U.S. Department of Transportation
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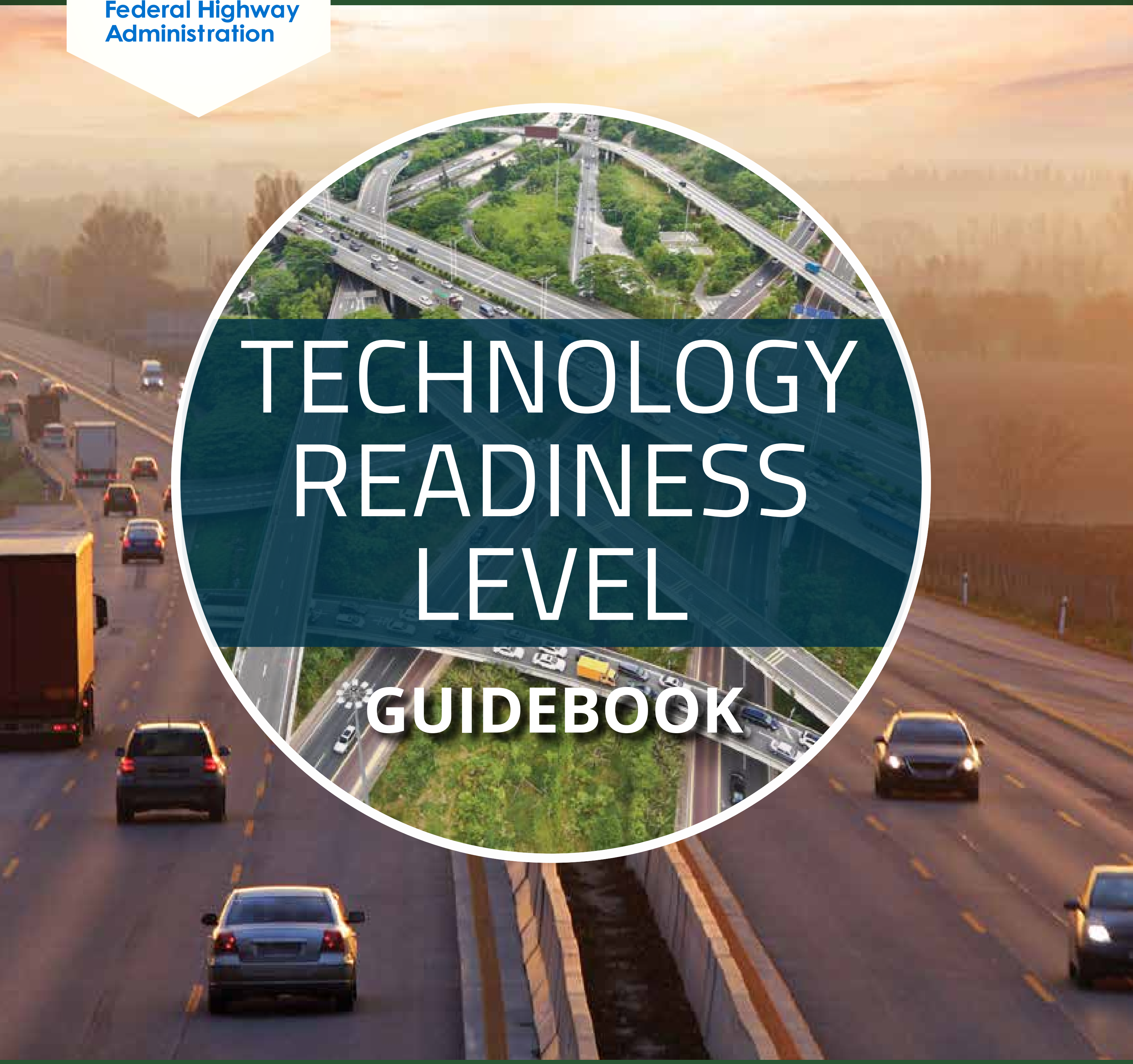

TECHNOLOGY READINESS LEVEL

GUIDEBOOK

EXPLORATORY ADVANCED **RESEARCH**

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FOREWORD

The mission of the Department of Transportation is to serve the United States by ensuring a fast, safe, efficient, accessible, and convenient transportation system. Ongoing research activities offer an opportunity to explore methods of making our transportation system more robust in all of these ways. From researching novel modes of transportation to developing advances in agent-based modeling of traveler behavior, research is at the core of making our system one that enhances the quality of life of the American people.

The Federal Highway Administration (FHWA) Exploratory Advanced Research (EAR) Program focuses on high-risk, high-reward research that bridges the gap between basic and applied research. It also supports the development of transformative research tools that can accelerate development of solutions for highway-related challenges. The value of this type of research lies in how researchers in Government, academia, and industry use the results. For EAR Program-sponsored projects that reach or exceed their anticipated results or develop other advances that have immediate or near-term value, the EAR Program is committed to providing the support necessary to apply those results toward advancing roadway-related tools and technologies.

In fulfilling its mission, the EAR Program identified the need for a system to describe the maturity of highway research products. Numerous mechanisms exist for sharing research results, including technical reports, fact sheets, and demonstrations, but capturing the core of the research project while offering tangible next steps is a more difficult undertaking. The EAR Program uses Technology Readiness Level (TRL) Assessments along with other tools to help identify which research products to emphasize for transition and which audiences would be interested in the results.

The lessons presented in this Guidebook will help those working in transportation research to conduct an evaluation that will likely rank the maturity of a technology and describe the followup steps for advancing their efforts.

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16. Abstract

This guidebook provides the necessary information for conducting a Technology Readiness Level (TRL) Assessment. TRL Assessments are a tool for determining the maturity of technologies and identifying next steps in the research process. This guidebook offers background on the TRL Scale, walks through every aspect of preparing for and conducting a TRL Assessment, and provides helpful tools and tips throughout. TRL Assessments are flexible evaluation tools and can be used in a variety of settings to fit the needs of the agency conducting them. Having a simple mechanism to determine and communicate technology maturity improves research outcomes and program management.

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Introduction

Researchers use evaluation as a key component of the research process. Funding agencies use evaluation tools to rank the maturity level of a technology within the context of the research process. Agency researchers examine how a technology was developed and how that technology functions within its defined operating environment at the time of the examination. They include this information in their evaluation before ranking the maturity level. In some cases, the researchers evaluate a technology to determine its readiness for inception into a technology system (deployment). In other cases, they evaluate it to determine if funding should continue to support the research.

A Technology Readiness Level (TRL) Assessment is a tool for determining the maturity of a technology and provides a foundation for identifying next steps in the research process. Researchers use TRL Assessments as a means to understand a research project's technological maturity, but the assessments have their limitations. TRL Assessments can help improve communication, research outcomes, and contract management, but they do not address risk, cost, or the feasibility of deployment. Therefore, examiners should use TRL Assessments alongside other evaluation techniques to obtain a complete picture of a research project's maturity.

This Guidebook provides the necessary information for conducting a TRL Assessment. It offers background on the TRL Scale (shown in appendix F),[1] walks through every aspect of preparing for and conducting the TRL Assessment, and provides many helpful tools and tips throughout. The Guidebook begins with an explanation of the TRL Scale, because it provides the foundation for the TRL Assessment. Researchers follow a specific process for conducting the TRL Assessment, as shown in figure 1.

This Guidebook is broken into the four sections below:

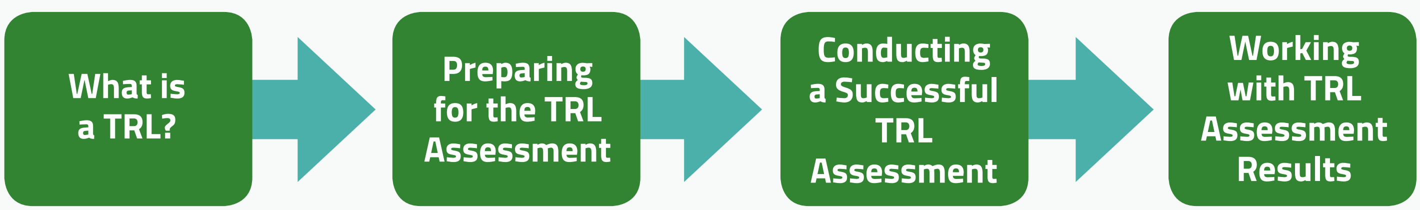


Figure 1. TRL Assessment process.

