073	$2,133,082,890	$1,913,744,818
Total	$482,762,548	$2,627,334,630	$2,144,572,082

Table B-22. I-30: Benefit Details.

I-30	Safety Savings	Environmental Savings	Operations Savings	Freight Savings
Near term	$10,432,112	$34,595,952	$12,916,706	$0
Mid-term	$64,247,826	$63,176,568	$308,882,575	$0
Long term	$286,213,468	$81,431,919	$1,391,821,114	$373,616,390
Total	$360,893,406	$179,204,439	$1,713,620,394	$373,616,390

Table B-23. I-30: Summary of Economic Impacts.

I-30	Economic Output	Employment Impacts	Wage Impacts
Near term	$19,867,108	45.1	$3,891,564
Mid-term	$475,090,435	1,079.6	$93,060,578
Long term	$2,715,408,832	6,170.5	$531,893,505
Total	$3,210,366,375	7,295.2	$628,845,647

I-35 Corridor Results

Table B-24. I-35: Summary of Benefits and Costs.

I-35	Total Costs	Total Savings	Net Benefits
Near term	$22,435,641	$14,350,577	−$8,085,063
Mid-term	$40,963,752	$86,392,024	$45,428,272
Long term	$52,788,946	$334,631,068	$281,842,122
Total	$116,188,339	$435,373,669	$319,185,330

Table B-25. I-35: Benefit Details.

I-35	Safety Savings	Environmental Savings	Operations Savings	Freight Savings
Near term	$2,589,758	$8,554,263	$3,206,556	$0
Mid-term	$15,949,493	$15,628,704	$54,813,827	$0
Long term	$71,052,102	$20,158,245	$243,420,721	$0
Total	$89,591,353	$44,341,212	$301,441,104	$0

Table B-26. I-35: Summary of Economic Impacts.

I-35	Economic Output	Employment Impacts	Wage Impacts
Near term	$5,289,178	13.0	$1,316,284
Mid-term	$90,414,791	222.2	$22,500,959
Long term	$401,519,741	986.6	$99,923,685
Total	$497,223,710	1,221.8	$123,740,928

I-45 Corridor Results

Table B-27. I-45: Summary of Benefits and Costs.

I-45	Total Costs	Total Savings	Net Benefits
Near term	$14,134,454	$9,167,993	−$4,966,461
Mid-term	$25,807,164	$50,766,523	$24,959,360
Long term	$33,257,036	$218,666,056	$185,409,019
Total	$73,198,654	$278,600,572	$205,401,919

Table B-28. I-45: Benefit Details.

I-45	Safety Savings	Environmental Savings	Operations Savings	Freight Savings
Near term	$1,657,440	$5,458,363	$2,052,189	$0
Mid-term	$10,207,684	$9,976,113	$30,582,726	$0
Long term	$45,473,503	$12,873,969	$160,318,584	$0
Total	$57,338,627	$28,308,446	$192,953,499	$0

Table B-29. I-45: Summary of Economic Impacts.

I-45	Economic Output	Employment Impacts	Wage Impacts
Near term	$3,491,011	6.0	$706,438
Mid-term	$52,024,749	90.0	$10,527,679
Long term	$272,720,428	471.9	$55,187,447
Total	$328,236,188	568.0	$66,421,564

APPENDIX C. EXAMPLE MODEL RUNS/OUTPUT REPORTS ON MAJOR STUDY CORRIDORS

MAJOR STUDY CORRIDORS

To assess the impacts of autonomous freight traffic on the Texas highway freight network, three pavement sections from I-10, I-35, and I-45 corridors were selected to analyze the impacts on pavement performance, such as rutting and cracking, as Figure C-1 shows. Because rutting mainly develops in the first few years after construction, the permanent deformation in the fifth year after construction is used to evaluate rutting. The cracking initiation time is used to evaluate the impact on cracking.

