Strategic Research PROGRAM

Connected Vehicle Test Bed at the Riverside Campus

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CONNECTED VEHICLE TEST BED AT THE RIVERSIDE CAMPUS

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**Abstract**
The Texas A&M Transportation Institute (TTI) shares an industry vision where no vehicles collide and users can interact with automated and connected transportation to transform how people live, work, and interact with our environment. Connected transportation has the potential to enhance the safety of the transportation system by expanding that vision to include communication between the transportation infrastructure and various modes of transportation. In this project, TTI researchers developed a framework and a Concept of Operations to design and operate an automated and connected vehicle test bed in the Riverside Campus. The researchers were also engaged in discussion with external agencies, other researchers, and private industry to understand their needs for a test bed and how TTI can leverage it to bring in additional research. The researchers acquired and tested technology components to understand how vehicles equipped with Dedicated Short Range Communication (DSRC) technology interact with roadside infrastructure. Lessons learned from the test would be valuable to design a test bed in more detail to develop and test automated and connected vehicle applications.

**Key Words**
 Automated Vehicle, Connected Vehicle, Test Bed, DSRC, V2I, V2V, Connected Transportation, AV/CV

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Connected Vehicle Test Bed at the Riverside Campus

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EXECUTIVE SUMMARY

The Texas A&M Transportation Institute (TTI) shares an industry vision where no vehicles collide and users can interact with automated and connected transportation to transform how people live, work, and interact with our environment. Connected transportation has the potential to enhance the safety of the transportation system by expanding that vision to include communication between the transportation infrastructure and various modes of transportation.

No single organization has yet emerged as a thought-leader in this connected infrastructure aspect, and TTI has the opportunity to create that thought-leading approach. TTI can achieve this vision by conducting research, development, and testing on how vehicles, users, telematics, and infrastructure all work together in a connected environment—vehicle to infrastructure (V2I) or infrastructure to vehicle (I2V) technologies. This vision should be supported by a state-of-the-art automated and connected transportation system test bed.

The test bed will be an initial step in TTI’s goal to build awareness and obtain new sponsor funding for developing, testing, and deploying various applications and technical services in an automated and connected transportation system. TTI will use the test bed to develop and test automated connected vehicle applications utilizing V2I and I2V communication in a controlled environment.

In this project, TTI researchers developed a framework and a Concept of Operations to design and operate an automated and connected vehicle test bed in the Riverside Campus. The researchers were also engaged in discussion with external agencies, other researchers, and private industry to understand their needs for a test bed and how TTI can leverage it to bring in additional research. The researchers acquired and tested technology components to understand how vehicles equipped with Dedicated Short Range Communication (DSRC) technology interact with roadside infrastructure. Lessons learned from the test would be valuable to design a test bed in more detail to develop and test automated and connected vehicle applications.
INTRODUCTION

Significance of the Project

Why Is This Project Important?

Automated vehicles (AVs) and connected vehicles (CVs) have emerged as new technologies with potential to change the future mobility of goods and people. The United States Department of Transportation (USDOT) is leading several initiatives to develop the CV technology in partnership with universities, private firms, auto manufacturers, and equipment manufacturers. Vehicle manufacturers such as BMW®, Volvo®, and Nissan® are developing AVs.

States such as Michigan, Florida, Virginia, New York, and California have collaborated with their universities in testing CV applications in their states mostly pertaining to I2V (and V2I) type applications. Texas has not followed suit and has fallen behind its peers.

As it currently stands, TTI has limited capabilities and experience in designing, testing, and implementing AV/CV technology applications. Having a test bed will ensure TTI can develop the necessary first-hand experience in integrating field infrastructure and vehicle components as well as develop specific applications for both technologies.

Will It Enhance the Research Diversity Efforts of TTI?

The federal government and auto industry expects rollout of CV technology in a few years after an anticipated National Highway Transportation Safety Administration (NHTSA) ruling in 2015. The auto industry expects gradual introduction of AV in the next decade. If TTI does not get first-hand experience on both technologies now, it will fail to compete nationally against leading universities when federal and state governments start rolling out competitive bids to develop and deploy CV technology based applications.

TTI can sell its professional services for developing CV applications, researching human factors issues, and assessing the public agency benefit of deploying AV/CV infrastructure. In addition, TTI may be able to sell CV application packages and services to state departments of transportation, infrastructure concessionaires (e.g., North Texas Tollway Authority [NTTA], private firms), and metropolitan planning organizations. These prospects clearly show that the project has potential to attract funding from existing and new sponsors.

Will It Allow TTI to Better Compete for Funding?

The work proposed here is a first step to elevate TTI’s capabilities in AV/CV research and development. By establishing this test bed, TTI can develop the expertise to help private and public agencies develop AV/CV applications. Moreover, by the time AV/CV technology starts entering the consumer market, TTI will have the time and a test bed along with necessary capabilities in place to sell AV/CV technology related applications and services.
**Will It Complement Another Research Project?**

In the near future, AV/CV technology will influence research in almost all aspects of transportation, as universities, private companies, and the government will start to develop and implement new applications to take advantage of the technology. One of the largest benefits of the technology is increased safety, and addressing the human factors aspects of the safety benefits is a paramount research focus. Others include transportation operations in which information from vehicles and infrastructure will be used to improve overall mobility, as well as traffic management center operations, incident response, and numerous other facets of operations.

Both AV and CV technologies are also expected to generate big data in both scope and size since a vehicle’s relative position, speed, origin-destination pattern, etc. will be available to agencies in highly granular forms much more frequently (on an almost real-time basis). Such data may also influence how agencies plan and model infrastructure improvements.

**Goals and Objectives of the Project**

**Goals of the Project**

A key goal of the project was to take the first step toward creating a world-class vehicle and transportation infrastructure testing facility at the Riverside Campus. The test bed will be used to develop and test AV/CV components and applications. TTI plans to leverage the test bed to obtain new sponsor funding and pursue major initiatives planned by USDOT, Department of Defense (DOD), and NHTSA.

**Objectives of the Project**

Following are the objectives of the project:

- Discuss with external partners and private industry to understand their need for a test bed.
- Learn to configure and integrate equipment designed to communicate using DSRC, which operates at 5.9 GHz, because CV application largely hinges on DSRC technology.
- Learn to retrofit test vehicles with DSRC capable onboard receivers and radios, retrofit roadside equipment with DSRC capable radios write software programs to process and evaluate test data.
- Develop a framework/concept of operations document that would guide the development of a test bed in the Riverside Campus.

**Work Plan and Activities**

**Activity 1 – Conduct an Internal (TTI Only) Brainstorming Session**

The project team defined the project’s goals and objectives, discuss tasks, and leveraging and partnering potentials with outside agencies (public and private sector). The team discussed areas of application (V2I/I2V) that the test bed would test within the scope and budget of this project.
Activity 2 – Discuss with Public and Private Agencies about Partnering with the TTI Test Bed

The project team discussed with several public and private agencies to leverage this research with additional funding/equipment support/marketing. Initial potential institutional partners included Texas Department of Transportation (TxDOT), NTTA, and DSRC equipment providers that may be able to leverage the project with additional soft and hard dollar funding.

Activity 3 – Assess Requirements to be an Affiliated Test Bed

The team analyzed the benefits and dis-benefits of affiliating the TTI test bed with the USDOT. There are benefits for being one—marketing and collaboration potential. However, it requires TTI to enter into an agreement with the USDOT.

Activity 4 – Develop a Concept of Operations for the Test Bed

The team developed high- and mid-level conceptual architecture of the test bed based on the Connected Vehicle Reference Implementation Architecture (CVRIA). The concept of operations is the framework for testing and developing V2I (I2V) applications at the test bed.

Activity 5 – Procure and Install Equipment

Using TTI’s capital expenditure program, the team purchased Road Side Units (RSUs) and On Board Units (OBUs). The project procured 1) two RSUs with DSRC radios/antennas, communication, and power equipment, 2) two vehicle awareness devices able to broadcast basic safety messages to RSUs, and 3) two aftermarket safety awareness devices able to receive mobility messages from RSUs to broadcast to driver.

The team then equipped one or more TTI vehicles with OBUs and installed RSU on existing utility poles or other vertical structure at the Riverside Campus according to the design set up need to test applications (identified in Task 1).

Activity 6 – Test and Document Various Aspects of the DSRC Technologies

The project team tested the DSRC equipment to understand data transfer mechanisms between OBUs and RSUs, latencies, antenna placements, RSU selection by OBUs, advanced programming interface capabilities, and data storage requirements.

Activity 7 – Perform a Market Assessment

The project team prepared a high-level market assessment to expand the current work by extending the test bed to real-world corridors (e.g., IH35) and determined magnitude of investment needed to develop and test future enhancements.

