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Automated Vehicles at Highway-Rail Grade Crossings: Final Report

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13. ABSTRACT (Maximum 200 words)

While the number of highway-rail grade crossing (HRGC) incidents remains relatively constant over the last 4 years, HRGCs still represents a significant safety concern for the transportation industry. Per the 2011 crossing collisions and casualties' statistics, approximately 250 fatalities and 950 non-fatal injuries occur each year at HRGCs in the United States. As Automated Vehicle (AV) testing has started to become more prevalent and widespread, AVs will need to interact with HRGCs as human drivers do presently. One way to enhance AV interaction with HRGCs is through Connected Vehicle (CV) technology. This technology and other approaches were considered in this research regarding safe AV traversals on HRGCs.

This report summarizes work performed by Battelle Memorial Institute, including the objectives, scope, and findings of the technology survey (included in its entirety in Appendix A); Concept of Operations (ConOps) and Requirements (included in Appendix B); and the stakeholder engagement. The report provides project conclusions and recommendations for further advancement in understanding, concepts, and requirements of AV traversals on HRGCs.

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

$[(x-32)(5/9)]$ °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
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1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

$[(9/5) y + 32]$ °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

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Centimeters: 0 1 2 3 4 5 6 7 8 9 10 11 12 13
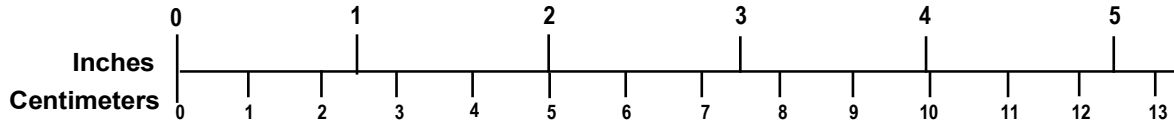
QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
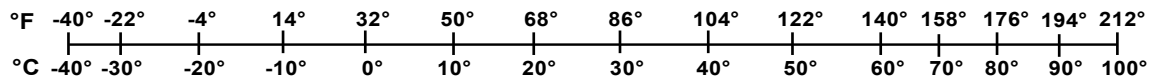
For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Contents

Tables

Executive Summary

This report documents a project funded by the Federal Railroad Administration where Battelle Memorial Institute conducted research to identify a base set of requirements needed for an Automated Vehicle (AV) to traverse a highway-rail grade crossing (HRGC). The work was performed at Battelle's Columbus, OH, facility from August 2017 to May 2018. A Concept of Operations (ConOps) and Requirements document was developed to explore the requirements of how an AV will move across an HRGC. Due to uncertainties and differing perspectives amongst rail and participating stakeholders (i.e., the AV, Automated Driver Assistance Systems, North American railroad industries, and the Federal Highway Administration), the future development of associated technologies holds several constrained assumptions, concepts, and requirements. The stakeholders and the Battelle team used these unresolved concerns to expand into a base set of concepts for sample use cases. The use cases were an added layer to the basis of the ConOps real-world scenarios, where complex conditions were explored to produce possible performance outcomes and information needed for AVs moving along HRGCs. It is recommended that a representative stakeholder group continue to encourage development to reach a consensus on a sufficiently broad and refined set of ConOps scenarios and detailed requirements to support the evaluation.

While the number of HRGC incidents has remained relatively constant over the last 4 years (around 2,000 incidents per year), they still represent a significant safety concern for the U.S. transportation industry. Approximately 250 fatalities and 950 non-fatal injuries occur each year at HRGCs in the United States [1]. As AV testing starts to become more prevalent and widespread, AVs will need to interact with HRGCs as human drivers do presently. One way to enhance AV interaction with HRGCs is through Connected Vehicle (CV) technologies. This technology and other approaches were considered in this research.

1. Introduction

This report presents the results of research performed by Battelle Memorial Institute to identify a base set of requirements needed for an Automated Vehicle (AV) to traverse a highway-rail grade crossing (HRGC).[1] HRGC is the term selected for this project to define the area where a roadway intersects railroad tracks, between the stop bars, which is where vehicles are to stop. Other terms used to describe this same intersection include railway-highway crossing, highway rail intersection, grade crossing, and level crossing. This report summarizes project activities, objectives, scope, findings of the technology survey, and findings derived from stakeholder engagement. A project conclusion is provided, with recommendations for further advancement of understanding, concepts, and requirements. The technology survey is included in its entirety in Appendix A. The Concept of Operations (ConOps) and Requirements document is included in its entirety in Appendix B.

1.1 Background

HRGCs continue to be a significant safety concern for the United States Department of Transportation (DOT). While the number of grade crossing incidents has remained relatively constant over the last four years (around 2,000 incidents per year), they still represent a significant safety concern. Approximately 250 fatalities and 950 non-fatal injuries occur each year at grade crossings in the United States [1].

Progression from "No Automation" toward "Full Automation" of highway vehicles is rapidly evolving due to AV technology. According to the National Highway Traffic Safety Administration (NHTSA), 94 percent of serious crashes are the result of human error [2]. Transferring the control of the vehicle from a human to an automated system, can reduce road accidents, and increase overall safety.

With AVs only recently emerging into the market, there is limited information available and very little research has been published regarding the safe interaction of an AV with an HRGC.

Addressing the potential safety concerns and identifying solutions regarding AV technology when interacting with an HRGC is possible, and will help reduce the possibility of new hazards that are introduced by AVs.

1.2 Objectives

The objectives of this project were to:

- Identify what information AVs may need to negotiate HRGCs

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[1] It is important to note that the terminology used in the technology survey when referring to AVs was autonomous vehicles. As the project progressed, it was recognized that the correct term to use was Automated Vehicles, as defined by Society of Automotive Engineers (SAE) International. The decision was made to not modify the appendices to present the original investigation.

- Create a ConOps and Requirements document that explores the base scenarios an AV will encounter when traversing an HRGC
- Develop a set of requirements that addresses the basic functions, characteristics, and requirements of AVs, HRGCs, infrastructure, and trains

1.3 Overall Approach

The overall approach of this research was to identity the standards related to the AV and North American railroad industry, as well as the technological challenges for current AV technologies, and to review related research projects. As a result, a technology survey was conducted to understand the current state of AV development. Additional information related to the findings and detailed descriptions can be found in Section 2.

Based on the findings from the technology survey, a ConOps and Requirements document was created. This document begins by defining simplifying assumptions, and then presents base scenarios of an AV approaching an HRGC and lists associated high-level requirements supporting these base scenarios.

Following these sections, the document presents a set of performance-affecting, real-world conditions and develops a set of use cases that illustrate possible operational and informational AV needs by applying representative conditions to the base scenarios. The intention for presenting performance-affecting conditions and example use cases with sample operational and informational considerations is that these constructs serve as a starting point to provide a process for stakeholders to consider, refine, and further develop. Ultimately, an agreed-upon set of more detailed assumptions and scenarios may serve as the basis for a set of requirements suitable for evaluation by all stakeholders. More information can be found in Section 3, and the ConOps and Requirements document can be found in Appendix B.

To identify any potential gaps and to refine the concepts and requirements previously developed, a stakeholder engagement workshop was hosted, and several small group follow-up discussions were subsequently held. Base scenarios created in the previous task were presented to stakeholders at the workshop, while select use cases were discussed with participating stakeholders in follow-up conversations. More information about stakeholder engagement can be found in Section 4.

Based on the information obtained from the previous tasks, a comprehensive set of conclusions and recommendations were compiled and presented in Section 5 of this document.

1.4 Scope

Simplifying assumptions were established with a focus on basic system functionality during the creation of the ConOps and Requirements document. To help maintain the focus on base scenarios and requirements, assumptions about specific technologies or solutions were avoided. One exception to this was to recognize established and existing railroad warning systems and markings.

It is important to note that the concepts and requirements are exploratory by nature and designed to be used as a first step in understanding how AV and HRGC systems should interact. Detailed requirements were not developed in this project, although considerations for the development of

detailed requirements based on more complex conditions were explored through the development of sample use cases and presented as referenced in the section above. Moreover, the base scenarios and the use cases presented in the ConOps and Requirements document each represent only a subset of the multiple ways an AV can interact with an HRGC.

1.5 Organization of the Report

This report is organized into six sections, followed by the appendices. The introductory section discusses the objective and approach, as well as the scope of the project. The subsequent sections summarize the technology survey, the ConOps and Requirements document, and stakeholder engagement by providing the objective, approach, and findings of each task deliverable. Following these three sections, a concluding section presents the key takeaways from each of the previous task deliverable sections and recommendations for how the results of this project can be used to further the development and understanding for how an AV may interact with an HRGC. Lastly, the technology survey, and ConOps and Requirements document are attached in their entirety as Appendix A and Appendix B, respectively.

2. Technology Survey

This section presents the methodology and results from the technology survey conducted. The goal was to assess the current state of AV and railroad technology, and to develop an understanding for how an AV may interact with an HRGC. The technology survey is provided in Appendix A of this report.

2.1 Objective

A technology survey was conducted that detailed how automated and CV technologies, the HRGC environment, and AVs interact with HRGC . Past and ongoing related projects, as well as the different industry standards applicable to the research, were identified and documented. This was completed to identify potential performance needs to guide the comprehensive development of a set of high-level requirements that describe safe traversal of an HRGC by an AV. The focus throughout this project has been on Level 4 and Level 5 AVs with the AV performing the dynamic driving task.

2.2 Approach

The technology survey begins by explaining the various levels of automation as defined by SAE, and then details the characteristics of an AV, a CV, and a Connected Automated Vehicle (CAV) [3]. Next, the rail crossing environment is explored , including warning device types, the application of preemption, safety protocols used by vehicles and trains traversing HRGCs, and the interactions of driver-controlled vehicles traversing HRGCs [4] [5]. Following this, a set of CV research projects are presented that focus on the interaction of CVs and HRGCs that have implications for AVs. The next section provides an assessment of the standards, rules, and guidelines related to AV interaction with an HRGCs. This includes focused reviews of AV policies, CV standards and regulations, standards related to rail crossing safety and operations, design specifications and guidelines for passive and active grade crossings, and Federal regulations for locomotives and grade crossings.

The document continues with an exploration of how AVs interact with the environment. This includes the different sensors and methods that have been reportedly used to support AV operations, details on how AVs approach intersections and stops, and a summary of how AVs interact with infrastructure in one deployment initiative. Included are several examples of AV system limitations, such as the incorrect identification of road objects as traffic signs, environmental obstructions, inadequate lighting, and poor weather conditions [6]. The document concludes with overarching lessons learned and a list of key stakeholder organizations and individuals who are potential candidates to review project concepts and requirements.

2.3 Findings

Although the interaction between AV and HRGC is not a subject for which research and findings have been published, the technology survey provided results of how AVs function and of their limitations. It revealed the different elements that comprise an HRGC with Active Warning Devices (AWDs) and Passive Warning Devices (PWDs) and provided insight into how an AV might utilize information from these warning devices to determine the presence of an HRGC and

whether a train is approaching. An awareness of the capabilities and limitations of current-generation AV sensing systems suggests that multiple sources of key information should be provided and used, and that wireless communication from external sources may be beneficial.

3. Concept of Operations and Requirements

The findings from the technology survey served as a foundation for development of the ConOps and Requirements document. This section presents the approach used to develop the ConOps scenarios and requirements, the organization of the document, and the findings that resulted from developing the concepts and requirements. The ConOps and Requirements document is attached in Appendix B of this report.

3.1 Objective

The ConOps and Requirements document was developed to explore how an AV may interact with and determine if it is safe to proceed across an HRGC. Assessing how an AV can traverse an HRGC included identifying the information an AV needs and determining the actions an AV must perform to obtain that information. Once the basic concepts were finalized, a set of core requirements for AVs at HRGCs were developed to address the functional needs of the system. The requirements outline high-level operational functions needed for an AV to traverse an HRGC.

3.2 Approach

The technology survey completed in Task 1 served as the foundation for developing the ConOps scenarios. The technology survey summarized the current state of the technology, identified applicable standards in the AV and railroad industries, reviewed past research projects, and revealed specific AV challenges.

The findings from the technology survey indicated that AVs have multiple types of sensors to receive information from their surroundings, however, the performance of these sensors can be impaired due to challenging and unavoidable real-world conditions. For example, an AV interpreted a red balloon located in front of a stoplight as a red light or was unable to see a traffic light due to a high-profile vehicle such as a bus in front of the vehicle prohibiting the AV from seeing ahead [7]. Conditions like these are common and challenge the ability of the AV to make a prediction using its onboard sensors and algorithms.

While sensors are required to perform AV driving tasks, error can be reduced and mitigated through connectivity with the AV's environment. The development of CV technology has proven connectivity between vehicles and infrastructure to be an effective method of increasing safety and mobility. The Battelle team leveraged its CV development and deployment experience, including a proof of concept Rail Crossing Violation Warning development project, to introduce Connected HRGC scenarios.

For each ConOps scenario, it was determined that the AV and CAV must perform the same four common actions to traverse an HRGC:

1. The AV or CAV must detect the presence of an HRGC ahead.

2. The AV or CAV must be able to identify if the HRGC has AWDs or PWDs.

3. If the AV is connected, it should be able to receive available connected information from a Connected HRGC, Connected Train, or queued CAVs, if applicable.

7

4. The AV or CAV must be able to identify the location where the vehicle must stop (e.g., the HRGC stop bar, when present and detectable).

The common actions described above outlined the basis for the creation of the ConOps scenarios. Eleven scenarios were created, laying the framework for the requirement development process. System elements which may comprise the scenarios include an AV, a train, an HRGC, and queued vehicles. Iterations of the ConOps scenarios featured unique system element details:

- The AV may or may not be connected.

- The train may or may not be connected.

- The HRGC may or may not be connected.

- The HRGC may possess AWDs or PWDs.

- The AV or CAV may either be approaching or stopped at the HRGC.

- The train or Connected Train may be approaching, occupying, or departing the HRGC.

- Queued vehicles, which may or may not be connected, may or may not be present beyond the HRGC.

Although there is an understanding from the technology survey and previous project experience that complex and unpredictable variables such as weather, obstructions, and lighting conditions can impact an AVs ability to perform, they were eliminated through the use of simplifying assumptions. These assumptions were applied to the development of ConOps scenarios and requirements to enable a focus on exploring the basic information needs of AVs for traversing an HRGC. Although it is recognized that AVs will likely use multiple sources of information, another simplifying assumption was to restrict the focus of the ConOps scenarios to an AV/CAV using a sole source of key information. However, following the development of base concepts and requirements, the impacts of complex and unpredictable variables and conditions, and multiple information sources, are considered as discussed below.

The requirements development process began by grouping the ConOps scenarios into categories based on the types and status of system elements described above. The requirement categories include the following:

1. **General Scenario Requirements** – This section includes requirements that apply to: general connectivity, both AVs and CAVs, only AVs, only CAVs, Connected Trains, and Connected HRGCs. These requirements apply to all ConOps scenarios whenever the specified system elements exist.

2. **CAV and Connected HRGC Requirements** – In addition to the General Scenario Requirements that pertain to all scenarios, these requirements apply only to the scenarios where CAVs and Connected HRGCs are both present.

3. **CAV and Connected Train Requirements** – In addition to the General Scenario Requirements that pertain to all scenarios, these requirements apply only to the scenarios where CAVs and Connected Trains are both present.

4. **AVs/CAVs Approaching an HRGC with PWDs** – Regardless of whether the vehicle is an AV or CAV, the vehicle will obtain the information about its surroundings at an HRGC with PWDs in the same fashion.

5. **AVs/CAVs Approaching an HRGC with AWDs** – Regardless of whether the vehicle is an AV or CAV, the vehicle will obtain the information about its surroundings at an HRGC with AWDs in the same fashion.

The requirements were grouped into these specific categories based on how the vehicle performs the four common actions, given the characteristics of its surroundings. For example, AVs and CAVs may obtain the same type of information, however, they may do so differently. In the ConOps scenarios, an AV approaching an HRGC with AWDs will scan for the status of the lights to determine if a train is approaching (in range) or occupying the HRGC. "In range" means that the train is approaching or departing and close enough to the HRGC to be detected by the train detection system at the HRGC with AWDs, or by the approaching AV or CAV. Alternatively, CAVs approaching an HRGC will look to receive a status information broadcast by a Connected Train, regardless of whether the HRGC is connected or what type of warning devices are present. Thus, CAVs and AVs have various and different methods for detecting the status of a train.

A key theme during stakeholder engagement was the need to consider the challenging real-world conditions that may affect the way an AV performs. To provide a basis for further development and refinement of the assumptions, conditions, scenarios, and requirements, Section 5 of the ConOps and Requirements document explores a set of performance-affecting real-world conditions and develops a set of use cases that illustrate possible operational and informational AV needs by applying representative conditions to the base scenarios. Ultimately, an agreed-upon set of more detailed assumptions and scenarios can serve as the basis for refined requirements.

3.3 Findings

Throughout the requirements development process, Battelle applied its previous CV and AV project experience, findings from the technology survey, and internal as well as acquired external subject matter expert knowledge to develop a set of requirements that suggest how an AV should perform at an HRGC. With little published information available about the way AVs perform under various conditions and a lack of shared agreement amongst representative stakeholders, lower level detailed requirements were not attempted.

Detailed requirements including interface behavior, operational conditions, physical constraints, integration specifics, verification and validation methods, production, maintenance and disposal constraints, and applicable standards will be possible once stakeholders are brought together to advance and agree upon decisions regarding how AVs should respond and what information they should rely upon. Such requirements will need to be sensitive to the level of automation under which the AV is operated. Ultimately, the requirements may additionally need to conform with Federal guidelines and regulations.

4. Stakeholder Engagement

Battelle performed stakeholder engagement to seek input from subject matter experts in both the AV and rail industries, and government entities. This section presents the approach taken and summarizes the findings.

4.1 Objective

Battelle engaged stakeholders to validate ConOps scenarios using their industry expertise and to gain additional input on what information AVs will need to negotiate HRGCs. Stakeholder feedback was used to refine the requirements developed for AVs at HRGCs, to develop and refine use cases for further development, and to make final recommendations and conclusions to guide future development and refinement of the concepts and requirements.

4.2 Stakeholder Workshop

After the ConOps scenarios were finalized, Battelle hosted an interactive workshop with stakeholders that spanned 90 minutes on April 4, 2018, to discuss select scenarios with subject matter experts from the AV, Automated Driver Assistance Systems (ADAS), CV, highway, and railroad industries. Selected scenarios served as a representative subset of the operational concepts and included AVs, CAVs, non-connected trains, Connected Trains, Connected HRGCs, HRGCs with AWDs, HRGCs with PWDs, and different vehicle and train locations. The six scenarios discussed in the workshop are described below:

1. The AV approaches an HRGC with AWDs without a train approaching in range or occupying the HRGC.

2. The AV approaches an HRGC with AWDs, vehicles queueing, without a train approaching in range or occupying the HRGC.

3. The AV approaches an HRGC with AWDs activated and a train occupying the HRGC.

4. The AV approaches an HRGC with PWDs and a train occupying the HRGC.

5. The CAV approaches a Connected HRGC with AWDs activated and a train occupying the HRGC.

6. The CAV approaches an HRGC with PWDs and a Connected Train approaching in range of the HRGC.

Battelle presented the simplifying assumptions at the beginning of the workshop to set the stage for the scope of work being performed, and then described each of the scenarios to the stakeholders. After each scenario was described, Battelle presented questions to the stakeholders that would challenge the way an AV would perform in that scenario. Subject matter experts representing government and industry actively participated and shared their expertise on what information AVs will need to traverse an HRGC and how they thought it may do so. The stakeholders generally agreed with the ConOps scenarios presented and the way an AV should operate at an HRGC.

4.3 Stakeholder Follow-Up Meetings

Following the workshop described above, Battelle compiled key takeaways and created use cases that expanded the ConOps scenarios by applying performance affecting conditions. Specific conditions, previously excluded by simplifying assumptions for the ConOps base scenarios, were used to create unique challenges identified in the workshop. The set of sample use cases built around these expanded ConOps scenarios aimed to expose operational and information source options for consideration.

Battelle hosted a series of 60-minute follow-up meetings with interested industry stakeholders during the week of April 16, 2018. Participating stakeholders included experts from the AV/ADAS industry, railroad industry, and the Federal Highway Administration (FHWA). The purpose of these meetings was to gain additional insight on the informational sources an AV might need to traverse an HRGC if the challenges from the use case scenarios were presented in a live environment.

Table 1 summarizes the use cases discussed with the specified industry expert representatives and potential information sources that stakeholders believed would benefit the AV. Refer to Table 1 in Appendix B for the complete list of use cases. It should be noted that the use case descriptions may differ slightly from the ConOps scenario names found in Appendix B. This is because the ConOps names were later revised to reflect input from stakeholders.

Table 1. Use Cases Discussed in Stakeholder Engagement Follow-Up Meetings

Use Case Scenario #	Use Case Description	Industry/Entity Discussed with	Potential Information Sources Identified
1	The AWD lights at the HRGC are non-functional.	FHWA, Railroad	• High-definition maps • Connected Train broadcasting train position and speed • Connected HRGC broadcasting train position and speed
2	The approach to the HRGC is located on a steep grade prohibiting the AV from detecting queued vehicles beyond the HRGC.	AV/ADAS, FHWA, Railroad	• Wayside vehicle detection equipment beyond the HRGC • Connectivity between queued vehicles and approaching vehicle • Connectivity between queued vehicles and HRGC with connectivity between HRGC and approaching AV
3	A hi-rail or maintenance vehicle is within the vicinity of the HRGC upon an AV approaching	Railroad	• Maintenance vehicle broadcasting work zone information • High-definition maps with real-time work zone information
4	The train is stopped within range of the HRGC and the AWDs are activated.	Railroad	• Connected Train broadcasting train status
5	The Connected HRGC communication system is non-operational.	AV/ADAS	• Redundant information sources needed
6	The crossbuck sign cannot be identified due to sun glare (or other reasons).	AV/ADAS	• High-definition maps • Connected HRGC broadcasting stop bar location information
7	The HRGC stop bar is obstructed and cannot be identified by the AV.	FHWA	• High-definition maps • Connected HRGC broadcasting stop bar location information
8	The train occupying the HRGC is composed of flatcars instead of high-profile cars, i.e., box cars.	AV/ADAS	• Connected Train broadcasting position and speed
9	The skew angle at the roadway and HRGC is sharply skewed (e.g., 45-degrees).	AV/ADAS	• Connected Train broadcasting position and speed

4.4 Findings

The workshop and follow-up meetings provided valuable feedback used to validate the ConOps scenarios and requirements, and to further develop and refine the use cases. As AV technology continues to be developed, government agencies and industry stakeholders should be encouraged to collaborate to determine how an AV will perform and interact when within close proximity of an HRGC. Refinement of the concepts and requirements will likely encourage stakeholders to

support how AVs should operate to meet the challenges that severely limit present day technologies.

The most significant takeaway from the workshop was universal agreement that collaboration amongst stakeholders—to include AV industry, railroad industry, roadway users, and government entities—is imperative to advance the concepts and requirements of AVs to traverse an HRGCs. The list below summarizes the results and conclusions from the workshop and follow-up meetings:

- Railroad companies are unlikely to share or broadcast specific train data to AVs approaching an HRGC due to safety and reliability risk concerns, unless it can be demonstrated via thorough analysis that safety is improved.

- AVs may be able to traverse an HRGC without receiving information from the train.

- There is a need for AVs to collect and consider data from multiple and redundant sources. Whenever possible, AVs should not rely on a sole source of information. Connectivity between the AV and HRGC or between a train or other vehicles can serve as a complementary source of data in addition to the AV's sensor package.

- An AV's ability to accurately predict when a detected moving object will collide with the AV is challenged when the AV is in motion or when the object being detected (e.g., a train) is travelling at a high speed.

- High-definition maps can serve as another input and redundant source of information. Maps can include the following details: locations of HRGCs, stop bars, sign locations, and HRGC geometry.

- Level 4 and Level 5 AVs should not rely on input from vehicle passengers in any situation. While a legal driver may optionally choose to drive the AV, it should not be assumed that a legal driver will always be in the vehicle or be able to take control if necessary.

- An AV should be allowed to take evasive actions, to include violating traffic laws (e.g., disobey traffic signs/controls), when the safety of vehicle occupants is endangered due to a predicted severe collision.

- Consideration needs to be given to the expectations for AV operation when the AV detects that current conditions are outside of its operational design domain (ODD). One option is to geo-fence known problem areas. Another possibility is to accept remote navigation assistance either from a lead vehicle or a remotely-controlled station (a service beginning to be offered by start-up companies) [8].

- There are safety risks associated with relying on visual inputs from the AV's sensor package alone, including imposter traffic signs or objects resembling signs that may mislead an AV.

- The installation of special signage for AVs may help to ensure detectability of key information under challenging conditions.

- An AV's ability to traverse an HRGC can be significantly impacted by adverse weather conditions.

- Complex HRGC geometry and topography can hinder the ability of an AV to detect visual or audible cues for determining whether it can traverse the HRGC. The addition of on-board sensors based on different technologies (such as Light Detection and Ranging [LiDAR]) may improve performance.

- Varying train lengths can present potential challenges to an AV. If accurate and timely details about the length of the train are not known, the AV will need to rely on fewer sources of information (perhaps only direct on-board detection) about when the train no longer presents a threat to traversing the HRGC.

- The use of connectivity may remove, or augment, the dependence of artificial intelligence, such that higher confidence-based decisions are possible.