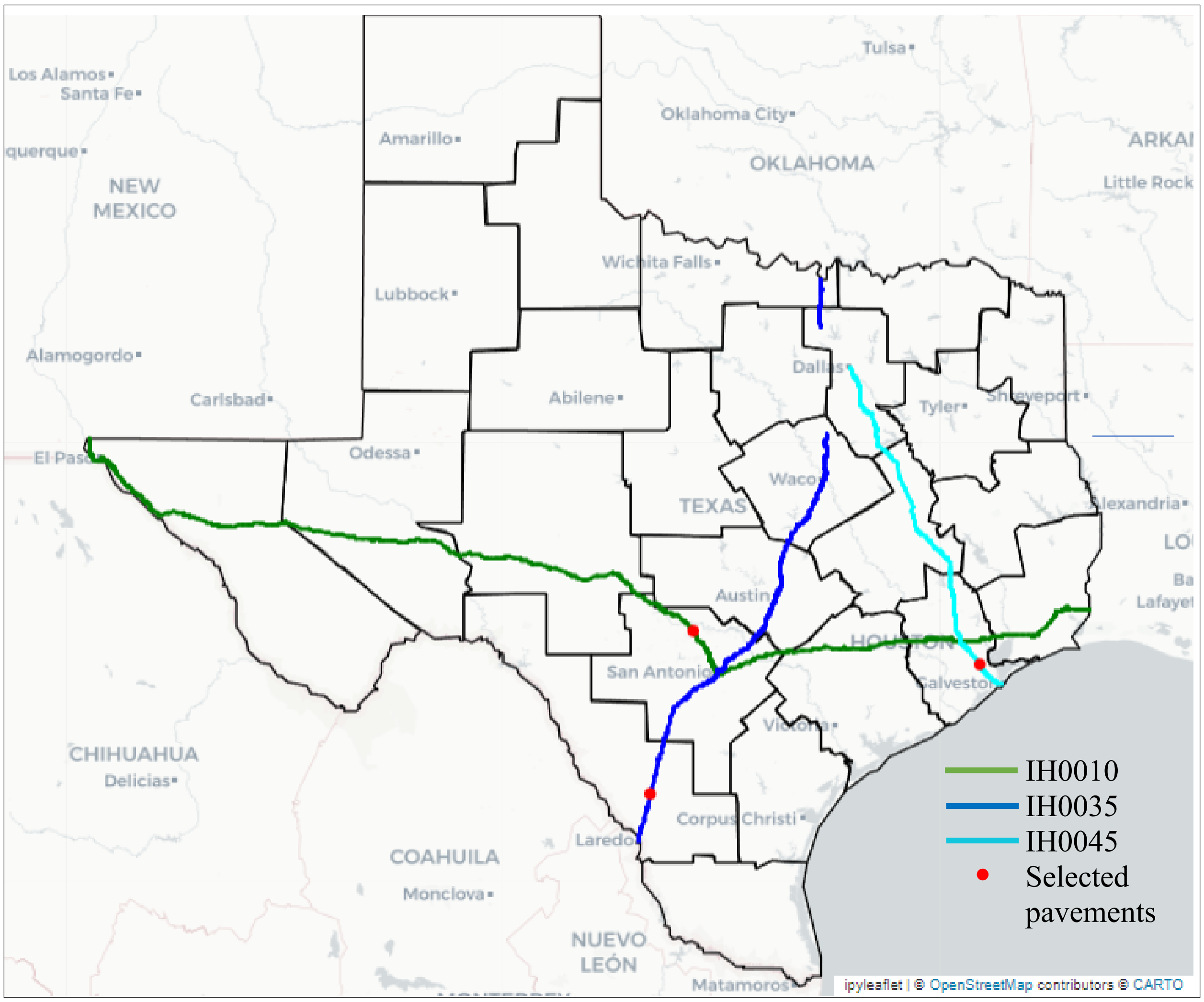


Figure C-1. Selected Pavement Sections from Three Corridors.

IMPACTS OF INCREASED AUTOMATED TRUCKS ANALYZED

The impact of increased numbers of automated trucks (ATs) was first studied, as Figure C-2 shows. Results indicate that increasing the AT percentage in total trucks has a negative impact on the pavement performance. Increasing the AT percentage can increase the rutting and accelerate cracking initiation over time.

Several hardening options used to reduce the negative pavement impacts of ATs could be employed. These include requiring programmatic wheel wander for ATs, increasing asphalt concrete (AC) layer thickness, and designating a lane for AT-only use.