Activity 8 – Prepare a Final Project Report

The project team prepared a final project report including documentation of work performed under above-mentioned activities.
TTI’S VISION FOR A TEST BED

TTI has a unique opportunity to support the development and test a range of applications supporting CV technologies. Using the test bed environment, TTI will be able to evaluate third party applications and hardware, perform technical feasibility, understand deployment issues, and identify use cases. The Riverside Campus test bed will:

- Advance the AV/CV technologies, research, and practice.
- Demonstrate, evaluate, and confirm how various systems and technologies work together.
- Demonstrate, evaluate, and confirm interoperability between various hardware components.
- Help understand capital and maintenance costs for private and public sectors to develop CV technologies.
- Strengthen relationships between TTI and external partners toward future development of the technologies.

TTI would use the test bed as a real-world laboratory to develop and test AV/CV technologies and applications utilizing V2I and I2V communication in a controlled environment. The test bed will provide opportunities to perform research, develop, and test products and technologies related to:

- Vehicles sending and receiving data from other vehicles and road side infrastructure.
- Road side infrastructure sending and receiving data to a central processing location through wireless or wire line communication.
- Process and archive collected data for the purpose of research and development as well as communicate information to the stakeholders and external entities.

By establishing a fully functional test bed, TTI can develop the expertise to help private and public agencies develop AV/CV applications. Moreover, by the time AV/CV technology starts entering the consumer market, TTI will have the necessary capabilities in place to sell AV/CV technology related applications and services. Having a test bed will ensure TTI first-hand experience in integrating field infrastructure and vehicle components as well as develop specific applications for both technologies.
PARTNERING POTENTIALS WITH EXTERNAL AGENCIES

State and Federal Transportation Agencies

TxDOT is a leader in deploying intelligent transportation system (ITS) technology on the state’s primary roadway network and international border crossings. The CV technology, especially V2I is of special interest to TxDOT since it owns and manages the “I” part of V2I. TxDOT will play a lead role in deploying the CV infrastructure on the state and interstate highway system with a mission to reduce crashes and improve mobility. It will also play a pivotal role in formulating policies to regulate operation of AV/CVs.

TTI will continue to support TxDOT in its mission by providing expertise in AV/CV technology testing and deployment. The test bed at Riverside will play a critical role in providing that expertise. In this regard, TxDOT has requested proposals from universities in Texas for research projects on the topic, to which TTI has responded on several occasions. TxDOT has also shown a great interest in creating a test bed in the state and has sought TTI’s assistance. At this point, all the discussions between TTI and TxDOT are preliminary.

Similarly, on the federal level USDOT is leading the initial stage development of the CV technology through various programs (e.g., Safety Pilot, University Transportation Center). It has established a program by which test beds scattered around the country can share information and exchange ideas to improve the CV technology. USDOT will continue to fund the testing and deployment of CV technology and support individual states in similar activities.

Regional Transportation Agencies

Regional transportation agencies such as metropolitan planning organizations, toll authorities, regional mobility authorities, and port authorities also benefit from the deployment of AV/CV technologies. The agencies plan, program, and fund AV/CV deployment projects in their corresponding regions and corridors.

NNTA approached TTI about the impact on its future operation due to AVs. It envisions that AV technology could improve the traffic throughput on its facilities. It is also interested in using CV technology to reduce wrong way driving crashes on its facilities. The test bed can develop and test such applications before they are deployed on NTTA’s toll facilities.

Private Companies and Equipment Providers

Southwest Research Institute (SwRI) has shown keen interest in collaborating with TTI, and they have experience in developing AVs for combat operations for DOD. Partnership with SwRI might be of value in developing and testing AV applications. SwRI is also interested in deploying a CV test bed on IH35/SH21 with TTI as a partner.

DSRC manufacturers, which received awards from USDOT to supply equipment for its Safety Pilot program, are also interested in collaborating with TTI. These companies are willing to let TTI test their products and develop applications so that they can market their products by saying that their equipment has been independently tested in a controlled environment.
Transcore® is a global provider of technology solutions for transportation systems including on-board diagnostics, tolling equipment, etc. Transcore at present does not manufacture 5.9 GHz equipment, but is highly interested in collaborating with TTI in deploying DSRC capable field equipment in a large-scale test environment.

Regarding AV, the memorandum of understanding TTI has with Google® can be fruitful if they agree to lend TTI one of their Google Cars to test AV applications. If that materializes, then TTI can start developing and testing AV applications. If not, then TTI can still pursue Google to lend a Google Car or provide license to its kit at a reduced price.
ASSESSMENT OF AFFILIATING THE TEST BED WITH USDOT

USDOT’s Affiliated Test Bed Program

The Affiliated Test Bed, organized by the Intelligent Transportation Systems Joint Program Office of USDOT, focuses on deployment of CV technology, the wireless exchange of critical safety and operational data between vehicles and specific road infrastructure. The affiliation will help ensure future CV applications are based on common implementations of the communications technology and will harness the collective abilities of its members.

Goals of the Affiliated Test Bed include information exchange between members, sharing deployment lessons learned, developing a common technical platform for V2I communications, and expanding test bed options for users.

Agencies with the Affiliation

Agencies have to sign a Memorandum of Agreement (MOA) with the USDOT to become part of the affiliated test bed program. The purpose of this MOA is to create a non-binding, precompetitive affiliation of 5.9 GHz DSRC infrastructure device makers, operators of V2I installations, and developers of applications that use V2I communications.

So far, the following entities have signed such an agreement:

- Siemens.¹
- Southwest Research Institute.²

Affiliation Requirements

In order to become affiliated with USDOT, the entities do not have to have an operational test bed. However, the entities should have resources and expertise to assist the government in developing the CV technology.

The MOA outlines that the entities signing the MOA shall:

- Assign personnel to attend the regular web meeting, video teleconference, or teleconferences.
- Participate in at least one Specific Task by contributing to at least one task as consistent with or identified in the Statement of Work.
- Suggest to the government topics to be considered for additional Statements of Work.
- Assist the government in the creation, publication, and distribution of reports, reviews, and other data pertinent to the research and analysis performed under the MOA.


- Be responsible for the cost of its personnel’s attendance at, and participation in, meetings, video teleconferences, teleconferences, and other activities relating to work under the MOA.
- Report all inventions to the government within a time defined in the MOA.

**Benefits to TTI and the Test Bed due to Affiliation**

One of the key benefits to TTI or any other entities affiliated with USDOT is that they can actively contribute to the development of CV and at the same time learn what other test beds and equipment vendors are progressing. TTI can also identify itself as a member of the Affiliated Test Beds and can use the Affiliated Test Bed mark on documents, promotional materials, and websites. This could be a great marketing tool for TTI’s test bed and promotion of its expertise in the field.
CONCEPT OF OPERATIONS FOR THE TEST BED

Purpose of the ConOps

The Concept of Operations (ConOps) for the design and deployment of the AV/CV test bed at the Riverside Campus describes high-level goals and objectives of the test bed, identifies user needs, and details high-level design of the test bed. Goals and objectives of the ConOps outlined in the document are intended to be high-level and may not necessarily be quantifiable or testable. Future documents including functional requirements, architectures, and location of devices will be developed when specific applications and tests are performed at the Riverside Campus. The purpose of this document is to describe the needs for a test bed from the stakeholder perspectives. The ConOps:

- Provides a resource for development of engineering requirements and supports decision makers in their assessments and evaluations of the test bed.
- Lays a foundation to design, test, and deploy AV/CV related technologies and applications at the Riverside Campus.
- Provides an understanding of strengths and capabilities of the Riverside Campus to function as a test bed.
- Lays key considerations necessary to expand the facility to perform more advanced and complex tests in the future.

The ConOps is intended to be a living document with amendments in the future as a result of changes in technologies and test bed participants/partners.

Intended Audience of the ConOps

The ConOps helps stakeholders focus on the proposed system’s capabilities to meet TTI’s objectives and understand the effect of the proposed system on other internal and external systems and practices. Stakeholders include researchers from TTI, external partners comprising of federal and state governments, private sector agencies, system engineers/architects, system implementers, equipment manufacturers, and application developers. The ConOps also helps system engineers/architects understand the constraints, assumptions, requirements, and priorities set forth to design the test bed and develop CV applications in the future.

Content and Organization of This ConOps

The ConOps is an early and critical step in the systems engineering process. The purpose of a ConOps document is to provide a description of why a system is needed and how it would be used considering the viewpoints of the various stakeholders. The main purposes of a ConOps are to:

- Document the environment and use of the system in a non-technical and easy-to-understand manner.
- Present the information from multiple viewpoints.
- Bridge the gap from the problem and stakeholder needs to system level requirements.
Overall, the ConOps will describe the basic who, what, when, where, why, and how of a AV/CV test bed at the riverside campus.

- Who – the stakeholders are, their responsibilities, how they will use the system.
- What – the existing components or systems to be examine and/or integrated together.
- When – the timeline over which the system will be developed and operated.
- Where – the geographic limits of the system.
- Why – the problems or issues the system will solve.
- How – the resources needed to plan, design, deploy, and operate the system.