[1]All references within this document to the "TRL Scale" refer to a modified TRL Scale developed by the Volpe Center for Highway Transportation R&T on behalf of FHWA.

1. What is a TRL?

The TRLs are formal metrics that support assessments of a particular technology and provide the ability to consistently compare levels of maturity between different types of technologies. The TRL Scale uses a set of questions designed to measure progress of a technology toward maturity. The National Aeronautics and Space Administration (NASA) originally developed the concept of TRLs. Later, other Federal agencies, notably the U.S. Department of Defense, adapted the TRL concept.

The TRL Scale assesses the maturity of a technology in terms of certain characteristics, as measured by successful tests. The scale considers two aspects of the completed tests:

- How complete was the technology when it was tested? (Was it a paper-and-pen concept, a system of equations, a component, a subsystem, or the complete system?)
- How representative was the test environment?
  - Was it a computer simulation, a controlled laboratory experiment, a demonstration at a proving ground, or a real-world test?
  - How similar was the tester to the ultimate technology user? Was the tester the developer of the technology, another expert in the field, or a user with no more specific knowledge than the typical technology user?

Why Use the TRL Scale?

The TRL Scale focuses on completed tests and a typical testing progression toward technology adoption. Assessment panel members can use the scale to identify immediate next steps for a research or technology development project. Technical experts and program managers can use the TRL Scale as a guide to structure discussions about the state of development (or maturity) of a single technology. All parties to the assessment can reach a shared understanding of the technical state of the project by considering and debating the questions that comprise the TRL Scale. During its discussion, the panel can uncover technical gaps and questions that point toward next steps in the technology's development. The discussion also helps to identify remaining steps and approximate the level and duration of effort needed to move a technology from its current state into deployment.

What Not to Do with the TRL Scale?

The TRL Scale focuses solely on the tests completed in the development of a technology, so the range of appropriate uses for it as an assessment tool is fairly narrow. **The TRL Scale does not identify risks or challenges in technology development**, such as:

- The difficulty of advancing the technology to the next level of readiness.
- The potential impact or benefit of the technology.
- The market for a technology.

Because of this limitation, assessors should include these indicators beyond the TRL when evaluating a project. The table below provides an explanation of the appropriate and inappropriate uses of the TRL Scale. Researchers must decide if the TRL Scale is an appropriate assessment tool for each technology product, as shown in table 1.

1. What is a TRL? cont.

Table 1. Appropriate and inappropriate uses of the TRL Scale.

Appropriate Uses	Inappropriate Uses
Identify technical gaps to be filled to advance the technology.	Evaluate investment required to advance the technology.
	Estimate the technical impact of the technology.
Perform a rough portfolio analysis in terms of technology maturity.	Analyze the market for the technology.
	Use as a single indicator for whether projects should continue.
Serve as a "shorthand" when discussing the project status, internally and externally.	Use to evaluate projects designed to facilitate implementation of an existing technology.
	Use to evaluate projects that include multiple subprojects with different user communities or underlying technologies.

Understanding the TRL Scale

TRLs range from Level 1 (basic research) to Level 9 (implementation). To achieve a specific TRL, the technology must meet all of the requirements within that level and prior levels. Each level indicates a different measure of maturity and contains different requirements to determine the level of technical maturity.

The remainder of this section walks the reader through a description and requirements for each TRL and uses a real-world transportation technology example—Electronic Toll Collection (ETC)—to highlight the research maturity process of a set of technologies toward deployment. The TRL Scale has four categories: basic research, applied research, development, and implementation (figure 2).

Basic Research	Applied Research	Development	Implementation
1 Basic principles and research.	4 Components validated in a laboratory environment.	6 Prototype demonstrated in relevant environment.	9 Technology refined and adopted.
2 Application formulated.	5 Integrated components demonstrated in a laboratory environment.	7 Prototype demonstrated in operational environment.	
3 Proof of concept.		8 Technology proven in operational environment.	

Figure 2. The four categories of the TRL Scale.

1. What is a TRL? cont.

To illustrate the requirements for each TRL, a set of example projects and their related TRLs are provided at the end of this guidebook.

The ETC Examples

Basic Research

Table 2. Descriptions and requirements of TRLs 1, 2, and 3.

TRL	Description	Requirements
1	**Basic principles and research**	▪ Do basic scientific principles support the concept? ▪ Has the technology development methodology or approach been developed?
2	**Application formulated**	▪ Are potential system applications identified? ▪ Are system components and the user interface at least partly described? ▪ Do preliminary analyses or experiments confirm that the application might meet the user need?
3	**Proof of concept**	▪ Are system performance metrics established? ▪ Is system feasibility fully established? ▪ Do experiments or modeling and simulation validate performance predictions of system capability? ▪ Does the technology address a need or introduce an innovation in the field of transportation?

The TRL Scale begins with basic research, as shown in table 2. For the case of ETC, the basic research focused on radio transponders. The precursor to ETC was radio-frequency identification (RFID) technology. Researchers developed radio transponders leading up to and during WWII. Military personnel used them to identify whether planes were Allied or enemy in an application called "identification, friend, or foe."

1. What is a TRL? cont.

Following WWII, patent applications in the 1950s and 60s identified ETC as a potential application for radio transponder technology, and economist William Vickrey proposed a hypothetical ETC system in *The American Economic Review* in 1963 (Vickrey, 1963). Still, there was no proof of concept until the early 1970s, when researcher Mario Cardullo developed a passive radio transponder with memory and demonstrated the concept to potential ETC users (Cardullo, 2003). The first three levels of the TRL Scale describe this kind of basic research. TRLs four and five capture the transition into applied research. Once TRL 5 is complete, research enters the development phase. Implementation marks a technology reaching TRL 9. The TRL Scale continues with applied research, as shown in table 3. A patent for automated toll charging (figure 3) was awarded in 1971 (United States Patent and Trademark Office, 1971), accessed through https://www.google.com/patents/US3602881.

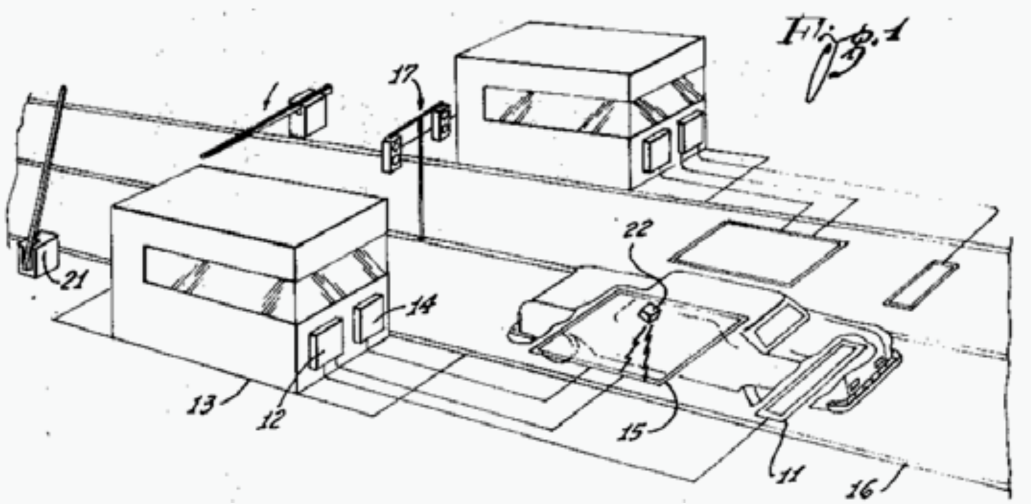


Figure 3. Illustration. Automatic toll charging system, U.S. Patent 3602881.

Source: United States Patent and Trademark Office, www.uspto.gov.

Applied Research

Table 3. Descriptions and requirements of TRLs 4 and 5.