Required Programmatic Wheel Wander

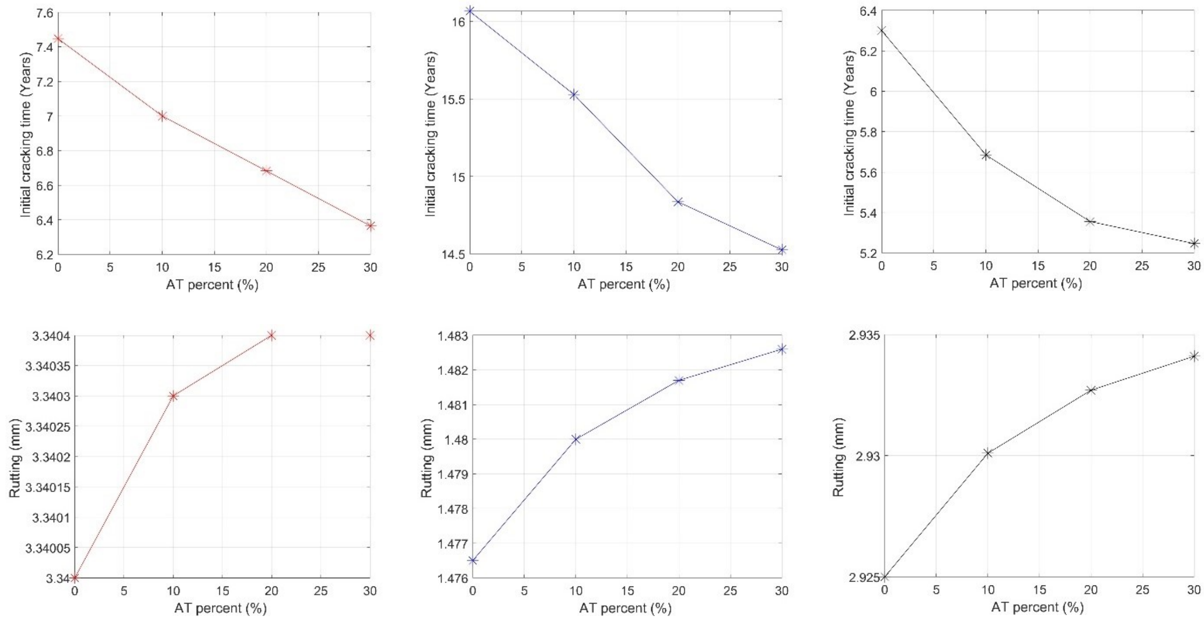
Requiring programmatic wheel wander for ATs may be the most economic hardening option, and Figure C-3 shows the impact of wheel wander of ATs on pavement performance. With the increase of wheel wander of ATs, the rutting decreases and cracking initiation time increases, but its effect on reducing rutting is not sufficient.

Increase in AC Layer Thickness

Increasing the AC layer thickness may be the most effective way to reduce the negative impacts of ATs on pavement performance. However, increasing the AC layer thickness will also increase the cost for pavement construction. Figure C-4 shows the impact of the thickness increase of the AC layer on pavement performance. Increasing the AC layer thickness not only decreases rutting but also increases the cracking initiation time considerably.