Referenced Documents

While preparing the ConOps, the following documents were referenced:


Description of the Riverside Campus

The Riverside Campus is a former United States Air Force base with large expanses of concrete runways and parking aprons that are well-suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and evaluation of roadside safety hardware and physical security systems. The 2000-acre facility has four inactive runways, one active runway, and a large area of service concrete apron. Figures 1 and 2 show the aerial view and map of the facility. The Riverside Campus has numerous paved secondary roads positioned in a grid-type arrangement. This facility has low and high speed testing capacity and is currently used simultaneously by multiple divisions within TTI and by other organizations part of the Texas A&M University (TAMU) System.
The TTI Roadside Safety and Physical Security Division uses portions of the campus as a test bed on a daily basis for low and high speed full-scale crash tests. The TTI Proving Ground (which is part of the Roadside Safety and Physical Security Division) averages 60 to 100 full-scale crash tests each year. As a result, multiple test installations are under construction at any given time. The TTI Proving Ground is accredited under ISO/IEC 17025:2005 to perform tests under ASTM F2656-07, the AASHTO Manual for Assessing Safety Hardware, NCHRP Report 350, EN-1317, and PAS-68. Under the accreditation process there are written procedures for all
aspects of the full-scale crash testing with internal and external audits verifying safety and compliance with the procedures listed under the accreditation.

The TTI Operations and Design Division has conducted numerous testing at the Riverside Campus aimed at evaluating sign and pavement marking retroreflectivity, sign legibility, sign visibility, work zone lighting, work zone traffic control devices, pedestrian traffic control devices, rumble strips, and alcohol impaired driving. Some of these studies were conducted at night.

The Proving Ground Program from the Roadside Safety and Physical Security Division maintains well-equipped instrumentation laboratories, calibration facilities, and shops, which are staffed by highly-skilled personnel who design, fabricate, assemble, and install sophisticated mechanical, electronic, and photographic instrumentation in test vehicles and on test devices for the collection of data generated by experimental research. The program is divided into following sections that support the researchers needing to perform tests inside the campus:

- The Electro-Mechanical Research Instrumentation Section designs, fabricates, calibrates, and maintains measurement and control systems for a variety of research projects. Although a large number of instrumentation system components are available commercially, many unique components and systems must be designed and fabricated in-house.
- The Photographic Research Instrumentation Section is responsible for the photographic documentation and data acquisition from crash tests and other related research. The photo-instrumentation group has an extensive inventory of high speed video cameras (including one HG model camera for use in on-board or high G applications) and documentary film cameras.
- The Construction Section fabricates prototype devices and constructs full-scale test installations. The section is staffed with six full-time experienced individuals and equipped with extensive industrial equipment including a front end loader, track hoe, back hoe, maintainer, and various forklifts and trucks.
- The Evaluation and Reporting Section provides an interdisciplinary approach to experiment planning, testing, data reduction and analysis, and report writing. The section staff is well-versed in the evaluation criteria and reporting formats of various testing specifications. Drafting for the Division is also accomplished by this section.
- The Central/Western Field Test Center, operated by the Proving Ground Program, is one of two national centers for calibration and correlation of highway friction measurement systems. Over 20 states visit the Center periodically to have their systems calibrated and correlated with the national reference system at the Field Test Center. Over 300 evaluations have been completed on state friction measurement systems since the Center’s creation in 1973 by Federal Highway Administration.

Since there are multiple users of the facility inside the Campus at the same time, coordination between divisions and agencies is needed, and testing planning processes are mandatory. Before performing a test at any location at the Riverside Campus, availability of the test site needs to be checked, and proper site reservation needs to be completed. Availability of the test site can be verified under the Riverside Map on the following website [http://fcor.tamu.edu/](http://fcor.tamu.edu/). This map is updated with the latest reservations from TTI and other Texas A&M agencies. Reservation of the
test site can be achieved by filling adequate forms at http://fcor.tamu.edu/riverside-scheduling.aspx.

Whenever scheduling problems occur, Duane Wagner from TTI Facilities, Safety and Support Services can be directly contacted. He can also assist anyone with the process of reserving a desired site inside the Campus. Alternatively, Bob Rudder from the Texas A&M Facilities Coordination can be contacted for planning purposes.

When a test site is reserved, it can be accessed for testing. However, caution still needs to be used when reaching the desired location, since other sites might need to be crossed. In addition, if testing occurs near to the Unexploded Ordnance (UXO) training location, warning needs to be given to UXO personnel, even on the same day.

If power is needed anywhere on the Riverside Apron and/or Runways, generators or solar panels can be used. It is not permitted to cross runways with power lines, thus it is suggested to use wireless communication from the test side to Riverside offices, if needed. Wireless communication Worldwide Interoperability for Microwave Access (WiMAX) can be used, and necessary instrumentation (modem) is available for use, upon TTI approval.

**Utilizing a Systems Engineering Approach**

Figure 3 shows the traditional systems engineering approach. The ConOps is a critical component of the early planning process and defining the baseline requirements for the project. As stated, the ConOps describes the high-level goals and objectives of the test bed, identifies user needs, and details high-level design criteria for the test bed.

As illustrated in Figure 4, within the systems engineering process, the overall objective of determining design requirements for the Riverside test bed project followed a linear approach.
Given the identification of the project vision, and corresponding goals and objectives, the range of stakeholders was identified. Each of these user categories had specific needs, which were then clearly identified.

![Figure 4. Systematic Process for Project Development.](image)

The process then detailed the physical layout necessary for the test bed environment, followed by each of the known operating environments for the project, (i.e., the operational scenarios) and ensures that the user groups and user needs for each scenario are not only identified but can be met by the system functions detailed in each scenario. Following the operational scenarios, these system functions are accumulated to provide an overall list of functional requirements for the overall test bed project.

**Vision**

The vision of this project is to describe the foundational resources required for TTI to participate in the national research arena in the area of AV/CV technologies and applications by establishing an AV/CV test bed at the TTI Riverside Facility.

**Goals and Objectives**

Researchers at TTI working in the AV/CV arena require a test bed in which they can conduct research and application development related to AV/CV technologies. The facility needs to be multi-faceted, allow for numerous different types of testing, have broad appeal to a wide user group, and have concrete resources in place to facilitate research and testing.

The specific objective of the facility is to allow the design and testing of AV/CV applications by emulating 1) various types of roadway environments (e.g., high speed, low speed), 2) configurations (e.g., merge, multi-lane, diverge, ramps, intersections), and 3) vehicle types (e.g., passenger cars, buses, trucks, bicycles, pedestrians).
Stakeholders

A variety of stakeholders are envisioned for the AV/CV test bed, including:

- Researchers.
- TTI Administration.
- System engineers/architects.
- System implementers.
- Equipment manufacturers.
- Application developers.

Each stakeholder role listed above could come from a variety of agencies, including TTI, the federal government, state government, and private sector agencies.

Researchers are envisioned to be the primary users of the AV/CV test bed. TTI researchers in particular would be the primary users of the test bed environment, as they conduct research for a variety of state and federal sponsors. A wide variety of research is needed in the AV/CV arena, including communications, applications, equipment, environments, vehicles, and how those components all interact with each other at both low-speeds and high-speeds. Collaborative agreements and funding with other research agencies could also place other researchers at the facility, undoubtedly working cooperatively with TTI researchers.

TTI Administration is a primary stakeholder in this endeavor and has a vested interest in the outcome by supporting the development of the test bed through funds, allocation of agency resources, and the ability to promote the resulting facility for research.

System engineers and architects would most likely use the test bed to mock-up particular characteristics of the real roadway network, such as a low-speed environment or a high-speed environment. The usefulness of the test bed to service this purpose is the ability to construct the mock-up in a closed and controlled environment and examine different solutions to the problem being investigated. One particularly relevant example is the type and range of the communications environments required for AV/CV applications. This is an area that still needs significant work and refinement.

System implementers will need to assess and refine numerous factors pertaining to AV/CV operations in a variety of environments, prior to implementing them in a real-world environment. Using the AV/CV capabilities at Riverside to conduct these assessments would be a critical step to accomplish prior to real-world deployments.

Original Equipment Manufacturers (OEM) could use the controlled testing environment at Riverside to test out new products. This is particularly true for equipment makers other than vehicle manufacturers who may be small start-ups without deep resources to construct their own AV/CV testing environment.

Application developers could deploy their applications in vehicles within the Riverside AV/CV environment and test and catalog results under different communication environments,
geometries, and environmental conditions such as an induced loss of communications or rapid switching between different modes of communications.