- Failure-modes and effects must be taken into consideration for connected system components.

- The integration of a closed-loop system such as Positive Train Control (PTC) represents an architectural and design challenge for the concept of a connected system involving highway vehicles.

- The trucking community and road builder representatives should be included in future stakeholder engagement efforts to provide additional perspectives.

- The Federal Railroad Administration (FRA) should collaborate with the Rail-Highway Crossings Program at the FHWA to be aligned with and inform funding decisions aimed to eliminate HRGC hazards known to FRA and its stakeholders.

- If AVs are unable to traverse certain HRGCs, the FHWA may consider prioritizing them for being connected depending on difficulty or danger.

- All high rail vehicles do not shunt the track. For the high rail vehicle use case, it should be assumed that it does not shunt the track.

- The railroad industry's biggest concern is the mean time between hazardous events. New systems can increase the probability/potential of a hazard occurring. The system may help solve one problem and simultaneously introduce another.

- Priority should be assigned to the most problematic types of HRGCs or use cases as a method for considering the best solution for given HRGCs.

5. Conclusion

Battelle performed tasks to explore the information that an AV needs to traverse an HRGC and the ways it may do so. First, a technology survey was conducted to summarize the current state of the technology, identify applicable standards in the AV and railroad industries, review past research projects, and reveal specific AV challenges. Next, a ConOps and Requirements document was developed to determine how an AV should respond to specified scenarios, and to understand what information an AV requires and how it can obtain that data.

In the ConOps, base scenarios and requirements were developed to support basic operational functions and information needs. Select use cases reflecting performance affecting conditions and recognizing operational performance expectations and information needs were then created. Finally, Battelle hosted a stakeholder engagement workshop and four follow-up meetings with stakeholders from the AV, ADAS, and railroad industries, as well as government entities including FHWA and FRA, to help validate and refine the assumptions, conceptual scenarios and use cases, and requirements.

Key takeaways from this project are summarized below:

- There is little publicly available information about AV functionality and performance.

- How Level 4 and 5 AVs will function is not fully understood. Only a limited set of current model consumer vehicles are capable of Level 2 automated driving.

- The AV industry is not currently focused on the interaction between AVs and HRGCs.

- Currently, the AV industry does not expect AVs to manage all use case scenarios that human drivers encounter. Difficult-to-navigate HRGCs may be geo-fenced and may be considered as outside an AVs operational design domain.

- Coordination and communication between stakeholders impacted by an AV interacting with an HRGC are essential in preparation for deployment of Level 4 and 5 AVs.

- There is a consensus among the stakeholders that redundancy and multiple sources of information are vital for AV reliability and safety. Connected information between AVs or rail infrastructure may complement onboard AV sensors.

- There is a consensus among the stakeholders that failure modes challenge reliance on connectivity for safety-critical information.

- An agreement was observed amongst stakeholders on the need for detailed mapping to improve AV reliability, as an additional source of information that can supplement sensor and connectivity data. An additional benefit of leveraging multiple sources of data is the ability to validate the correctness of each source.

- Railroad industry representatives are hesitant to consider the idea of connectivity between AVs and trains due to safety and liability concerns with trains or wayside rail equipment broadcasting train information in an open-loop system.

- SAE and NHTSA standards and programs such as Federal Motor Vehicle Safety Standards (FMVSS) and New Car Assessment Program (NCAP) are expected to be impacted.

5.1 Recommendations

Most HRGC accidents today are attributed to human error. It can reasonably be expected that automation would dramatically reduce the number of accidents, especially those attributed to inattentiveness or alcohol/drugs. However, current-generation AVs are subject to many of the same challenges as human drivers, including adverse weather, equipment faults, and obstructed views. These are problems that need be solved. There are opportunities to continue to advance research on AV interaction with HRGCs. The following recommendations for future research and concept and requirement development are based directly on the results of this project:

- Continued stakeholder meetings or forums are encouraged for collaboration and planning between impacted industries.

  - Recommended participating stakeholder industries or entities include: AV original equipment manufacturers (OEMs), ADAS, CV, railroad, FRA, roadway user groups (including trucking industry), and FHWA and local transportation departments and planning organizations that build, maintain, and ensure safe and efficient operations on roads.

  - Other interested stakeholder groups include mapping companies, communication equipment suppliers, railroad signal equipment manufacturers, insurance companies, and standards entities (e.g., SAE, NHTSA).

- Additional ConOps and use case scenarios should be created to advance the understanding of the breadth and depth of challenges an AV can face at HRGCs. A source for these use cases should include HRGC accident investigations.

- Solutions may not work equally well on all HRGCs. Problematic HRGCs should be prioritized. One option for prioritization is to assess the FRA accident cause database and determine where accidents occur most frequently, and which are most impactful. ConOps and use case scenarios that apply to the most prominent causes of accidents should be addressed with higher priority.

- Detailed requirements that are measurable and definable should be developed from the ConOps and use case scenarios once there is an expectation or understanding for how AVs will function.

- Verification testing should be conducted on detailed requirements.

With little information publicly available about the way Level 4 or 5 AVs will operate or function, it is not understood how AVs will traverse HRGCs. There is some published evidence available about how AVs operate through the California Department of Motor Vehicles' Autonomous Vehicle Disengagement Reports 2017 [9]. These are a list of reports written by each AV OEM, which they are required to publish if they operate or test AVs on public roads in the State of California. Each report contains differing levels of detail as to what caused the disengagement.

Research throughout this project indicates that the AV industry is not currently focused on the interaction between AVs and HRGCs. After engaging with stakeholders from the AV, ADAS, and railroad industries, it is recommended that these interdisciplinary discussions continue to take place as a collaborative effort towards problem-solving in a world with AVs. Coordination and communication between stakeholder groups will be essential to further develop research on

AV interaction at HRGCs. All stakeholder groups play a different role and have a different motivation for how they envision this interaction taking place.

As forums and working groups are established and there is increased communication between industries, a clearer understanding of how an AV will be expected to perform will be developed. This will allow detailed and verifiable requirements to be written and tested against the ConOps and use case scenarios. Testing these requirements will help to ensure safe future interactions between AVs and HRGCs. As these requirements are tested, they can be refined or adjusted to reflect advancements in the state of the art, regulatory policies, and updated standards that will be impacted.

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Appendix A. Highway-Rail Grade Crossing for Autonomous Vehicles

Technology Survey

Final Report – October 30, 2017

U.S. Department of Transportation

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16. Abstract

Highway-rail grade crossings continue to be a large safety concern with many departments of transportation. While the number of highway-rail grade crossing incidents has remained relatively constant over the last four years (around 2000 incidents per year), they still represent a significant safety concern for the transportation industry. Approximately 250 fatalities and 950 non-fatal injuries occur each year at highway-rail grade crossings in the United States. Connected vehicle technologies offer the potential of reducing highway-rail grade crossing incidents by providing travelers, either through their vehicles directly or with handheld, portable devices, with better, timelier advance warnings that a train is approaching a crossing. With the introduction of autonomous vehicles, the potential exists to remove the human factor element altogether and thus further enhance crossing safety.

This document includes a detailed technology survey of the connected vehicle, autonomous vehicle, freight, and transit systems, as well as lessons learned from tangential industry systems. The research will ensure that the most current advances in technology are being applied to this project by researching and focusing on existing work done for other connected vehicle projects and how those projects interface with autonomous vehicles. The outcome will guide this project in creating a solid set of requirements that can be used to design a system that can be deployed at highway-rail intersections to interface with autonomous vehicles equipped with this technology, ensuring a safer experience.

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Table of Contents

List of Tables

List of Figures

Executive Summary

With recent advancements in automated and autonomous vehicle (AV) technology, the Federal Railroad Administration is proactively exploring how these vehicles will perform at grade highway-rail intersections (HRI).

Battelle, on behalf of The Federal Railroad Administration, performed a technology survey to assess potential performance needs by researching connected and autonomous vehicles, freight and transit systems, as well as lessons learned from comparable applications in industry systems. The objective of this technology survey is to guide the comprehensive development of a set of requirements to inform the design of a deployment-ready system to ensure a safe experience for AVs at HRIs.

Battelle concludes that current infrastructure in place will require modifications and AVs will require a certain level of functionality to safely interface with an HRI, as explained in this report. AVs are highly dependent on the use of sensors to detect surroundings to predict the proper response for any given scenario. This high-level of dependence is problematic in imperfect environmental conditions, areas where a lack of infrastructure or poor infrastructure conditions are present, or when these vehicles face a scenario they have never encountered before. These challenges can be resolved with a level of connectivity between the infrastructure, a locomotive, and the AV. This communication channel will provide an additional input for the AV to make the best decision possible and will aid in eliminating part of the predictivity element in AVs.

Chapter 1. Background

At grade Highway Rail Intersections (HRIs) continue to be a significant safety concern for the United States Department of Transportation (U.S. DOT). While the number of highway-rail grade crossing incidents has remained relatively constant over the last four years (around 2000 incidents per year), they still represent a significant safety concern. Approximately 250 fatalities and 950 non-fatal injuries occur each year at HRIs in the United States.

Connected Vehicle (CV) and Autonomous Vehicle (AV) technologies can play an integral role in reducing these fatalities and serious injuries at rail crossings. Over the past decade, the U.S. DOT has awarded several contracts to assess and develop CV technology with a focus on improving safety and mobility. CV technology has proven to be effective at providing travelers with timely information to make roadways safer. With over ninety percent of vehicle crashes in the U.S. being due to errors made by drivers on the road, AVs are expected to significantly reduce incidents [1]. The introduction of AVs that also employ CV technology will help maximize safety.

Research focused on the interaction of AVs with an HRI is very minimal compared to the research efforts that have been made in the connected vehicle and HRI area. With AVs only recently emerging into the market, there is limited information and limited published research studies available. Conversely, there is much information available on CVs given that the government has been heavily invested in this research for over a decade. The following chapters describe the current state of AV technology and the challenges being encountered.

Autonomous Vehicles

AVs, as defined by the National Highway Traffic Safety Administration (NHTSA), are vehicles in which some aspects of safety-critical control functions occur without direct driver input. Safety-critical inputs may include steering, throttle, braking, etc. AVs use high-definition camera technologies, LIDAR, and radar, allowing the car to see what is in its environment, to measure distances around the car, and to determine the distance of objects from the vehicle. These technologies combined with software applications to help vehicles identify safety risks and warn the driver of potential collision.

AVs differ from automated vehicles as an AV is completely independent; not subject to any outside control [2]. An automated vehicle on the other hand, involves some level of coordination between the vehicle and the roadway infrastructure [2]. Automated vehicle technology, combined with software applications, help vehicles identify safety risks and warns the driver of potential collision.

The continuing evolution of AVs aims to deliver greater safety benefits that will, in the future, not require any input from the driver as the vehicle operates in self-driving mode. In October 2016, the NHTSA adopted the Society of Automotive Engineers (SAE) six levels for automated driving systems, ranging from no automation to full autonomy [3]. The levels outline a general guideline for the level of AV technologically in the automobile. Level 5 automation, for instance, is more technologically advanced and requires no driver input compared to Level 2 automation, which requires the driver to be engaged with the driving task even though the vehicle has combined automated functions. SAE's six levels of automation are below in Table 1. Additional information on the SAE levels of autonomy can be found in Appendix C.

Table 1. Levels of Automation Summary

Level	Name	Definition
0	No Automation	The driver performs <u>all</u> driving tasks including steering, braking, throttle, and power.
1	Driver Assistance	The vehicle is still being controlled by the driver in this level, but some driving assist features (e.g. steering, acceleration, etc.) may be included in the vehicle design and done autonomously by the vehicle.
2	Partial Automation	In this level, the vehicle has combined automated functions, such as cruise control and lane centering. The driver is disengaged from physically operating the vehicle by removing his or her foot from the pedal. However, the driver must remain engaged with the driving task, monitor the environment, and must always be ready to take control of the vehicle at any time.
3	Conditional Automation	In this level, having a driver is a necessity, but is not required to monitor the environment and may shift safety-critical functions to the vehicle, under certain traffic or environmental conditions. The driver must be ready to take control of the vehicle at all times with notice from the vehicle.
4	High Automation	The vehicle can perform all driving functions under certain conditions. The vehicle's performance is limited to the operational design domain (ODD) of the vehicle, meaning it does not perform under every driving scenario. The option exists for the driver to control the vehicle.
5	Full Automation	Dissimilar to Level 4 automation, the vehicle is capable of performing all driving functions under all conditions. In this system, the vehicle's performance is similar to that of a human driver that in every driving scenario, including extreme environments the vehicle can be operated. The option exists for the driver to control the vehicle.

Source: SAE International and J3016, September 27, 2017

Currently in the United States, there are no AVs available for consumer purchase above a Level two automation capability. Level three and four AVs are currently being used in industry solely for research and are not available for consumer purchase.

**Table 2. Summary of Currently Available Automatic Safety Features**

Convenient Features	
Cruise Control	an electronic device in a motor vehicle that can be switched on to maintain a selected constant speed without the use of the accelerator
Seat Belts	a belt or strap securing a person to prevent injury
Antilock Brakes	an automobile safety system that allows the wheels on a motor vehicle to maintain tractive contact with the road surface according to driver inputs while braking, preventing the wheels from locking up (ceasing rotation), and avoiding uncontrolled skidding
Advanced Safety Features	
Electronic Stability Control	a computerized technology that improves a vehicle's stability by detecting and reducing loss of traction (skidding)
Blind Spot Detection	use a variety of sensors and cameras to provide a driver with information about objects that are outside his range of vision
Forward Collision Warning	uses radar (all-weather) and sometimes laser (LIDAR) and camera (employing image recognition) to detect an imminent crash
Lane Departure Warning	uses a GPS or highway infrastructure sensor, and tracks the vehicle's orientation and position relative to the lane boundary and issues a timely visual, auditory and/or haptic (tactile) warning to alert the driver that the vehicle is leaving the lane
Advanced Driver Assistance Features	
Rearview Video Systems	also known as a backup camera, is a safety technology that helps prevent back-over crashes by providing an image of the area behind the vehicle
Automatic Emergency Braking	the vehicle detects an imminent crash and applies the brakes to prevent, or limit the severity, of the collision
Pedestrian Automatic Emergency Braking	also known as pedestrian impact mitigation braking—is an emerging safety technology that provides automatic braking for vehicles when pedestrians are in the forward path of the vehicle's travel and the driver has taken insufficient action to avoid an imminent crash
Rear Automatic Emergency Braking	detect an impending rear crash with another vehicle in time to avoid or mitigate the crash
Rear Cross Traffic Alert	detects vehicles from the left or right rear of vehicle trying to back out of a space
Lane Centering Assist	continuous active steering to stay in between lanes (active steer, autosteer, etc.)

Source: NHTSA, October 3, 2017

The frontrunners for developing and/or testing AVs include Ford, Google, General Motors, Audi, BMW, and Volvo [4]. Table 3 lists various safety features available in the consumer vehicle market.

Connected Vehicles

CV research sponsored by U.S. DOT leverages the transformative capabilities of wireless technology to make surface transportation safe and smarter. There are two main types of CV communications, vehicle-to-infrastructure (V2I and vehicle-to-vehicle (V2V). V2I communications are between vehicles and deployed roadside communication devices which capture vehicle generated data while providing information pertaining to safety, mobility or environmental conditions. V2V is the wireless exchange of vehicle data between vehicles. A CV is a vehicle equipped with Dedicated Short-Range Communication (DSRC) technology that enables it to "talk" to other vehicles, personal devices, and infrastructure on a rapid and continuous basis, along with real-time vehicle performance parameters. DSRC is a two-way short-to-medium-range wireless communication capability that permits high data transmission, critical in communications-based active safety applications. Vehicle communication via DSRC can reduce fatalities and serious injuries in traffic accidents. Figure 1 shows vehicles communicating via CV technology while moving harmoniously through an intersection.
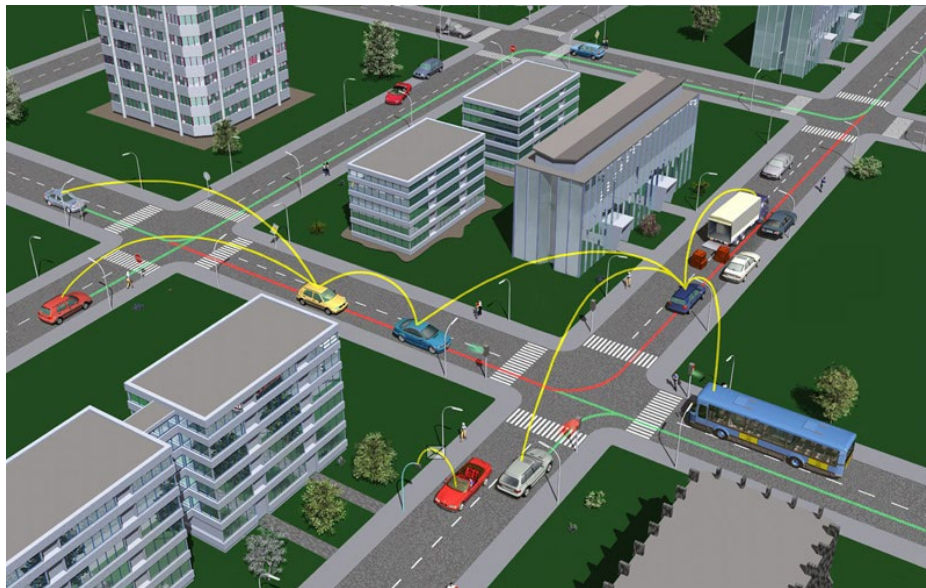
Source: Automotive World October 20, 2017

Figure 1. Connected Vehicle Technology

DSRC is intended for highly secure, high-speed wireless communication between vehicles, personal devices, and infrastructure. In 2004, the Federal Communications Commission allocated 75 MHz of spectrum in the 5.9 GHz band for use in vehicle safety and other mobility applications [5]. The key functional attributes of DSRC include low latency, limited interference, and acceptable performance during adverse weather conditions.

CV applications allow drivers to receive warnings and alerts of potential dangerous situations. Examples of different CV applications include the following:

- **Enhanced Pedestrian in Crosswalk Warning (E-PCW)**: This application leverages V2I technology to detect pedestrians at a connected intersection and notifies the driver when a pedestrian has the intent to cross or is in the action of crossing the crosswalk.
- **Forward Collision Warning (FCW)**: Alerts the driver when the closing speed of his/her vehicle with respect to the vehicle it is trailing, or a stationary obstacle it is approaching, is excessive.
- **Rail Crossing Violation Warning (RCVW)**: Using V2I technology, this application presents the driver with a warning to stop when the vehicle is predicted to traverse a rail-crossing being occupied by a locomotive.
- **Curve Speed Warning (CSW)**: Notifies the driver when the vehicle is traversing a curve at a higher speed than deemed safe.

According to U.S. DOT, widespread deployment of CV technology will enable innovative mobility deployments such as cooperative cruise control and vehicle platooning. This technology also improves surface transportation by enabling increased roadway throughput, reduced congestion, and mitigation of unnecessary braking and stopping at junctions. A reduction in fuel consumption and lowered vehicle emissions can be expected.

Connected Autonomous Vehicles

V2V and V2I communications can enhance the AV safety and efficiency by providing greater situational awareness. A connected autonomous vehicle (CAV), is a vehicle that leverages AV and CV technologies. The full benefits of vehicle automation can be achieved only through connectivity. By integrating CVs with AVs, the safety of roadways can be improved, transportation capabilities expanded, and mobility options extended to everyone—from the disabled, and the elderly, to the inexperienced teenage driver. Figure 2 shows what constitutes a CAV.
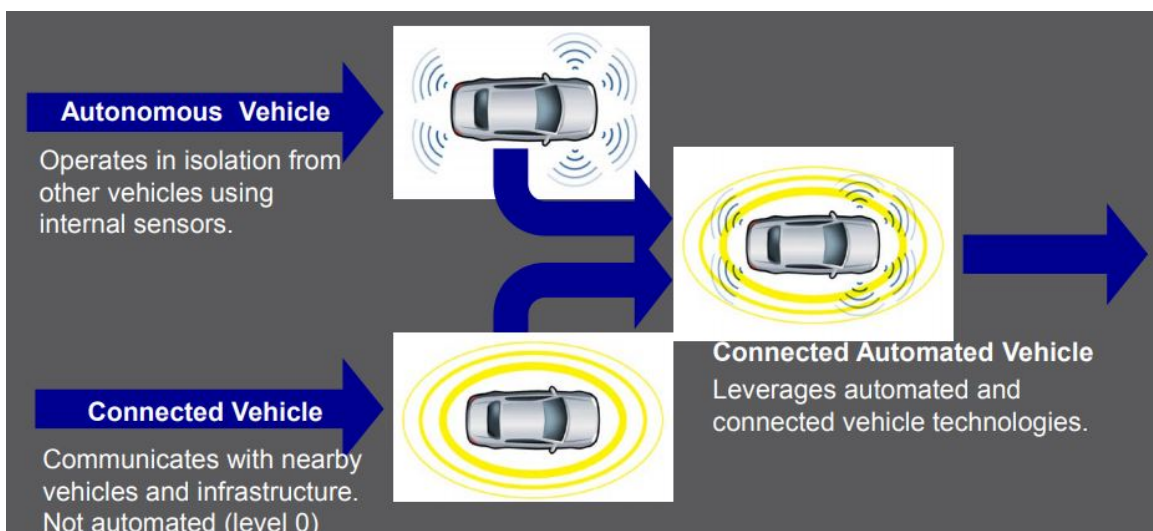
Source: Department of Transportation, October 17, 2017

Figure 2. Connected Automated Vehicles (CAVs)

The Federal Highway Administration (FHWA) is moving forward with research that advances the concept of CVs integrated with AV functionality. Even though the private sector is moving quickly in this space, the

U.S. DOT is playing a significant role in deploying AV. Not only is it facilitating development and deployment, but also working to ensure that automation enhances safety, mobility, and sustainability. The U.S. DOT is working closely with industry partners to identify available opportunities [6].

Chapter 2. Rail Crossing Environment

As of 2015, there were 129,582 public grade crossings and 80,073 private grade crossings throughout the United States [7]. State highway authorities have jurisdiction over and are required to maintain public grade crossings [8]. Private grade crossings include roadways located on privately owned lands not intended for the use of the public such as a farm or industrial area [7]. These crossings are not under the jurisdiction or maintained by a public highway authority [7]. Both public and private grade crossings are comprised of two separate types: active and passive crossings.

The following information describes the current environment at rail crossings. Understanding the environment an AV will encounter at a rail crossing will provide insight in creating requirements to ensure a safe traversal.

Types of Grade Crossings

Active grade crossings provide active forms of warnings to give advanced notice to motorists of a locomotive approaching the rail crossing, activated by a detection circuit in the track [9]. The appropriate active devices to warn road users are defined in the FHWA's Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways [10]. This manual defines the standards to be applied for installing active warning and traffic control devices on public and private infrastructure [8]. Active warning and control devices include flashing light signals, bells, automatic gates, and highway traffic signals [9]. The type of warning device installed at public grade crossings is determined by state highway authorities and approved by FHWA [8]. All types of warning devices implemented are to protect motorists rather than trains [8]. Figure 3 is representative of the types of active warning devices installed at active grade crossings.
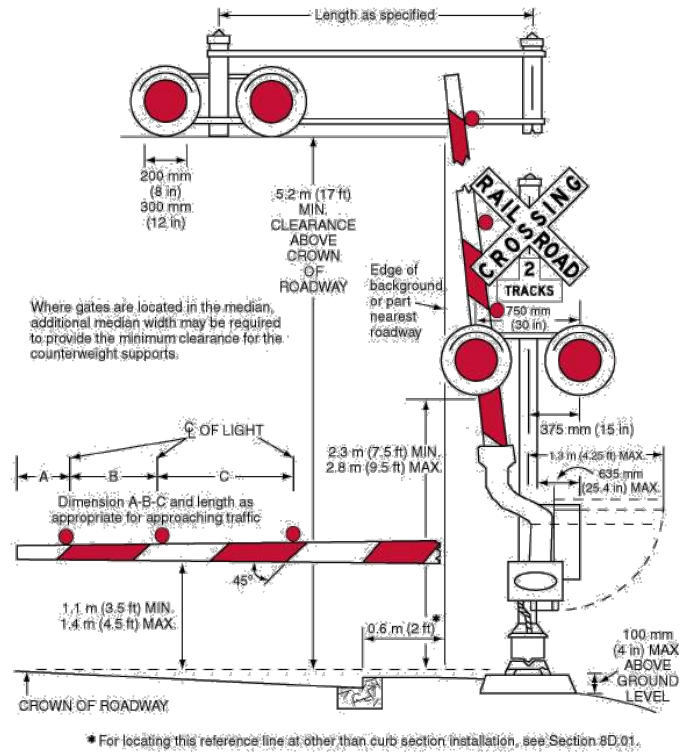
Figure 3. Active Grade Crossing Warning Devices

Passive grade crossings implement passive warning devices to indicate a rail crossing is present and to communicate to the driver to take precaution as needed [9]. Figure 4 illustrates examples of passive warning devices, consisting of crossbucks, yield or stop signs, and pavement markings [7]. Active grade crossings are not limited to active warning devices as they also contain passive warning devices [9].
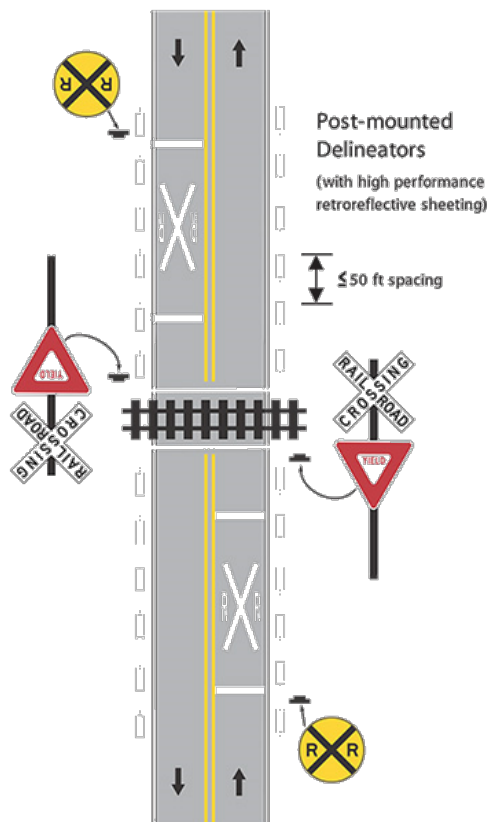
Figure 4. Passive Grade Warning Devices

Preemption at Rail Crossings

When a signalized Highway-Rail Intersection (HRI) is within 200 feet of a rail crossing, the traffic signal controller (TSC) and the railroad control equipment should be interconnected [9]. The two conditions requiring this interconnectivity are listed below:

- Highway traffic queues have potential to extend across a neighboring rail crossing [11].
- Traffic backed up from a downstream rail crossing could interfere with the signalized intersection [11].