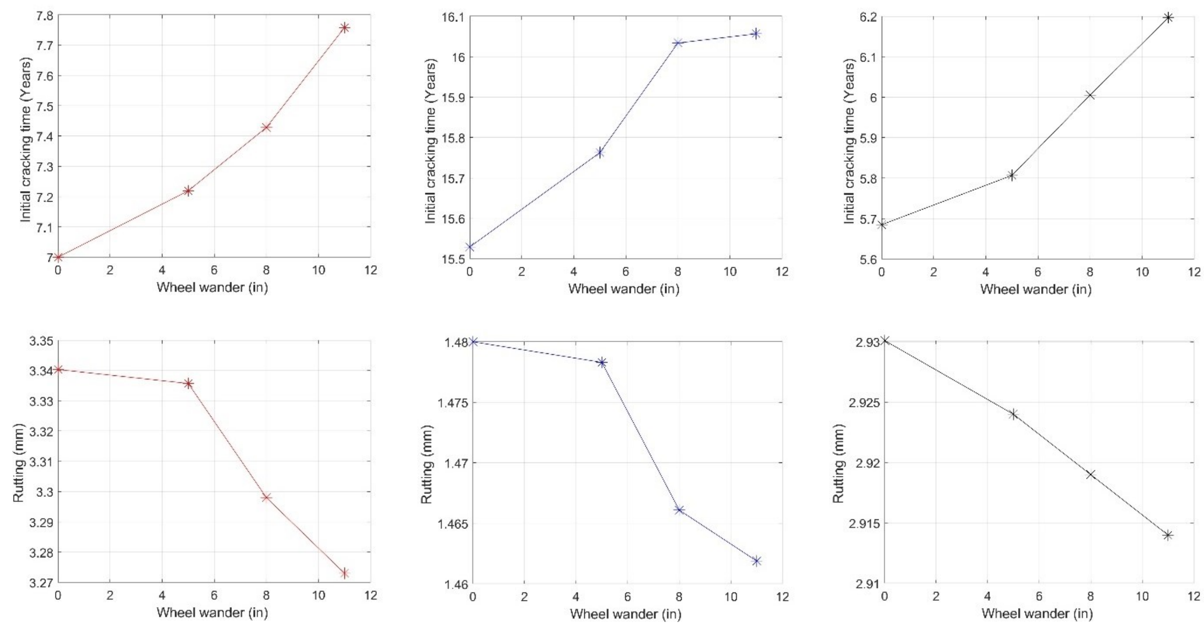
Designated Lane(s) for AT Use

Designating a lane for AT-only use can decrease the overall truck traffic on this lane. With the decrease of general truck traffic, the rutting development of this lane decreases, and the cracking initiation time increases, as Figure C-5 shows. Although designating a lane for AT-only use is not as effective as the second hardening option of increasing the thickness of all lanes, it can bring some other potential benefits. For example, an increased number of ATs may reduce highway capacity and cause inconvenience for passenger vehicles. Thus, designating a lane for AT-only use can help improve safety and relieve congestion flow and may make this the safest hardening option. Additional information is available in TxDOT Report 0-6984-R1, which examines lane use by automated/autonomous trucks and traffic impacts.



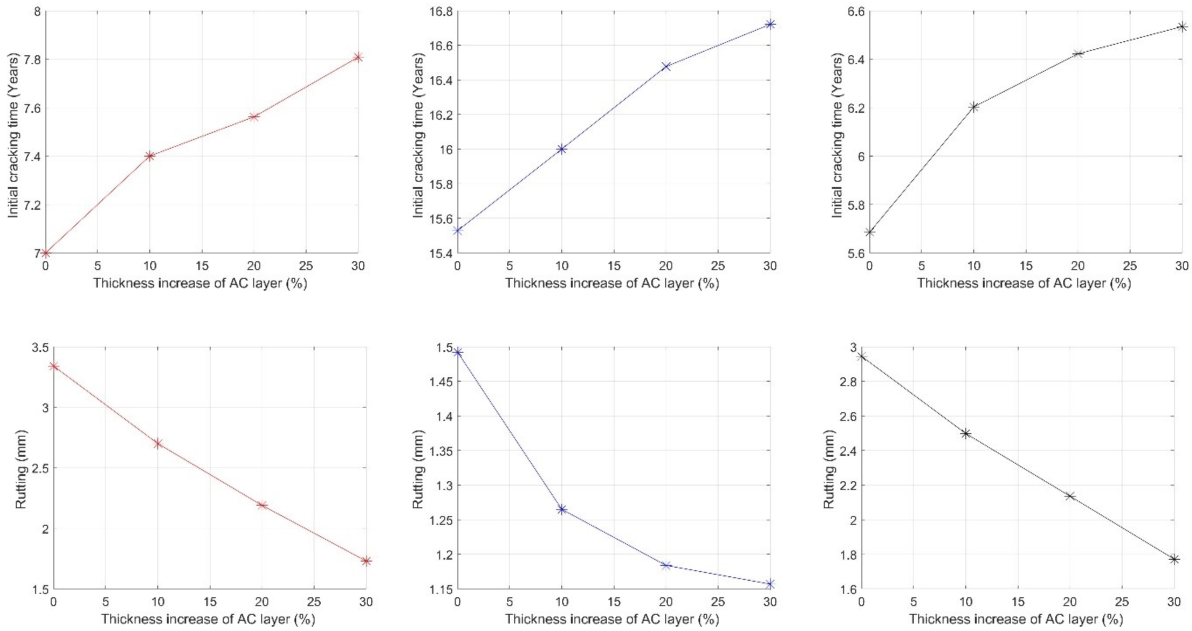
(a) I-10 Section (b) I-35 Section (c) I-45 Section

Figure C-2. Impact of Increased Numbers of Automated Trucks on Pavement Performance.