TRL	Description	Requirements
4	**Components validated in laboratory environment**	▪ Are end-user requirements documented? ▪ Does a plausible draft integration plan exist, and is component compatibility demonstrated? ▪ Were individual components successfully tested in a **laboratory environment** (a fully controlled test environment where a limited number of critical functions are tested)?
5	**Integrated components demonstrated in a laboratory environment**	▪ Are external and internal system interfaces documented? ▪ Are target and minimum operational requirements developed? ▪ Is component integration demonstrated in a laboratory environment (i.e., fully controlled setting)?

1. What is a TRL? cont.

TRLs four and five capture the transition to applied research. In the early 1970s, researchers at the Los Alamos National Laboratory began to develop and validate RFID tags for use in tracking systems for the U.S. Department of Energy—which was researching how to track nuclear materials—and the U.S. Department of Agriculture, which had the objective of tracking livestock (Violino & Roberti, 2005).

Throughout the 1970s and 1980s, laboratory research continued on RFID systems. As the technology matured and moved into development activities, Federal research led to the spinoff of private companies, such as Identronix and Amtech.

> **The TRL Scale focuses on completed tests and a typical testing progression toward technology adoption. Assessment panel members can use the scale to identify immediate next steps for a research or technology development project. Technical experts and program managers can use the TRL Scale as a guide to structure discussions about the state of development (or maturity) of a single technology.**

1. What is a TRL? cont.

Development

Table 4. Descriptions and requirements of TRLs 6, 7, and 8.

TRL	Description	Requirements
6	**Prototype demonstrated in relevant environment**	▪ Is the operational environment (i.e., user community, physical environment, and input data characteristics, as appropriate) fully known? ▪ Was the prototype tested in a realistic and relevant environment outside the laboratory? ▪ Does the prototype satisfy all operational requirements when confronted with realistic problems?
7	**Prototype demonstrated in operational environment**	▪ Are available components representative of production components? ▪ Is the fully integrated prototype demonstrated in an **operational environment** (i.e., real-world conditions, including the user community)? ▪ Are all interfaces tested individually under stressed and anomalous conditions?
8	**Technology proven in operational environment**	▪ Are all system components form-, fit-, and function-compatible with each other and with the operational environment? ▪ Is the technology proven in an operational environment (i.e., meets target performance measures)? ▪ Was a rigorous test and evaluation process completed successfully? ▪ Does the technology meet its stated purpose and functionality as designed?

The TRL Scale is used to measure the development of a technology product, as shown in table 4. After TRL 5 is reached, research enters the development phase. In the 1980s, researchers tested early ETC prototypes on closed courses and public roads (TRB, 2016). As tests continued, the researchers replaced small temporary installations with larger deployments that had more readers and transponders. Limited vehicles (test, government, or commercial vehicles) used the systems during initial pilot phases. The public started using them after research proved them safe and effective.

1. What is a TRL? cont.

Implementation

Table 5. Description and requirements of TRL 9.

TRL	Description	Requirements
9	**Technology refined and adopted**	▪ Is the technology deployed in its intended operational environment? ▪ Is information about the technology disseminated to the user community? ▪ Is the technology adopted by the user community?

Implementation marks a technology reaching TRL 9. Researchers can use TRL 9 to measure a product's implementation (table 5). For the case of ETC, early adopters of fully deployed systems included Texas in 1989 (North Texas Tollway Authority, n.d.) and Oklahoma in 1991 (U.S. Department of Transportation, 2016). As the years passed, more states tested and adopted ETC and extended the concept in various ways, including: open road tolling, standardized transponders, and high occupancy toll lanes. As of 2009, FHWA requires all new toll facilities with Federal funding to use ETC. Figure 4 shows ETC system in use at George Washington Bridge.

Figure 4. Photo. Fully operational ETC at George Washington Bridge in New Jersey.

2. Preparing for the TRL Assessment

Researchers should provide their assessment panel with a clear understanding of the TRL Scale and how it captures the maturity of a technology at different stages of development. Next, the researchers should present panelists with a discussion of several key elements to think about as they consider using the TRL Scale to assess the research project. If TRL Assessments are the right tool for evaluating a project, then proper preparation for the assessment will help to ensure it is accurate. Preparation involves four major components: selecting panelists, establishing clear goals for the assessment, formalizing timing and location, and creating materials, as shown in figure 5.

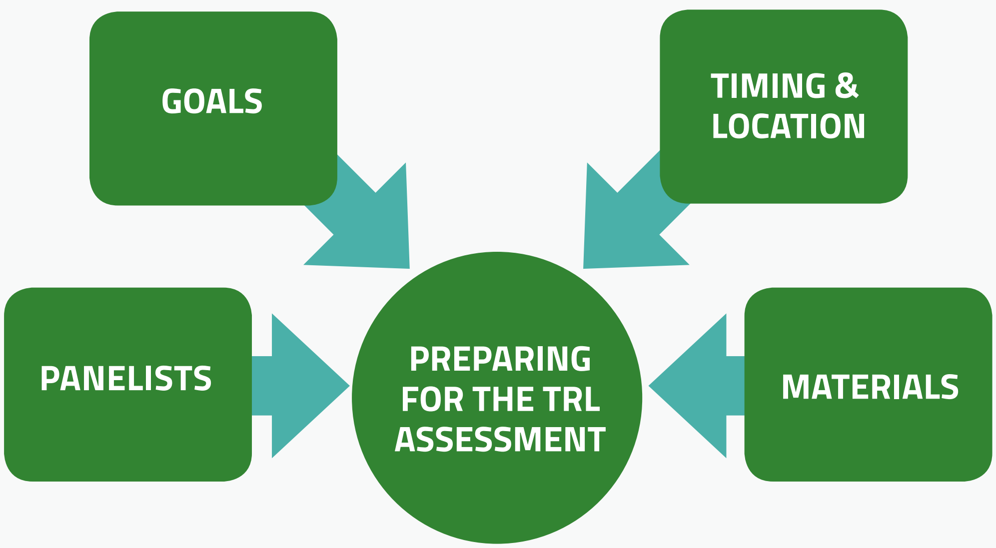


Figure 5. Major components of a TRL Assessment.

Selecting Panelists—The Experts and User Community

Convening a well-rounded panel of experts to assess the maturity of a technology is essential to the success of a TRL Assessment. For most research projects, a panel of four to six stakeholders, researchers, and subject matter experts provides an effective balance. Panelists should at a minimum be knowledgeable about the technology being discussed, the potential users of the technology, or the application environment. Panel members must not have conflicts of interest and must not disclose information about intellectual property or sensitive information.

The panel, the Principal Investigator (PI) of the project, a notetaker, and at least one sponsoring-agency representative should attend the TRL Assessment. If possible, a neutral moderator should facilitate the discussion.

2. Preparing for the TRL Assessment cont.

Establishing Goals—"Why are we assessing this technology?"

When conducting TRL Assessments, it is important to establish evaluation parameters for the discussion. Projects may include many different components, and the panel needs a clear focus on a distinct technology or set of components to assess the research accurately. Panel members can be involved in and assist with focusing on the technology, and all panel members should agree on the goal of the TRL Assessment before the assessment begins.

> **TRL Assessments should be focused** | Narrow the project down into its specific components and evaluate their maturity separately to draw the most utility from the TRL Assessment. Make sure the panelists know and agree ***exactly*** on what they are evaluating.

Further, defining the operating environment is key for determining whether the technology is a functional tool for the intended user community. Before the TRL Assessment, all panelists should clearly understand the purpose of the TRL Assessment and what aspects of the project they will evaluate.

> **Operating Environment** | For the assessment, be clear about the setting or settings in which the technology is meant to work.

Formalizing Timing and Location—The Nuts and Bolts

Timing

A TRL Assessment is most effective if held within 4 to 6 months before the end of a research project's funding cycle. At this point, the majority of the research will have been completed and the TRL Assessment will have maximum relevance. This timing also presents an opportunity for the research team to incorporate the TRL Assessment's findings into any final reports, complete other assessments, and find potential followup funding sources.

TRL Assessments usually last from 3 to 4 hours. However, planners can schedule longer meetings to accommodate technology demonstrations or laboratory tours or to assess complex systems where the panel may be considering the maturity of multiple components or component integration.