User Needs

Table 1 details the minimum requirements necessary for research across the identified stakeholder. In addition to the minimum requirements outlined in Table 1, TTI intends to affiliate this test bed with the USDOT, a step that entails additional requirements. The USDOT requirements must provide for external agencies to plug in to the facility and test various applications. However, the external agencies must have a prior agreement with the TTI to do so. The following additional requirements are necessary to receive affiliation from the USDOT:

- Media access for proper implementation of IEEE 802.11p CSMA/CA (or other radio service standard).
- Channel use for proper implementation of the Part 90 FCC channel plan.
- Communication security/privacy for suitable implantation of privacy protection and communication security similar to the plan used in the Southeast Michigan 2014 project.
- Application message standards for implementation of (open) application-level message standards.
- Extensibility for providing the capability to host additional applications in the future.
### Table 1. Minimum Stakeholder Requirements.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Researchers</th>
<th>TTI Administration</th>
<th>System Engineers</th>
<th>System Implementers</th>
<th>Equipment Manufacturers</th>
<th>Application Developers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability to operate the facility in a safe manner, adhering to all system</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>and Riverside guidelines for the conduct of research in a shared facility.</td>
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<tr>
<td>Ability to capture data/images from tests for stakeholder publications,</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>such as presentations, promotional materials, and internal documents.</td>
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<tr>
<td>Sufficient runway space to mark the existing pavement in a variety of</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>configurations necessary for testing (low-speed and high speed).</td>
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<tr>
<td>Sufficient vehicle path space to provide for a high-speed run-up and</td>
<td>X</td>
<td></td>
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<td>turn-around capability for vehicle testing.</td>
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<tr>
<td>Sufficient right-of-way on vehicle path space to provide for installation</td>
<td>X</td>
<td></td>
<td>X</td>
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<td>of temporary channelizing devices.</td>
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<tr>
<td>Sufficient right-of-way on vehicle path space to provide for installation</td>
<td>X</td>
<td></td>
<td>X</td>
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<td>of temporary signage.</td>
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<tr>
<td>Sufficient roadside right-of-way to provide for permanent or temporary</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>installation of infrastructure such as 5.9 GHz DSRC radios, cellular or</td>
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<tr>
<td>other wireless infrastructure, ITS devices, communication equipment, and</td>
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<td>power supply.</td>
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<tr>
<td>Two-way communications with all field sensors.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Transfer data to/from field sensors from other nearby field infrastructure</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>and remote servers.</td>
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<tr>
<td>Store, process, and analyze test data in both near-real time and after</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>completion of the tests.</td>
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<tr>
<td>Tools, facilities, and storage necessary for outfitting vehicles with</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>necessary equipment for the AV/CV test bed environment.</td>
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<td>The ability to schedule and run tests using multiple vehicles traversing</td>
<td>X</td>
<td></td>
<td>X</td>
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<td>the prescribed vehicle paths for both low-speed and high-speed environments.</td>
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<tr>
<td>Real-time monitoring and surveillance of the tests being conducted in the</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>facility to ensure visibility to the researchers and observers.</td>
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<tr>
<td>Two-way communications with all individuals involved in testing, including</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
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<td>field observers, drivers, and test overseers.</td>
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</tbody>
</table>
**AV/CV Test Bed System Overview**

The test bed will require necessary services to be in place to fulfill the needs of its users (stakeholders) who will conduct the tests at the facility. At this stage, it is not necessary to allocate a dedicated space in the campus for the test bed. Depending on the nature of the test, any portion of the campus except the permanently occupied space by agencies can be used, depending on prior approval of the TAMU Facilities Coordination Office.

In terms of a general concept for the Riverside Campus test bed, Figure 5 shows how the physical components of the test bed will be connected with one another. This arrangement may vary for different use cases or applications being tested.

Depending on the application being tested, different parts of the Riverside Campus may be used (e.g., runways versus street grid). Some applications may be performed by emulating a layout within the runways. For initial testing, it is envisioned the RSEs will be installed on existing utility poles or on raised portable poles. In the future as tests become more frequent, a network of fixed RSEs would be installed. Because there are no fiber networks on the runways or in the street grid, data from RSU will be transmitted to the back office via short range wireless communication such as WiMAX. The back office will be connected to TTI’s network to provide local and remote access to TTI researchers, external partners (through firewall), and to the public via web servers. It is not clear at the moment, what information will be shared with the external partners or with the web.
Figure 5. General Concept for Riverside Campus AV/CV Test Bed.

Nomenclature for AV/CV Test Bed Physical Components

Descriptions and diagrams for an AV/CV test bed can be complex. To assist in this complex process, the USDOT has defined a Connected Vehicles Reference Implementation Architecture. The CVRIA can be used to construct a set of system architecture viewpoints that describe the functions, physical and logical interfaces, enterprise relationships, and communication protocol dependencies within a CV environment. The CVRIA will also support policy considerations for certification, standards, core system implementation, and other elements of the CV environment. It is logical for all developing test beds to portray their architecture in the CVRIA nomenclature to ensure consistency, understanding across stakeholders, and conformity to national standards. Across the CVRIA, language and components have been standardized so that disparate implementations across the nation can take place and ensure communication and data consistency. Within the architecture, diagrams can be created for the following viewpoints:

- **Enterprise** – shows the relationships between organizations and the roles those organizations play within the CV environment.
- **Functional** – show the processes and the data flows that satisfy the system requirements.
- **Physical** – shows the physical objects (systems and devices) as well as the high-level interfaces between them.
- **Communications** – shows the communications protocols required to support communications among the physical objects that participate in the CV environment.

Additionally, diagrams can be created for various levels within viewpoints to allow for varying levels of detail. The following level diagrams are defined and can be created:
• Level 0 – shows high-level physical objects and interconnections.
• Level 1 – shows project specific physical and application level objects and interconnections.
• Level 2 – shows application level detail objects and interconnections.

The test bed design described in subsequent sections includes physical objects, application objects, and layout of the physical components. Physical objects define major physical components necessary to deploy a CV environment whether that is a test bed or a real-world deployment. The following are the definitions of the physical objects.

A Driver represents the person that operates a licensed vehicle inside the test bed. Included are operators of private, transit, commercial, and emergency vehicles where the interactions are not particular to the type of vehicle (i.e., interactions supporting vehicle safety applications). Thus, the Driver originates driver requests and receives driver information that reflects the interactions that might be useful to all drivers, regardless of vehicle classification. This object also supports interactions for mobility applications that are primarily intended for drivers of private passenger vehicles. Information and interactions that are unique to drivers of a specific vehicle type (e.g., fleet interactions with transit, commercial, or emergency vehicle drivers) are covered by separate objects.

Vehicle OBUs represents vehicles with OBUs that are communicating with one another and with the RSUs. These vehicles may be traditional vehicles without automation and driverless functions, fully AV, or vehicles retrofitted with automation kits. This object provides a source and destination for information transfers between CVs. The host vehicle on-board equipment, represented by the Vehicle OBU physical object, sends information to, and receives information from the remote Vehicle OBUs to model all CV V2V communications. OBUs represent the on-board devices that provide the vehicle-based processing, storage, and communications functions necessary to support CV operations. The radio(s) supporting V2V and V2I communications are a key component of the Vehicle OBU. This communication platform for the vehicle is supported by processing and data storage capability in the OBU that provide the basic communications functions and higher level CV applications. The Vehicle OBU interfaces to other on-board systems through a vehicle bus (e.g., CAN). In addition to the vehicle bus interface, the OBU also provides an interface to a location data source. Finally, a driver interface is included that supports visual, audio, and haptic interaction with the driver. Configuration of vehicle OBUs may vary depending the application being tested. OBUs may be connected with TTI/TAMU fleet and/or vehicles owned by external partners.

The Local Current Situation Data Warehouse is a Transportation Information Center that provides data collection, fusing, and repacking functions, but only for data that are relevant in the immediate future. Examples of data handled by this TIC are vehicle situation data, or intersection situation data. In a physical form, it could reside in a local or remote server inside or outside the Riverside Campus.

The Local Current Traveler Information Warehouse is a Transportation Information Center that provides data collection, fusing, and repacking functions, but only for data that are relevant over a long time period. Examples of data handled by this TIC are speed limits, traffic signal locations, and road restrictions.
**ITS Roadway Equipment** represents the ITS equipment that interfaces with and supports the RSU. This physical object includes traffic detectors, environmental sensors, traffic signals, dynamic message signs, cameras and video image processing systems, grade crossing warning systems, and ramp metering systems. Lane management systems and barrier systems that control access to transportation infrastructure such as roadways, bridges, and tunnels are also included. This object also provides environmental monitoring including sensors that measure road conditions, surface weather, and vehicle emissions.

**Roadside Equipment** represents the roadside devices that are used to send messages to and receive messages from nearby vehicles with OBU's using DSRC. Communications with adjacent ITS Roadway Equipment and back office centers that monitor and control the RSU are also supported. Depending on the type of application or scope of application being tested, information could be sent to mobile devices via cellular signals or could interface with other parts of the OBU using Bluetooth or USB connections. RSUs will operate from a fixed position and may be permanently deployed or a portable device. An RSU will include a processor, data storage, and communications capabilities that support secure communications with passing vehicles, other roadside equipment, and centers that provide back office support.