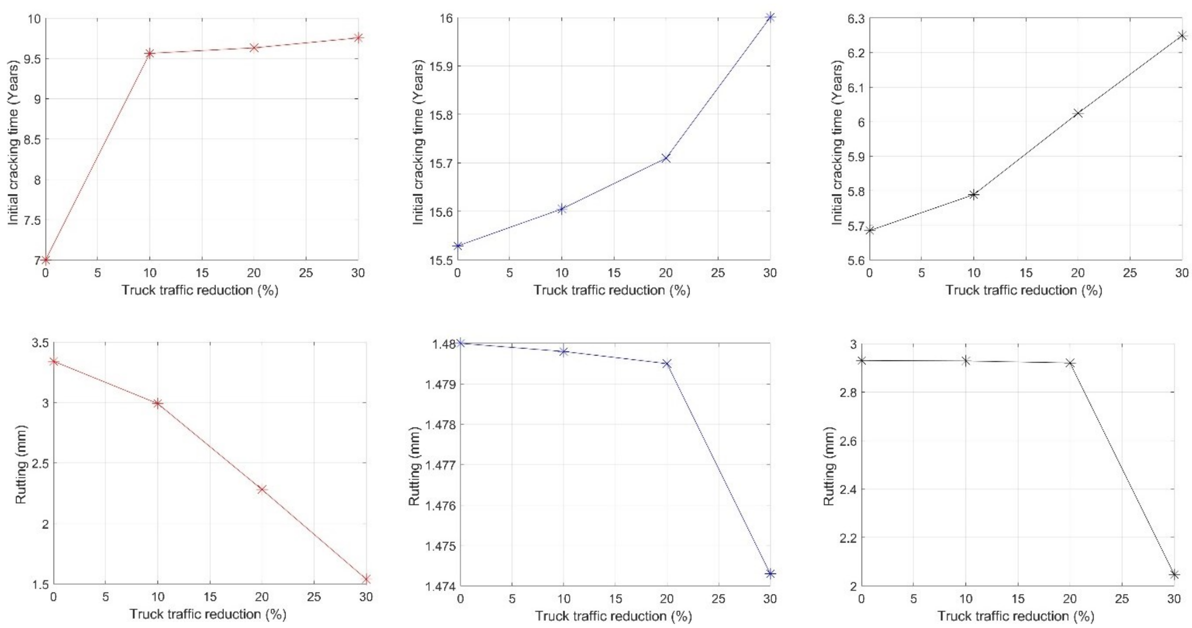
(a) I-10 Section (b) I-35 Section (c) I-45 Section

Figure C-3. Impact of Wheel Wander of Autonomous Trucks on Pavement Performance.



(a) I-10 Section (b) I-35 Section (c) I-45 Section

Figure C-4. Impact of Increase in Asphalt Concrete Layer Thickness on Pavement Performance.



(a) I-10 Section (b) I-35 Section (c) I-45 Section

Figure C-5. Impact of Truck Traffic Reduction on Pavement Performance.

Appropriate hardening actions for a specified roadway can be determined based on ADT. Figure C-6 shows the ADT distribution of pavement sections on I-10, I-35, and I-45 corridors in 2021. For pavements with high or medium ADT, it is appropriate to designate a lane for AT-only use and adopt a low wheel wander for ATs to improve safety and smooth traffic flow. Such pavement sections are primarily located in larger cities, as Figure C-7 and Figure C-8 show. For pavements with lower ADT, a larger wheel wander for ATs can be adopted as an appropriate hardening option. When designing new pavements or rehabilitating some pavements, a thicker AC layer can be adopted by considering AT use.

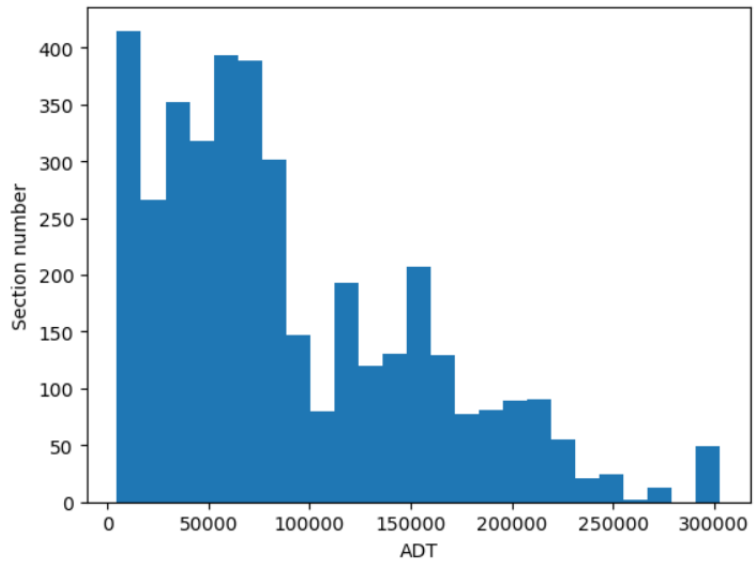


Figure C-6. Average Daily Traffic Distribution of Pavement Sections on I-10, I-35, and I-45 Corridors in 2021.