Location

Location options include the research site, a neutral locale, or the funding agency. Typically, a TRL Assessment requires only a small, audiovisual-capable conference room. Panel organizers may also conduct TRL Assessments via webinar or teleconference, although panelists may consider virtual settings more challenging to facilitate an active discussion.

2. Preparing for the TRL Assessment cont.

Creating Materials—Getting to the Starting Line

A comprehensive set of materials is an essential foundation for the TRL Assessment panel's discussion. In advance of the TRL Assessment, panel members should receive documentation of the research project so that they arrive at the TRL Assessment with all of the information they will need to fairly and fully evaluate the maturity of the research. In addition to receiving the TRL Scale, the panel should be provided with a short framing document that details the goals of the TRL Assessment and specifies the key technology, applications, and operating environments to be assessed during the TRL Assessment.

An example of a Framing Document is included in appendix A.

Creating this framing document for the panel often shapes the goals or aims of the TRL Assessment, and typically requires a good deal of thought and synthesis to succinctly describe the research conducted and the critical elements of the technology to be reviewed.

Documentation

Panel organizers provide the panel with—or offer them access to—technical deliverables for a project, in addition to these framing documents. Deliverables may include the research project proposal; technical reports produced by the research team; and any interim and final reports, presentations, or published papers. If possible, the project PI should complete a "self-assessment" of the project using the TRL Scale and share it with the panel in advance of the TRL Assessment. This will help the PI to better understand the types of questions that the panel will be trying to answer during the TRL Assessment.

Review

The panel should be given ample time to review the project materials provided. A minimum of 1 week should be sufficient time for panelists to review and ask any clarifying questions that they may have. Convening a brief preassessment conference call with the panelists approximately 1 week before the TRL Assessment is a good way to ensure that the panelists understand the TRL Assessment process (and to confirm any last-minute meeting logistics). This conference call also is an opportunity to ask the panelists to review the initial TRLs in advance of the panel meeting. Having these prediscussion scores makes the assessment easier and ensures that the panelists have reviewed the project documentation in advance of the meeting. (The preassessment conference call also is an opportunity for panel members to introduce themselves, their expertise, and biases relating to the technology. This also can take place at the start of the panel meeting.)

3. Conducting a Successful TRL Assessment

Once the panel members for the TRL Assessment have been identified, goals have been set, timing and location logistics have been confirmed, and the materials have been prepared and distributed, the day of the TRL Assessment is quite straightforward. The PI presents a brief technology overview at the beginning of the TRL Assessment, the panel deliberates the presentation in private, and then the panel discusses its findings with the PI.

It is important to give the panel enough time for a robust discussion, but longer TRL Assessments are not necessarily better. Planners should think about how much time will be needed to discuss the technology in an efficient and focused manner. Assessments should include a well-thought-out agenda. A sample panel meeting agenda is provided in table 6.

Table 6. Example agenda for TRL Assessment panel meeting.

Time	Agenda Item
9:00 a.m.	Welcome and Introduction of Panelists
9:10 a.m.	Overview of TRL Assessment Process
9:20 a.m.	Technology Overview—PI Presentation with Q&A
10:00 a.m.	Technology Readiness Level Deliberation
11:30 a.m.	Discussion of TRL Assessment Results with PI + Q&A

The TRL Assessment process typically begins with a brief welcome and broad overview of the need that the funded research is trying to address. Once this background has been set, the panel facilitator introduces the panelists and gives them an opportunity to share their expertise as it relates to the research project. In the absence of a dedicated facilitator, the project sponsor may take on this role.

After introductions, the panel facilitator provides a brief overview of the TRL Assessment process before the assessment begins. After that is complete, the project PI provides a technology overview presentation, which typically lasts about 60 minutes, depending on the complexity of the research and testing completed. This presentation should detail the technology developed, how the technology was tested, and proposed next steps. If the project features a research team that spans multiple institutions with distinct research foci, it may make sense to have the PI or co-PI leading each strand of the project presentation on their research activities. The technology overview portion of the agenda should include enough time for clarifying questions from the panel, because the PI will not be participating in the actual assessment.

After the PI has completed his or her presentation and answered panelist questions, the PI leaves the room and the panelists begin deliberations. To begin the assessment portion of the agenda, each panelist shares his or her initial TRL score for the project and a short explanation for why he or she decided on that score. This exercise sets a baseline for the panel discussion, and the panel begins to deliberate the TRL questions one by one to determine a final panel score. To increase efficiency, it is typically best to begin the discussion at one level below the lowest initial TRL—for example, the panel can begin its discussion at TRL 4 if the lowest initial TRL score is 5. Determining what work is required to reach a higher TRL score is more important than coming to a consensus on an exact score.

After the panel has concluded its discussions and agreed upon a TRL score for the project, the PI and project team should rejoin the assessment meeting to hear the panel's findings and have an open discussion about potential next steps for the research. This is an important opportunity for the PI and the panel to discuss the project and the PI to learn the panel's thoughts on why the technology's maturity is ranked where it is and how that maturity can be improved.

It is important to document both the panel's discussion as well as the subsequent conversation between the panel and the PI. The panel facilitator or a notetaker should complete a TRL Assessment Report after the TRL Assessment has concluded. The TRL Assessment Report should include information about the goals and technology's operating environment, drawing as necessary from the framing document. The report also should incorporate comments from the discussion at the TRL Assessment, including why the TRL score for the project was selected and any recommendations for future work. The TRL Assessment Report is a useful tool for sharing information about the project with potential funders of additional work. The report also should provide a concise overview of the project and next steps.

An example of a TRL Assessment Report can be found in appendix C.

4. Using the Results of TRL Assessments

The results of TRL Assessments can be used strategically to support the goals of the agency sponsoring the research. For example, the Federal Highway Administration (FHWA) Exploratory Advanced Research (EAR) Program sponsors longer term and higher risk research. The program seeks to fund cutting-edge research that can provide improvements to national transportation systems. To maximize the value of its research and ensure that important results are not forgotten, the EAR Program uses TRL Assessments along with other tools to help identify which research products would benefit from follow-on support and which audiences would be interested in the results. TRL Assessments provide a useful foundation for the use of other research planning and evaluation tools, such as logic models and mind maps, by subjectively capturing the current level of maturity of a research project. In addition, because TRL Assessments typically identify possible next steps to advance a research project to a higher TRL, these assessments can be used as the basis for scoping cost and level of effort for future research work plans. Figure 6 suggests where on the TRL Scale various Federal transportation-related research programs fall, as well as potential hand-off points among funders working at different TRLs.

!

It is important to designate a notetaker in advance of the panel meeting. The notetaker's job will be easier if the person is familiar with the TRL process and technology. It is, therefore, important to be clear about technical jargon, acronyms, and implicit assumptions.