**Riverside AV/CV Test Bed Physical Components**

Figure 6 shows the Layer 0 architecture that illustrates communication links between various physical objects within the test bed. In the diagram, communication links are shown as peer-to-peer. These links are shown in two colors, pink and green. Pink indicates trusted and confidential communication, while green indicates trusted, non-confidential communication. The two types of communication are critical in real-world deployment only. In the test bed environment such a distinction is not critical. However, it has been left in place to allow testing applications that require trusted or confidential communication. Local traveler information includes messages from nearby ITS equipment (e.g., dynamic message sign) or from a traffic management center to the RSU so that it can transmit messages to vehicle OBU’s. Such messages may include small area-wide alerts such as inclement weather, queue formations, etc. Driver information may include travel advisories, vehicle signage data, fixed sign information, traffic control device status (e.g., signal phase and timing data), detour information, etc.
A Level 0 diagram is expanded to include Level 1 information by including application objects within each physical object. Application objects define the functionality and interfaces that are required to support CV application. While these application objects have been identified though the CVRIA and are necessary for the full suite of CV applications, many of them are not necessary for test bed applications and will not be provided in the short term. As the test bed matures and more in depth tests are performed, all the following application objects will have to be developed and deployed.

Figure 7 identifies the Level 1 physical diagram that includes the application objects and illustrates communication flows with the physical objects. A brief description of the application objects follows:

- **RSU Basic Traffic Data Collection** will monitor the vehicle situation data provided by the vehicles and will distill these data into traffic flow measures that are then shared with interested centers.
- **RSU Traveler Information Communications** will include field elements that distribute information to vehicles for in-vehicle display. The information may be provided by a center (e.g., variable information on traffic and road conditions in the vicinity of the field...
equipment) or it may be determined and output locally (e.g., static sign information and signal phase and timing information). It will include an interface to the center or field equipment that will control the information distribution and the short-range communications equipment and provide information to passing vehicles.

- **Vehicle Driver Information Reception** will receive advisories, vehicle signage data, and other driver information and present this information to the driver in test bed vehicles using in-vehicle equipment. Information presented may include fixed sign information, traffic control device status (e.g., signal phase and timing data), advisory and detour information, warnings of adverse road and weather conditions, travel times, and other driver information.

- **Vehicle OBU Situation Data Generation** will create vehicle situation data messages and share those messages with other entities in the vehicle’s proximity, and also with the situation data warehouse.

- **Data Access Management** will provide management and control of data collection and distribution, and the provision of data to other transportation entities. It will allow the creation of data distribution profiles, such as subscriptions and pipes, and the assignment of permissions and rights to provide and access these data.

- **Data Collection and Aggregation** will collect transportation-related information, the short-term storage, and organization of these data, including categorization, aggregation, and sampling.

- **Object Discovery Registration and Lookup** is the first point of contact for new devices that wish to operate within the test bed. This service will provide mechanisms for devices to register their existence, contact information (which could be an IP address, for example), what types of information services and data they provide, the mechanisms they use to provide data and information services, and over what time and spatial context those services and data are relevant. Subsequent to registration, devices may query this service to discover data provision and service information about other participants, enabling devices to learn about one another and interoperate in a relatively automated fashion.

- **Peer-to-Peer Data Exchange** will allow message delivery functionality in the vehicle OBU that facilitates the exchange of data between the vehicle and other known entities, including centers and roadside equipment.

- **Security Credential Management System Bootstrap** will manage the distribution (both initial provisioning and refresh) and revocation of digital credentials used by the test bed objects to authenticate and preserve the integrity of information they exchange.

- **TMC Traffic Information Dissemination** will disseminate traffic and road conditions, closure and detour information, incident information, driver advisories, and other traffic-related data to test bed centers, and driver information systems. It will monitor and control information display systems such as dynamic message signs. It will also manage dissemination of driver information through these systems.
OPERATIONAL SCENARIOS

Within the structure of systems engineering, operational scenarios are used to describe how the system (the Riverside AV/CV test bed) behaves under different various conditions. Each different condition is an operational scenario. Under each scenario, this section describes roles and responsibilities of the various users of the system.

For the test bed, three initial operational scenarios have been developed. Note that the initial scenarios focus on the work zone environment as TTI has internationally recognized expertise in this arena, which can be broadened by bringing it to a CV environment, and the current facilities at Riverside are conducive to applications that can be created and tested within a relatively short spacing with temporary infrastructure. The three scenarios are:

- Operational Scenario 1 – Warnings about upcoming work zone.
- Operational Scenario 2 – Queue warning at work zones.
- Operational Scenario 3 – Warnings about hazards in a work zone.
Additional operational scenarios are envisioned for the future as infrastructure and expertise becomes more available.

**Operational Scenario 1 – Warnings about Upcoming Work Zone**

As defined by the CVRIA, the Warnings about Upcoming Work Zone application provides information about the conditions that exist in a work zone to vehicles that are approaching the work zone. This application provides approaching vehicles with information about work zone activities that may result in unsafe conditions to the vehicle, such as obstructions in the vehicle’s travel lane, lane closures, lane shifts, speed reductions, or vehicles entering/exiting the work zone.

**Goal**

The goal is to provide approaching vehicle(s) with information about the presence of a work zone to avoid collisions and unsafe conditions.

**Objective(s)**

The objectives are to:

- Collect status of vehicles approaching a work zone.
- Inform drivers about length of work zone ahead.
- Inform drivers to reduce speed.
- Inform drivers about closure of specific lanes.
- Instruct drivers to change lanes.

The physical layout of the facility required to test operational scenario 1 with a single test vehicle is portrayed in Figure 8. Figure 9 displays the same scenario with two test vehicles involved.
Figure 8. Facility Layout for Operational Scenario 1 – Single Vehicle.

Figure 9. Facility Layout for Operational Scenario 1 – Multiple Vehicles.

Test Procedure for Operational Scenario 1 – Single Vehicle:

1. TTI test vehicle drives toward the work zone.
2. RSU detects OBU. Note the detection range.
3. OBU sends Geographical Positioning System (GPS) position, lane position, and speed to RSU, which sends it to the laptop, emulating the back office of an operating agency.

4. Application in the back office creates a response or Road Side Alert (RSA) payload consisting of:
   a. Length of work zone (next XX Miles).
   b. Suggested speed.
   c. Closure of specific lanes.
   d. Move to specific lane.

5. The back office laptop delivers the RSA payload to the RSU.

6. RSU delivers the RSA payload to the OBU.

7. OBU sends the RSA payload to the laptop. Driver reads the payload message.

8. Log travel time of payload delivery between components.

Test Procedure for Operational Scenario 1 – Multiple Vehicles

1. TTI test vehicles drive toward the work zone.

2. RSU detects both OBUs. Note the detection range.

3. Both OBUs send GPS positions, lane positions, and speed to RSU, which sends it to the laptop, emulating the back office of an operating agency.

4. Application in the back office laptop creates a response RSA payload specific to both test vehicles consisting of:
   a. Length of work zone (next XX Miles).
   b. Suggested speed.
   c. Closure of specific lanes.
   d. Move to specific lane.

5. The back office laptop delivers the RSA payload to the RSU.

6. RSU delivers the RSA payload to both OBUs.

7. OBUs send the payload to their laptops. Drivers read the payload messages.

8. Log travel time of payload delivery between the components.

Anticipated Outcomes from Testing Operational Scenario 1

Overall, the expected results of testing this operational scenario are to understand the optimal position of RSU within the work zone to broadcast RSA. This information is also applicable to a wide variety of other CV safety applications and forms a foundation for understanding real-world infrastructure deployment needs. Specifically, the following outcomes are anticipated:

- Understand practical radio range of RSU DSRC radios.
- Identify latency between OBUs and RSU at different linear positions.
- Identify latency between OBU and RSU based on Basic Safety Message (BSM) +RSA payloads and positions.
- Identify latency for payloads from a back office laptop to RSU to OBU to aftermarket safety devices (ASD) for different detection range.
Operational Scenario 2 – Queue Warning at Work Zones

Goal

The goal is to provide warnings to vehicles approaching a queue at unsafe speed to avoid rear end collisions.

Objective(s)

The objectives are to:

- Communicate queue warnings and queue characteristic information to motorists approaching the queue.
- Communicate queue response strategies to the motorists.

Figure 10 shows the physical layout of the facility required to test operational scenario 2 with a single test vehicle.

Test Procedure for Operational Scenario 2

1. TTI test vehicles drive toward the work zone. One (TV2) is cruising at 30 mph close to the work zone. The other one (TV1) is speeding at 50 mph toward the work zone.
2. RSU detects both OBUs.
3. Both OBUs send GPS positions, lane positions, and speed to RSU, which sends the data to the laptop, emulating the back office of an operating agency.

4. Application in the back office laptop creates a response RSA payload specific to TV1, the approaching vehicle:
   a. Suggested speed to avoid collision.
   b. Closure of specific lanes.
   c. Move to specific lane.

5. The back office laptop delivers the RSA payload to the RSU.

6. RSU delivers the RSA payload to TV1 OBU.

7. OBU sends the payload to its laptop. Driver of TV1 reads the payload message.

8. Log travel time of payload delivery between the components.

An alternative test procedure has been constructed for operational scenario 2 that uses V2V communications instead of V2I.