The interconnectivity between these two systems allows a traffic signal controller to be aware of a train approaching the nearby HRI and activate its preemption sequence [11].

In one scenario, a locomotive is traveling down the tracks and approaching an HRI, the train is detected by railway installed hardware and a preemption signal is sent to the TSC at the nearby intersection [11]. Upon the TSC receiving the preemption input, the operational mode is shifted to a mode of operation with a different set of timing and rules [13]. Preemption signals are not exclusive to railroad crossings [11]. Drawbridges, emergency vehicles, and transit vehicles are also capable of generating preemption inputs [11]. The principle behind traffic signal preemption at highway-rail intersections is to prevent vehicles

traversing an HRI being "trapped" in an HRI by vehicles stopped by the traffic signal on the far side of the HRI [11]. It is illegal for vehicles to stop on the tracks at a highway-rail grade crossing; however, high traffic volume, non-clearing queues, and adjacent signalized intersections can sometimes cause motorists to stop on tracks with no path from egress.

Light Vehicle and Transit Vehicle Safety Protocol

While each state's laws vary, most of states have laws specifying a stopping distance between the vehicle being operated and the rail crossing. The types of vehicles that are required to stop at active and passive grade crossings also differ. Below are examples of required safety protocols in two different states.

The State of Ohio requires vehicles to obey the following safety regulations:

- "Vehicles must stop within 50 feet, but not less than 15 feet from the nearest rail if signaled to do so or if an approaching train is plainly visible" [12].
- "Special vehicles, buses, or motortrucks transporting employees, buses transporting passengers, school buses, and vehicles transporting hazardous materials are required to stop [12].

The State of Colorado has a slightly different safety regulation than Ohio for vehicles approaching a grade crossing. The safety regulation is described below:

- "Any driver of a motor vehicle approaching a railroad crossing sign shall slow down to a reasonable speed" [12].
- "If required to stop, driver shall stop at the marked stop line. If there is no line, driver shall stop no less than 15 feet nor more than 50 feet from the railroad crossing [12].
- "The driver of a school bus, or the driver of any vehicle carrying hazardous materials, is required to stop vehicle, listen, and look before proceeding across railroad tracks [12].

Locomotive Protocol

All locomotives are required to follow safety protocols when approaching an HRI. Safety protocols for locomotives can be broken down into three core areas: **headlights**, **train horns**, and **reflectorizing** [13].

Every single locomotive is equipped with **headlights** that are required to be illuminated whenever the locomotive is in motion [13]. Some locomotives use headlights that are stationary, while others use oscillating headlights, so the light beam can sweep across the tracks [13]. While roof lights can be utilized to serve as markers in yards for known whereabouts or indicators at HRIs, they are not required by the Federal Railroad Administration (FRA) [13]. In the 2004, the FRA considered a regulation requiring strobe lights, but this was never implemented. An in-depth cost and benefits analysis was performed, but the results did not support the proposed regulation to use alerting lights at grade crossings [13]. The FRA did issue a final ruling on locomotive headlights that requires auxiliary lighting and for the lights to form a triangle at the front of the locomotive [13]. Refer to Figure 5.

Figure 5. Locomotive with Headlights Forming a Triangle, as Required by the FRA

All locomotives are equipped with air-powered **horns** to be used as a warning upon approach [13]. The FRA has a requirement for the horn to produce a sound level between 96 dB(A) and 110 dB(A) at 100 feet in front of the locomotive [13]. There are some exceptions to this rule. If a train is travelling faster than 60 mph, engineers will not sound the horn until it is within one quarter mile of the crossing, even if the warning is less than 15 seconds [14].There is also a "good faith" exception for locations where engineers can't precisely estimate their arrival at a crossing and begin to sound the horn no more than 25 seconds before arriving at the crossing [14]. As a locomotive approaches a crossing, the engineer shall sound the horn with a series of two long blasts followed by a short blast and then one long blast [14]. An additional requirement set forth by the FRA specifies the locomotive must sound the horn at a minimum of 15 seconds and no more than 20 seconds when approaching a public grade crossing [14]. Refer to Figure 6.

Figure 6. Air Horns Installed on the Roof of a Diesel-Electric Locomotive

In addition to this regulation, locomotive companies may implement additional self-imposed safety protocols. Union Pacific Railroad for example, follows its General Code of Operating Rules, which encompasses a series of sound descriptions that indicate when a specific kind of event is occurring. Refer to Table 3 below. The "o" is indicates a short sound and the "=" represents a long sound [15].

Table 3. Locomotive Horn Signals

Sound	Indication
Succession of short sounds	The whistle is sounded in an attempt to attract attention to the train. It is used when persons or livestock are on the track at other-than-road crossings at grade.
=	When train is stopped. The air brakes are applied, and pressure is equalized.
= =	Train releases brakes and proceeds.
o o	Acknowledgment of any signal not otherwise provided for.
o o o	When train is stopped: means backing up, or acknowledgment of a hand signal to back up.
o o o o	A request for a signal to be given or repeated if not understood.
= o o o	Instruction for flagman to protect rear of train.
= = = =	The flagman may return from west or south.
= = = = =	The flagman may return from east or north.
= = o =	Train is approaching public crossings at grade with engine in front.
o =	Inspect the brake system for leaks or sticking brakes
= o	Train is approaching men or equipment on or near the track, regardless of any whistle prohibitions. After this initial warning, "o o" sounds intermittently until the head end of train has passed the men or equipment.

Source: Union Pacific Railroad, October 3, 2017

Locomotives however, are required by law to <u>not</u> sound their horn when approaching a Quiet Zone unless there is an emergency and it is required [14]. A Quiet Zone is a section of track that passes   through a community [14]. Communities can apply for the grade crossing to have Quiet Zone status if the set of minimum safety requirements are met [16]. Some of these requirements include installing advance warning devices with flashing lights and crossing gates. The Automated Horn System (AHS), commonly used at Quiet Zones, is a stationary horn mounted at a rail crossing, rather than on a locomotive, that provides an audible warning to motorists and pedestrians [17]. These systems are proven to eliminate noise pollution in quiet communities and remain a viable warning solution as they are used in conjunction with other active warning systems [17]. Refer to Figure 7 and Figure 8.

Figure 7. Sound Contour Map Comparing a Train Horn Sound with an AHS

Figure 8. Automated Horn System Contains a Speaker and Status Light

The AHS uses a track circuit to detect a train approaching, similar to detecting a preemption signal. Upon detecting an oncoming locomotive, the roadside installed speaker will play a digital sound of a train horn. The light installed alongside the horn facing the locomotive will illuminate to indicate to the engineer that the system is working [17]. Refer to Figure 9 for a diagram of the AHS.
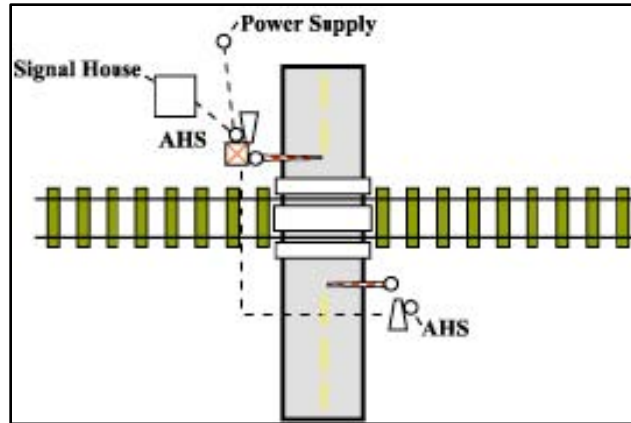
Figure 9. Automated Horn System Diagram

Approximately twenty-five percent of collisions at HRIs involve a motorized vehicle striking a train that is occupying the crossing [13]. Locomotives are often difficult to see due to their dark colorization [13]. This, coupled with poor lighting conditions, limited visibility around a turn, or a heavily wooded area greatly contrib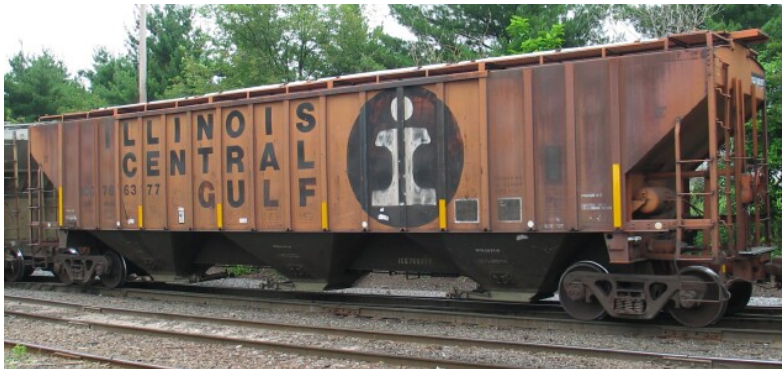utes to accidents with motor vehicles [13]. The FRA mandated the use of yellow and white **reflective materials** to be installed on all freight rail cars [13]. Refer to Figure 10 for an example of the required reflectors.

Figure 10. Rail Car with Yellow Reflectors

User Case Scenarios at Rail Crossings

Numerous potential interfaces exist between vehicles, locomotives, and railroad crossings. This relationship can be described as a "common boundary or interconnection between systems, equipment, concepts, or human beings [18]. A comprehensive understanding of the interfaces involved between the systems is crucial to exploring the concept of AV at HRIs. The following are two user case scenarios that demonstrate the interaction between a motorist and an HRI. These scenarios examine the interfaces

between the driver and the infrastructure and also indicate the duties the AV will be responsible for when a driver is no longer required.

- **Scenario 1:** a light vehicle and locomotive simultaneously approach an active HRI. A light vehicle is defined by the Environmental Protection Agency as a vehicle that has a maximum Gross Vehicle Weight Rating of less than 8500 lbs. [19].
- **Scenario 2:** a light vehicle and locomotive simultaneously approach a passive HRI.

Scenario 1.

1. Light vehicle approaches the intersection between the highway and rail crossing, obeying local traffic laws and actively scanning the area between the front of the vehicle and the HRI for a train.
2. Light vehicle continues on its path observing the grade crossing to determine if it is active or passive and responds accordingly. In this scenario the grade crossing is active.
3. Light vehicle's driver is not required to respond unless the active warning devices are activated.
4. Locomotive is traversing over the railroad tracks at a fixed speed down a fixed path with the locomotive's lights on and obeying the speed limit.
5. Locomotive's engineer should constantly be monitoring the front of the locomotive while traveling down the tracks to ensure there is no obstruction or emergency requiring action.
6. Once the locomotive reaches a specified distance from the HRI, the track circuit detects the train and relays an electrical signal to the HRI controller at the crossing.
7. A signal is then sent to the highway traffic lights and the light transitions to a stop phase.
8. The locomotive engineer must sound the air horn, unless specified otherwise, to notify the motorist approaching the HRI that the locomotive is approaching as soon as the locomotive is between 15 and 20 seconds away from reaching the HRI.
9. Upon the relayed signals being received by the hardware at the crossing, warning devices are activated to provide an additional warning to the driver that a train is approaching.
10. If there is not an emergency on the tracks, the locomotive will proceed down the tracks under normal protocol.
11. The driver of the light vehicle must process and react to the active and passive grade warnings by reducing speed and stopping at the indicated stopping area, stopping at a distance identified by the roadside signs and/or road markings.
12. After the driver has stopped the vehicle, the train continues through the HRI as there were no obstructions or emergencies. The active warning devices will continue to be active until the train has cleared the island track circuit.
13. The warning devices disengage and devices such as warning gates rise to allow the vehicle to traverse the intersection.
14. Light vehicle must proceed slowly and verify it is safe to cross the railroad tracks by looking down both sections of track and listening at the intersection for any additional trains that could be approaching.
15. Once the driver deems the area as safe to continue, they can resume operating under normal protocol.

Scenario 2.

1. Light vehicle approaches the intersection between the highway and rail crossing, obeying local traffic laws and actively scanning the area between the front of the vehicle and the HRI for a train.

2. Light vehicle continues its path, observing to determine if the grade crossing is active or passive and responds accordingly. In this scenario the grade crossing is passive.

3. Light vehicle's driver must recognize the passive stopping bar and crossbucks markings conveyed on the pavement, start to slow down and identify the location where it must stop in case a locomotive is on approach or present.

4. Locomotive is traversing over the railroad tracks at a fixed speed down a fixed path with the locomotive's lights on and obeying the speed limit.

5. Locomotive's engineer should constantly be monitoring the front of the locomotive while traveling down the tracks to ensure there is no obstruction or emergency requiring action.

6. There are no active warning devices to activate at the intersection as there is no circuit track to detect the presence of a train.

7. The locomotive engineer must sound the air horn to notify the motorist approaching the HRI that the locomotive is approaching as soon as the locomotive is between 15 and 20 seconds away from reaching the HRI.

8. Vehicle must continue to slow down and be prepared to stop.

9. Vehicle's driver shall look both ways and listen for the train as the vehicle approaches the HRI.

10. As the vehicle's driver has heard the horn or has seen the train, vehicle shall come to a complete stop and wait for the train to pass prior to continuing through the intersection.

11. After the train has passed, the driver must slowly approach the intersection and look both ways and listen to make sure another train is not approaching from either side.

12. Once the intersection is clear, the driver can proceed.

Chapter 3. Highway-Rail Grade Crossing Projects

The following is a list of CV research projects involving an HRI and a connected vehicle found during this literature review:

- Vehicle-to-Infrastructure Prototype Rail Crossing Violation Warning Application [20]

- Rail2x: Demonstration of Vehicle2x Technologies for Rail-Related Applications [21]

- Transmission Range Evaluations for Connected Vehicles at Highway-Rail Grade Crossings [22]

- An approach for Integrating DSRC Technologies with PTC for Road-Rail Intersection Safety [23]

- Improving Road Safety and Public Health with real Time and Predictive Train Crossing Information [24]

- Identification of Railroad Requirements for the Future Automated and Connected Vehicle Environment [25]

These studies provide useful information that can be applied to scenarios involving the interaction of an AV and an HRI. The project "Vehicle-to-Infrastructure Prototype Rail Crossing Violation Warning Application" [20], is the first project in the nation implementing CV technology to detect the approach and presence of a train in an HRI.

The project titled "An approach for Integrating DSRC Technologies with PTC for Road-Rail Intersection Safety" [22], proposes the integration of DSRC technologies with the Positive Train Control system to relay information to the road user such as direction of travel, estimated time of arrival and duration of closing.

"Identification of Railroad Requirements for the Future Automated and Connected Vehicle Environment" will provide proposed requirements the Railroad will need to take into consideration in preparation for the deployment of AV on the roads.

The lessons learned during the development and implementation of all these projects along with all the research and information gathered could be used to identify requirements related to AV/HRI interactions.

Vehicle-to-Infrastructure Prototype Rail Crossing Violation Warning Application [20]

U.S. DOT sponsored the Vehicle-to-Infrastructure Prototype Rail Crossing Violation Warning Application (RCVW) project. The primary focus of this project was developing and applying Intelligent Transportation Systems concepts for HRIs that employ track-circuit based train detection.

The RCVW system was developed to provide real-time, condition-based audible and visual alerting to vehicle operators. RCVW will enhance situational awareness by predicting and warning drivers approaching or stopped within active rail crossings of imminent rail crossing violations.

For HRIs equipped with active warning devices and interconnected with traffic signal controllers at nearby intersections, a preemption signal is issued when an HRI is active. The Code of Federal Regulations (CFR) Title 49, Part 234, specifies that this signal must be issued at least 20 seconds before train arrival. However, factors such as the roadway speed limit, railway speeds, design of the active warning devices, HRI hazard zone size (inclusive of number of tracks), HRI warning device placement, and additional site-specific factors are considered in determining if more than 20 seconds is required.

When the system receives a preemption signal, it will broadcast an HRI Active message. If an equipped vehicle is within the HRI approach zone, it may issue alerts, and, if necessary, a crossing violation warning. This warning is determined by an algorithm executed by the vehicle subsystem, which includes factors such as typical reaction times, assumed worst case positional inaccuracy, vehicle speed, braking performance, road parameters, and weather. It is critical that the Vehicle Based Subsystem (VBS) receives timely HRI Active messages and issues actionable RCVWs.

The RCVW system concept is illustrated in Figure 11. This figure depicts an active HRI with an approaching train, activated rail warning devices, and a Roadside Based Subsystem (RBS) communicating with CVs approaching the HRI when a train is detected as approaching or present.

A conceptual block diagram of integrated RCVW system components is illustrated in Figure 12.
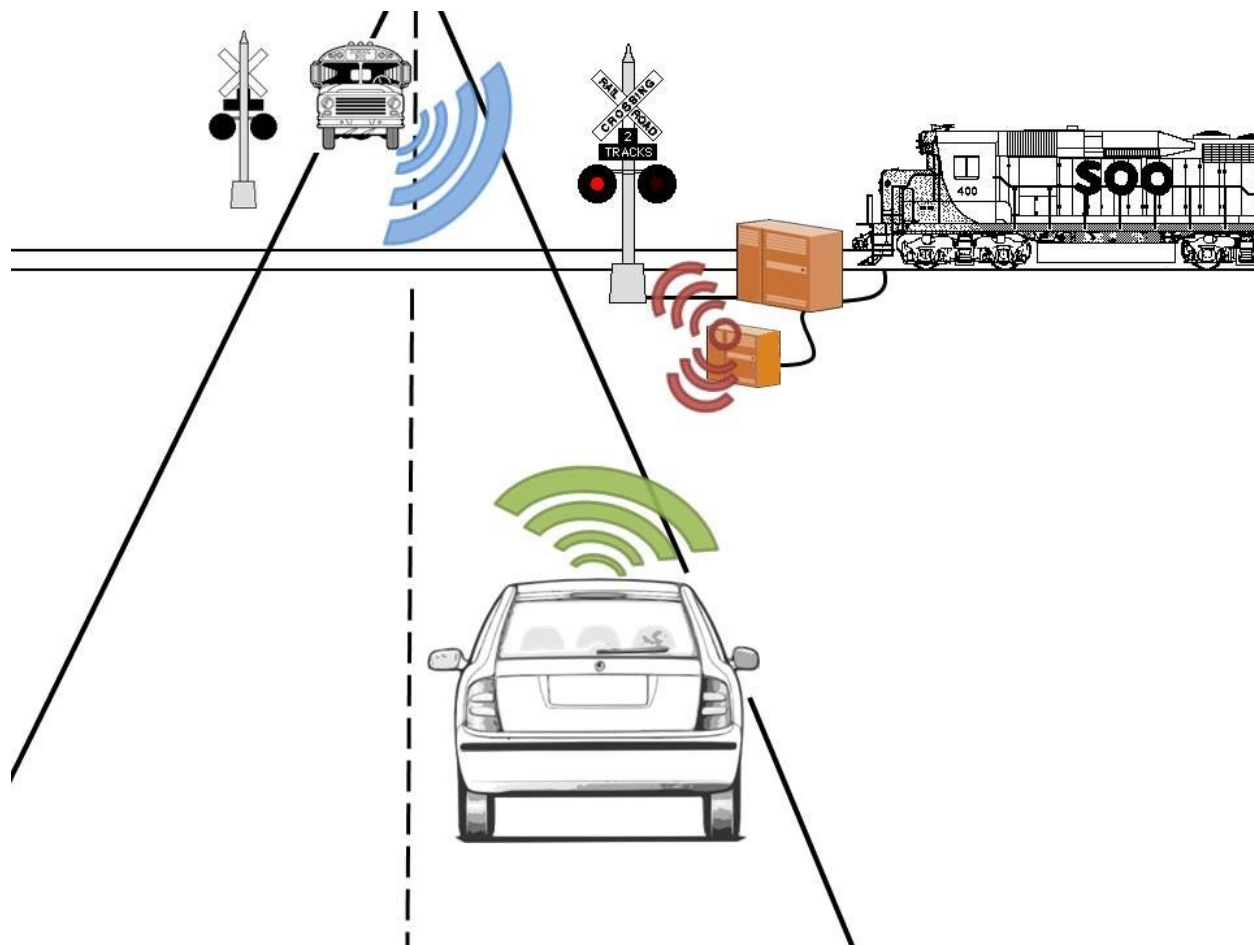
Source: Adapted from Volpe, November 15, 2017

Figure 11. RCVW Application Concept

Figure 12. Conceptual Block Diagram of Integrated RCVW System Components

Rail2x: Demonstration of Vehicle2x Technologies for Rail-Related Applications [21]

The German Aerospace Center's Institute of Transportation Systems located in Braunschweig, Germany demonstrated a rail-to-infrastructure system. The objective of this system was to demonstrate the use of CV technology on a rail vehicle for safety applications.

The demand for a larger distribution of information between the railroad system and other forms of transportation is increasing. This can be addressed by incorporating CV technology into rail vehicles and railroad infrastructure without risking the safety and performance of the railway automation and protection systems. This can be accomplished, without modifying any of the established safety mechanisms present at an active grade crossing, by adding technology that will distribute rail information.

When a rail vehicle passes the make-contact point, advisory light signals are activated at the grade crossing, indicating road vehicles must leave the crossing or stop before reaching it. A rail vehicle equipped with an OBS identifies by geo-fencing that it has passed the contact point and sends an activation message to an RBS located at the grade crossing. After receiving the activation trigger, the RBS broadcasts Signal, Phase, and Timing (SPaT) that have been modified to reflect the operational rules of the grade crossing in question. The user interface in the road vehicle warns the driver of rail unit movement toward the grade crossing. This is shown in Figure 13.

The system proposed in this project can be integrated on both active and passive grade crossings. It does not require a preemption signal.
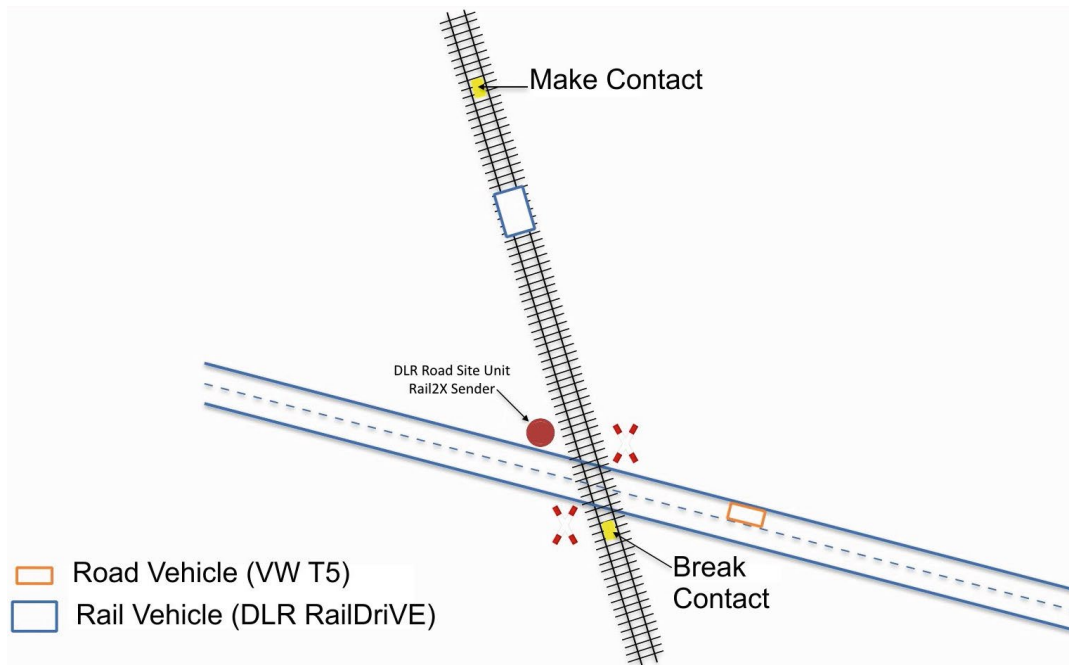
Source: DLR Institute of Transportation Systems October 17, 2017

Figure 13. Topology Layout

Transmission Range Evaluations for Connected Vehicles at Highway-Rail Grade Crossings [22]

Bowhead Logistics Solutions and the Department of Civil Engineering at the University of Lincoln-Nebraska performed a study to evaluate the transmission range requirements of CVs at HRIs to explore potential safety improvements.