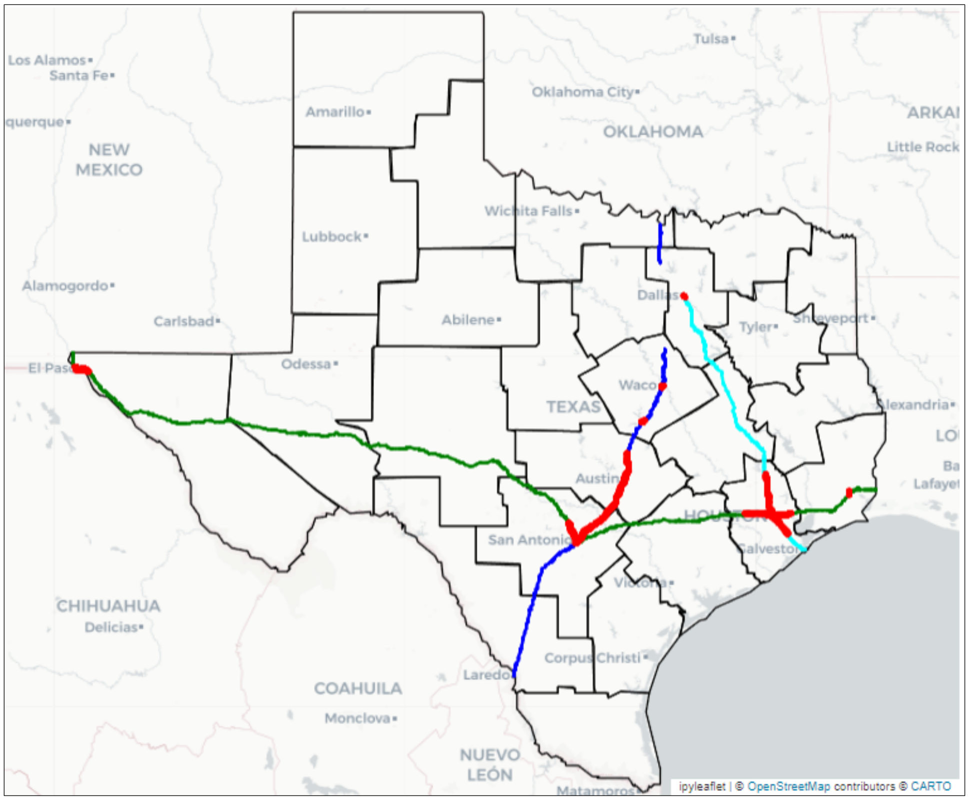


Figure C-7. Location of Pavement Sections with Average Daily Traffic Greater than 10,0000 on I-10, I-35, and I-45 Corridors.