Conclusion

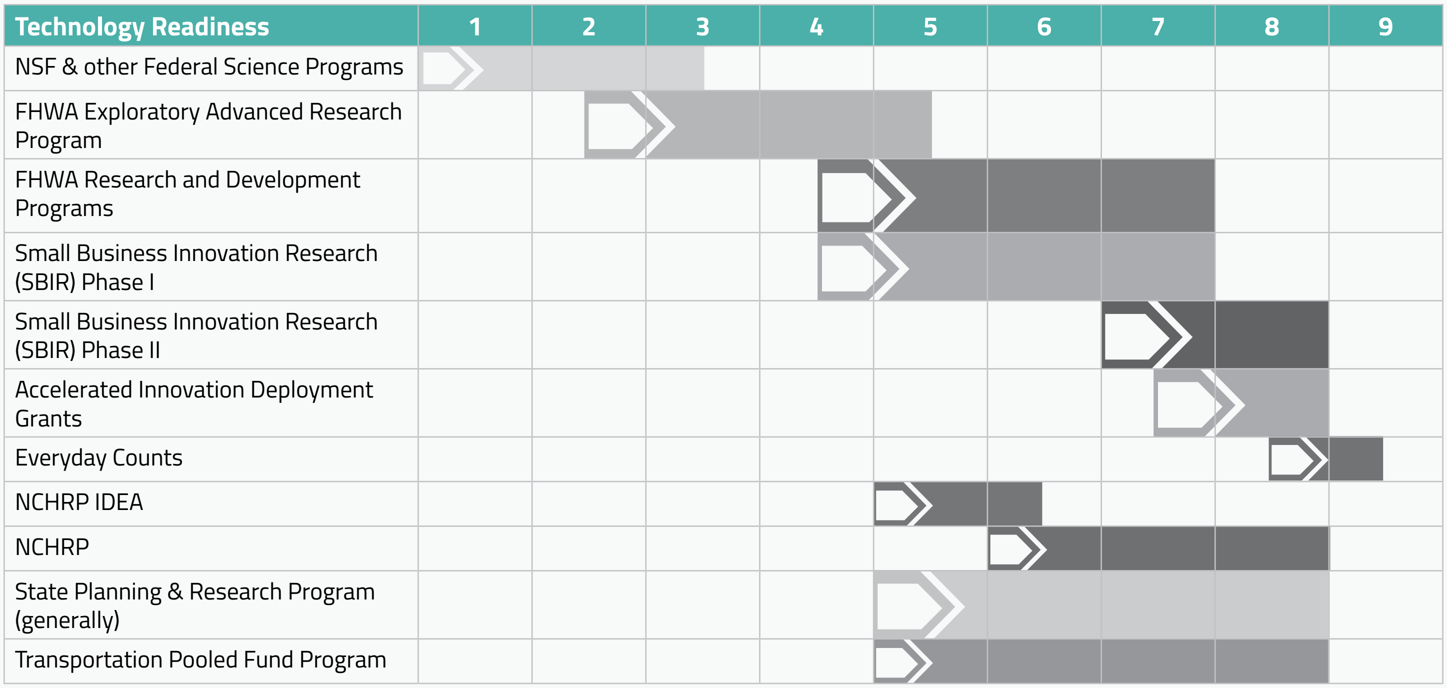


Figure 6. Chart. TRLs across Federal funders in transportation.

The TRL Assessments are an important instrument for evaluating technology maturity within the research and development process. TRL Assessments are flexible evaluation tools and can be used in a variety of settings to fit the needs of the agency conducting them. Having a simple mechanism to determine and communicate technology maturity improves research outcomes and program management. Technology readiness is measured across a spectrum of transportation programs, as shown in figure 6.

Appendix A. Technology Framing Documents

Example 1

This sample Technology Framing Document highlights circa 1970s RFID technology, the predecessor of modern ETC technology.

Technology Overview

RFID technology uses electromagnetic fields to identify tags or transponders that are attached to certain objects. Tags can be attached to vehicles, animals, and other items to be identified by a stationary RFID reader. The technology is designed to avoid line-of-sight issues and, therefore, the transponders can be installed within objects. In the early 1970s, the U.S. Department of Energy's Los Alamos National Laboratory initiated research into RFID transponder technologies capable of communicating specific information, such as a tracking identification (ID) or license number, when activated by a nearby reader (Landt, 2001). While this research focused on tracking of nuclear materials, RFID technology may have applications in other fields.

Technology Framing

The potential applications of RFID technology can be used by transportation agencies, the nuclear industry, and the farming industry, among many others. Any industry that could benefit from using tags to identify objects could use this technology. To accurately assess the technological maturity of the platform in reference to these use cases, the technology must be separated into its core components. The components of RFID technology include hardware and software (see details below).

Technology Components

RFID technology consists of the following components:

- Hardware.
  – RFID tags and readers.
- Software.
  – RFID software.

Hardware

The RFID system uses fixed readers and RFID tags, or transponders. Users program each transponder using RFID software, so that fixed readers can identify them individually. When a tag enters a reader's field, the system registers that tag's identifier. Depending on the application, this trigger can lead to many physical or nonphysical actions. The simplest applications are for the tag's identifier to be added to a catalog or displayed on a screen.

Software

RFID software includes a set of codes that programs an RFID transponder to emit specific identifying information when triggered by an RFID reader.

Technology Readiness Assessment

This Technology Readiness Assessment will evaluate the core components of the ETC technology, the RFID reader and tag hardware, and the RFID software. The assessment panel will discuss the maturity of these functions and select the appropriate TRL.

Application

The TRL Assessment will assess the use of the RFID technology for identifying vehicles. The identifiers for these vehicles will be their tag number, along with their vehicle identification number.

Operating Environment

The intended operating environment is a manned gate or checkpoint through which vehicles must pass to enter a facility or continue down a road.

Appendix A. Technology Framing Documents cont.

Example 2

This sample Technology Framing Document describes modern ETC technology.

Technology Overview

Example Company's ETC system builds on early radio transponder and RFID technology to wirelessly track vehicles traveling at moderate speeds for toll collection purposes. The system is designed to improve safety at tolling checkpoints by automating toll collection to increase vehicle throughput and decrease traffic incidents at checkpoints. A secondary result of the system is reduced labor costs associated with toll booth staffing.

Technology Framing

Potential users of the ETC system include state DOTs, Federal agencies, and large parking facilities such as those at airports. To accurately assess the technological maturity of the platform in reference to these use cases, the technology must be separated into its core components. The components of the ETC system include the hardware, software, and data the system produces.

Technology Components

The ETC system consists of the following components:

- Hardware.
  - RFID tags on individual vehicles and RFID readers.
  - Roadside cameras for license plate detection.
- Software.
  - Cooperative Operations for Low-Latency Electronic Collection of Tolls (COLLECT) software.

Hardware

The ETC system relies on RFID tags and readers to provide vehicle identification and to trigger the toll charges. The small RFID tags are located on the front windshield of the vehicle, and the readers are typically mounted onto a stationary surface (such as a toll collection booth or on a gantry mounted above the roadway). The readers provide the ETC infrastructure, while the RFID tags are used to distinguish the vehicles and determine responsibility for the charges. Cameras detect and capture license plate numbers to confirm and match RFID tags with vehicle owners.

Software

The COLLECT software is an online software tool meant to standardize and simplify reporting of tolls that have been collected and those that need to be collected. When an RFID tag triggers an RFID reader, an entry is added to the COLL (Commonly Labeled List) with the vehicle tag number, time, toll fee, due date, and address. The system also automatically charges the payment information on file. If none is on file, a bill is automatically printed and sent to the owner of the vehicle.

Technology Readiness Assessment

This Technology Readiness Assessment will evaluate the core components of the ETC technology, the RFID tag and reader and camera hardware, and the COLLECT software. The assessment panel will discuss the maturity of these functions and select the appropriate TRL.

Application

The TRL Assessment will assess the use of the ETC system for collecting tolls from drivers automatically.

Operating Environment

The intended operating environment is any roadway that has a need for electronic tolling.

Appendix B. Principal Investigator Questionnaire

Presentation Preparation Worksheet for TRL Assessments

This worksheet is intended for use by PIs and presenters as a tool for identifying and organizing the specific information that panelists need to know before conducting a TRL Assessment. The information identified in this worksheet should be included in the PI's or presenter's 30–45-minute PowerPoint presentation, delivered to panelists at the start of a TRL Assessment.

Instructions for Presenters: Answer the following questions based on the technology being assessed and any testing or prototypes that have been developed. Please use this worksheet to inform the content of your presentation.

DEFINITIONAL: What is the technology? Where and how is it used? Who is the user? What are the subsystems and components of the technological system?

Table 7. PI Questionnaire.

1. Describe the technology.	
What is the technology?	
Have preliminary engineering designs for system components been developed?	
Have drawings, diagrams, outlines, or other conceptual aids been prepared?	
Are there remaining technical or design-related challenges? Please describe.	
2. Describe the various constituent parts of the technology. How do they fit together and interact with one another?	
What are the subsystems and components of the technological system? What is the status of those subsystems and components?	

Appendix B.
Principal Investigator Questionnaire cont.

3. Describe the envisioned deployment of this technology.	
Where will this technology be deployed?	
What problem(s) has this technology been developed to solve or address? At the point of implementation, will this technology address these problems sufficiently (if not, why not)?	
What is the operational environment for this technology (at the point of implementation)?	
Describe the end users of the technology, and how they will use it.	
(From an operational perspective) What needs to be done to or with the technology, as it exists today, before the technology can be deployed in the manner envisioned?	