This study assumes trains have onboard computers and antennas that transmit train location and speed information to CVs in the vicinity of the rail crossing via DSRC communication.

Incidents, injuries, and death occur at both passive and active grade crossings. Active grade crossings have a higher incident rate of accidents compared to passive crossings due to higher traffic volumes. The majority cause of accidents at active HRIs is due to vehicles violating the control/warning devices present, while at passive HRIs, motorists commonly disregard the traffic warning signs. The study discusses that the technology currently being used is not sufficient to allow a driver to make the right decision when approaching an HRI. A driver will have a lower risk of a collision with a train if he is informed of the train's location and speed.

The conclusion of this study indicates that an a locomotive OBS, broadcasting its precise location and speed would reduce the incidence of vehicle-to-train collisions.

The study analyzes the transmission range required for CV applications at HRIs.

The study makes the following assumptions:

- A single track and two-lane highway
- Straight sections with no curves on the highway
- The highway-rail intersecting angle is 90°
- The highway pavement is dry
- No line of sight obstruction between highway vehicles and the approaching train
- The sight distance to the train is 300 m under fair weather conditions
- The speed of an approaching train is constant
- CV drivers are obedient to the onboard warning of a train and will stop their vehicles

An Approach for Integrating DSRC Technologies with PTC for Road-Rail Intersection Safety [23]

R Systems International published a paper that discusses the possibilities for integrating DSRC radios with the Positive Train Control (PTC) technologies being deployed by all locomotive companies

PTC is being deployed on locomotives to increase safety by monitoring train speed, train location, and status of wayside devices.

PTC communication is composed of various wireless technologies, enabling communication between the equipped locomotive, wayside assets, and the central dispatching office. The wireless network evaluated to handle this communication was the industry standard 220MHz, which is a narrowband network consisting of a defined message set.

The standard for the interface between the rail subsystem and the highway subsystem at an HRI is IEEE 1570-2002; it defines the communication protocol. It enables a traffic controller device to preempt operations, allowing vehicles to clear an HRI when a train is approaching.

The study proposed upgrading the communication segment of the PTC system to be able to handle DSRC communication, as well as upgrading the DSRC infrastructure located at an HRI to handle the 220MHz PTC interface.

With this upgrade, the wayside system would be able to relay information to an RBS about an approaching train. This information would be used to calculate the direction of travel, estimated time of arrival, and duration of closing. This could then be distributed to the road user through in-vehicle indicators.

The study proposes two integration architectures, each process the CV/AV and PTC interface differently.

1. **Architecture Integration Plan A:** locally interfaces V2I and PTC to reduce delays.

2. **Architecture Integration Plan B:** introduces a software at the central dispatching office where CV/AV communicates directly with PTC. This plan has an increased delay compared to Plan A, but simplifies the implementation.

The framework proposes technology features to be assessed such as determining the feasibility of DSRC technologies at an HRI to provide the following information:

- Conveying information about vehicles fouling the track to a rail operator
- Indicating the arrival of a train at a rail crossing to a road operator via an advance warning

Improving Road Safety and Public Health with Real Time and Predictive Train Crossing Information [24]

National Research Council Canada is conducting research on "Improving road safety and public health with real-time and predictive train crossing information."

The research project leverages the 2016 Transport Canada mandate that requires road authorities and railway companies to share safety-related information with each other.

Information communicated between grade crossings and vehicles include the following:

- Status of a crossing (blocked, clear or predicted time of blockage)
- Start time of a blocked grade crossing
- Predicted clearing of the grade crossing

There has been a need to identify warning systems that are less costly than flashing lights, bells, and gates, but more active than crossbucks. As a result, the project created a new trackside train detection system. When a rail vehicle is detected, data is then broadcast to road users in several formats such as variable message signs, mapping and navigational apps, and in-cabin display.

Identification of Railroad Requirements for the Future Automated and Connected Vehicle Environment [25]

Texas A&M Transportation Institute is conducting research on "Identification of railroad requirements for the future automated and connected vehicle (AV/CV) environment."

The research focuses in the following:

- Obtaining information on the types of data and information that a vehicle needs to operate safely and effectively near a rail crossing
- The impediments to acquiring this data
- Different implementations that could benefit both rail and highway systems and defining future research needs

Chapter 4. Standards, Rules, and Guidelines

Autonomous Vehicle Policies

Federal Automated Vehicles Policy [32]

In September of 2016, U.S. DOT published the Federal Automated Vehicles Policy. The policy is divided in four main components:

- Vehicle Performance Guidance for Automated Vehicles
- Model State Policy
- Current Regulatory Tools
- Modern Regulatory Tools

Vehicle Performance Guidance for Automated Vehicles: outlines a 15-point safety assessment for designing, developing, testing, and deploying safe AVs.

- Data recording and sharing
- Privacy
- System safety
- Vehicle cybersecurity
- Human-machine interface
- Crashworthiness
- Consumer education and training
- Registration and certification
- Post-crash behavior
- Federal, state, and local laws
- Ethical considerations
- Operational design domain
- Object and event detection and response
- Fall back (minimal risk condition)
- Validation methods

Model State Policy: makes a distinction between Federal and state responsibilities for AV regulation, suggests guidelines to establish policies aiming at creating a consistent national framework for AV deployment and testing.

Current Regulatory Tools: outlines the current regulatory rules that can be used to accelerate safe AV development.

Modern Regulatory Tools: discusses potential new tools and authorities that may aid safe AV development and deployment of related technologies.

The policy will be revisited and updated on a yearly basis, including public comment, industry feedback, and real-world experience **State Legislation and Executive Orders Regarding Autonomous Vehicles.**

Twenty-one states and the District of Columbia have passed legislation related to AV. Governors in five states have issued executive orders [33]. This is shown in Figure 14.

None of these legislations discuss interactions with railroads.
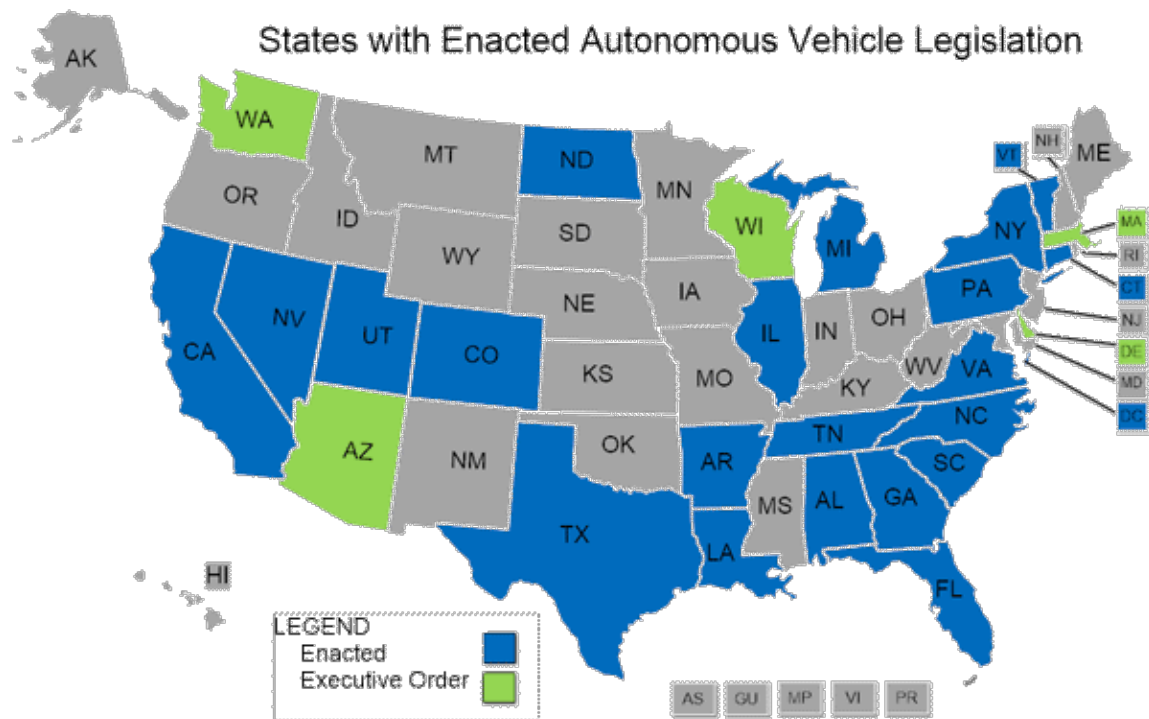
Source: National Conference of State Legislatures, October 17, 2017

Figure 14. States with Enacted Autonomous Vehicle Legislation

Connected Vehicles Standards and Regulations

The following standards support CV deployment and NHTSA rulemaking on V2V communications:

SAE J2735 DSRC Message Set Dictionary [5]

This standard specifies a message set, its data frames and data elements. It assures that DSRC applications are interoperable [5]. It can also be used by applications that might be deployed along with other wireless communication technologies besides DSRC.

DSRC Message List [27]

mapData (MAP): Provides intersection and roadway lane geometry data for one or more locations.

SPaT: Provides the current signal / phase timing data for one or more signalized intersection.

Basic Safety Message (BSM): All equipped vehicles broadcast a stream of BSM at a rate of 10Hz. Nearly all application exchanges (V2V, V2I, V2X) are based upon BSM content. The BSM at a minimum includes:

- Timestamp
- Temporary ID
- Latitude, longitude and elevation
- Positional accuracy
- Heading
- Speed

The BSM can also include the following optional fields that could be used by other V2I applications:
- Transmission state
- Steering wheel angle
- Acceleration brake system status
- Vehicle size

Common Safety Request: Not deployed at this time.

Emergency Vehicle Alert: Not deployed at this time.

Intersection Collision: Intended to inform nearby users that a dangerous condition exists or is likely to exist. It can be sourced by both vehicles and infrastructure.

 National Marine Electronics Association (NMEA) Corrections: Not deployed at this time.

Probe Data Management: Reports details of collected probe data to RBSs.

Road Side Alert: Supports creating informational messages from public safety vehicles by a responder in the field.

Real Time Correction Message (RTCM) Corrections: Broadcast RTCM corrections over the DSRC channel. These are used by the road user's Global Navigation Satellite System (GNSS) device to maintain lane level accuracy.

Signal Request Message: Used by authorized parties to request services from a traffic signal controller.

Signal Status Message: Used to reflect the current operational state of the intersection.

Traveler Information Message: Provides the means to inform the public about incidents and pre-planned roadwork events.

Personal Safety Message: Similar to the BSM, but related to pedestrian users.

SAE J2945 family of standards [28]

This family of standards describe use cases and performance requirements for J2735 messages

J2945/0: Minimum Performance Requirements

J2945/1: On-Board Minimum Performance Requirements for V2V Safety Communications

J2945/2: V2V Safety Awareness

J2945/3: Weather and Road Reporting

J2945/4: Traffic Incident Message (TIM)

J2945/5: Mayday Systems

J2945/6: Coordinated Maneuvers (Platooning and Cooperative Adaptive Cruise Control)

J2945/7: Transit Systems

J2945/8: Freight Systems

J2945/9: Performance Requirements for Safety Communications to Vulnerable Road Users

J2945/10: SPaT and MAP

IEEE 802.11p [28]

This standard specifies the extensions to IEEE 802.11 that are necessary to provide wireless communications in a vehicular (CV) environment.

Specifies the physical and the medium access control layer in the Open Systems Interconnection OSI model.

IEEE 1609 [5, 29]

This family of standards for Wireless Access in Vehicular Environments (WAVE) define the set of services and the architecture that enable secure V2V and V2I wireless communication. These standards are the foundations for a range of applications such as vehicle safety, automated tolling, enhanced navigation, traffic management, and others.

IEEE 1609.2-2016 Standard for Wireless Access in Vehicular Environments (WAVE) - Security Services for Applications and Management Messages: defines secure message formats and processing within the DSRC / WAVE system.

IEEE 1609.3-2016 Standard for WAVE - Networking Services: defines network and transport layer services.

IEEE1609.4-2016 Standard for WAVE - Multichannel Operations: describes various standard message formats for DSRC applications and provides enhancements of the IEEE802.11

IEEE 1609.12-2016 Standard for WAVE - Identifier Allocations: specifies allocations of WAVE identifiers defined in the IEE 1609 series of standards.

LTE-V2X [30]

LTE-V2X is an extension of 3GPP Device-to-Device (D2D) functionality that uses the LTE transmission protocol for direct communication between devices. The main characteristics behind LTE-V2X are:

- Capability to communicate without the need of a base station. Communication is D2D without the need of network coverage
- Operation on a dedicated unlicensed carrier or spectrum
- Supporting low latency, high density and high speed

Despite recent efforts, LTE-V2X has not reached maturity and there are many technical issues that are still being discussed such as:

- Frequency errors due to inaccurate frequency synchronization

- Doppler frequency shifts present on LTE's technology as a result of transmissions by moving vehicles, which adds frequency errors

- LTE's limited ability of detecting weak messages in the presence of strong messages

- LTE's synchronization concept puts a limit on the communication range between users

- Resource allocation for LTE-V2X is more complex when compared to IEEE802.11p resulting in over-allocation or under-allocation

- LTE's heavyweight design of its waveform and frame-format results in higher overhead

- LTE's does not have a protocol to prevent message collisions in the case two users are using the same wireless channel

- Implementing cybersecurity protection on the LTE technology implies higher costs due to the current architecture of LTE's modems. The Safety critical domain must be separated from the non-safety critical domain

SAE J3016 – Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles [31]

In 2016 SAE International published its Surface Vehicle Recommended Practice that provides a classification on the levels of automation for on-road motor vehicles and provides functional definitions for advanced levels of driving automation.

The classifications given in this recommended practice are descriptive and informative rather than normative, and technical rather than legal.

Standards Related to Rail-Crossing Safety and Operations

There is no set of official rules or policies from any Federal agency about selecting traffic control devices or other measures at HRIs.

The MUTCD sets the requirements in terms of the physical characteristics, design, and installation of HRI traffic control devices [10].

The U.S DOT and FHWA *Guidance on Traffic Control Devices at Highway-Rail Grade Crossings* provides engineers with guidelines to select traffic control devices or to improve HRIs. However, these are not considered rules, policies, or standards [34].

The U.S DOT *Railroad-Highway Grade Crossing Handbook* provides legal and jurisdictional considerations. It includes examples of several types of traffic control devices at grade crossings, depending on the physical and geometrical characteristics of the crossing. It gives guidelines for selecting and identifying active control devices. As with the other documents previously mentioned, the information is to be taken only as guidelines and best practices [35].

Design Specifications and Guidelines Related to Passive and Active Grade Crossings

Part 8 of the MUTCD contains the design specification and guidelines for both passive and active grade crossings.

The following information include quoted excerpts of guidelines and specifications taken from specified paragraphs in the MUTCD that should be taken into consideration when creating requirements an AV / HRI interaction. For a complete set of rules and information about traffic devices, consult the MUTCD [10].

Section 8A.02

- Paragraph 1: "Because of the large number of significant variables to be considered, no single standard system of traffic control devices is universally applicable for all highway-rail grade crossings."
- Paragraph 2: "The appropriate traffic control system to be used at a highway-rail grade crossing should be determined by an engineering study involving both the highway agency and the railroad company"

Section 8A.03

- Paragraph 11: "Highway-Light Rail (LTR) grade crossings in semi-exclusive alignments shall be equipped with a combination of automatic gates and flashing-light signals, or flashing-light signals only, or traffic control signals, unless an engineering study indicates that the use of Crossbuck Assemblies, STOP signs, or YIELD signs alone would be adequate."
- Paragraph 12: "Highway-LRT grade crossings in mixed-use alignments may be equipped with traffic control signals unless an engineering study indicates that the use of Crossbuck Assemblies, STOP signs, or YIELD signs alone would be adequate."

Section 8A.04

- Paragraph 1: "All signs used in grade crossing traffic control systems shall be retro reflectorized or illuminated as described in Section 2A.07 to show the same shape and similar color to an approaching road user during both day and night."
- Paragraph 2: "No sign or signal shall be located in the center of an undivided highway, unless it is crashworthy (breakaway, yielding, or shielded with a longitudinal barrier or crash cushion) or unless it is placed on a raised island."

Section 8A.08

- "When a grade crossing exists either within or near a temporary traffic control zone, lane restrictions, flagging (see Chapter 6E), or other operations shall not be performed in a manner that would cause highway vehicles to stop on the railroad or LRT tracks, unless a flagger or uniformed law enforcement officer is provided at the grade crossing to minimize the possibility of highway vehicles stopping on the tracks, even if automatic warning devices are in place."

Section 8B.03

- "The Grade Crossing commonly identified as the Crossbuck sign, shall be retro reflectorized white with the words RAILROAD CROSSING in black lettering."

Section 8C.04

- Paragraph 2: "The automatic gate shall consist of a drive mechanism and a fully retro reflectorized red- and white-striped gate arm with lights. When in the down position, the gate arm shall extend across the approaching lanes of highway traffic."
- Paragraph 3:" In the normal sequence of operation, unless constant warning time detection or other advanced system requires otherwise, the flashing-light signals and the lights on the gate arm (in its normal upright position) shall be activated immediately upon detection of approaching rail traffic. The gate arm shall start its downward motion not less than 3 seconds after the flashing-light signals start to operate, shall reach its horizontal position at least 5 seconds before the arrival of the rail traffic, and shall remain in the down position as long as the rail traffic occupies the grade crossing."
- Paragraph 4:" When the rail traffic clears the grade crossing, and if no other rail traffic is detected, the gate arm shall ascend to its upright position, following which the flashing-light signals and the lights on the gate arm shall cease operation."

- Paragraph 7: "Gate arms shall have at least three red lights."
- Paragraph 8: "When activated, the gate arm light nearest the tip shall be illuminated continuously and the other lights shall flash alternately in unison with the flashing-light signals."
- Paragraph 9: "The entrance gate arm mechanism shall be designed to fail safe in the down position."

Section 8C.07

- "Wayside horn systems used at grade crossings where the locomotive horn is not sounded shall be equipped and shall operate in compliance with the requirements of Appendix E to 49 CFR Part 222."

Section 8C.08

- Paragraph 2: "Rail traffic detection circuits, insofar as practical, shall be designed on the fail-safe principle."
- Paragraph 3: "Flashing-light signals shall operate for at least 20 seconds before the arrival of any rail traffic, except as provided in Paragraph 4."
- Paragraph 4: "on tracks where all rail traffic operates at less than 20 mph and where road users are directed by an authorized person on the ground to not enter the crossing at all times that approaching rail traffic is about to occupy the crossing, a shorter signal operating time for the flashing-light signals may be used."

Federal Regulations Related to Locomotives and Grade Crossings

Federal rules and regulations related to railroad operations are contained in 49 CFR Chapter II [36]. Here is a list of rules that should be considered when deploying AV.

49 CFR part 222

Use of Locomotive Horns at Public Highway-Rail Grade Crossing. The rule details the standards set for sounding locomotive horns when approaching and traversing public highway-rail grade crossings. It also details the creation of quiet zones, where the locomotive horns must not be sound.

The use of a wayside horn may be used in lieu of a locomotive horn only at active highway-rail grade crossings. The rule is described in subpart C (Exceptions to the Use of the Locomotive Horn) of the rule.

49 CFR part 224

Reflectorizing of Rail Freight Rolling Stock. The rule details the standard set for applying, inspective and maintain retroreflective material to rail freight rolling stock. This will aid in the detection of a train passing by a highway-rail crossing.

49 CFR part 229 subpart 125

Headlights and auxiliary lights. This rule explains the minimum intensity the headlight of a locomotive must have and sets the rule that lights must be on as long as the locomotive is functioning.

Chapter 5. Autonomous Vehicle Infrastructure Interactions

Autonomous Vehicle Sensory Inputs

Without a driver providing the logic and decision making behind the wheel, the inputs required to operate a vehicle must be fulfilled by an AV. Different levels of AV will require variable operator interaction and sensing capabilities required to independently navigate through the environment.

The AV needs to have a constant stream of data for navigation, guidance, and safety. It is estimated that for every eight hours of driving, an autonomous vehicle will generate/process roughly 40 terabytes of data originating from the hundreds of on-vehicle sensors [37].

This data is provided by different technologies and sensors implemented in the vehicles. This is seen in Figure 15.
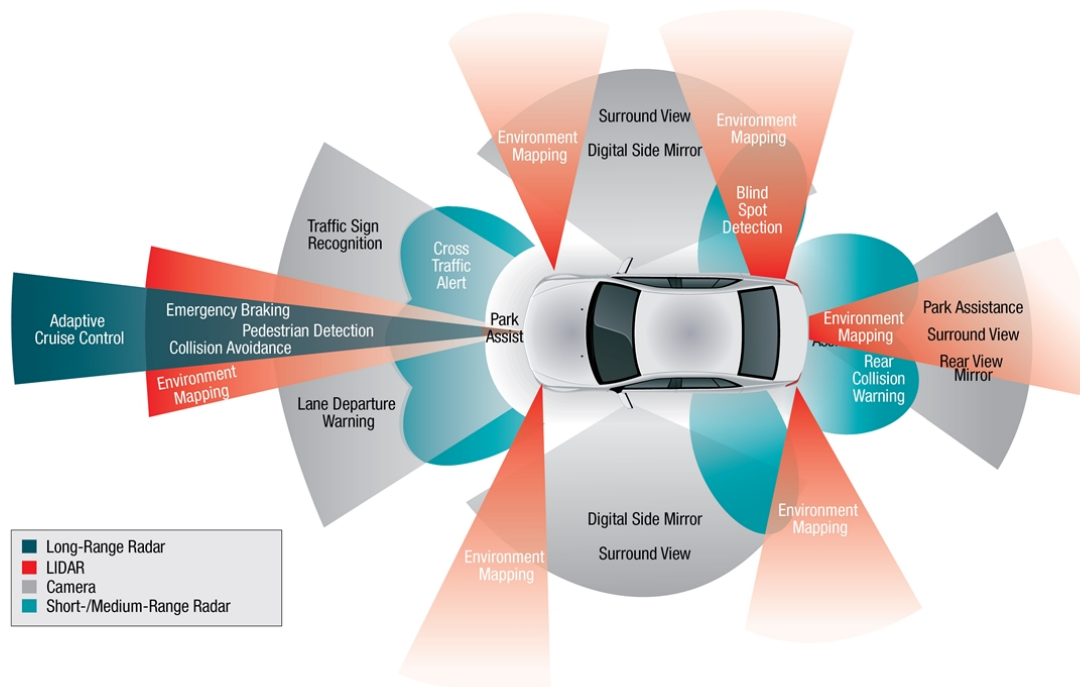
Source: SAE International October 17, 2017

Figure 15. Sensors in an Autonomous Vehicle

Sensors and Systems

Global Positioning System (GPS) and Global Navigational Satellite System (GNSS)

GNSS is an umbrella term that encompasses all global satellite positioning systems [38].

For this report, we will be using the terms GPS and GNSS synonymously. GPS is a network of orbiting satellites that send precise details of their position in space back to earth [39]. When used in a vehicle, the GPS system can calculate the vehicle's speed and location.

The GPS system computes present position based on complex analysis of signals received from at least four of the constellation of over 60 low-orbit satellites [40]. The level of accuracy for most of the systems varies from one meter, to five cm from the next-generation GPS technology (which is expected to find its way to driverless cars by 2022) [41].

Inertial Navigation Systems

Inertial navigation systems are used in conjunction with GPS to enhance accuracy. They use a combination of gyroscopes and accelerometers to determine vehicle position, orientation, and velocity.

These systems can function without the need of any external signal. They consist of three pairs of gyroscopes and accelerometers; each pair oriented to the orthogonal X, Y, and Z axes. These sensors kick in when the GPS signal is lost, providing data on the rotational and linear motion of the vehicle [40].

Ultrasonic Sensors

Used in many of today's vehicles, ultrasonic sensors provide short distance data typically used in parking assistance systems or backup warning systems.

The system uses high frequency sounds waves, which in turn bounce off nearby objects. The sensor can identify how far the vehicle is from an object and alert the driver the closer it gets [42].

Radar

Radar determines the distance between the obstacle and the sensor using radio waves. This technology has been used for many years in ship and plane navigation systems. Radar sensors send electromagnetic waves that when reflected are used to determine the range and speed of an object. [43].

Camera / Video Detection

Several cameras generate images of the vehicle's surroundings, imitating human eyesight. The benefit is the capability to detect color and fonts, allowing the vehicle to interpret traffic signs, traffic lights, or lane markings [43]. The video detection system is also capable of detecting road lane stripes and other objects.

LIDAR

The LIDAR system continually transmits pulses of laser light and then measures how long it takes for the reflected light pulses to return to the sensor. It allows the vehicle to generate 3D maps that are then used to navigate the vehicle. It has a range of 500 m (1640 ft.). The technology allows the vehicle to detect obstacles in the road such as pedestrians, cyclist, and other vehicles [44].

Autonomous Vehicle Navigation

A multitude of sensors all serving different functions enable an AV to effectively navigate through its environments as described in the Autonomous Vehicle Sensory Inputs section. These vehicles rely on their sensors performing at a high level of confidence and working seamlessly in unison in contrast to non-autonomous vehicles that depend on a driver to observe and react to all inputs to make all decisions for safe operation. While drivers are reliant upon their vision to recognize lane markings[1], AVs are currently dependent upon their sensors to maintain the correct lane [45].