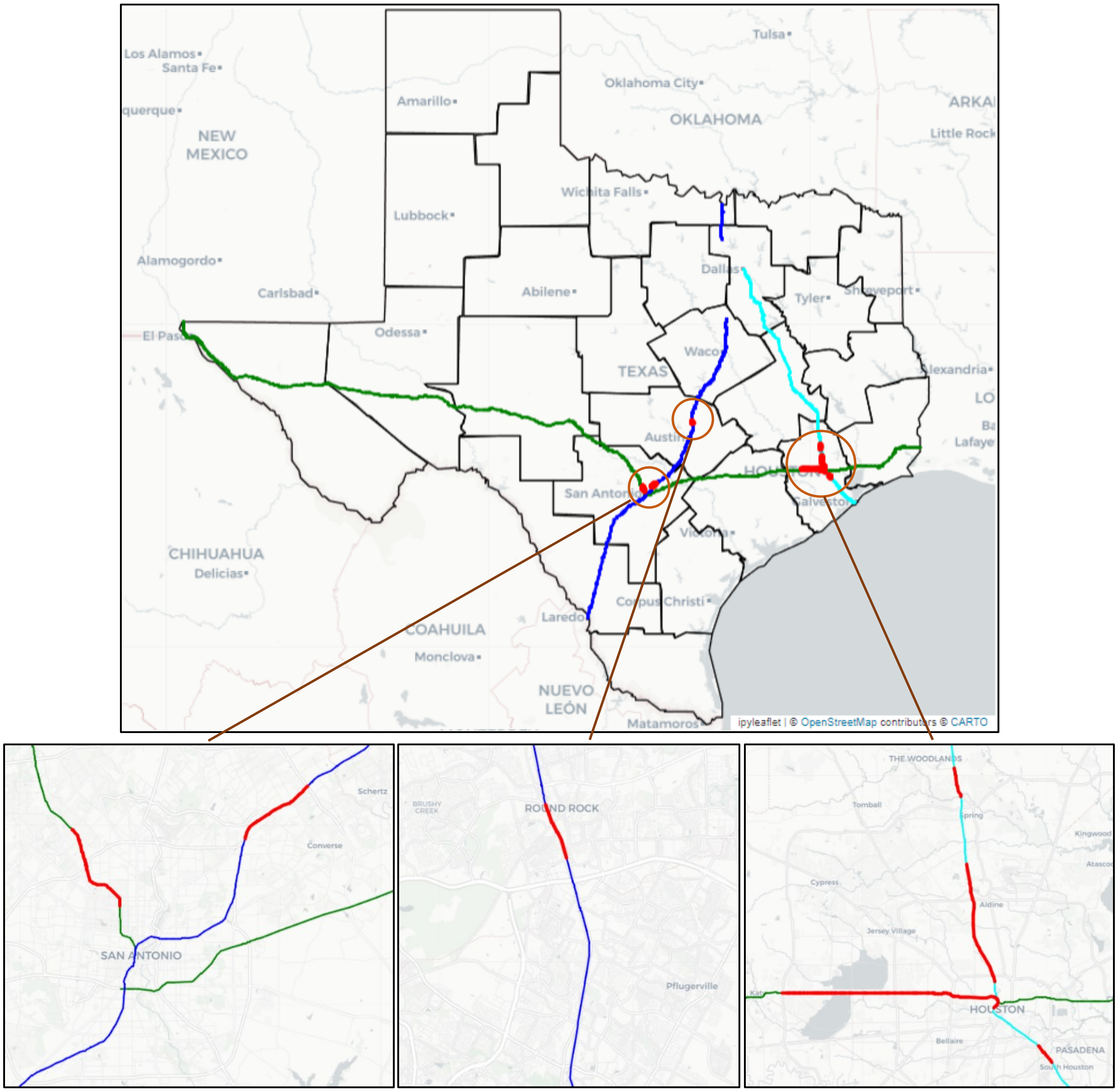


Figure C-8. Location of Pavement Sections with Average Daily Traffic Greater than 20,0000 on I-10, I-35, and I-45 Corridors.

The pavement susceptibility to cracking and rutting is shown in Figure C-9 and Figure C-10, respectively. For cracking:

- Pavements with high risk correspond to a cracking initiation time of less than 5 years.
- Pavements with medium risk correspond to a cracking initiation time ranging from 5 to 10 years.
- Pavements with low risk correspond to a cracking initiation time longer than 10 years.

For rutting:

- Pavements with high risk correspond to permanent deformation greater than 10 mm in the 10th year after construction.
- Pavements with medium risk correspond to permanent deformation ranging from 2 to 10 mm.
- Pavements with low risk correspond to permanent deformation less than 2 mm in the 10th year after construction.