**V2V Test Procedure for Operational Scenario 2**

1. TTI test vehicles drive toward the work zone. TV2 is cruising at 30 mph close to the work zone. TV1 is speeding at 50 mph toward the work zone.

2. RSU is not involved in this test.

3. OBUs from both vehicles come in range of one another.

4. TV1 OBU receives GPS position, lane position, and speed from TV2 OBU.
   a. Assumes that TV2 OBU is constantly broadcasting its position and speed.

5. TV1 OBU sends the payload to its on-board laptop.

6. The TV1 laptop determines that there is an unsafe condition ahead and sends a warning message to the driver. Warning message will include:
   a. General warning.
   b. Reduce speed to X mph.
   c. Move to different lane if possible.

7. Driver of TV1 reads the message and slows the vehicle and/or moves to another lane.

8. Log travel time of payload delivery between the components.

**Anticipated Outcomes from Testing Operational Scenario 2**

Overall, the expected results of testing this operational scenario are to understand the optimal time lag between queue detection and warning an approaching vehicle approaching the end of queue to avoid collision. This type of information may be applicable to other CV safety applications. Specifically, the following outcomes are anticipated:

- Understand range of OBU DSRC radios and what distance they establish communication.
- Understand latency between the two radios to establish communication.
- A test vehicle in the front is slowly moving (simulating queuing) and another test vehicle approaches from behind at much higher speed.
- Understand latency between the two OBUs and the RSU, which sends the warning message to the approaching test vehicle to avoid collision.
Operational Scenario 3 – Warnings about Hazards in a Work Zone

Goal

The goal is to provide warnings to construction workers in a work zone about potential hazards from approaching vehicles.

Objective(s)

The objective is to enable road side infrastructure to provide warnings to workers in a work zone when vehicles are approaching in a manner that might create unsafe conditions.

Figure 11 shows the physical layout of the facility required to test operational scenario 1 with a single test vehicle.

![Figure 11. Facility Layout for Operational Scenario 3.](image)

Test Procedure for Operational Scenario 3

1. TTI test vehicle drives toward the work zone at 50 mph.
2. RSU detects both the OBU.
3. OBU sends GPS positions, lane positions, and speed to RSU, which sends it to the back office laptop.
4. Application in the back office laptop decides if the vehicle is approaching at unsafe speed and if so creates an RSA message.
5. The back office laptop delivers the RSA message payload back to the RSU.
6. RSU delivers the RSA payload to a networked device (carried by construction workers or warning signals in the vicinity) via WiMAX.
7. The networked device consumes the RSA payload and alerts the motorist.
8. Log travel time of payload delivery between the components.
Anticipated Outcomes from Testing Operational Scenario 3

Overall, the expected results of testing this operational scenario are to understand the optimal time/distance when vehicles with unsafe speed approach a work zone and a message is sent to a construction worker. Specifically, understand the latency between the RSU and static warning devices (e.g., mobile phones, warning sound generator) to warn construction workers about hazardous condition.

Core System Functions to Support Operational Scenario Testing

The operational scenarios discussed in previous sections are require a core set of functions within the test bed environment to facilitate safe operations and data analysis. As listed in Table 2, these functions primarily related to the capture and storage of data necessary to do post-mortem analyses of the test bed runs and provide for a visual record of the tests. There are multiple ways to provide these core functions, and this document does not prescribe a particular methodology, merely the required functional output.
<table>
<thead>
<tr>
<th><strong>System Function</strong></th>
<th><strong>Description and Discussion</strong></th>
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<tr>
<td><strong>Traffic data collection</strong></td>
<td>A critical piece of information required across all operational scenarios is the collection of basic speed data within the test layouts. This information must be collected at multiple times and/or locations throughout the test to establish speed profiles and confirm basic operational assumptions about the equipment operations. The benefit of this information to corridor users is helping them understand the impacts of the construction activities on their trip and consider alternate routes. If fixed infrastructure is not available, the information may be captured and determined after the fact via a GPS logging device.</td>
</tr>
<tr>
<td><strong>Traffic data capture</strong></td>
<td>All data elements created and/or captured within the test bed environment must be stored for analysis. Data storage can take place via an in-field infrastructure component such as a laptop communicating with sensors over wireless networking.</td>
</tr>
<tr>
<td><strong>RSU data capture</strong></td>
<td>All data elements received by, and sent by, any RSUs must be stored for later analysis. Data must be time stamped and unit stamped (in the case of multiple RSUs). Data storage can take place via an in-field infrastructure component such as a laptop communicating with sensors over wireless networking.</td>
</tr>
<tr>
<td><strong>OBU data capture</strong></td>
<td>All data elements received by, and sent by, any OBUs must be stored for later analysis. Data must be time stamped and unit stamped (in the case of multiple OBUs in test vehicles). Data storage can take place via an in-field infrastructure component such as a laptop communicating with sensors over wireless networking.</td>
</tr>
<tr>
<td><strong>ASD data capture</strong></td>
<td>All data elements received by any ASDs within the test bed environment must be captured and stored for later analysis. Data must be time stamped and unit stamped (in the case of multiple OBUs in test vehicles). Data storage can take place via an in-field infrastructure component such as a laptop communicating with sensors over wireless networking.</td>
</tr>
<tr>
<td><strong>Visual test data capture</strong></td>
<td>A visual recording of tests under any operational scenario is useful for identifying problems, safety concerns, and general operations. Under the operational scenarios detailed in this document, a single camera view along the longitudinal length of the test bed environment should be suitable for all needs.</td>
</tr>
<tr>
<td><strong>Protected facility</strong></td>
<td>The test bed facility must provide a protected environment free of interference from other tests, devices, communications, and people. This requirement is a baseline concern for the safety of all personnel and vehicles.</td>
</tr>
<tr>
<td><strong>Constant communication</strong></td>
<td>Before, during, and after a test bed scenario, test bed operators need to have constant 2-way communication with drivers, field personnel, and Riverside employees to direct all operations and as a baseline concern for the safety of all personnel and vehicles.</td>
</tr>
</tbody>
</table>
Risk Management Strategies and Safety

At the Riverside Campus, the runways are available to perform tests related to AV/CV technologies. However, the runways are also extensively used by other programs from TTI and TAMU. Hence, coordination with facilities services is important before planning tests inside the facility. The facilities services will ensure all other TTI programs and TAMU programs are informed of the tests. A fleet of TTI vehicles can also be reserved to retrofit with OBUs and use them in the tests. If sections of the runways are to be blocked, then they will facilitate it.

Before obtaining approval for testing in the facility, researchers should submit a safety plan to minimize the risk of collision with vehicles and fixed objects. A standard operating procedure to conduct tests in the facility is highly desirable. Escort vehicles would be used to minimize the risk of collisions between test vehicles and other vehicles. For AV tests, there should be procedures to remotely override and disable vehicle’s control.

Partnerships with External Agencies

Future testing at the Riverside test bed can and should take place in conjunction with external users as per the listing of stakeholders. At a minimum, the group of researchers could be wider than simply TTI. The use of the facility in this wider role is not new to TTI, as the Crash Test group operates in a similar fashion. Policies and guidelines necessary to partner with agencies external to TAMU must be developed, addressing safety, operations, the intellectual property rights of TTI and partner agencies, and data generated during the tests. While the recognition of this need is within the scope of a ConOps document, the actual creation of these policies is not. This section serves as a reminder that these agreements must develop prior to embracing researchers and other stakeholders outside of TTI. Going forward, TTI will have to develop policies and guidelines to collaborate with external agencies specifically private entities. TTI should:

- Create a policy and guidelines to collaborate with agencies external to TAMU.
- Create a policy and guidelines to partner with agencies external to TTI but internal to TAMU.
- Formalize partnerships with agencies using non-disclosure agreement, memorandum of understanding, etc.
- Protect intellectual property rights of TTI and partner agencies and data generated during the tests.
PROCURE AND TEST DSRC EQUIPMENT

One of the objectives of the project was to procure DSRC equipment (both OBU and RSUs) from vendors, perform bench tests, understand configuration process, and perform basic data exchange tests at Riverside and other locations.

Vendors of DSRC Equipment in the United States

TTI purchased two sets of OBU and RSU from SAVARI® Networks Inc. and ARADA® Systems Inc. Both companies supplied DSRC radios to the USDOT’s Safety Pilot program. SAVARI is headquartered in California. ARADA is based in Windsor, Canada, with offices in California, India, and Taiwan. TTI also bought a J2735 sniffer from 3M®. The sniffer can identify if DSRC radios in its range are transmitting basic safety messages. The sniffer is a useful tool since it allows engineers to confirm if DSRC equipment is transmitting messages from radios during tests and deployments.

Equipment Pricing

TTI purchased the DSRC equipment using its capital expenditure budget. Table 3 lists the DSRC equipment TTI purchased as part of this project, along with purchase price, and total number of units.

Table 3. List of DSRC Equipment Procured.