According to the U.S. DOT, the U.S. transportation infrastructure system is ranked 12th in the World Economic Forum's 2014-2015 global competitiveness report. U.S. DOT reported that 65% of the roads in the United States are in poor condition [45]. The U.S. DOT uses the International Roughness Index (IRI) as a proxy for overall pavement condition. Pavements with an IRI value less than 95 inches per mile are considered to have "good" ride quality. Pavements with an IRI value of greater than 170 inches per mile are considered to have "poor" ride quality.

Volvo recently encountered this issue when the automaker's semi-autonomous prototype refused to drive itself at the Los Angeles Auto Show since the vehicle could not detect lane markings [45]. As dependent as AVs are on their sensors, their sensors are dependent on acceptable infrastructure being in place. There are three million miles of paved road in the U.S. with poor markings and uneven signage [45]. The need for more sophisticated sensors and maps are imposing these developments on automakers to compensate for the deficient infrastructure currently in place for AVs [45].

Tesla, Volvo, Mercedes, Audi, and others are developing vehicles that are capable of driving on highways, switching lanes, and parking without human interaction [45]. These same vehicles are puzzled when lane markings are faded or there are impaired or non-compliant signage or lights [45]. "If the lane fades, all hell breaks loose," Christoph Mertz, a research scientist at Carnegie Melon University, explained [45]. One of the greatest challenges applying to both rail crossings and roadways, is the infrastructure being managed by thousands of different state and local bureaucracies [45].

Standardized signage and road markings are more prevalent in other developed countries compared to the United States, making it simpler for AVs to navigate [45].

A well-maintained road, including clear lane markings, good pavement condition, and standardization of all traffic signal systems throughout the United States is imperative for successful AV deployment.

Autonomous Vehicles at Intersections and Stops

As drivers approach an intersection or a stop in non-autonomous vehicles, a number of factors (contingent upon the type of intersections being approached) such as traffic lights, stop signs, yield signs, pavement markings, and more, notify drivers they are approaching a point where an action may be required. The driver is required to make these identifications and respond accordingly to ensure safe operation of the vehicle. By removing the driver and making the vehicle autonomous, the vehicle will become responsible for correctly identifying telltales in the surrounding environment. Trivial functions and

---

[1] Drivers also have the ability to determine their relative position in the roadway by other means.

duties such as recognizing a traffic light at an upcoming intersection or spotting a stop sign must be fulfilled by sensors on the AV.

Google's AV sensors (unspecified) are used in coordination with image-processing technology to help identify current infrastructure telltales such as traffic lights or four-way stops [46]. Environmental obstructions, inadequate lighting, and poor weather conditions are proving to be a few of the biggest challenges for AVs in such a dynamic and wide-ranging environment [46].

Google's hardware engineer, Daniel Rosenband, who works on their AV, spoke at the Hot Chips conference in California and shared Figure 16, Figure 17, and Figure 18 to highlight some of the difficulties detecting traffic lights [45]. "There are some really hard problems left to solve. Traffic light detection and signal recognition are hard problems," he said [45]. "In most cases, the image-processing code searches a video frame for a bright red or green circle to determine if there is one in front of the camera [45]. There will be times when that naïve approach fails to work properly, and other objects are identified as traffic signals", Rosenband explained [45]. Figure 16 for example, could be mistaken for a go signal, Rosenband pointed out, "the car needs to be far more aware" [45].
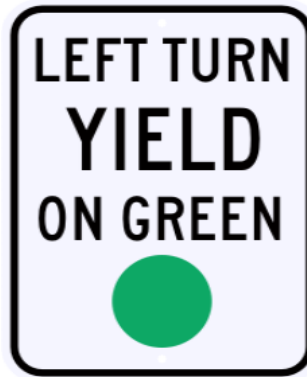
Source: The Register October 10, 2017

Figure 16. An Example of a Sign that May be Misinterpreted by an Autonomous Vehicle

Figure 17 is an example of an environmental obstruction. The Google AV is detecting a red balloon on a white stick in front of the traffic light and interpreting it as a red light.

Source: The Register October 10, 2017

Figure 17. Red Balloon on a White Stick Identified by Google Self-Driving Car Interpreted as a Red Light

Figure 18 is representative of a scenario in poor lighting conditions and a visual obstruction. A portion of the traffic light is being obscured and the AV cannot identify the bottom light, and therefore is unable to tell if the light is a solid or flashing.
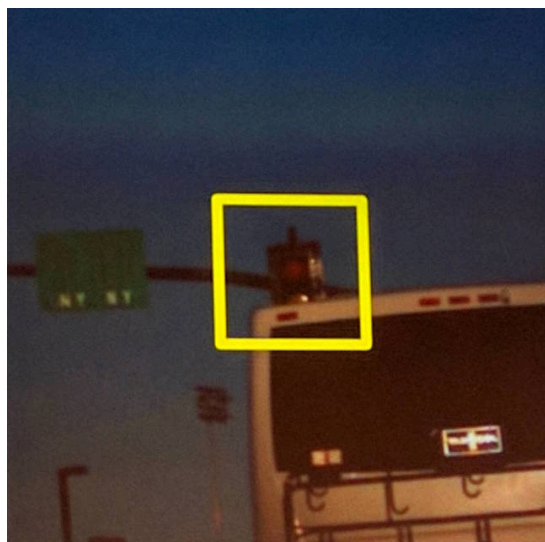
Source: The Register October 10, 2017

Figure 18. Google Self-Driving Car Unable to Detect Traffic Light Due to Obstruction

Figure 19 is illustrative of a scenario when lighting was poor. The Google AV detected multiple light sources and was unsure how to respond.

Figure 19. Google Self-Driving Car Detecting Multiple Lights on a Sunny Day Scenario

Four-way junctions with no traffic lights create their own unique set of challenges for AVs. Oftentimes at four-way stops, non-autonomous vehicles may arrive at the same time and there is no affirmative indicator for the right-of-way [45]. Motorists often rely on eye contact with another motorist to know when it's safe to traverse the intersection. When a pedestrian crosses a crosswalk in front of a vehicle, the pedestrian commonly relies on eye contact with the driver to obtain a level of comfort that the driver will not continue in its path. It is also trivial for motorists to hand gesture to a pedestrian signifying the pedestrian has the right-of-way and to cross the crosswalk or mid-block area. This is an obstacle for AVs as they do not communicate or detect the same indicators drivers and pedestrians use. "We have to make it comfortable for the person in the car; you don't want the vehicle to inch forward and then slam the brakes, and also you want to be courteous to other drivers," Rosenband said. [45]

Figure 20 is a picture of a stop in San Francisco, CA where a set of cable car lines pass through and traffic lights are not installed. This junction introduces a challenge to AVs to understand how to navigate without a traffic light present as they rely on detecting them for SPaT information.

Figure 20. Street Image of the California St. & Powell St. Intersection in San Francisco, CA

Las Vegas V2I Deployment Initiative

V2I technology is communication between infrastructure and a vehicle via DSRC technology. Conversely, V2V technology is communication between vehicles via DSRC technology.

The Battelle Team's research found the Las Vegas V2I Deployment Initiative to be the only publicly known attempt at integrating AV with traffic signal controllers.

In December of 2016, Audi launched their V2I technology initiative in Las Vegas, NV, which does not require strict adherence to the CV arena [47]. Audi partnered with Traffic Technology Services, a technology company and information provider to the automotive industry, to help facilitate traffic data transfer to vehicles for the Traffic Light Information application [47]. This application allows a vehicle to receive real-time traffic signal information from the traffic management system via a cellular connection [47]. As the vehicle approaches a connected traffic light, the application displays the time remaining until the signal changes to green via the driver instrument panel or heads-up display, depending on the vehicle [47]. This additional information is aimed at reducing stress and better informing the driver of time remaining before the light changes [47]. This application is available on select 2017 Audi A4, Q7, and A4 all road models via an Audi connect PRIME subscription [47].

Figure 21. Traffic Light Information Application Displayed in the Driver Instrument Panel
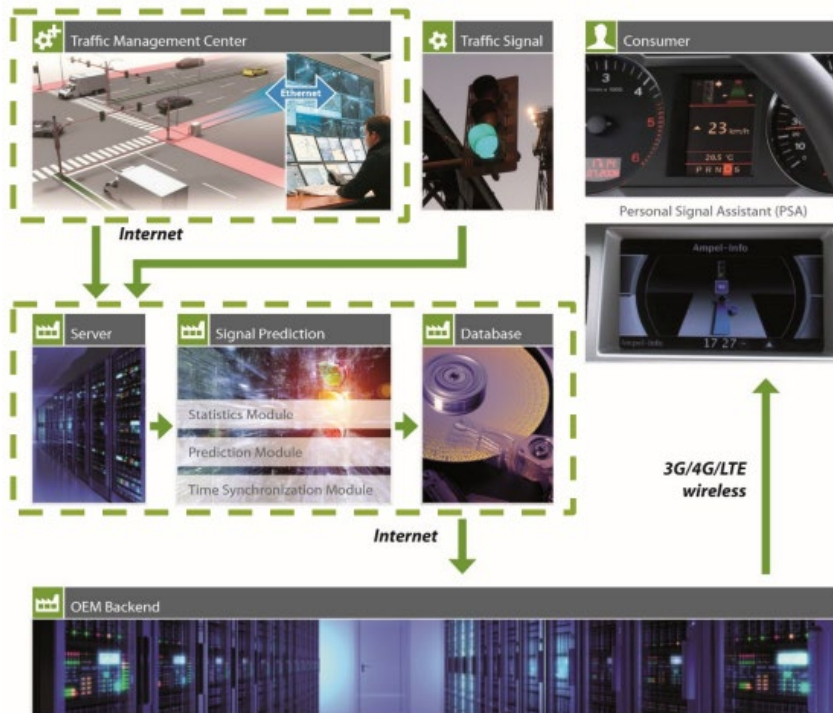
Figure 22. Flow Diagram of Traffic Light Information Application

In future developments, Audi has visions to explore integration with traffic management systems into vehicle start/stop features, navigation systems to optimize routing, and predictive speed recommendations to the driver to maximize the number of green lights a driver can make in one sequence [47]. These applications are aimed at improving efficiency and mobility [47].

This offering from Audi is new, still developing, and only works in select areas. It is expected that Audi could bring the same technology to other areas in the future.

Chapter 6. Lessons Learned

Sensor Limitations

The sensors needed to acquire the required data have some limitations that need to be addressed.

GPS coverage in downtown environments is more difficult because the "whole sky" is frequently not visible. Additionally, to achieve "centimeter" accuracy, a vehicle's GPS system must be able to connect to a reference station to receive digital location corrections. A network of these reference stations, spaced by 20 to 50 kilometers will be required [48].

Currently, ultrasonic sensors can only be used at very low speeds. They serve their intended purpose and there is currently no further development needed.

The reach of image sensors needs to be increased up to 225 m to enable a more anticipatory driving. Weather limitations such as fog, rain, or intense impinging solar glare currently increase the risk of failures of optical sensors and need to be overcome. Recognition algorithms need to be improved.

Current 2D radars are not able to determine an object's height as they only scan horizontally. This can cause problems. 3D radars currently being developed could solve this issue.

Since rare metals are needed for production, LIDAR sensors are currently much more expensive than radar sensors. LIDAR systems use pulses to provide detailed "images" around the entire vehicle [43].

AV Interactions with an HRI

After investigating if any studies or projects had been completed examining how AVs interact with HRIs, the Battelle Team concluded that none currently exist. Although there wasn't any publicly available information regarding this topic, it's probable AV researchers are examining this issue.

AV at Active HRIs

The visual and audio cues of an active HRI presented in chapter 2 of this document along with the possibility of equipping an active crossing with DSRC technology as we see in chapter 3, will provide an AV with the information needed by the sensors to detect the presence of a train in an HRI.

AV at Passive HRIs

As a non-autonomous vehicle approaches a passive HRI, the driver is responsible for understanding the safety protocol and how to respond to the many possible scenarios at a crossing. Mentioned in the Types of Grade Crossings section, passive crossings are limited to indicators such as pavement markings, crossbucks, and yield or stop signs [7].

Before an AV can determine how to traverse a rail grade crossing, the vehicle must "comprehend" that it is approaching a crossing. An AV must be able to detect passive grade warnings and to respond

accordingly. Research conducted did not indicate that the interaction between AVs and passive grade crossings is being investigated or explored.

Given the knowledge about the types of passive grade warnings that exist and current AV capabilities, inferences can be made about the relationship between them. A combination of cameras and sensors are being used to detect infrastructure telltales such as traffic lights, road signs, and pavement markings. AVs may be able to detect passive grade warnings for locating a passive rail crossing in a similar manner.

Once the warnings have been detected and processed, the AV must determine if a locomotive is occupying or approaching an HRI and, if true, "act" to prevent a predicted collision. Research showed that AV locomotive detection has not been examined. Analysis of safety regulations followed by both vehicles and locomotives when approaching a passive crossing may inform how an AV might be able to detect the presence, or imminent arrival, of trains. Explained in the Light Vehicle and Transit Vehicle Safety Protocol section, vehicles are required to follow safety regulations set forth by each state. Safety protocols include stopping at a specified distance to listen and visually check for an on-coming locomotive. Locomotive protocol requires the train to continuously travel with its headlights on, as well as sounding its horn at a predetermined distance from the crossing when approaching. An inference could be made that if the AV is able to detect the train's triangular light pattern and sound of the horn, it may know a locomotive is approaching the rail crossing.

An AV could benefit from the technology currently being used for CVs. Explained in the Connected Autonomous Vehicle section, V2V and V2I communications can enhance the safety and efficiency of AV to help overcome some of the gaps identified in this research on autonomous vehicle.

Chapter 7. Stakeholders

Innovation and advancements in AV, rail, and highway-rail grade crossing technologies are driven by key stakeholders in the automotive and rail industries. As the United States Government begins to prepare for AV acceptance, precautions must be taken to ensure safety is not compromised at the vehicle or infrastructure level. The safety protocols currently in-place may or may not be the same safety measures as those required for AVs approaching HRIs. The existing audible and visual warnings given to drivers in vehicles may not be sufficient for an AV. It is critical for dialogue to be established with key stakeholders to ensure a seamless/transparent transition. Table 4 provides a list of key stakeholders from various industries and organizations identified by Battelle's subject matter experts. The Battelle Team will engage with the stakeholders to gain knowledge and guidance prior to eliciting a set of requirements and developing a Concept of Operations.

Table 4. Key Stakeholders Identified by Battelle

Industry	Organization	Contact	Position
Autonomous Vehicle	General Motors (GM)	Peter B. Kosak	Executive Director of AV Program
Autonomous Vehicle	Keolis	Christopher Barker	Vice President of New Mobility, Communications and Marketing
Autonomous Vehicle	Waymo	Timothy Papandreou	Strategic Partnerships
Private Transportation	Transdev	Andrew Chatham	Director of Product Development
CV R&D	U.S. DOT Test Bed Program	John Corbin	FHWA Lead for Connected/Autoamted Vehicles and Emerging Tecnologies
CV R&D	Truner Fairbank and Highway Research Center	Dale Thompson	Team Leader, Transportation Enabling Technologies
CV R&D	Utah DOT	Blaine Leonard	ITS Program Manager
Transportation	AASHTO	Gumadda Murthy	Assoicate Program Director
Rail	Union Pacific Railroad	Mark Bess	Senior Manager, Operating Services
ITS	PATH	Trevor Darrell	Faculty Director

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Appendix B. Acronyms

Acronyms	Abbreviations
AHS	Automated Horn System
AV	Autonomous Vehicle
CAV	Connected Autonomous Vehicle
CFR	Code of Federal Regulations
CV	Connected Vehicle
D2D	Device-to-Device
DSRC	Dedicated Short Range Communications
FRA	Federal Railroad Administration
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HRI	Highway-Rail Intersection
IRI	International Roughness Index
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LIDAR	Light Detection and Ranging
LTE	Long-Term Evolution
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
NMEA	National Marine Electronics Association
OBU	On-Board Unit

Acronyms	Abbreviations
PTC	Positive Train Control
RCVW	Rail Crossing Violation Warning
RSU	Roadside Unit
RTCM	Real Time Correction Message
SAE	Society of Automotive Engineers
SPaT	Signal, Phase, and Timing
TIM	Traffic Incident Message
TSC	Traffic Signal Controller
U.S. DOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WAVE	Wireless Access in Vehicular Environments

Appendix C. SAE Levels of Automation

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	Monitoring of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability (*Driving Modes*)
Human driver monitors the driving environment						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

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Source: SAE International and J3016, September 27, 2017

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Appendix B. Highway-Rail Grade Crossing Requirements for Automated Vehicles

Concept of Operations and Requirements

Final Report – May 2018

U.S. Department of Transportation

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15. Supplementary Notes

16. Abstract

While the number of highway-rail grade crossings (HRGC) has remained relatively constant over the last four years (around 2000 incidents per year), they still represent a significant safety concern for the transportation industry. Approximately 250 fatalities and 950 non-fatal injuries occur each year at HRGCs in the United States. As automated vehicle (AV) testing starts to become more prevalent and widespread, AVs will need to interact with HRGCs just as human drivers do presently. One way to enhance AV interaction with HRGCs is through Connected Vehicle(CV) technologies, CVs offer the potential of reducing HRGC incidents by providing travelers with better, timelier advance warnings that a train is approaching, or occupying, an HRGC, either directly through vehicle interfaces or after-market safety devices.

Based upon assumptions identified in Chapter 1, this document builds a set of conceptual scenarios in Chapter 2 and Chapter 3. Following this, additional scenario constructs and conditions that could be applied in future efforts to expand the concepts are identified in Chapter 3. The document concludes in Chapter 4 with a set of requirements derived from the assumptions and operational concepts developed in Chapters 1-3. The intent of this document is to serve as a basic framework of system components, conditions, assumptions, operational scenarios, and requirements that can be assessed and further developed to advance understanding of the concepts and requirements that need to be considered for automated vehicles to safely traverse HRGCs. Use Cases that introduce challenging conditions to AVs and CAVs based off the ConOps scenarios are described in Chapter 5.

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Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

The objective of the Highway-Rail Grade Crossing (HRGC) Requirements for Automated Vehicles (AV) project was to explore what information Automated Vehicles (AVs) may need to negotiate an HRGC. HRGCs are also commonly referred to as highway-rail intersections, railway-highway crossings, grade crossings, and rail crossings. For this project, HRGC is defined to be the area of roadway bound by the stop bars, where vehicles are to stop at rail crossings (this area is also known as the Highway-Rail Intersection Hazard Zone). This Concept of Operations (ConOps) and Requirements document was drafted as a foundation upon which to assess the functional characteristics and needs of an AV approaching and traversing an HRGC. After introducing the approach used to define the constructs, this ConOps and Requirements document presents conceptual and simplifying assumptions by providing ConOps scenarios and specifying conceptual-level functional, processing, and performance requirements.

ConOps scenarios were developed after performing a literature review to assess current AV and railroad warning device technologies, and synthesizing input from a workshop convened to gather industry expert input and opinion on how an AV might ideally traverse an HRGC. A set of eleven scenarios were conceived to investigate potential AV capabilities and challenges at HRGCs. A graphic and text description are provided to describe the unique characteristics of each scenario. The scenarios focus on the interaction of the AV at the HRGC, and address only the approach of the AV towards the HRGC and its traversal of the HRGC. First and last mile challenges are not addressed under the scope for this document.

Research performed during the literature review indicated a potential opportunity to enhance safety through connectivity between the AV and the train or the HRGC. In addition to AV approaches and traversals for conventional HRGC scenarios, supplementary scenarios were created to explore the idea of connectivity and sharing of information between Connected Automated Vehicles (CAVs), Connected Trains, and Connected HRGCs to make the traversing AVs safer.

In addition to non-connected trains, the following key system components comprise the ConOps scenarios and associated Requirements:
- **AV** – The terms Autonomous Vehicle and Automated Vehicle have been used interchangeably by the industry. The Society of Automotive Engineers (SAE) International recommends the use of Automated Vehicle when referring to a vehicle that has systems that perform part or all of the dynamic driving tasks. This recommendation will be followed for this project. The focus of AVs in this document are on highly automated vehicles – Level 4 or above.
- **CAV** – an AV that is equipped with technology that communicates with Connected Trains, Connected HRGCs and other CAVs
- **Connected Train** – a train that broadcasts information to CAVs at, or, approaching an HRGC.
- **Connected HRGC** – an HRGC that receives grade crossing activation status from railroad infrastructure and transmits HRGC status and configuration data to a CAV.
- **Active Warning Devices (AWDs)** – lights, bells, and gates activated through a train detection circuit that provides motorists with an active warning that a train is present.
- **Passive Warning Devices (PWDs)** – signs and pavement markings that provide motorists with a warning that a rail crossing is ahead

The ConOps scenarios are divided into two chapters:

1. Active HRGC scenarios – HRGC with AWDs (Chapter 2)
2. Passive HRGC scenarios – HRGC with PWDs (Chapter 3)

Beyond the scenarios describing AV-train interaction, each ConOps chapter presents scenarios where a train will not be interacting with an AV. Following the ConOps scenarios considered, a list of scenarios *not considered* to be within the scope of this project are presented. The following tables present details of the eleven scenarios considered in Chapter 2 and Chapter 3, which serve as the basis for Requirements presented in Chapter 4. Table 1 provides a description for each scenario and lists the chapter in which the scenario can be found.

Table 1. High-Level Overview of ConOps scenarios

ConOps Scenario #	ConOps Scenario Description	Chapter #
1	AV approaches an HRGC with AWDs no train approaching or occupying the HRGC	2
2	AV approaches an HRGC with AWDs, vehicles queuing, and no train approaching or occupying the HRGC	
3	AV approaches an HRGC with AWDs activated and a train occupying the HRGC	
4	Train departs HRGC with AWDs, then the AV departs	
5	CAV approaches a Connected HRGC with AWDs activated and a train occupying the HRGC	
6	Train departs Connected HRGC, then the CAV departs	
7	AV approaches an HRGC with PWDs and a train occupying the HRGC	3
8	Train departs HRGC with PWDs, then the AV departs	
9	CAV approaches an HRGC with PWDs and a Connected Train approaching in range of the HRGC	
10	Connected Train departs HRGC with PWDs, then the CAV departs	
11	CAV approaches an HRGC with PWDs, vehicles queuing, and no train approaching or occupying the HRGC	

For each ConOps Scenario, Table 2 describes the vehicle and HRGC type, the position of the vehicle and train (if applicable), and the detection method used by the approaching vehicle to identify key sources of information. "In range" terminology is used to mean that the train is approaching or departing and close enough to the HRGC to be detected by the train detection system at an HRGC with AWDs, or by an approaching AV or CAV via its onboard sensors or radios. The key information needed by the approaching AV or CAV includes train presence (i.e., approaching, or occupying, the HRGC), location where the vehicle must stop (HRGC stop bar), and information about queued vehicles beyond the HRGC. The nature of the key information available, shown in Table 2, is dependent upon the vehicle type (AV or CAV), whether the HRGC has AWDs or PWDs, and whether connected information is available (from queued CAVs, a Connected HRGC, and/or a Connected Train).

In practice, when multiple sources of key information are available, the CAV may depend on the most reliable source; however, in the base scenarios presented it is assumed that the CAV will depend on connected information. For example, when a CAV approaches a Connected HRGC with AWDs (see ConOps scenario 5), it will depend on Connected HRGC information rather than attempting to detect crossing status via the AWD warning lights. Likewise, the CAV will depend on Connected HRGC information rather than scanning pavement markings for the HRGC stop bar location. Connected HRGC details are available sooner and may be interpreted more reliably than non-connected HRGC details. Similarly, when a CAV approaches an HRGC with PWDs and queued CAV traffic (see ConOps scenario 11), it will depend on vehicle position details from the queued CAVs. Using connected train information allows the approaching CAV to discern train location more precisely. Using CAV position information from queued vehicles reduces the amount of information processing required for the AV to determine queue space availability and increases the confidence in determining that availability.

Table 2. Detection of Information Methods Used by Vehicles Approaching an HRGC

ConOps Scenario #	Vehicle Type	Type of HRGC	Detection Method Used by Approaching Vehicle for:		
			Train	HRGC Stop Bar	Queued Vehicle(s)
1	AV	HRGC w AWD	*No train approaching in range or occupying*	Detection of stop bar pavement marking	Not Present
2	AV	HRGC w AWD	*No train approaching in range or occupying*	Detection of stop bar pavement marking	Detection of AV beyond HRGC
3	AV	HRGC w AWD	Detection of AWD flashing lights (train occupies HRGC)	Detection of stop bar pavement marking	Not Present
4	AV	HRGC w AWD	Detection of AWD flashing lights (train departs HRGC)	Detection of stop bar pavement marking	Not Present
5	CAV	HRGC w AWD	Receives communication from Connected HRGC (train occupies HRGC)	Receives communication from Connected HRGC	Not Present
6	CAV	HRGC w AWD	Receives communication from Connected HRGC (train departs HRGC)	Receives communication from Connected HRGC	Not Present
7	AV	HRGC w PWD	Detection of train presence (train occupies HRGC)	Detection of stop bar pavement marking	Not Present
8	AV	HRGC w PWD	Detection of train presence (train departs HRGC)	Detection of stop bar pavement marking	Not Present
9	CAV	HRGC w PWD	Receives communication from Connected Train (train occupies HRGC)	Detection of stop bar pavement marking	Not Present
10	CAV	HRGC w PWD	Receives communication from Connected Train (train departs HRGC)	Detection of stop bar pavement marking	Not Present
11	CAV	HRGC w PWD	*No train approaching in range or occupying*	Detection of stop bar pavement marking	Receives communication from CAV beyond HRGC

In ConOps scenarios 3, 5, 7, and 9, the train is occupying (but could also be approaching in range of) the HRGC or Connected HRGC. Scenarios 4, 6, 8, and 10 are a continuation of scenarios 3, 5, 7, and 9, respectively, with the train departing the HRGC or Connected HRGC. When a train is present, the AV or CAV stops at the HRGC stop bar regardless of whether queued traffic has formed beyond the HRGC.