TESTING: How and where has the technology—and constituent elements—been tested? What was the result? How representative is the test environment to the intended operational environment?

4. How have the technology's *subsystems, components*, and *concepts* been tested (individually)? Please describe the results.	
Have experiments on system components been conducted? In what settings were these experiments undertaken?	

Appendix B.
Principal Investigator Questionnaire cont.

5. How has the integration of the various components and systems been tested?	
How will their expected functionality be confirmed, both individually and in combination?	
6. Has a demonstration of the *full technology* been conducted, or a prototype constructed? Please describe the results.	
What was the scale and setting of the demonstration, compared to the envisioned deployment of this technology? Was this demonstration indicative of how the final technology may be expected to perform in the field?	
Have computer simulations for system design, construction, or operations been conducted? Have case studies been conducted for other components of nonhardware or software technologies? Please describe the results.	
7. Describe the most recent test conducted on the full technology. What precisely was tested, why, and how did it go?	
What metrics exist for defining the development's progress for technology?	
8. How has the user community been included in the technology development process?	
Have usability experiments been conducted or prototypes deployed to intended users?	

Appendix B. Principal Investigator Questionnaire cont.

If prototypes have been produced and field-tested with the intended end users, do those users use the technology as intended? If not, how has it been adapted?	
If feedback from these users about the technology has been received, how has the technology been revised (if at all) to address this feedback?	
(From a "proof-of-functionality" perspective) What tests or trials should be performed on, with, or using the new technology, as it exists today, before the end user can confidently use it?	

Other Notes:

Appendix C. TRL Assessment Report Example

This document represents a sample TRL Assessment Report of ETC technology from the mid-1980s, when researchers were piloting the initial ETC system.

Technology Readiness Assessment of FHWA EAR Program Project "Example Company: Electronic Toll Collection"

Introduction

This report summarizes the Technology Readiness Level (TRL) Assessment of the Federal Highway Administration (FHWA) Exploratory Advanced Research (EAR) Program-funded project "Electronic Toll Collection" (ETC). On May 11, 1985, the EAR Program convened a panel of experts to assess the maturity of Example Company's ETC system; specifically, its ability to capture tolling moments and collect payment. The intended operating environment is any roadway that has a need for electronic tolling.

The remainder of this report provides information about the FHWA EAR Program, a summary of the TRL Assessment process and the TRL Scale, and the proceedings of the assessment panel.

EAR Program Background

The FHWA EAR Program focuses on high-risk, high-reward research that bridges the gap between basic and applied research and development. It also supports the development of transformative research tools that can accelerate development of solutions for highway-related challenges. In fulfilling its mission, the EAR Program identified the need for a system to describe the maturity of highway research products. Such a system would allow experts and nonexperts to: (1) document and communicate the maturity of the research at a specific stage of development; (2) indicate how the project might relate to other research; and (3) determine what steps might advance the maturity of a given research product. The John A. Volpe National Transportation Systems Center developed the TRL Scale for the EAR Program with these capabilities in mind.

About Technology Readiness Assessments and the TRL Scale

TRLs are formal metrics that support assessments of a particular technology and provide the ability to consistently compare levels of maturity between different types of technologies. The TRL Scale uses a set of questions designed to measure progress of a technology toward maturity. NASA originally developed the concept of TRLs. Other Federal agencies, notably the U.S. Department of Defense, adapted the concept later.

The TRL Scale assesses the maturity of a technology in terms of certain characteristics, as measured by successful tests. The scale considers two aspects of the completed tests:

- How complete was the technology when it was tested? (Was it a paper-and-pen concept, a system of equations, a component, a subsystem, or the complete system?)
- How representative was the test environment?
  - Was it a computer simulation, a controlled laboratory experiment, a demonstration at a proving ground, or a real-world test?

Appendix C.
TRL Assessment Report Example cont.

To use the TRL Scale for successfully evaluating a technology, the EAR Program convened a panel of outside experts and a project's principal investigator (PI) to review the technology and provide an assessment of its maturity, as well as to recommended next steps and additional testing required to advance the technology to a higher TRL.

Technology Overview

The ETC system developed by Example Company consists of the following subsystem components:

- A small **RFID tag** that can be read by the RFID reader is located within each vehicle.
- The **COLLECT Software** (Cooperative Operations for Low-Latency Electronic Collection of Tolls) is meant to collect all the data associated with tolling actions and automatically extract payments from existing accounts or distribute notices for payment.

The ETC system relies on RFID tags and readers to provide vehicle identification and to trigger the toll charges. The small RFID tags are located on the front windshield of the vehicle, and the readers are typically mounted onto a stationary surface (such as a toll collection booth or on a gantry mounted above the roadway). The readers provide the ETC infrastructure, while the RFID tags are used to distinguish the vehicles and determine responsibility for the charges. Cameras are used to detect and capture license plate numbers to confirm and match RFID tags with vehicle owners.

The COLLECT software is an online software tool meant to standardize and simplify reporting of tolls that have been collected and those that need to be collected. When an RFID tag triggers an RFID reader, an entry is added to the COLL (Commonly Labeled List) with the vehicle tag number, time, toll fee, due date, and address. The system also automatically charges the payment information on file. If none is on file, the system automatically prints and mails a bill to the owner of the vehicle.

Proceedings of the Panel Assessment

EAR Program Manager John Smith opened the meeting with a brief discussion of the goals of the TRL Assessment process and provided an overview of the EAR Program's role in supporting research on the ETC system. The panelists introduced themselves and then the panel facilitator outlined the structure of the panel assessment.

The project's PI, Dr. Jane Doe, presented an overview of the research, including summaries of key tests conducted over the course of the project. She presented examples of how the system—including the RFID tags and COLLECT software—works. She summarized the project's accomplishments during the research period and highlighted areas for next steps.

Following Dr. Doe's presentation, the panel convened to begin the technology readiness assessment. The panel—including both in-person and remote participants—coalesced around a TRL score of 6 or 7 for the Example Company's technology. Following the panel's discussion, Dr. Doe returned to review a summary of the findings and the potential next steps for the research suggested by the panel.

Appendix C.
TRL Assessment Report Example cont.

Findings and Recommendations from the Panel Assessment

Potential applications of the ETC technology may be used on any roadway that has a need for electronic tolling. Some users may seek to decrease congestion caused by manual toll systems. Others may want to increase compliance and gather data regarding tolls paid.

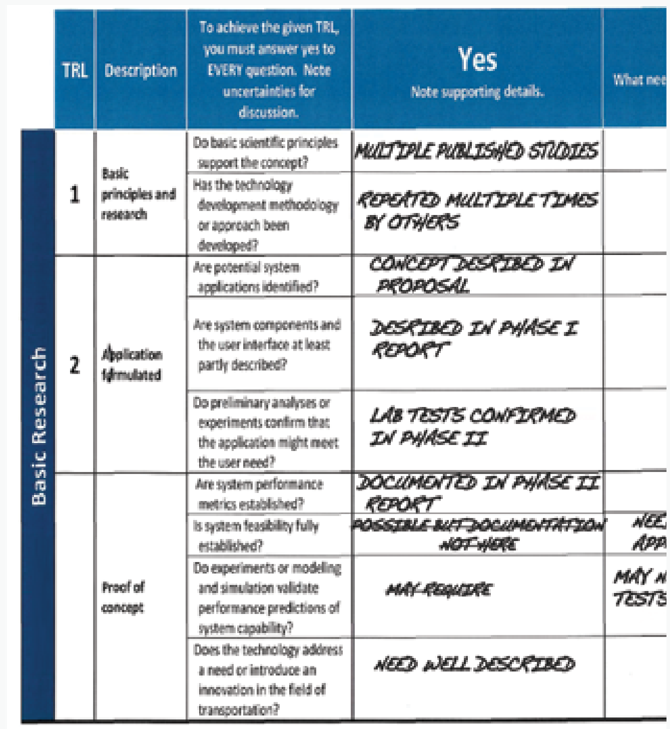
The panel determined that the ETC system reached a TRL of 7 (prototype demonstrated in operational environment). The technology operates very well in an operational environment. The panel questioned whether limitations in the COLLECT system would prohibit linking tolling locations. This may lead to an inability to analyze system-wide data.