<table>
<thead>
<tr>
<th>Equipment Description</th>
<th>Model Description</th>
<th>Manufacturer’s Name</th>
<th>Per Unit Rate (US$)</th>
<th>Total Units Purchased by TTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Side Unit</td>
<td>StreetWAVER102 (RSU) with Dual Radio in NEMA Enclosure</td>
<td>SAVARI Networks</td>
<td>6905.00</td>
<td>1</td>
</tr>
<tr>
<td>On Board Unit</td>
<td>MobiWAVE103 with Dual Radio and CAN Bus</td>
<td>SAVARI Networks</td>
<td>3000.00</td>
<td>1</td>
</tr>
<tr>
<td>Road Side Unit</td>
<td>Locomate</td>
<td>ARADA Systems</td>
<td>2800.00</td>
<td>1</td>
</tr>
<tr>
<td>On Board Unit</td>
<td>Locomate</td>
<td>ARADA Systems</td>
<td>1800.00</td>
<td>1</td>
</tr>
<tr>
<td>Handheld On Board Unit</td>
<td>Locomate Me</td>
<td>ARADA Systems</td>
<td>2000.00</td>
<td>2</td>
</tr>
<tr>
<td>J2735 Sniffer</td>
<td>Unknown</td>
<td>3M</td>
<td>4995.00</td>
<td>1</td>
</tr>
</tbody>
</table>

Procurement and Delivery

There was at least 3 to 4 weeks of lead time between order and delivery of DSRC equipment. Both companies provided easy access to a website to download user manuals, programmer’s manual, and quick start up guide. ARADA Systems charged Custom’s clearance fee of US$460 per shipment.

Technical Specifications of the DSRC Equipment

Each DSRC device (OBU or RSU) includes a GPS receiver, an Ethernet Interface, two DSRC radios, and other interfaces that include serial, CAN bus, and Bluetooth. Each DSRC radio consists of multiple channels (172–184) and is capable of either broadcasting or receiving...
messages on these channels. Each radio can also be configured to continuous mode, where it can either broadcast or receive messages on a specified channel, or switching mode, where it can broadcast messages on a certain channel and receive messages on a different channel. Both devices, RSU and OBU, run the Linux operating system and have a command line configuration environment.

**On Board Units**

The OBU is usually installed in a vehicle. It is capable of transmitting via one of the DSRC radios V2V SAE J2735 standard messages or V2I SAE J2735 standard messages. The OBU is also capable of receiving via the DSRC radios messages from other vehicles (V2V) and from the infrastructure (I2V). One of the main messages transmitted by the OBU is the Basic Safety Message. The BSM provides information about the vehicle state and is usually broadcast 10 times in a second by the vehicle with a variety of data content as required by safety and other applications. There are two types of the BSM messages: BSM Part I and BSM Part II. The Part I data will always be included in every BSM message. BSM Part II data are optional and are included as needed according to policies or requests from other vehicles or infrastructure.

The OBU is also capable of receiving BSM messages from other vehicles in its vicinity that are equipped with an OBU using the DSRC radios. It can also receive via the DSRC radios messages from the infrastructure, like the Signal Phase and Timing (SPaT), MapData (MAP), Traveler Information message (TIM), and RSA, once it is in the range of an RSU. One of the DSRC radios on the OBU is usually configured in the continuous mode to broadcast the BSM on one of the radio channels and to receive BSM messages from other vehicles or infrastructure messages. The second DSRC radio can be configured based on the need and applications in the switching mode to listen to the RSU Wave Service Announcements on one channel and send requests to the RSU on a different channel. Figure 12 shows images of OBU equipment acquired by TTI from ARADA and SAVARI.

![ARADA OBU and SAVARI ASD](image)

*Figure 12. Images of OBUs Acquired by TTI.*

**Roadside Units**

The RSU is usually configured to receive the BSM and other messages transmitted by vehicles equipped with an OBU or an ASD when they are in the vicinity of the RSU. The RSU is also used to transmit messages generated by roadside applications and intended for vehicles equipped...
with an OBU. Some of the messages broadcast by the RSU to vehicles (I2V) include: the SPaT, MAP, and TIM messages.

In order to be able to communicate with each other properly (i.e., the messages broadcast by OBU received by the RSU and vice versa), the RSU and the OBU have to be configured properly. The RSU should be configured to listen to the BSM vehicles on the same DSRC channel that the OBU is configured to broadcast the BSM on. Otherwise, the messages will be missed by the RSU. Same configuration rules apply for the messages that are broadcast by the RSU. The following describes the activities that were conducted by TTI researchers in testing the purchased OBUs and RSUs. Figure 13 shows images of the RSU equipment acquired by TTI from ARADA and SAVARI.

![ARADA RSU](image1) ![SAVARI RSU](image2)

**Figure 13. Images of RSUs Acquired by TTI.**

**J2735 DSRC Message Sniffer**

TTI acquired a J2735 messages sniffer tool from 3M that can capture DSRC messages broadcast over the air by OBUs and RSUs and decode them. The sniffer can be used as an independent tool to verify that both devices (OBU and RSU) are broadcasting the required messages and on the proper DSRC channel. The sniffer has also a Wireshark plugin that can decode the J2735 messages and display the contents of each message in real-time. Wireshark can also be used to capture and save the messages received into a .pcap log file.

**Wiring of RSU and OBUs**

**ARADA**

The ARADA OBU has a 120 V adapter that can be plugged into a 120 V outlet. The ARADA RSU is powered by a Power-over-Ethernet (PoE) adapter that in turn requires a 120 V outlet.

**SAVARI**

The SAVARI equivalent of the OBU is called ASD. It requires a 12 V DC source. The power connector has three wires: green, red, and black. The black wire connects to the negative 12 V DC connector while the red wire gets connected to the positive 12 V DC connector. The green wire is usually connected to the car switch when the ASD is installed in a vehicle. For desktop lab testing, the green wire was connected to the 12 V DC positive connector as per the vendor
instructions. The SAVARI RSU can be powered from either a 48 V DC PoE source or by 120 V AC power supply. The SAVARI RSU was installed in the field at Riverside and was wired by TTI personnel using the 48 V DC power supply and through a PoE connection.

**Device Configuration**

Each one of the OBUs and RSUs from both manufacturers has a default configuration. The default configurations on all the devices did not work properly when tested. Modifications to the default configuration were made to get the devices to talk to each other. One of the main problems was that the devices were configured to broadcast and decode received messages in secure mode. However, the security certificates on the devices were already expired and that is why the RSU was unable to decode the received BSM messages. The default configurations in the RSU and OBU were modified to remove the secure mode operation temporarily till the security certificates can be updated.

**Laboratory Testing of OBUs and RSUs**

*Lab Testing of the Ability of OBU to Transmit BSMs*

The ARADA OBU and the SAVARI ASD were configured in the lab to send the BSM message on DSRC channel 172. The J2735 sniffer was configured to listen to the messages sent by the devices on channel 172. The J2735 sniffer was able to capture and decode the BSM messages that were sent by both devices.

*Lab Testing of the Ability of RSUs to Receive BSMs*

After verifying the broadcast of the BSM by the ARADA OBU and the SAVARI ASD using the J2735 sniffer, the ARADA RSU was configured in the lab to receive BSM messages on the same DSRC channel 172 the devices were broadcasting on. The RSU was configured to log the messages received, and researchers verified manually that the messages were received and logged in files under the “/tmp/usb/” directory on the ARADA RSU. The SAVARI RSU was not tested in the lab because it required special wiring that was not available till it was installed in the field.

**Field Testing of OBUs and RSUs**

*Field Testing of the Ability of OBUs to Transmit BSM and Range of DSRC Transmission*

The ARADA OBU and the SAVARI ASD were installed in one of the TTI vehicles. Researchers also installed the J2735 sniffer in another TTI vehicle. The ARADA OBU has small DSRC antennas that were attached to the OBU installed on the dashboard of the TTI vehicle. The SAVARI ASD has magnetic antennas that were installed on the top of the TTI car. The J2735 sniffer also has magnetic DSRC antennas that were installed on the top of the TTI vehicle.

*TTI Gilchrist Bldg. Parking Lot Testing*

TTI conducted a series of tests in the TTI Gilchrist building parking lot. The purpose of the tests was to verify the range of the messages broadcast by the OBUs. The vehicle outfitted with the
J2735 sniffer was parked at the southwest corner of the parking lot. The vehicle outfitted with the OBUs drove around in the parking lot and sometimes went around the TTI Headquarters building. Every time the vehicle outfitted with OBUs went around the TTI Headquarters building and researchers lost the line-of-sight, the sniffer stopped receiving BSM messages broadcast by the OBUs because they were blocked by the building. Otherwise, the J2735 was able to receive the messages while the vehicle was driving in the parking lot. Figure 14 shows a setup of OBU devices and J2735 sniffers in the test vehicle.