Following the chapters defining scenarios and requirements, the document presents a set of performance-affecting, real-world conditions and develops a set of Use Cases that illustrate possible operational and informational AV needs by applying representative conditions to the base scenarios. These constructs serve as a starting point and example process for stakeholders to consider, refine, and further develop. Unlike in the ConOps scenarios, the Use Cases contain multiple, redundant sources of information to be considered.

Assumptions

There are numerous factors, conditions, and operational situations that may affect AV performance at HRGCs. It is not the intent of this document to identify and address them all. Rather, this document and the project under which it has been developed, aim to serve as a starting point for the necessary process that must be undertaken by manufacturers, regulators, and infrastructure designers to progress toward a shared understanding of AV needs. With these goals in mind, this document focuses on the development of foundational assumptions and scenarios onto which agreed-upon complexity can later be layered. The result is high-level functional, processing, and performance requirements, rather than detailed design requirements which specify solution-based approaches.

Conceptual and simplifying assumptions were, therefore, made for scenarios to constrain the scope considered in this ConOps and Requirements document. These assumptions are documented to clarify scenario conditions and to demonstrate the anticipated operation of AV systems. With self-driving technology still being developed and little information about AVs available to the public, it is not fully understood how AVs may operate. Very few requirements are defined for non-connected trains and non-connected HRGCs, as these system components are assumed to meet current standards and no new requirements are proposed for them.

The following assumptions are made for the ConOps scenarios and associated requirements:

General Assumptions

- There is no vehicle traffic upstream of the HRGC. Queuing traffic described in the scenarios takes place downstream of the HRGC.
- There are no users (drivers or passengers) in the AV or CAV.

Automated Vehicle Assumptions

- The AV operates at automation level of four or above according to National Highway Traffic Safety Administration's Automated Driving Systems 2.0, which is based on SAE International's levels of automation (i.e., the vehicle can perform all driving function under certain conditions).
- The AV is fully functional and operational.
- The AV has an unobstructed field of view with respect to the railroad track (no vegetation or structures blocking the view).
- The skew angles of the HRGC approach and departure are at 90 degrees.
- The AV travels at a speed that is less than or equal to the roadway speed limit.
- The AV maintains its lane as it approaches and traverses the HRGC.
- There are no vehicles between the approaching vehicle and the HRGC.

Connected Automated Vehicle Assumptions

- The CAV will follow all AV assumptions.
- The CAV may have access to the configuration of the HRGC ahead.
- The CAV can receive relevant data from Connected Trains that are in range of the HRGC.
- While approaching the HRGC, the CAV determines when the Connected Train will intersect the HRGC.

Train Assumptions

- The train is occupying or approaching the HRGC and traveling at a constant speed.
- The train is fully functional and operational.
- There is only a single train approaching, or occupying, the HRGC.
- All train cars are of detectable height.

Connected Train Assumptions

- The Connected Train will follow all train assumptions.
- The Connected Train systems for determining geographic location and speed, and communicating that information, are fully functional and operational.
- The Connected Train broadcasts its geographic location and speed.

Infrastructure Assumptions

- The HRGC is fully functional and operational, including its communication and signaling components.
- The HRGCs with passive warning devices (PWDs) and active warning devices (AWDs) follow the Manual on Uniform Traffic Control Devices (MUTCD) guidelines.
- The grade at the roadway and HRGC is flat and does not obstruct the sight line to queued traffic.
- Weather and road conditions do not prevent the AV or CAV from acquiring key infromation souces.
- There are no obstructions in the roadway or on the railroad tracks.
- All signs, warning devices, and roadway markings are unobstructed and discernable.
- There is a single-track present at the HRGC.
- The HRGCs are located on public roadways.

Connected Infrastructure Assumptions

- The connected infrastructure will follow all infrastructure assumptions.
- The connected infrastructure uses a wireless method to communicate with CAVs.
- The connected infrastructure communicates when a train is present in the same detection zone used to activate AWDs.

Note: The ConOps scenarios illustrated throughout this document are not drawn to scale.

Common Actions for All Approaching Vehicles

All AVs and CAVs approaching an HRGC employ the same common approach:

- The AV or CAV detects the presence of an HRGC ahead.
- The AV or CAV determines if the HRGC has AWDs or PWDs.
- The AV or CAV receives connected information from a Connected HRGC, Connected Train, or queued CAVs.
- The AV or CAV detects or receives the location of the HRGC stop bar.

Chapter 2. Vehicle Approaching Highway-Rail Grade Crossing with Active Warning Devices

Scenario 1. AV approaches an HRGC with AWDs no train approaching or occupying the HRGC

This scenario begins with the AV approaching the HRGC without a train approaching in range or occupying the HRGC.

- *Common Actions, page 6*
- AV detects lights are not flashing on AWDs
- AV scans for vehicles queuing beyond the HRGC
- AV determines it is safe to cross the HRGC as no queued traffic or trains are present
- AV crosses the HRGC
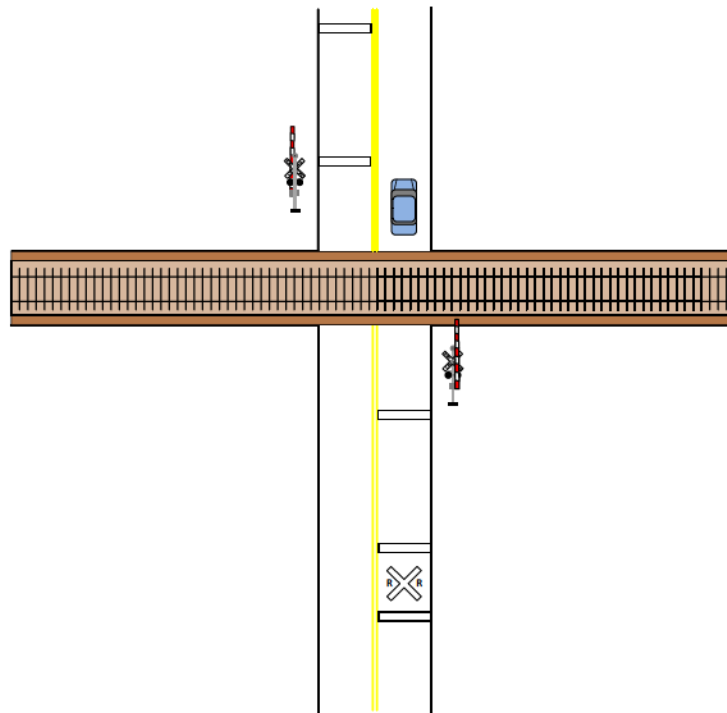
Figure 1. Scenario 1: AV approaches HRGC with AWDs without train approaching or occupying the HRGC

Scenario 2. AV approaches an HRGC with AWDs, vehicles queuing, and without a train approaching or occupying the HRGC

This scenario begins with the AV approaching the HRGC without a train approaching in range or occupying the HRGC, but with queued traffic prohibiting traversal of the HRGC.

- *Common Actions, page 6*
- AV detects lights are not flashing on AWDs
- AV detects the queue of vehicles downstream of the HRGC
- AV determines that joining the queue will position the vehicle inside the HRGC
- AV reduces speed and comes to a complete stop at the HRGC stop bar

Source: Battelle, 2018

Figure 2. Scenario 2: AV approaches HRGC with AWDS, vehicles queuing without train approaching or occupying the HRGC

Scenario 3. AV approaches an HRGC with AWDs activated and a train occupying the HRGC

- *Common Actions, page 6*
- AV detects AWD lights are flashing
- AV reduces speed and comes to a complete stop at the HRGC stop bar, while monitoring the flashing lights
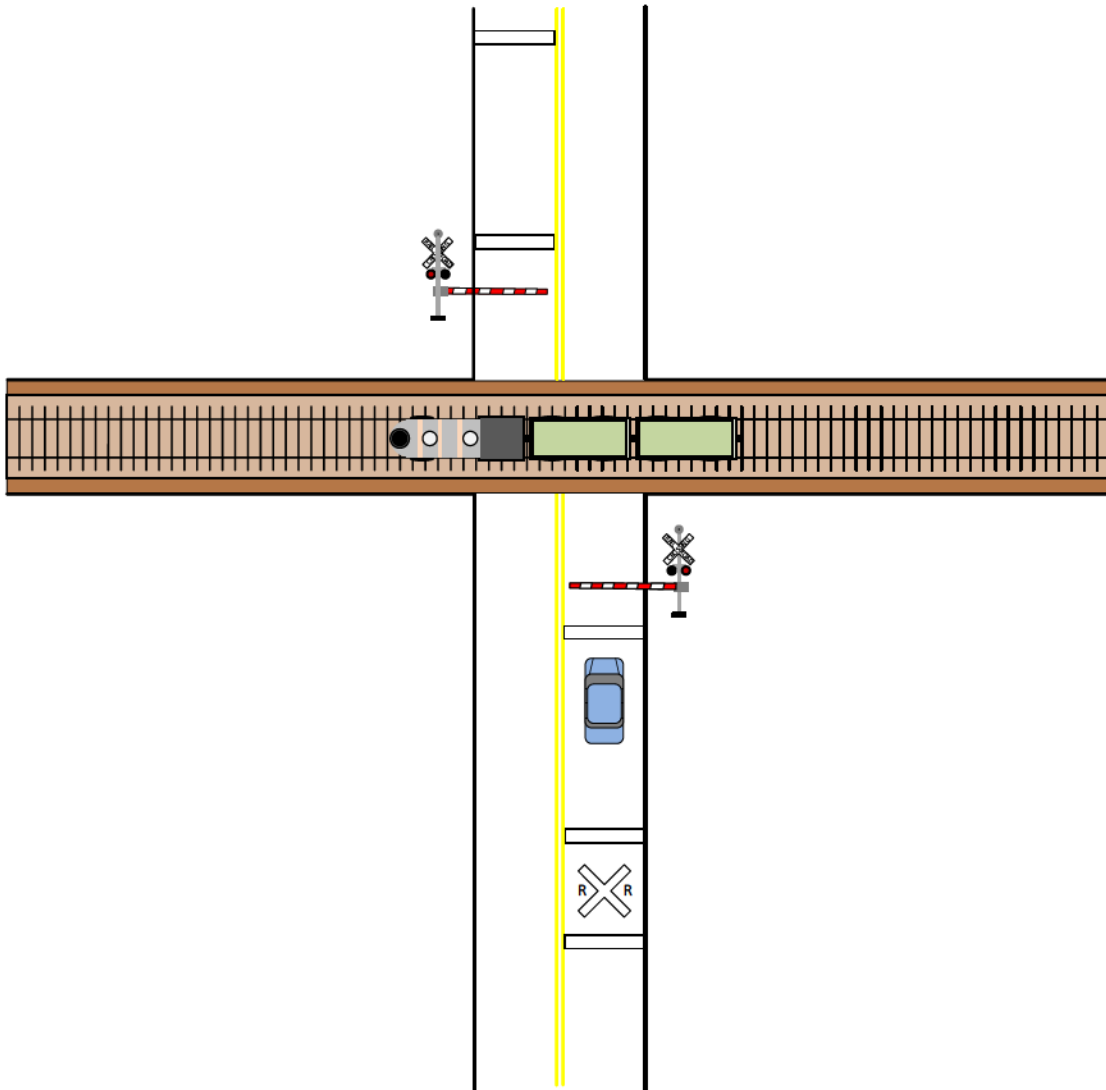
Source: Battelle, 2018

Figure 3. Scenario 3: AV approaches an HRGC with AWDs activated and a train occupying the HRGC

Scenario 4. Train departs HRGC with AWDs, then the AV departs

This scenario begins with the AV stopped at the HRGC stop bar and a train occupying the HRGC.

- Train travels through and clears HRGC
- Detection circuit is deactivated
- AWD lights deactivate
- AV detects AWD flashing lights are no longer active
- AV determines it is safe to cross the HRGC as no queued traffic or trains are present
- AV crosses the HRGC

Source: Battelle, 2018
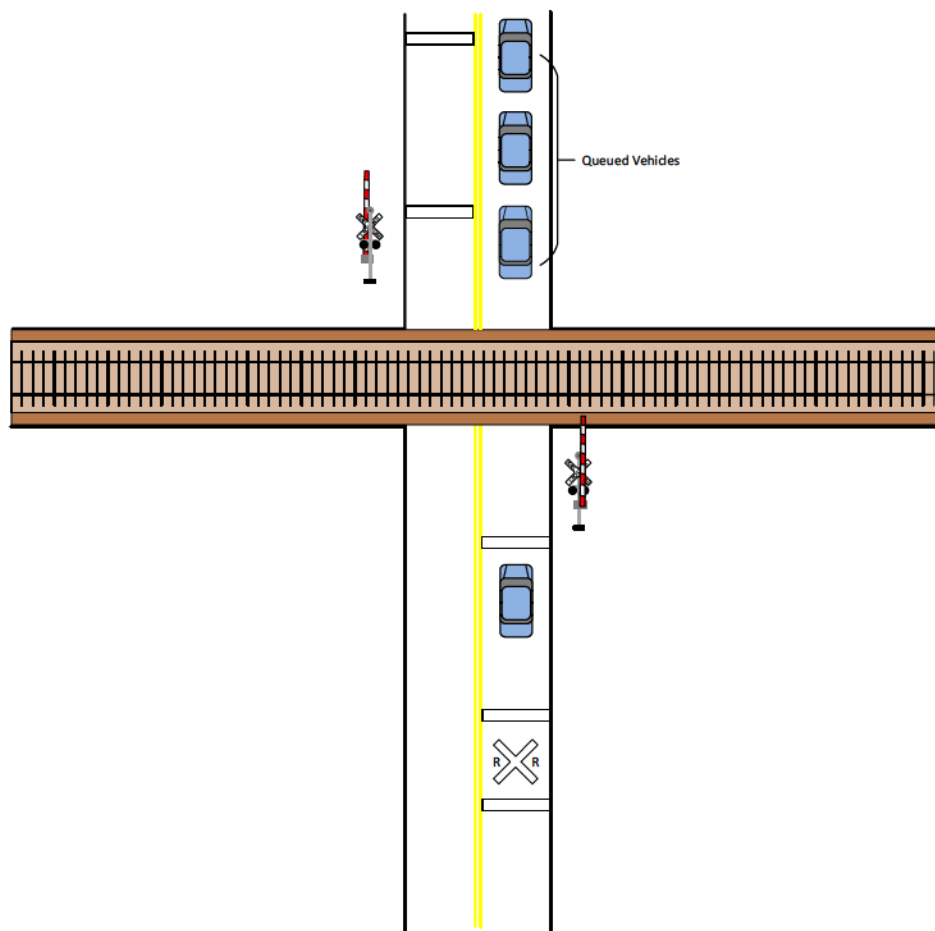
Figure 4. Scenario 4: Train departs HRGC with AWDs, then the AV departs

Scenario 5. CAV approaches a Connected HRGC with AWDs activated and a train occupying the HRGC

- *Common Actions, page 6*
- CAV determines that the HRGC is a Connected HRGC
- CAV receives the Connected HRGC's 'HRGC Active' message
- CAV reduces speed and comes to a complete stop at the HRGC stop bar
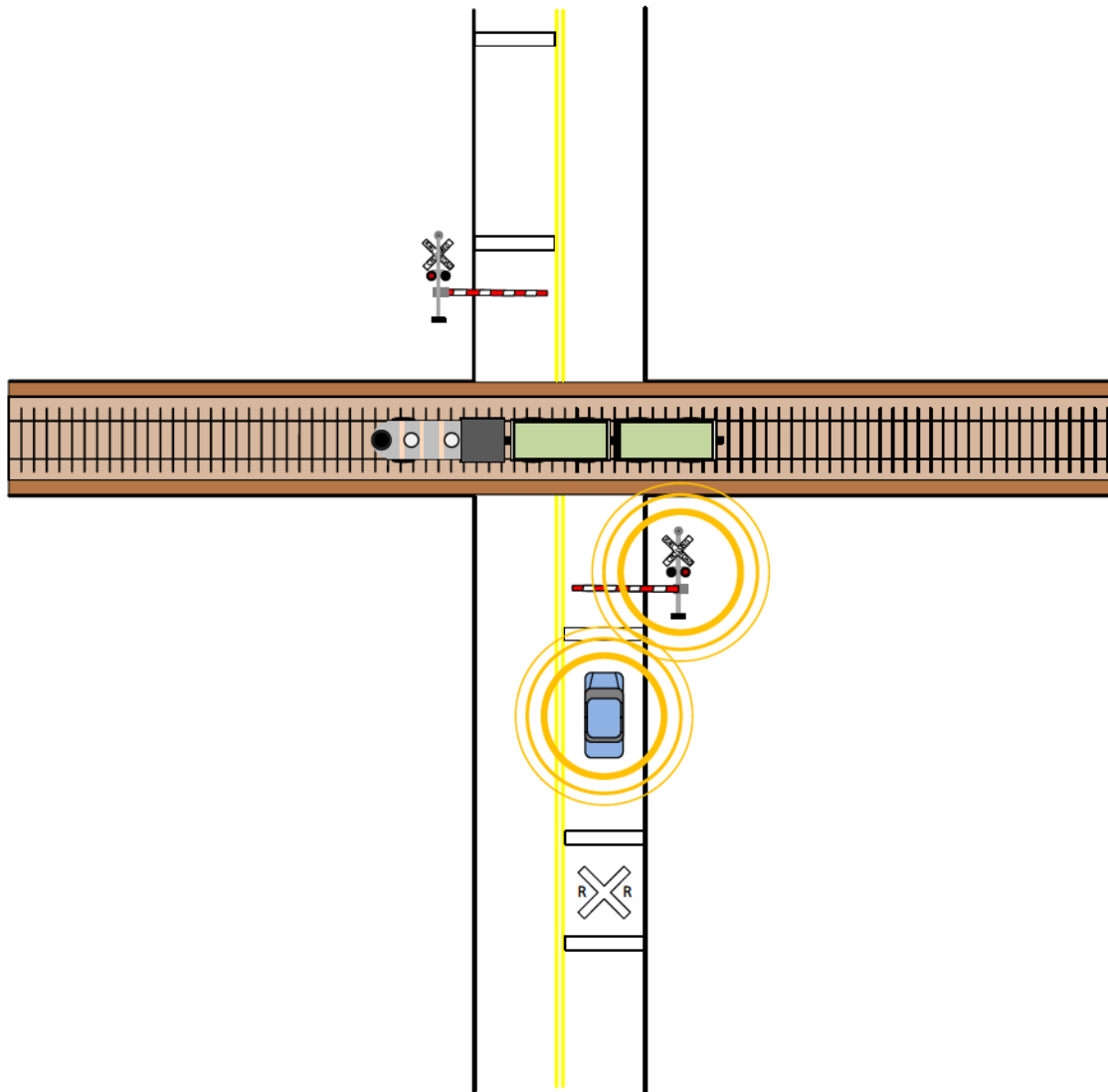
Source: Battelle, 2018

Figure 5. Scenario 5: CAV approaches a Connected HRGC with AWDs activated and a train occupying the HRGC

Scenario 6. Train departs Connected HRGC, then the CAV departs

This scenario begins with the AV stopped at the HRGC stop bar and a train occupying the HRGC.

- *Common Actions, page 6*
- Train travels through and clears HRGC
- Detection circuit is deactivated
- Connected HRGC stops broadcasting 'HRGC Active' message
- CAV no longer receives 'HRGC Active' message
- CAV "verifies" that the HRGC is not occupied
- CAV crosses the HRGC
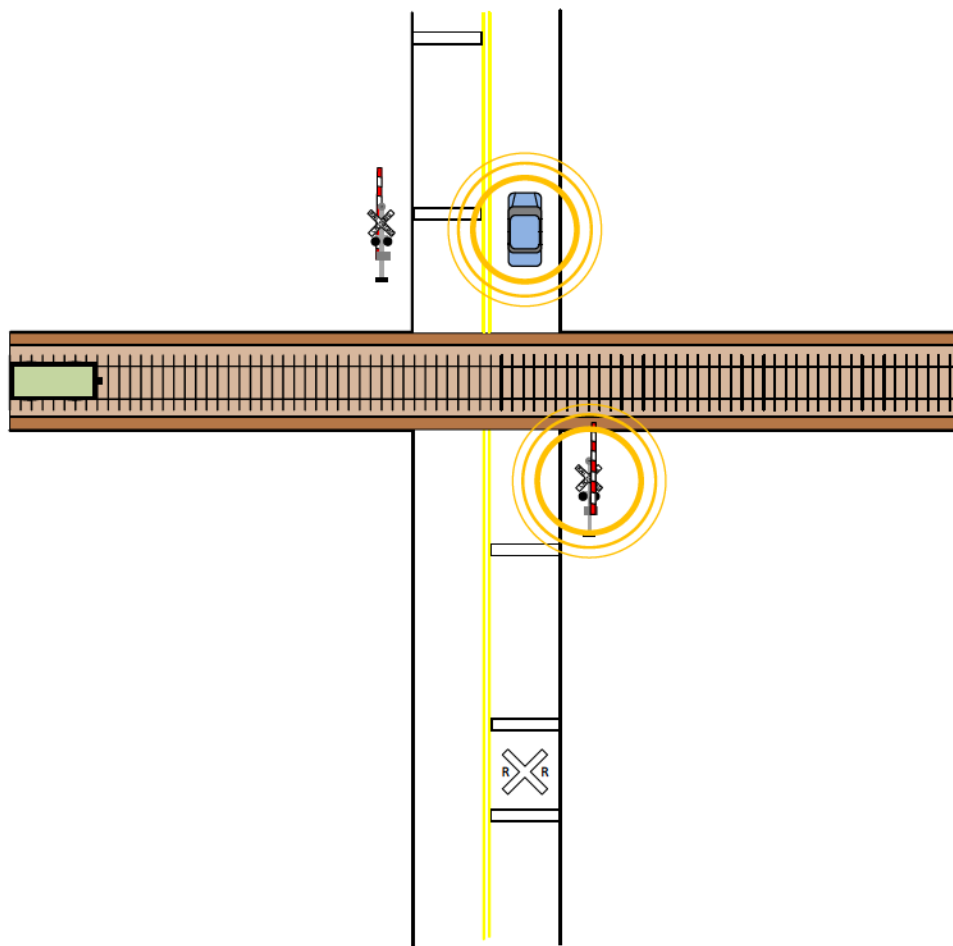
Source: Battelle, 2018

Figure 6. Scenario 6: Train departs Connected HRGC, then the CAV departs

Chapter 3. Vehicle Approaching Highway-Rail Grade Crossing with Passive Warning Devices

Scenario 7. AV approaches an HRGC with PWDs and a train occupying the HRGC

- *Common Actions, page 6*
- AV detects the presence of a train
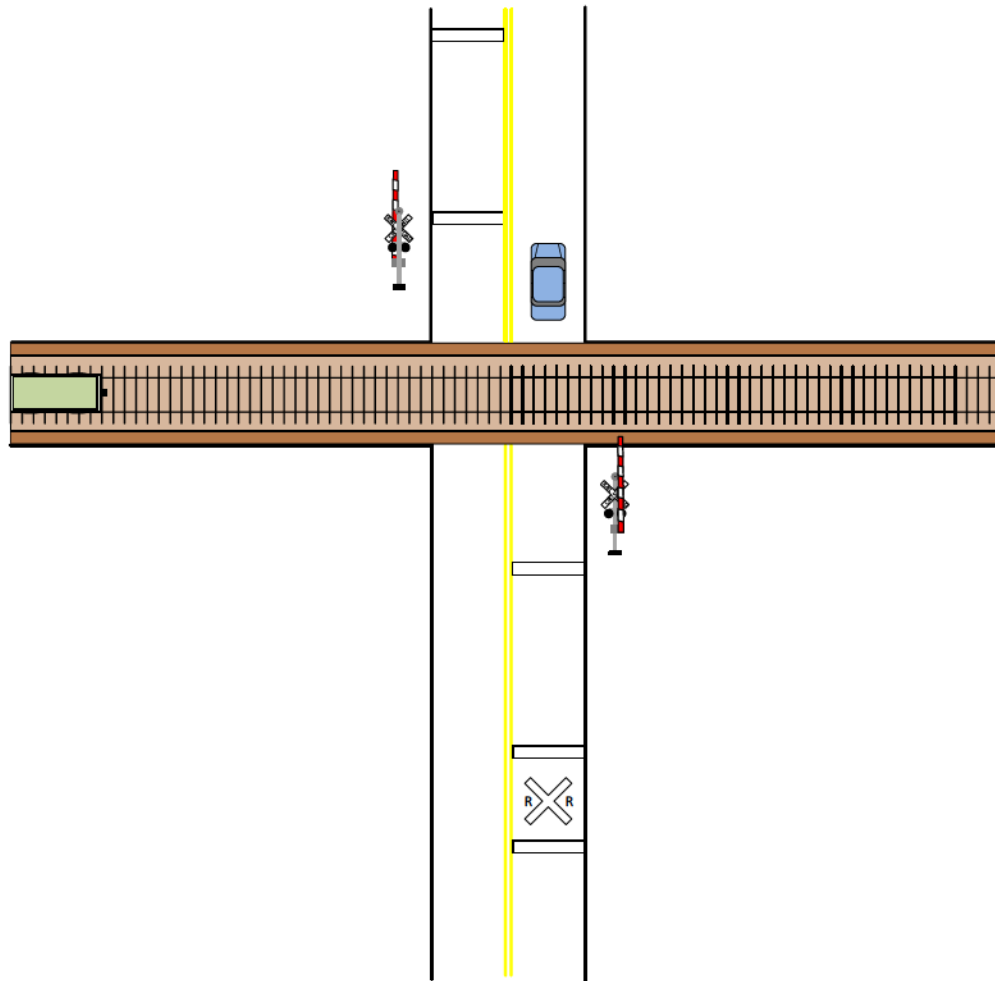- AV reduces speed and comes to a complete stop at the HRGC stop bar
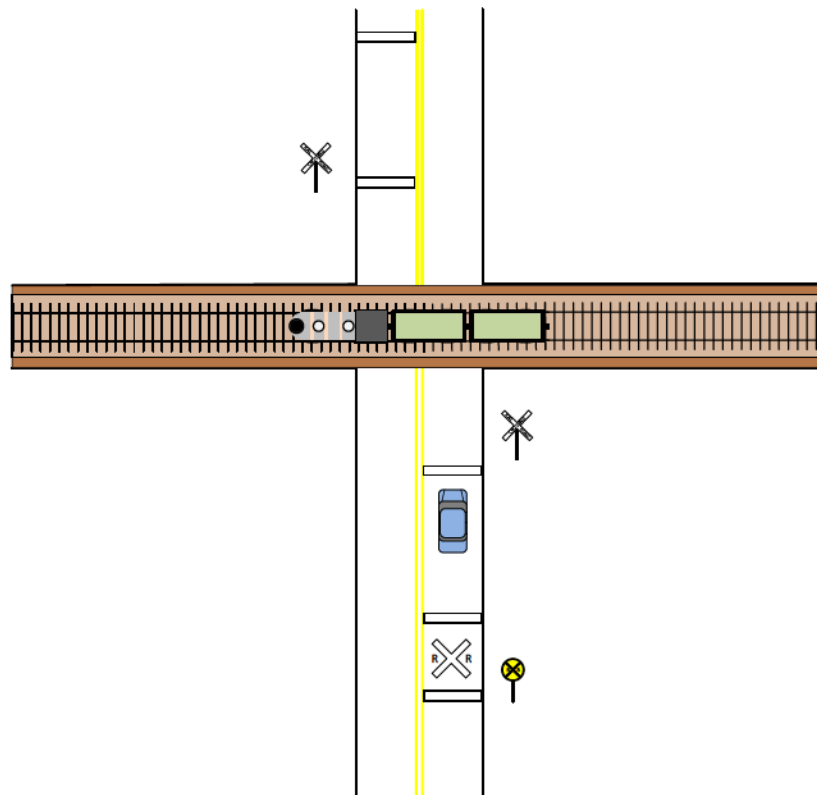
Source: Battelle, 2018

Figure 7. Scenario 7: AV approaches an HRGC with PWDs and a train occupying the HRGC

Scenario 8. Train departs HRGC with PWDs, then the AV departs

This scenario begins with the AV stopped at the HRGC stop bar and a train occupying the HRGC.