Possible Next Steps:

1. The panel suggested that more testing be done to link separate tolling locations in a network. This would allow for system-wide data analytics, which may be important to a subset of the target audience.
2. The panel suggested convening a virtual focus group of users to provide feedback.

Lessons Learned for Future Technology Readiness Assessments

The participants of the TRL Assessment offered feedback on how the TRL Assessment process can be improved in the future. The panel suggested providing panelists with project information further in advance of the panel meeting. Figure 7 shows an example of a partially marked-up TRL scoring sheet.



	TRL	Description	To achieve the given TRL, you must answer yes to EVERY question. Note uncertainties for discussion.	Yes Note supporting details.	What nee
Basic Research	1	Basic principles and research	Do basic scientific principles support the concept?	MULTIPLE PUBLISHED STUDIES	
			Has the technology development methodology or approach been developed?	REPEATED MULTIPLE TIMES BY OTHERS	
	2	Application formulated	Are potential system applications identified?	CONCEPT DESRIBED IN PROPOSAL	
			Are system components and the user interface at least partly described?	DESRIBED IN PHASE I REPORT	
			Do preliminary analyses or experiments confirm that the application might meet the user need?	LAB TESTS CONFIRMED IN PHASE II	
		Proof of concept	Are system performance metrics established?	DOCUMENTED IN PHASE II REPORT	
			Is system feasibility fully established?	~~POSSIBLE BUT DOCUMENTATION NOT HERE~~	NEE APP
			Do experiments or modeling and simulation validate performance predictions of system capability?	~~MAY REQUIRE~~	MAY N TESTS
			Does the technology address a need or introduce an innovation in the field of transportation?	NEED WELL DESCRIBED	

Figure 7. Illustration. Sample TRL worksheet.

Appendix D. Frequently Asked Questions

1. **How long will the assessment take?** For every panel member, the assessment involves two parts: (1) the independent work of reviewing the technology and documenting the TRL recommendation; and (2) the group work of discussing and reconciling different reviewers' perspectives of the technology. The time required for each step will depend on the complexity of the technology, the richness of the data available on it, and the objectives of the review. Simpler technologies take less time to review, especially if no critical decisions will be made based on the scoring discussion. At a minimum, expect several hours to review background documents or participate in a presentation about the project results and several hours to discuss and come to a consensus on the TRL. For larger, multiyear projects, expect to spend 1 day or more reviewing background information and a half-day or more participating in an assessment panel.

2. **When working through the TRL Scale, do I have to start at TRL 1?** No. If you have a technology that the group believes is fairly close to implementation, you may select a higher TRL and move forward. You might also find it useful to work backward instead. However, if time allows, a high-level review of the earlier TRLs may be very useful in orienting the team and possibly in identifying gaps in the research.

3. **For TRL 4: Is an "integration plan" a plan for integrating the technology into the operations of the organization?** No. In the context of the TRL, "integration plan" describes how the technology's components will interface and work together to make the technology system operational.

4. **For TRL 7: Say we have a technology that is clearly at TRL 7 by nearly all counts. Does the fact that we never really did laboratory testing mean that we should call it a TRL 4? That does not make sense.** No. If laboratory testing was not considered necessary and, instead, the technology development team went straight to prototype testing in a nonlaboratory environment, that does not mean that the technology is necessarily at TRL 4. However, it does raise the question of what lessons might have been learned if laboratory testing had been conducted and could point to a need for additional testing.

5. **For TRL 8: How well must a technology perform to confirm that it meets "its stated purpose and functionality as designed?"** To meet this criterion, the technology must operate as designed under typical and stress-test conditions.

6. **For TRL 8: If target performance measures were never clearly defined or documented, does that mean that TRL 8 has not been achieved?** Target performance measures are metrics that describe the intended functionality of the technology. If "desired performance" was defined only loosely, then technologies that meet that vaguely defined state can achieve TRL 8.

7. **For TRL 9: How broadly must the technology be adopted to reach TRL 9?** This will vary considerably depending on the goals of the project. Broad adoption is not required.

Appendix E. Example Projects and Associated Technology Readiness Levels

Table 8. Example 1. Innovative bridge design and rapid renewal: design tool kit.

	Research Product to be Assessed: A "guidebook" for designing, constructing, and reusing bridge systems that address rapid renewal needs. Includes detailed plans for light, simple bridges that are easier to design, fabricate, transport, and erect than traditional bridges. Features concepts for innovative foundation systems, sub- and super-structure systems, subsystems, and components.	
	Technology "As Implemented" (TRL 9): A printed or software guidebook that describes recommended best practices for accelerated bridge construction and installation.	
Level	**Operating Environment**	**Technology to be Assessed**
TRL 2-5	**Laboratory Environment:** A simulation or small-scale project. The user likely would be a member of the guidebook development team.	**Components:** The translation of the case studies into the guidance provided by the guidebook.
TRL 6	**Relevant Environment:** A single full-scale construction project on a controlled site, with project managers familiar with the guidebook and in contact with the development team.	**Prototype:** Case studies of bridge designs or aspects of design technique, and the logical organization and presentation of that knowledge base.
TRL 7-9	**Operational Environment:** The application of the guidebook to a physical project: a span of 100 to 400 ft, in nonwinter weather, in rural and urbanized areas throughout the United States, regardless of development density or traffic density. The user might be a state Department of Transportation engineer with bridge design experience overseeing the construction and installation of a bridge.	**Technology:** The complete guidebook and any ancillary material needed for its use.
	Project Web site:	**http://www.trb.org/Main/Blurbs/168046.aspx.**

Appendix E. Example Projects and Associated Technology Readiness Levels cont.

Table 9. Example 2. Increased understanding of driver visibility requirements.

Levels	Operating Environment	Technology to be Assessed
	Research Product to be Assessed: A software program to predict driver and autonomous vehicle response to different combinations of visual guidance—such as centerlines, edge lines, delineators, and raised pavement markers—to navigate curves in the roadway.	
	Technology "As Implemented" (TRL 9): An advisory software-based tool that helps designers specify the parameters of a new roadway.	
TRL 2-5	**Laboratory Environment:** The PC on which the software was developed, operated by one of the developers.	**Components:** Algorithms describing the visibility of certain marking types under design conditions, software-based implementation of those algorithms, subroutines for the presentation of the material and acceptance of user input, installation packages, and any instructions.
TRL 6	**Relevant Environment:** A PC used by a staff member not on the development team.	**Prototype:** The software absent some functionality and without adequate documentation; the "alpha" or "beta" version.
TRL 7-9	**Operational Environment:** A PC usable by any roadway engineer with no experience in roadway design software.	**Technology:** The software, including installation packages and user manual.
	Project Web site:	**http://www.fhwa.dot.gov/advancedresearch/pubs/seedarkear.cfm.**

Appendix E. Example Projects and Associated Technology Readiness Levels cont.

Table 10. Example 3. Anonymous traffic probes for travel time and origin-destination using Bluetooth IDs.

	Research Product to be Assessed: A Bluetooth-based tool that accurately measures travel time and arterial or freeway traffic.	
	Technology "As Implemented" (TRL 9): A hardware or software system that provides travel-time estimates to travelers and traffic management centers.	
Level	**Operating Environment**	**Technology to be Assessed**
TRL 2-5	**Laboratory Environment:** A bench test for individual Bluetooth sensors or a small network of sensors. The software developer or someone else knowledgeable about its operation conducts the software testing.	**Components:** Bluetooth sensors, installation hardware, data transmission, analysis, storage hardware or software, and user interface software.
TRL 6	**Relevant Environment:** A pilot test of a small network of Bluetooth traffic sensors in a parking lot generating data that, when processed, produces travel-time estimates. The software might be poorly documented and usable only by knowledgeable staff.	**Prototype:** A complete system—with all necessary parts in place—but with nonweather-resistant sensor housing and functional, but flawed, software.
TRL 7-9	**Operational Environment:** The *physical environment* in which the fully functional Bluetooth sensors will operate (e.g., 2- to 6-lane roads in any U.S. metropolitan area). The *software environment* in which sensor data is processed and transmitted (e.g., wireless transmission to PCs for data processing and distribution) to the user (i.e., Metropolitan Planning Organization staff or the traveling public).	**Technology:** A system composed of Bluetooth sensors, data transmission and storage equipment, software to convert the data into travel-time estimates and present them to users, and any necessary users' guides.
	Project Web site:	**http://www.sbir.gov/content/anonymous-traffic-probes-travel-time-and-o-d-using-bluetooth-ids-0.**

Appendix F. TRL Scale

Table 11. TRL Scale: Descriptions and requirements.