![Setup of the 3M J2735 Message Sniffer in the TTI Vehicle.](image)

**Riverside Campus Testing**

Researchers parked the vehicle outfitted with the J2735 sniffer in the middle of runway 35R at Riverside next to the pole where the SAVARI RSU was installed by TTI personnel. The vehicle outfitted with the OBUs moved from one end of the runway to the other in roundtrips at 60 mph. The sniffer received messages of the OBUs while the vehicle was around 500 feet away from the sniffer. Figure 15 shows a setup of RSU devices on Runway 35R at Riverside.
Field Testing of the Ability of RSUs to Receive BSM and Range of DSRC Reception

At the same time researchers were conducting the field tests using the J2735 sniffer to receive the BSM messages broadcast by the OBUs at Riverside, researchers installed both RSUs on a pole in the middle of the runway where the testing was conducted. The vehicle equipped with the J2735 sniffer was parked close to the pole where the RSUs were installed. Both RSUs were configured to log the received messages. Researchers encountered some problems in downloading the data from the RSUs, and researchers are trying to resolve the problems to get the data and map the location of the vehicle from the received BSMs on a map.

Process of Upgrading Firmware on OBU and RSU

During the testing researchers discovered that some of the functionality described in the manuals provided by ARADA was missing on the delivered devices (OBU and RSU). Researchers contacted the vendor and they indicated that the version of the software on the devices is an old one that needs to be upgraded. After receiving the new firmware, researchers had to install an FTP server on one of the laptops to be able to upgrade the OBU and RSU. Installing the FTP server on a laptop required getting permission from TTI’s Networking and Information Services (NIS).

Downloading Message Logs from RSU and OBU to a Laptop

In order to verify the reception of the BSM messages by the RSU, researchers enabled the logging of the received messages on the RSU. However, in order to verify the contents of the log files, researchers had to upload the files to a laptop. Each vendor has a different process for uploading files from the RSU to a laptop. The ARADA devices required the installation of an FTP server on a laptop and then logging into the ARADA devices and pushing the files to the laptop. Researchers installed an FTP server on a laptop after getting permission from NIS. However, pushing the files from the ARADA RSU to the laptop was not an easy process due to the networking restrictions on the laptop. Uploading files from the SAVARI devices required the use of a third party software and it was an easy and simple process.
MARKET ASSESSMENT

What Are the Services or Products That Will Be Sold?

TTI can sell its professional services for developing CV applications, researching human factors issues, and assessing the public agency benefit of deploying CV infrastructure. In addition, TTI may be able to sell CV application packages and services to state DOTs, infrastructure concessionaires (e.g., NTTA, private firms), and large metropolitan areas. It can also sell AV application packages and services to the defense and aerospace industry and large facility owners (e.g., inland and marine ports, military complex, airports).

What Is the Industry and Marketplace That Will Buy the Work?

An immediate market for CV applications is the $45 million USDOT provided to Crash Avoidance Metrics Partnership (CAMP) for V2I application research. If TTI establishes this test bed, it will put TTI at the forefront to pursue research with CAMP on V2I applications.

In addition, NTTA is interested in researching wrong-way driving applications with CV technologies. Transport Canada is interested in researching border wait time and approach management application using CV technologies. Rajat Rajbhandari is already in discussions with NTTA about a possible pilot for a wrong-way driving application and with Transport Canada for the border application.

There is also a potential for a significant effort with TxDOT, which is beginning to show interest in CV technologies. TTI and SwRI may be able to form a partnership with TxDOT to pursue the next round of CV deployment with the USDOT.

The immediate market for AV research is testing applications in the United States Army Tank Automotive Research, Development, and Engineering Center (TARDEC) pilot project to deploy AV on the Johnson Space Center (JSC) campus. One aspect of the TARDEC pilot would be to add a CV package to the automation package. With the test bed, TTI would be well-positioned to market Riverside as a testing location for the TARDEC project.

TTI is currently in the process of augmenting its human factors research capability. An AV/CV test bed will allow TTI to pursue NHTSA funding to research human/machine interface issues and needs.

What Is the Market for Test Bed?

In short term, TTI would market its capabilities to CAMP, NTTA, and TARDEC. However once AV/CV technology starts emerging and before they become ubiquitous, TTI can start marketing AV/CV services and solutions to roadway infrastructure operators and owners, not only in Texas but nationwide. Hence, its obvious market potential is huge, however, TTI must pre-position itself as a front runner to be able to sell packages and services to the market.
What Organizations in the Market Would Fund the TTI Work?

NHTSA recently allocated $45 million to CAMP, which could be a potential source of revenue for TTI concerning CV technology. In addition, TxDOT, USDOT, Transport Canada, and NTTA could continue to fund research and development activities.

The JSC is preparing a proposal to the DOD/TARDEC for a project to test and deploy AVs to deliver people and goods within its facilities for DOD operations in real world, non-hostile environments. They have proposed $10 million for the project, which is expected to commence later this year for the next 3 years. Table 4 lists funding opportunities associated with AV technology deployments.
Table 4. List of Funding Opportunities Associated with CV and AV Technology Deployments.

<table>
<thead>
<tr>
<th>Sponsor</th>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>USDOT/RITA</td>
<td>AV research program including infrastructure, which will be a significant opportunity for TTI. Also will include light vehicles, heavy vehicles, transit buses, and eventually motor coaches.</td>
<td>Multi-million $ in 2014 (estimated $5–10M per year for full program)</td>
</tr>
<tr>
<td>OEMs and USDOT</td>
<td>Field Testing; testing in simulated environment; infinite loops of commuting; simulated freeway drive with residence-to-employment scenarios; potential for high-speed (highway facsimile) test bed development at Riverside, working together with UMTRI, since they will have urban environment covered (UMTRI $8M investment, $2–3M coming from MDOT).</td>
<td>Unknown; NHTSA awarded $1.75M to VTTI through current IDIQ</td>
</tr>
<tr>
<td>NHTSA IDIQ</td>
<td>Includes automation, cyber security, and reliability. Cyber security work may necessarily have an infrastructure component, though NHTSA will first ask RITA to fund that.</td>
<td>No dollar amount as IDIQ; 5 years with 5-year extension option; Estimate $1–3M for 5 years for projects</td>
</tr>
<tr>
<td>OEMs</td>
<td>Research and testing, but lots of competition with VTTI and Stanford. Opportunity for TTI initially is on effect of degraded markings and non-standardized signage, V2I for work zones, SPAT, and changing infrastructure, and also interpretation of MUTCD. Later opportunity is on effects of surface condition, such as potholes.</td>
<td>$1M+ per year</td>
</tr>
<tr>
<td>AASHTO</td>
<td>AASHTO is observing for now; Horsley believes there is a good potential for AV/CV together; some states will be out in front (MI, CA, VA, etc.).</td>
<td>Unknown</td>
</tr>
<tr>
<td>TARDEC</td>
<td>Possibilities with SWRI and UM Dearborn; NASA pilot at JSC. Very interested in truck platooning and base, logistics, and drayage transportation.</td>
<td>$1M to $8M for ARIBO program</td>
</tr>
<tr>
<td>FHWA</td>
<td>Infrastructure-related research, and platooning to reduce following distances to improve roadway utilization. Could include effects of degraded markings, standardized signage. Might be very interested to fund work on embedding extra information in lane markings through geometric design/layout.</td>
<td>They have been spending $1–2M per year; they could spend $5–10M if RITA does not provide enough</td>
</tr>
<tr>
<td>FMCSA</td>
<td>Vehicle platooning. Also includes infrastructure interactions such as markings and design of on/off ramps.</td>
<td>&lt;$1M per year; RITA may provide more</td>
</tr>
<tr>
<td>FTA/RITA</td>
<td>Last mile transportation connecting transit station to destinations.</td>
<td>Unknown</td>
</tr>
<tr>
<td>State DOTs</td>
<td>Looking for expert help: what should they be doing? What licensing and operational requirements should they be considering?</td>
<td>Unknown; could begin assessing by leveraging our SWUTC study and existing relationships</td>
</tr>
</tbody>
</table>

Note: RITA = Research and Innovation Administration, OEM = Original Equipment Manufacturer, IDIQ = Indefinite Delivery and Quantity, AASHTO = American Association of State and Highway Transportation Officials, FHWA = Federal Highway Administration, FMCSA = Federal Motor Carrier Safety Administration, FTA = Federal Transit Administration
What Is the Current and Future Funding Outlook for Those Sponsors?

At this time, current and future funding outlook of these sponsors pertaining to AV/CV deployment programs is unknown.

What Types of Advertising and Marketing Is Needed?

TTI would present findings from the tests to state DOTs, USDOT, Transport Canada, and others through conferences and workshops. TTI would obtain television airtime and newspaper articles to relay successful tests of applications at the Riverside Campus.

What Types of Contracting Will Be Used (Bids, IDIQs, Subcontracts, etc.)?

Precise contracting mechanism is unknown at this time; however, the federal government can use both bids and IDIQs. TTI may also be a subcontractor to a larger consortium. Within the state of Texas, if TTI has enough capabilities and experience built up by the time entities in the state request proposals, TTI would be in a position where there will be very few universities to compete with.