- AV detects the train departing
- AV determines it is safe to cross the HRGC as no queued traffic or trains are present
- AV crosses the HRGC
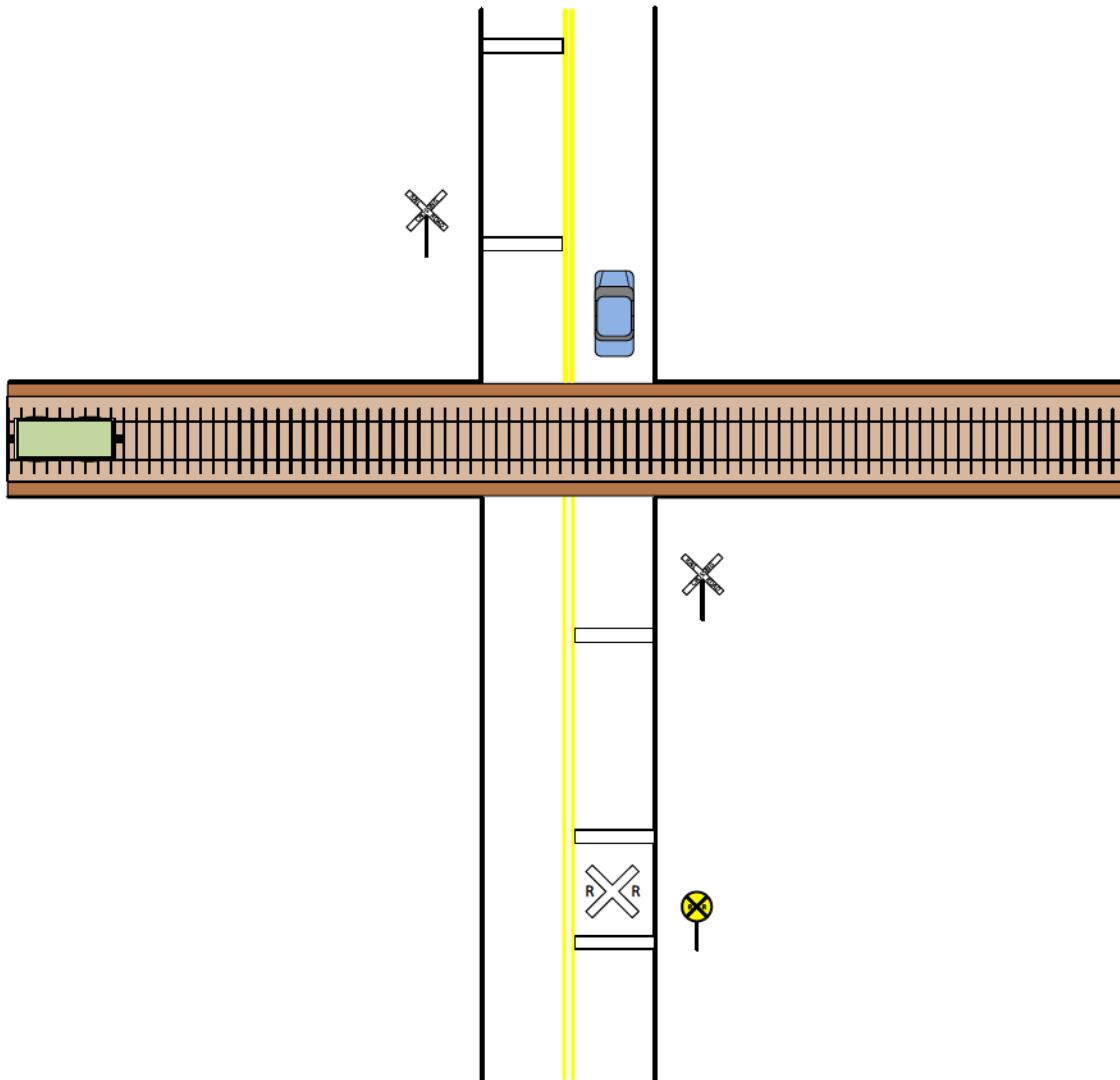
Source: Battelle, 2018

Figure 8. Scenario 8: Train departs HRGC with PWDs, then the AV departs

Scenario 9. CAV approaches an HRGC with PWDs and a Connected Train approaching in range of the HRGC

- *Common Actions, page 6*
- CAV receives location and speed information from the approaching Connected Train HRGC
- CAV calculates when the Connected Train will arrive at the HRGC
- CAV calculates the time it will arrive at the HRGC
- CAV determines it is not safe to traverse the HRGC
- CAV reduces speed and comes to a complete stop at the HRGC stop bar
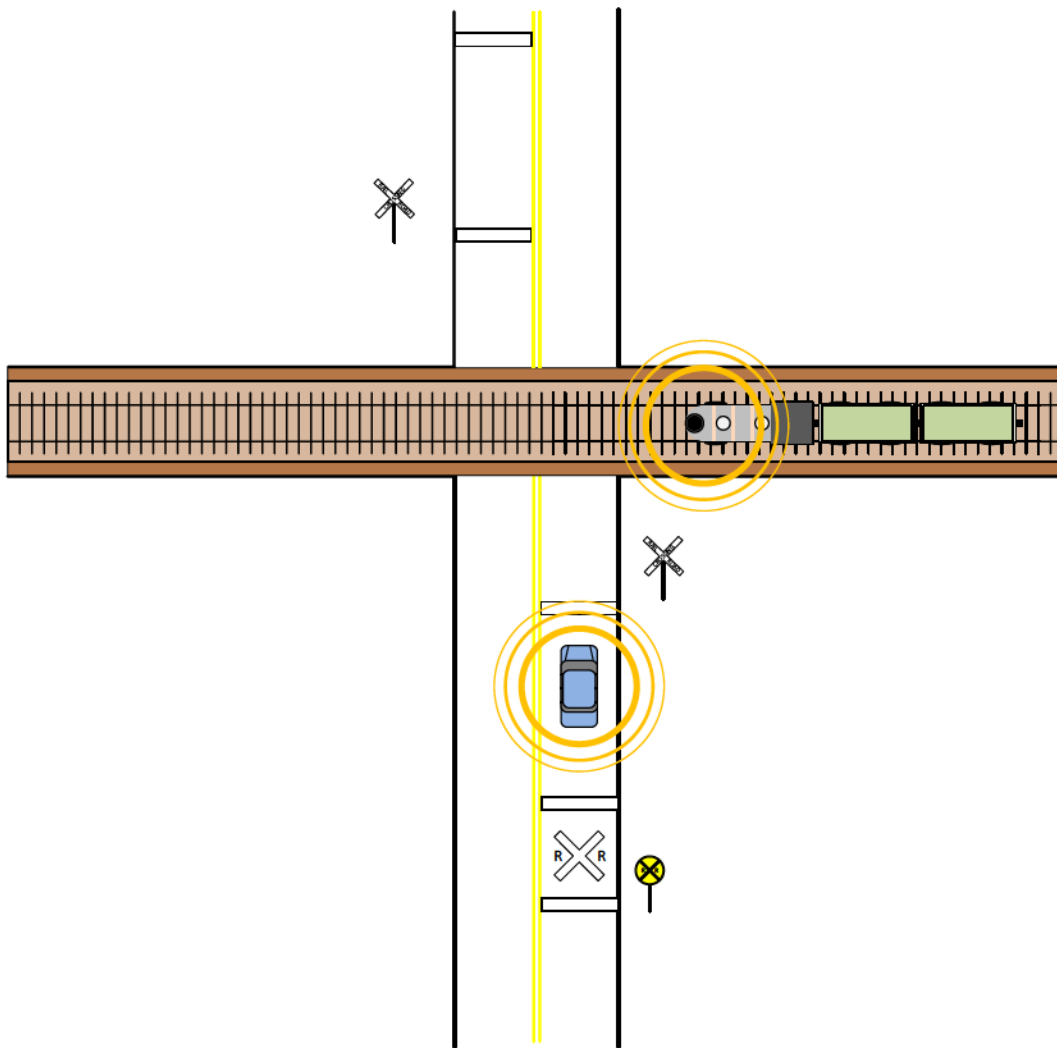
Source: Battelle, 2018

Figure 9. Scenario 9: CAV approaches an HRGC with PWDs and a Connected Train approaching in range of the HRGC

Scenario 10. Connected Train departs HRGC with PWDs, then the CAV departs

This scenario begins with the CAV stopped at the HRGC stop bar and a Connected Train approaching and then occupying the HRGC.

- *Common Actions, page 6*
- Train passes through and clears the HRGC
- CAV determines it is safe to cross the HRGC
- CAV crosses the HRGC
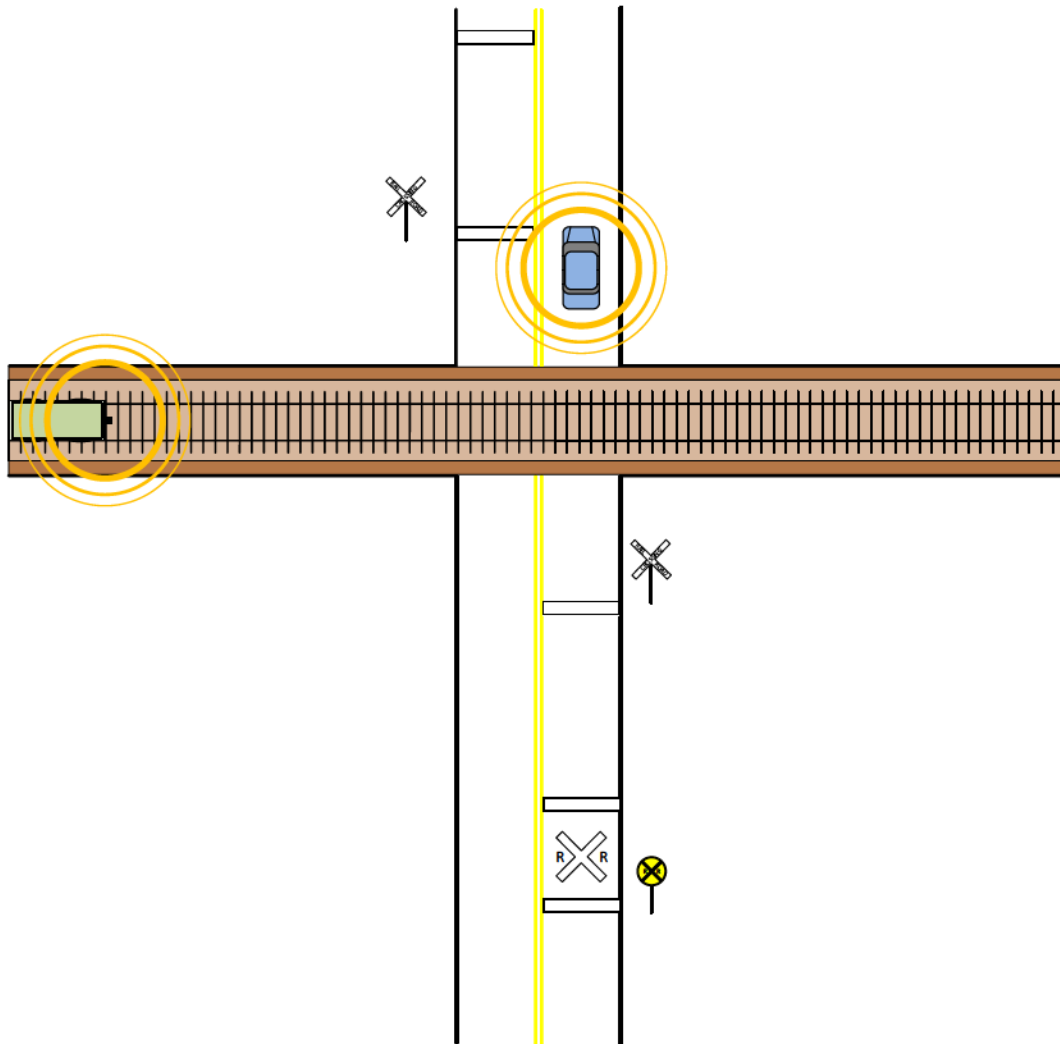
Source: Battelle, 2018

Figure 10. Scenario 10: Connected Train departs HRGC with PWDs, then the CAV departs

Scenario 11. CAV approaches an HRGC with PWDs, vehicles queuing, and without a train approaching or occupying the HRGC

- *Common Actions, page 6*
- CAV receives location information from a CAV queued and stopped beyond the HRGC
- The CAV calculates the stopping location if it joins the queue and determines that it is within the HRGC
- CAV reduces speed and comes to a complete stop at the HRGC stop bar
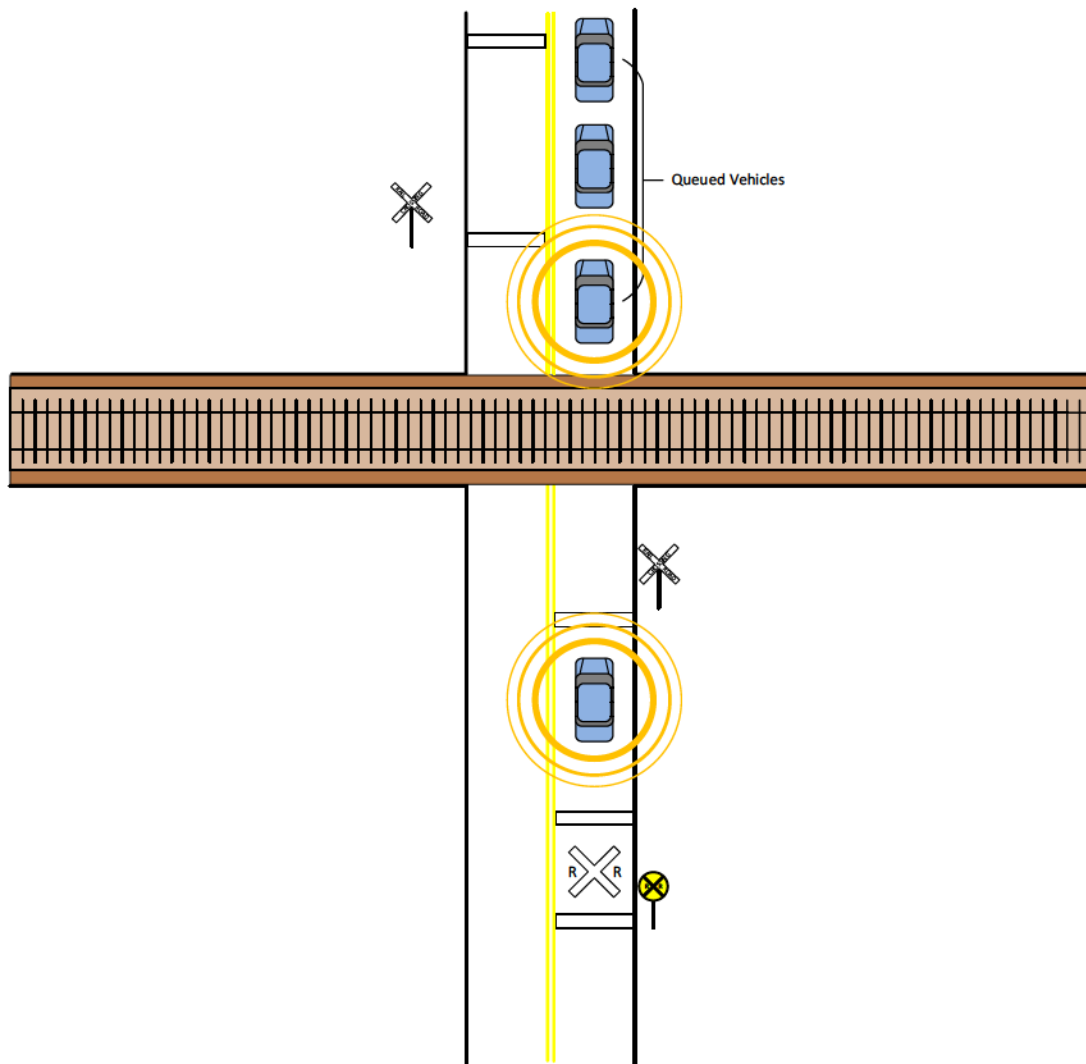
Source: Battelle, 2018

Figure 11. Scenario 11: CAV approaches an HRGC with PWDs, vehicles queuing, and no train approaching or occupying the HRGC

Chapter 4. Requirements

This chapter identifies functional, processing, and some high-level design and performance requirements identified to support the ConOps scenarios presented in Chapter 2 and Chapter 3 above. The identified requirements are organized into a general requirements section (Section 1) and four sections unique to ConOps scenario groups (Sections 2-4). Section 1 is sub-divided into general requirements for AVs and CAVs, Connected Trains, and Connected HRGCs. AV-specific requirements are not established for non-connected vehicles, non-connected trains, and non-connected HRGCs, as the ConOps scenarios including these components listed above assume that existing standards governing their design and operation are separately established.

All scenarios include the general AV and CAV requirements from Section 1, plus all requirements that apply to the specific ConOps scenario group from Section 2, 3, or 4. In addition, general Connected HRGC or Connected Train requirements from Section 1 will additionally apply when the scenario involves a Connected HRGC or Connected Train.

The System Requirements are organized into five sections.

1. General Requirements
2. CAV and Connected HRGC Requirements
3. CAV and Connected Train Requirements
4. All vehicles approaching an HRGC with PWDs and without connected communication
5. All vehicles approaching an HRGC with AWDs and without connected communication

1. General Requirements

A set of general requirements were created for AVs, CAVs, Connected Trains, and Connected HRGCs. The AV and CAV Requirements are common to both AVs and CAVs and therefore are not specific to AVs or CAVs. Conversely to the AV and CAV Requirements: the AV, CAV, Connected Train, and Connected HRGC requirements are unique respectively. Requirements were not created for non-connected trains or HRGCs as the assumption was documented in Chapter 1 that all trains and HRGC equipment perform in the same manner as it does in the year 2018 without any modifications being made to current operations. The requirements listed in the table below apply to all ConOps scenarios.

Table 3. General Scenario Requirements

System Requirement	System Requirement	ConOps Scenario Reference
General Connectivity Requirements		
Connected_Req_1	All connected components (i.e. Connected Trains, CAVs, and Connected HRGCs) shall comply with FCC required communication protocols.	All CAV Scenarios (5, 6, 9-11) All Connected Train Scenarios (9-10) All Connected HRGC Scenarios (5-6)
Connected_Req_2	All connected components (i.e. Connected Trains, CAVs, and Connected HRGCs) shall transmit messages at a mission-effective signal strength.	All CAV Scenarios (5, 6, 9-11) All Connected Train Scenarios (9-10) All Connected HRGC Scenarios (5-6)
Connected_Req_3	All connected components (i.e. Connected Trains, CAVs, and Connected HRGCs) messages shall comply with the SAE J2735 protocol.	All CAV Scenarios (5, 6, 9-11) All Connected Train Scenarios (9-10) All Connected HRGC Scenarios (5-6)
General Requirements for AVs and CAVs Approaching an HRGC		
AV_and_CAV_Req_1	The vehicle shall detect and process the presence of an HRGC in its path.	All Scenarios (1-11)
AV_and_CAV_Req_2	The vehicle shall determine if the HRGC in its path has AWDs or PWDs.	All Scenarios (1-11)
AV_and_CAV_Req_3	Upon the vehicle determining it should not traverse the HRGC, it shall stop at the HRGC stop bar.	All Scenarios (1-11)
AV_and_CAV_Req_4	The vehicle shall detect and process the location of an HRGC stop bar, while approaching an HRGC.	All Scenarios (1-11)
AV_and_CAV_Req_5	The vehicle shall stop without exercising emergency braking.	All Scenarios (1-11)
AV_and_CAV_Req_6	The vehicle shall detect vehicles queued downstream of the HRGC.	All Scenarios (1-11)
AV_and_CAV_Req_7	The vehicle shall determine if it can join a queue of vehicles downstream of the HRGC.	All Scenarios (1-11)
General AV Requirements		

System Requirement	System Requirement	ConOps Scenario Reference
AV_Req_1	The AV shall implement a sensor package for scanning and detecting objects, including queued traffic.	All AV Scenarios (1-4, 7, 8)
AV_Req_2	The AV shall implement a sensor package for scanning and detecting stationary roadway information, including roadway markings, traffic control signage, and control devices.	All AV Scenarios (1-4, 7, 8)
AV_Req_3	The vehicle's on-board sensor package shall interoperate with its safety systems.	All AV Scenarios (1-4, 7, 8)
AV_Req_4	The vehicle's on-board system shall process information received from on-board vehicle sensors.	All AV Scenarios (1-4, 7, 8)
AV_Req_5	When approaching the HRGC, the AV shall scan for the presence of an HRGC.	All AV Scenarios (1-4, 7, 8)
AV_Req_6	When approaching the HRGC, the AV shall scan for the location of the HRGC stop bar.	All AV Scenarios (1-4, 7, 8)
AV_Req_7	When approaching the HRGC, the AV shall scan for queued traffic downstream of the HRGC.	All AV Scenarios (1-4, 7, 8)
General CAV Requirements		
CAV_Req_1	The CAV on-board communication system(s) shall not interfere with the on-board sensor package or vehicle safety systems.	All CAV Scenarios (5, 6, 9-11)
General Connected Train Requirements		
Conn_Train_Req_1	The Connected Train on-board communication system shall not interfere with the safety systems of the train.	All Connected Train Scenarios (9-10)
Conn_Train_Req_2	The Connected Train shall broadcast speed and position	All Connected Train Scenarios (9-10)
General Connected HRGC Requirements		
Conn_HRGC_Req_1	The Connected HRGC wayside communication system shall not interfere with the safety systems of the HRGC equipment.	All Connected HRGC Scenarios (5-6)
Conn_HRGC_Req_2	The Connected HRGC shall continually broadcast HRGC configuration data that includes the location of the HRGC stop bar	All Connected HRGC Scenarios (5-6)
Conn_HRGC_Req_3	The Connected HRGC shall continually broadcast an HRGC Active message when the preemption signal has been triggered by the track-circuit detection system.	All Connected HRGC Scenarios (5-6)
Conn_HRGC_Req_4	The Connected HRGC shall stop broadcasting the HRGC Active message when the preemption signal has been deactivated.	All Connected HRGC Scenarios (5-6)

2. CAV and Connected HRGC Requirements

In addition to the requirements that pertain to all scenarios with CAVs and Connected HRGCs, Table 4 lists the requirements that apply to scenarios where CAVs and Connected HRGCs are both present. These requirements describe the functionality and relationship between them.