	TRL	Description	To achieve the given TRL, you must answer yes to EVERY question. Discuss any uncertain answers.
Basic Research	1	**Basic principles and research**	▪ Do basic scientific principles support the concept? ▪ Has the technology development methodology or approach been developed?
	2	**Application formulated**	▪ Are potential system applications identified? ▪ Are system components and the user interface at least partly described? ▪ Do preliminary analyses or experiments confirm that the application might meet the user need?
	3	**Proof of concept**	▪ Are system performance metrics established? ▪ Is system feasibility fully established? ▪ Do experiments or modeling and simulation validate performance predictions of system capability? ▪ Does the technology address a need or introduce an innovation in the field of transportation?
Applied Research	4	**Components validated in laboratory environment**	▪ Are end-user requirements documented? ▪ Does a plausible draft integration plan exist, and is component compatibility demonstrated? ▪ Were individual components successfully tested in a **laboratory environment** (a fully controlled test environment where a limited number of critical functions are tested)?
	5	**Integrated components demonstrated in a laboratory environment**	▪ Are external and internal system interfaces documented? ▪ Are target and minimum operational requirements developed? ▪ Is component integration demonstrated in a laboratory environment (i.e., fully controlled setting)?
Development	6	**Prototype demonstrated in relevant environment**	▪ Is the operational environment (i.e., user community, physical environment, and input data characteristics, as appropriate) fully known? ▪ Was the prototype tested in a realistic and relevant environment outside the laboratory? ▪ Does the prototype satisfy all operational requirements when confronted with realistic problems?
	7	**Prototype demonstrated in operational environment**	▪ Are available components representative of production components? ▪ Is the fully integrated prototype demonstrated in an **operational environment** (i.e., real-world conditions, including the user community)? ▪ Are all interfaces tested individually under stressed and anomalous conditions?
	8	**Technology proven in operational environment**	▪ Are all system components form-, fit-, and function-compatible with each other and with the operational environment? ▪ Is the technology proven in an operational environment (i.e., meet target performance measures)? ▪ Was a rigorous test and evaluation process completed successfully? ▪ Does the technology meet its stated purpose and functionality as designed?
Implementation	9	**Technology refined and adopted**	▪ Is the technology deployed in its intended operational environment? ▪ Is information about the technology disseminated to the user community? ▪ Is the technology adopted by the user community?

Appendix G. Additional Resources on the TRL Scale and the Use of TRLs for Assessment

For more information about TRLs and TRL Assessments, please visit the following:

- GAO report on TRL use: http://www.gao.gov/products/NSIAD-99-162.
- TRB paper comparing TRLs with other research assessment tools. Corporate Authors: Transportation Research Board, Washington, DC. Authors: Cuddy, Matt; Towery, Nate Deshmukh; Machek, Elizabeth; Myers, Jarred. Conference: Transportation Research Board 96th Annual Meeting. Publication Date: 2017. Monograph Title: TRB 96th Annual Meeting Compendium of Papers.

Glossary of Terms and Acronyms

COLL: Commonly Labeled List

COLLECT software: Cooperative Operations for Low-Latency Electronic Collection of Tolls

Deployment: The inception of a technology into its intended technology system

EAR: Exploratory Advanced Research

ETC: Electronic Toll Collection

FHWA: Federal Highway Administration

Framing Document: A short document that details the goals of the TRL Assessment and specifies the key technology, applications, and operating environments to be assessed during the TRL Assessment

GAO: Government Accountability Office

ID: Identification

NASA: National Aeronautics and Space Administration

NCHRP: National Cooperative Highway Research Program

NCHRP IDEA: NCHRP Innovations Deserving Exploratory Analysis

NSF: National Science Foundation

PC: personal computer

PI: Principal Investigator

Q&A: questions and answers

RFID: radio-frequency identification

SBIR: Small Business Innovation Research

TRB: Transportation Research Board

TRL: Technology Readiness Level

TRL Scale: Formal metrics for assessing a particular technology on its maturity level

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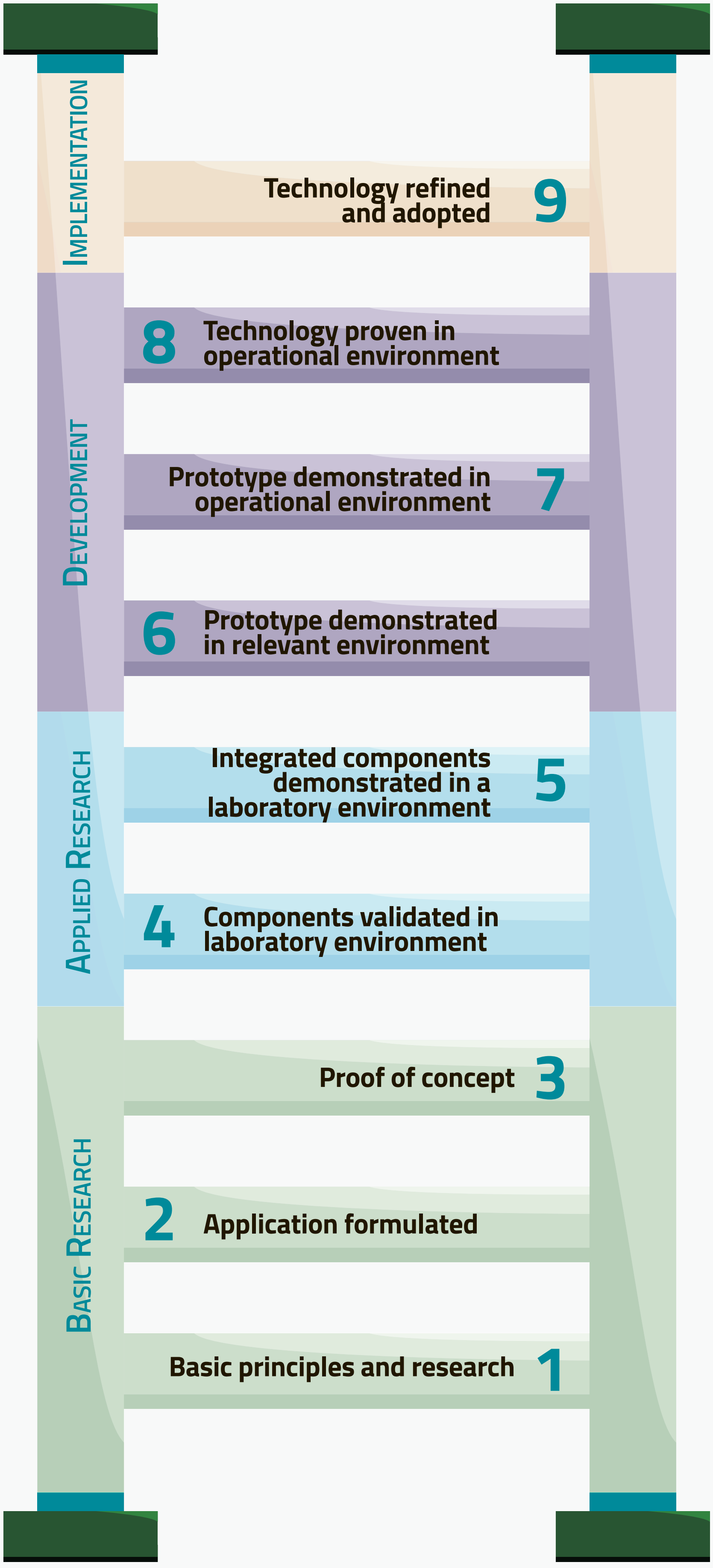
TRL SCALE LEVELS



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