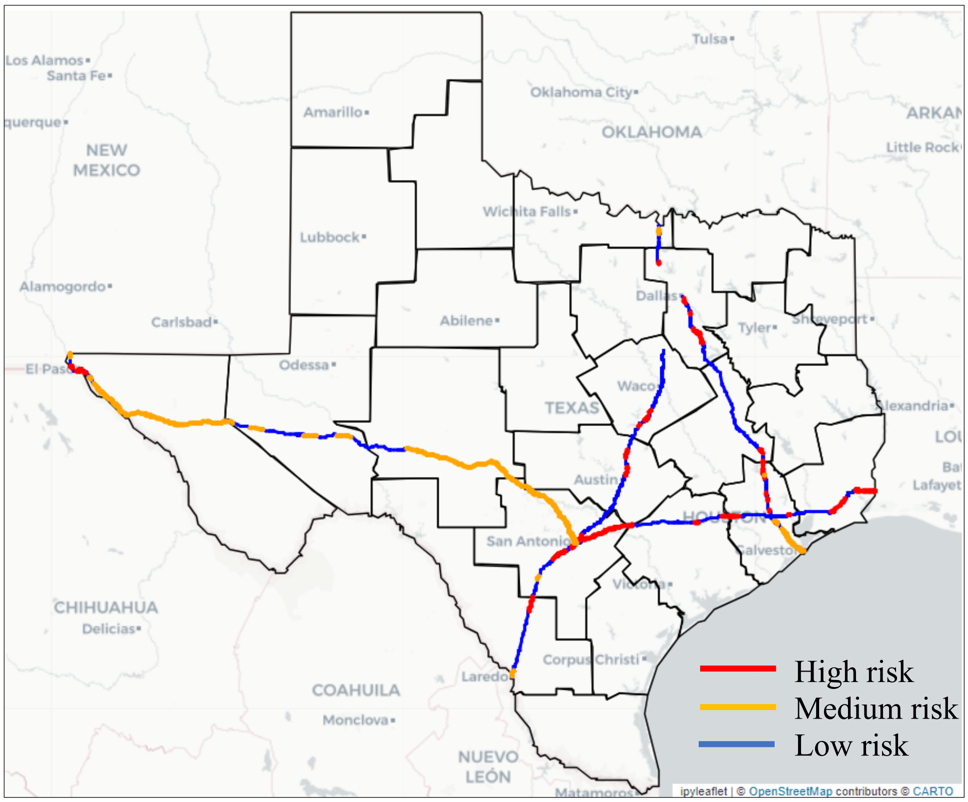


Figure C-9. Susceptibility of Pavements to Cracking on I-10, I-35, and I-45 Corridors.

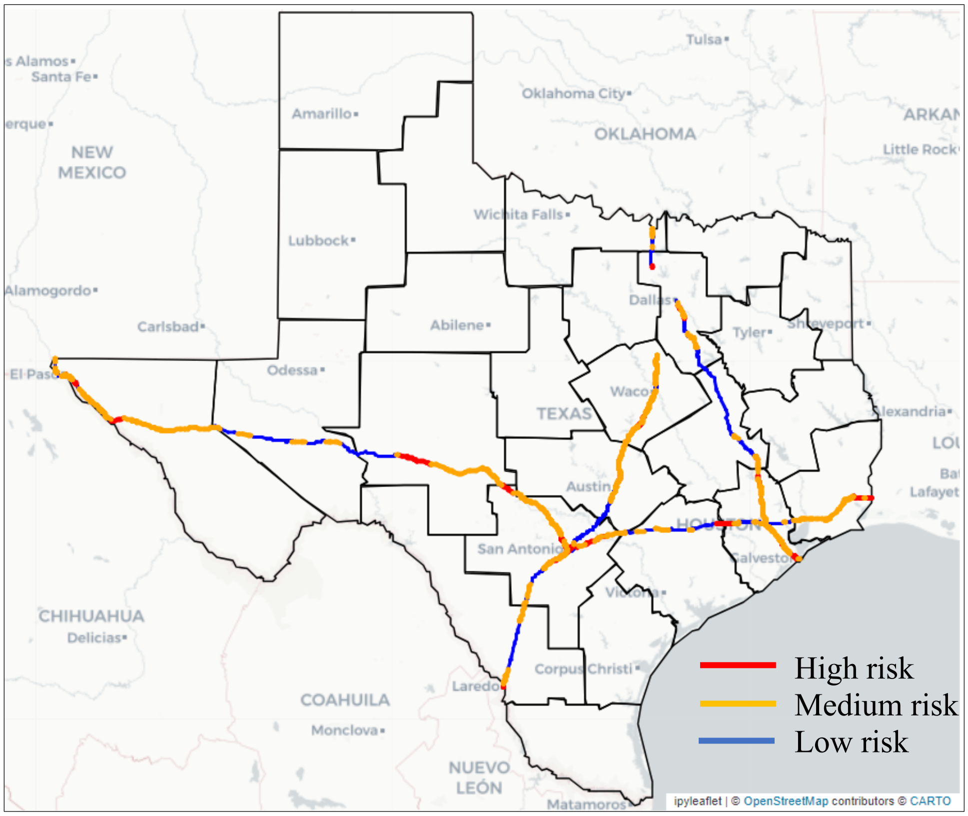


Figure C-10. Susceptibility of Pavements to Rutting on I-10, I-35, and I-45 Corridors.

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