Table 4. CAV and Connected HRGC Scenario Requirements

System Requirement #	System Requirement	ConOps Scenario Reference
CAV_Conn_HRGC_Req_1	The CAV on-board communication system shall receive and process HRGC Active messages, as well as HRGC configuration files from the Connected HRGC.	All CAV at Connected HRGC Scenarios (5-6)
CAV_Conn_HRGC_Req_2	Upon approaching a Connected HRGC, the CAV shall verify that the HRGC is Connected.	All CAV at Connected HRGC Scenarios (5-6)
CAV_Conn_HRGC_Req_3	The CAV on-board system shall process Connected HRGC configuration data that includes the location of the HRGC stop bar.	All CAV connected HRGC Scenarios (5-6)

3. CAV and Connected Train Requirements

In addition to the requirements that pertain to all scenarios with CAVs and Connected Train, Table 5 lists the requirements that apply to scenarios where CAVs and Connected Trains are both present. These requirements describe the functionality and relationship between them.

Table 5. CAV and Connected Train Scenario Requirements

System Requirement #	System Requirement	ConOps Scenario Reference
CAV_Conn_Train_Req_1	The CAV shall receive, and process train speed and position messages from Connected Trains.	All CAV at Connected Train Scenarios (9-10)
CAV_Conn_Train_Req_2	While approaching an HRGC, the CAV shall detect a Connected Train that is approaching, or occupying, the HRGC.	All CAV at Connected Train Scenarios (9-10)
CAV_Conn_Train_Req_3	The CAV shall receive the front-of-train and end-of-train locations of the Connected Train.	All CAV at Connected Train Scenarios (9-10)
CAV_Conn_Train_Req_4	The CAV shall determine when the Connected Train has cleared the HRGC.	All CAV at Connected Train Scenarios (9-10)

4. All Vehicles Approaching HRGC with PWDs and without Connected Communication Requirements

As noted in Table 2, AVs and CAVs may obtain the same information needed to traverse an HRGC, but can do so using different methods and different source of information depending on the scenario characteristics. Table 6 lists the requirements that apply to all vehicles, AVs and CAVs, as they approach an HRGC with PWDs. The requirements described in Table 3 are still applicable to these scenarios.

Table 6. All Vehicles Approaching an HRGC with PWDs and without Connected Communication

System Requirement #	System Requirement	ConOps Scenario Reference
Veh_at_HRGC_w_PWDs_1	When the vehicle is approaching an HRGC with PWDs, it shall detect and process a crossbuck sign.	All Vehicles Approaching HRGCs with PWDs (7-8, 11)
Veh_at_HRGC_w_PWDs_2	When the vehicle is approaching the HRGC, it shall scan for the physical presence of a train in-range and approaching the HRGC.	All Vehicles Approaching HRGCs with PWDs (7-8, 11)
Veh_at_HRGC_w_PWDs_3	When the vehicle is approaching the HRGC, it shall scan for the physical presence of a train occupying the HRGC.	All Vehicles Approaching HRGCs with PWDs (7-8, 11)
Veh_at_HRGC_w_PWDs_4	When the vehicle is approaching, and a train is not occupying the HRGC, it shall scan for queued traffic ahead.	All Vehicles Approaching HRGCs with PWDs (7-8, 11)

5. All Vehicles Approaching HRGC with AWD and without Connected Communication Requirements

As noted in Table 2, AVs and CAVs may obtain the same information needed to traverse an HRGC, but can do so using different methods and different source of information depending on the scenario characteristics. Table 7 lists the requirements that apply to all AVs and CAVs, as they approach an HRGC with AWDs. The requirements described in Table 3 are still applicable to these scenarios.

Table 7. All Vehicles Approaching an HRGC with AWDs and without Connected Communication

System Requirement #	System Requirement	ConOps Scenario Reference
Veh_at_HRGC_w_AWDs_1	While approaching an HRGC with AWDs, the AV shall detect, and process the crossbuck sign with AWD lights, and AWD light status (i.e., activated or not activated).	All Vehicles Approaching HRGCs with AWDs (1-4)

System Requirement #	System Requirement	ConOps Scenario Reference
Veh_at_HRGC_w_AWDs_2	While present at an HRGC with AWDs, the AV shall detect, and process the status of AWD lights (i.e., activated or not activated).	All Vehicles Approaching HRGCs with PWDs (1-4)
Veh_at_HRGC_w_AWDs_3	While the AWD lights are activated, the AV shall come to a complete stop and remain stopped at the HRGC stop bar.	All Vehicles Approaching HRGCs with PWDs (1-4)
Veh_at_HRGC_w_AWDs_4	The AV shall remain stopped at the HRGC stop bar, until the AWD lights have de-activated.	All Vehicles Approaching HRGCs with PWDs (1-4)

Chapter 5. AV and CAV Use Cases

For the development of the requirements in Chapter 4, simplifying assumptions were identified to determine the basic functions an AV must perform when approaching an HRGC. Those requirements lay the framework for the minimum functionality an AV must have to negotiate an HRGC. To cultivate a more comprehensive set of requirements for AVs, a significant number of challenging or limiting conditions must be considered.

During the requirements development process, Battelle hosted a stakeholder engagement workshop by webinar to present the assumptions used to create the requirements and select ConOps scenarios and seek input from subject matter and industry experts. Stakeholders from the AV and railroad industries participated in a live discussion alongside with government entities to discuss challenges and opportunities for solutions for AVs traversing HRGCs.

A key discussion topic amongst all stakeholders was of challenging conditions that may inhibit the way an AV performs. The stakeholder input in combination with past project and team experience was leveraged to develop a set of Use Cases to further examine these challenges. This chapter describes a limited number of Use Cases that introduce challenging conditions to the ConOps scenarios that are explained in Chapter 2 and Chapter 3. These Use Cases contest the simplified assumptions and requirements in real-world scenarios when challenging conditions will inhibit the performance of the vehicle.

Challenging Conditions

The Use Cases were derived from the literature review, research and testing experience, and stakeholder input. Table 8 provides a summary of Use Cases that address a representative subset of the following conditions:

A. Adverse Weather

- Snow covering lane and/or HRGC stop bar markings
- Sun glare reducing the contrast of road markings and detected objects (signage, vehicles, and trains)
- Falling or kicked up dirt, dust, fog, or rain or icy mix accumulation that reduces visibility of AV sensors.
- Iced over crossbuck signage

B. Obstructions

- Manmade or natural obstructions occluding sight lines of HRGC control devices
- Manmade or natural obstructions occluding sight lines of an approaching train

- Manmade or natural obstructions occluding the sight line of the roadway ahead of the vehicle

C. HRGC Approach and Geometry

- Stop or yield sign at HRGC
- Curved highway approach to an HRGC
- Skewed highway approach to an HRGC
- High profile crossing with queued traffic downstream of the HRGC
- Traffic light(s) integrated with the HRGC detection system
- Multiple railroad tracks
- Vehicle approach to the HRGC is parallel to the tracks

D. Detection of Moving Objects

- Bicyclists or pedestrians crossing ahead of an AV on approach to an HRGC
- Queued traffic (connected or non-connected) upstream of the HRGC
- High-speed trains
- Multiple trains on the tracks
- Hi-rail or maintenance vehicles near the railroad tracks
- Rail vehicles in the right-of-way

E. Degraded System Components

- Worn HRGC stop bar markings
- Onboard AV sensors used to detect AWD state, train location status, queue traffic, or HRGC stop bar location
- Onboard AV components used to process onboard sensor inputs and determine vehicle stop location, amount of queue space available, time to connected train arrival, distance to stop, etc.
- AWD signaling malfunction (i.e., fail-safe state)
- AWD light failure
- Vandalized/missing PWDs on the wayside
- Graffiti on wayside signage or pavement markings
- Connected HRGC communication detection or communication failure
- Connected Train communication failure

Table 8. Use Case Descriptions

Use Case #	Challenging Condition	Challenge for the Vehicle	ConOps Scenario Reference	Condition Set
1	The AWD lights at the HRGC are non-functional.	How does the vehicle respond if AWD lights cannot indicate a train is approaching?	Scenario 3	E
2	The approach to the HRGC is located on a steep grade preventing the AV from detecting queued vehicles beyond the HRGC.	How should the AV detect queued vehicles beyond the HRGC if the sensors cannot detect vehicles beyond the hill?	Scenario 2	B, C
3	A hi-rail or maintenance vehicle is within the vicinity of the HRGC upon an AV approaching.	How should the vehicle respond to obstructions on the railroad tracks that does not trigger the AWDs?	Scenario 3	D
4	The train is stopped within range of the HRGC and the AWDs are activated.	How should the vehicle respond to activated AWD if a train is stopped and not occupying the HRGC?	Scenario 3	E
5	The Connected HRGC communication system is non-operational.	How does the CAV distinguish between a non-operational Connected HRGC vs. a fully functional HRGC with AWDs?	Scenario 5	E
6	The crossbuck sign cannot be "seen" by the AV due to sun glare.	How should the vehicle identify an HRGC with PWDs if the crossbuck sign cannot be identified?	Scenario 7	A
7	The HRGC stop bar is obstructed and cannot be identified by the AV.	Where should the AV stop at the HRGC?	Scenario 7	A, B
8	The train occupying the HRGC is composed of flatcars instead of high-profile cars, i.e. box cars.	How should the vehicle detect different styles of rail cars?	Scenario 7	D
9	The skew angle at the roadway and HRGC is for example 45 degrees.	How should the vehicle detect the presence of a train with this skew angle?	Scenario 7	C

The ConOps Scenario Reference column lists the ConOps scenarios from which the Use Cases were created. Although the limiting condition can have an impact on additional ConOps scenarios, the focus is on the scenario listed. The Use Cases can be used to develop iterations of the respective scenarios listed in the ConOps Scenario Reference column.

Tables 9 through 18 contain a reference of the most applicable assumptions and requirements affected by the Use Cases. Although more assumptions and requirements are affected, those listed are most dramatically impacted by the challenging condition introduced by the Use Case.

Use Cases

Use Case 1. The AWDs lights at the HRGC are non-functional.

In all ConOps scenarios where an AV is approaching an HRGC with AWDs, the AV determines the status of the HRGC with regards to a train approaching or occupying the HRGC by detecting the flashing lights on the AWDs. If the AWD lights are non-functional, how should the AV respond? How should the AV know the lights are non-functional vs. deactivated? Responses to different failure modes and fail-safe states represent an enormous challenge for AVs.

This challenging condition would affect the following assumptions and requirements.

Table 9. ConOps Assumptions and Requirements Affected by Use Case 1.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• Scenario 3: AV approaches an HRGC with AWDs activated and a train occupying the HRGC	• The HRGC is fully functional and operational, including its communication and signaling components.	• Veh_at_HRGC_w_AWDs_1 • Veh_at_HRGC_w_AWDs_2

A list of possible resolutions to consider for how the AV may respond include:

- If the HRGC has gates and bells, the AV will use multiple sources of inputs such as the bell audible and/or a gate-down visual.
- If the train detection system has failed or lost power, the AV should remain stopped at the HRGC stop bar or navigate another route around the HRGC.
- The AV should detect a train approaching.
- The AV will stop, "look", and "listen" for a train.

Other potential sources of information may include:

- A Connected Train will broadcast train position and speed to approaching CAVs.
- A CAV will be remotely monitored and controlled from an "eye in the sky" that verifies if it is safe to traverse the HRGC.

Use Case 2. The approach to the HRGC is located on a steep grade preventing the AV from detecting queued vehicles beyond the HRGC.

In Scenario 2 of the ConOps, the AV detects vehicles queued beyond the HRGC as one of the checks performed to determine if it can traverse the HRGC. There is an assumption identified in Chapter 1 that states "the grade at the roadway and HRGC is flat and does not obstruct the sight line to queued traffic". This Use Case introduces a challenge to the AVs sensing capabilities when vehicles are queued beyond the HRGC and without the AV having a clear sight line to those vehicles.

This challenging condition would affect the following assumptions and requirements.

Table 10. ConOps Scenarios and Requirements Affected by Use Case 2.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• **Scenario 2: AV approaches an HRGC with AWDs, vehicles queuing, and without a train approaching or occupying the HRGC**	• **The grade at the roadway and HRGC is flat and does not obstruct the sight line to queued traffic.**	• **AV_and_CAV_Req_6** • **AV_and_CAV_Req_7** • **AV_Req_1** • **AV_Req_7**

Assuming the hill is steep enough to present a sight line challenge to the AV, a list of possible resolutions to consider for how the AV may respond include:

- In the future, all vehicles may be required to be connected to allow V2V communications. Some vehicles might need to achieve connectivity via after-market safety devices.
- AV sensor packages will be able to detect queued vehicles regardless of the surrounding topography.

Other potential sources of information may include:

- HRGCs sited at the top, or the bottom, of a steep grade will be Connected HRGCs that broadcast the position of queued CAVs to approaching CAVs.
- HRGC infrastructure will include a wayside unit to detect the presence of queued vehicles and to display that information and/or transmit messages to an AV approaching the HRGC.
- HRGC infrastructure will include signage such as the R8-8 sign (indicating "Do Not Stop on Tracks") installed at crossings with queueing issues.
- Connected HRGCs will transmit R8-8 message sign information to approaching CAVs.

Use Case 3. A hi-rail or maintenance vehicle is within the vicinity of the HRGC upon an AV approaching.

ConOps scenario 1 presents an AV approaching an HRGC without a train approaching or occupying the HRGC. Use Case 3 alters this scenario by introducing a maintenance vehicle near the HRGC – either on or not on the railroad tracks. The AV would be presented with the challenge of detecting and interpreting the presence of a hi-rail or maintenance vehicle in an HRGC.

This challenging condition would affect the following assumptions and requirements.

Table 11. ConOps Assumptions and Requirements Affected by Use Case 3.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• **Scenario 3: AV approaches an HRGC with AWDs activated and a train occupying the HRGC**	• **There is only a single train approaching and or occupying the HRGC.**	• **AV_Req_1**

A list of possible resolutions to consider for how the AV may respond include:

- The AV will be able to distinguish between different types of flashing lights and their intention.
- The AV will turn around and find another route.
- The AV will be able to traverse the HRGC if the maintenance crew flags the AV to continue through the HRGC or when other wayside treatments are present?
- The hi-rail or maintenance vehicle activate AWDs at the HRGC.

Other potential sources of information may include:

- A Connected hi-rail or maintenance vehicle will broadcast maintenance status to approaching CAVs.

Use Case 4. The train was approaching the HRGC but has stopped short of the HRGC; the AWDs have deactivated.

This Use Case explores the situation of a train being stopped for an extended period of time such that the AWDs become deactivated as a result of timing out. What happens in this situation if the AV is travelling past the HRGC stop bar and the train has started moving again? Even if the AWDs were to reactivate it may not provide sufficient warning time. Physically detecting a train as performed by vehicles at HRGCs with PWDs will represent a challenge.

This challenging condition would affect the following assumptions and requirements.

Table 12. ConOps Assumptions and Requirements Affected by Use Case 4.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• **Scenario 3: AV approaches an HRGC with AWDs activated and a train occupying the HRGC**	• **The train is occupying or approaching the HRGC and traveling at a constant speed.** • **The train is fully functional and operational.**	• **AV_Req_1** • **AV_Req_4**

A list of possible resolutions to consider for how the AV may respond include:

- The AV will be able to detect a train from its "driver" and passenger sides.
- The AV will detect the presence of a train when approaching or occupying an HRGC.
- The AV will remain stopped at the HRGC.
- The AV will turn around and find another route.
- The AV will stop, "look", and "listen" for a train.

Other potential sources of information may include:

- A Connected Train will communicate its position and speed to approaching CAVs and/or Connected HRGCs.

Use Case 5. The Connected HRGC communication system is non-operational.

This Use Case is an iteration of ConOps scenario 5 where a CAV is approaching a Connected HRGC with AWDs activated and a train occupying the HRGC. The Use Case examines the situation of the Connected HRGC communication system being non-operational. How will a CAV detect the train in this scenario? The most prominent issue introduced is how the CAV can verify the communication system is not functional for the vehicle to use another information source.

This challenging condition would affect the following assumptions and requirements.

Table 13. ConOps Assumptions and Requirements Affected by Use Case 5.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• **Scenario 5: CAV approaches a Connected HRGC with AWDs activated and a train occupying the HRGC**	• **The Connected HRGC is fully functional and operational.**	• **Conn_HRGC_Req_9**

A list of possible resolutions to consider for how the AV may respond include:

- The system will default to activation of the AWDs.
- The CAV will rely on its sensors.
- The CAV will have access to a network of HRGC status information.
- The CAV will alert authorities.
- CAVs will have access to onboard map data that includes grade crossing locations and wayside equipment details.
- CAVs will determine that a Connected HRGC is not operational by performing a status check of the Connected HRGC, or through lack of an expected status not received.
- The AV will stop, "look", and "listen" for a train.

Other potential sources of information may include:

- The local authorities transmit HRGC status information to the CAV.
- A Connected HRGC will continually broadcast a message to CAVs stating the HRGC is connected.

Use Case 6. The crossbuck sign cannot be identified by the AV due to sun glare.

In all ConOps scenarios, there are simplifying assumptions such as those listed in Table 14 that make conditions ideal for an AV to traverse an HRGC. In a real-world scenario obstructions and lighting conditions cannot be controlled and it is likely the AV will experience a wide-ranging set of these. This Use Case is an iteration of ConOps scenario 7 in which sun glare negatively impacts the AVs ability to detect the crossbuck. How should the AV respond to sun glare preventing the detection of the crossbuck?

This challenging condition would affect the following assumptions and requirements.

Table 14. ConOps Assumptions and Requirements Affected by Use Case 6.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• **Scenario 7: AV approaches an HRGC with PWDs and a train occupying the HRGC**	• **The AV is fully functional and operational.** • **The AV has an unobstructed field of view with respect to the railroad track (no vegetation or structures blocking the view).** • **Weather and road conditions are not adverse and do not prevent the subject vehicle from acquiring key information sources.**	• **AV_and_CAV_Req_1** • **AV_and_CAV_Req_2** • **AV_Req_2** • **AV_Req_5** • **Veh_at_HRGC_w_PWDs_1**

A list of possible resolutions to consider for how the AV may respond include:

- The AV will use multiple sensor types to detect a crossbuck.
- The AV will attempt to detect cues other than a crossbuck to detect an HRGC is ahead, such as tracks or roadway markings.
- The AV's sensors will have filters to mitigate sun glare.
- The AV will detect railroad tracks instead of a crossbuck to know an HRGC is ahead.
- The AV will scan for the presence of the train.
- The AV will use preloaded maps or database information to know an HRGC is ahead.
- AVs will be capable of detecting W10-1 Advance Warning signage when approaching an HRGC for an additional indication that an HRGC is ahead.

Other potential sources of information may include:

- A Connected HRGC will continually broadcast a message to CAVs stating the HRGC is connected.

Use Case 7. The HRGC stop bar is obstructed and cannot be identified by the AV.

As part of the Common Approach Actions for all vehicles described in Chapter 1, vehicles must determine the location of the HRGC stop bar on their approach to an HRGC. The HRGC stop bar is representative of where the AV should stop when the train is approaching or occupying the HRGC. This Use Case presents a challenge to the AV for detecting the appropriate place to stop if the HRGC stop bar is not discernable. For example, a puddle of water, snow, shadows, leaves, graffiti, or the stop bar being worn could lead to an AV being unable to locate the HRGC stop bar. Where should the AV stop if the HRGC stop bar cannot be located?

This challenging condition would affect the following assumptions and requirements.

Table 15. ConOps Assumptions and Requirements Affected by Use Case 7.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• **Scenario 7: AV approaches an HRGC with PWDs and a train occupying the HRGC**	• **Weather and road conditions are not adverse and do not prevent the subject vehicle from acquiring key information sources.** • **There are no obstructions in the roadway or on the railroad tracks.** • **All signs, warning devices, and roadway markings are unobstructed and discernable.**	• **AV_and_CAV_Req_4** • **AV_Req_2**

A list of possible resolutions to consider for how the AV may respond include:

- The AV accesses an onboard map database that contains this information.
- The AV will stop at the crossbuck sign.
- The AV will be programmed to stop a specified number of feet before the HRGC.
- The AV will be programmed to stop a specified number of vehicle lengths before the HRGC.
- The AV will be able to detect adverse road conditions.

Other potential sources of information may include:

- A Connected HRGC will broadcast HRGC stop bar location information.
- A CAV will have access to a high-definition map with the location of an HRGC stop bar.

Use Case 8. The train occupying the HRGC is composed of flatcars instead of high-profile cars, i.e. box cars.

This Use Case is an iteration of ConOps scenario 7 where an AV is approaching an HRGC with PWDs and a train is occupying the HRGC. In this scenario, an AV must detect the physical presence of a train for indication that a train is occupying the HRGC. If the train cars are flatcars instead of high-profile cars, how does this affect the detection of the train by AVs? With flatcars, the AV may be able to see over the car through to the other side of the HRGC. How might depth perception of detecting objects effect the AV to interpret this scenario?

This challenging condition would affect the following assumptions and requirements.

Table 16. ConOps Assumptions and Requirements Affected by Use Case 8.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• **Scenario 7: AV approaches an HRGC with PWDs and a train occupying the HRGC**	• **All train cars behind the locomotive are freight cars.**	• **AV_Req_1** • **Veh_at_HRGC_w_PWDs_2** • **Veh_at_HRGC_w_PWDs_3**

A list of possible resolutions to consider for how the AV may respond include:

- The AV will be able to detect all train types and combinations of train cars.
- The AV will detect other visual cues such as the wheels of the train rather than the body of the train cars.
- The AV will detect the reflective markings on the flatcars to indicate a train is at the HRGC.

Other potential sources of information may include:

- A Connected Train will broadcast its position and speed to approaching CAVs.
- A CAV will have access to real-time train speeds and locations.

Use Case 9. The skew angle at the roadway and HRGC intersection is 45 degrees.

For all ConOps scenarios, there is a simplifying assumption that states all HRGC and roadway intersections are at a 90-degree skew angle. This Use Case presents a variation of ConOps scenario 7, by changing the skew angle to 45 degrees and changing the train location from occupying to approaching. By changing these characteristics, a dilemma zone is introduced as the AV and train are approaching the HRGC at the same time. At a skew angle of 90 degrees, the broadside of the train presents significantly more surface area for the AV to detect. This Use Case highlights potential challenges with the detection capabilities of an AV detecting a train approaching from obtuse and acute angles.

This challenging condition would affect the following assumptions and requirements.

Table 17. ConOps Assumptions and Requirements Affected by Use Case 9.

ConOps Scenario Referenced	Assumptions Affected	Requirements Affected
• **Scenario 7: AV approaches an HRGC with PWDs and a train occupying the HRGC**	• **The skew angle of the HRGC approach and departure is at 90 degrees.**	• **AV_Req_1** • **Veh_at_HRGC_w_PWDs_2** • **Veh_at_HRGC_w_PWDs_3**

A list of possible resolutions to consider for how the AV may respond include:

• The AV will be able to detect a train at all intersecting skew angles.

The AV will detect other train cues such as its horn or sounds associated with a moving train. Other potential sources of information may include:

• A Connected Train will broadcast its position and speed to approaching CAVs.
• A Connected HRGC will broadcast the configuration of the HRGC to approaching CAVs. CAV.

As mentioned in the beginning of the chapter, the Use Cases above are not a conclusive set of all the challenges an AV could encounter, while traversing an HRGC. The development of AVs will continue to transpire over the next decade and will require many more Use Case considerations. The bulleted lists of possible resolutions and other potential sources of information offer suggestions as to how a system with AVs might operate. They are intended to identify the list of different stakeholders that may be affected by the implementation of any given resolution. The operation of the system containing AVs at HRGCs will require additional stakeholder engagement meetings and forums from a combination of public and private industries to solve this challenge as mentioned from various stakeholders participating in the webinar. Once Use Cases are considered and it is agreed upon from the stakeholders how AVs shall operate, specific verifiable requirements can be written and clear understanding of how AVs perform can be understood.

Acronyms

Acronyms	Abbreviations
AV	Automated Vehicle
AWD	Active Warning Device
CAV	Connected Automated Vehicle
ConOps	Concept of Operations
FRA	Federal Railroad Administration
HRGC	Highway-Rail Grade Crossings
PWD	Passive Warning Device
SAE	Society of Automative Engineers

U.S. Department of Transportation

Abbreviations and Acronyms

Acronyms	Abbreviations
ADAS	Advanced Driver-Assistance Systems
AHS	Automated Horn System
AV	Automated Vehicle
AWD	Active Warning Device
CAV	Connected Automated Vehicle
ConOps	Concept of Operations
CV	Connected Vehicle
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standards
FRA	Federal Railroad Administration
HRGC	Highway-Rail Grade Crossing
LiDAR	Light Detection And Ranging
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PTC	Positive Train Control
PWD	Passive Warning Device
SAE	Society of Automotive Engineers
DOT	United States Department of Transportation