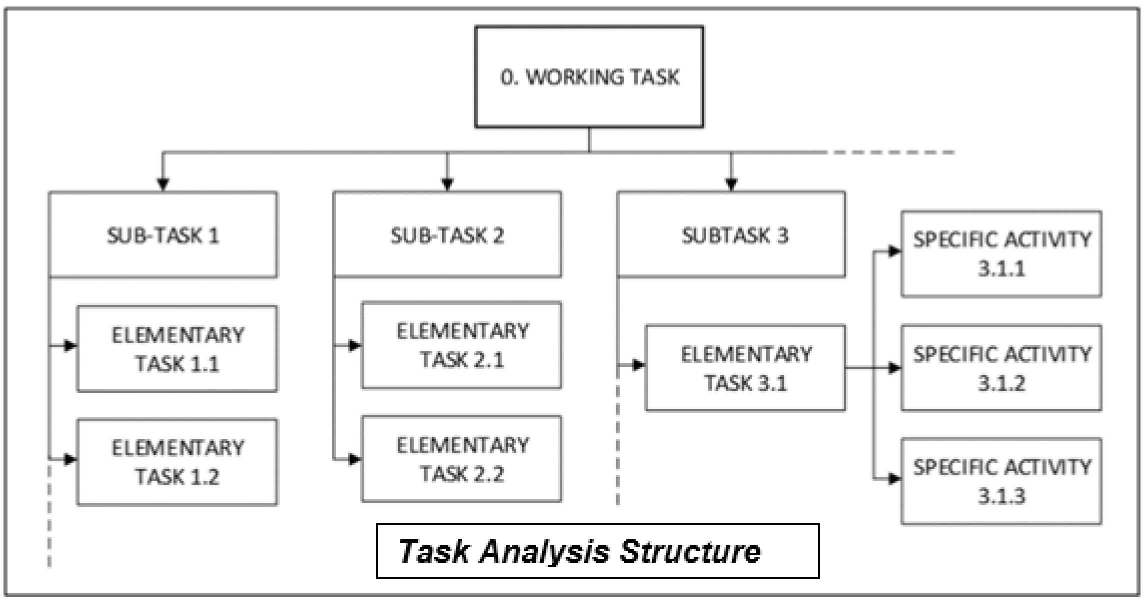
U.S. Department of Transportation
Federal Railroad Administration

Office of Research, Development and Technology
Washington, DC 20590

Human Factors Considerations for Hydrogen Rail Refueling and Maintenance



DOT/FRA/ORD-26/17 Final Report | August 2026

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
25 August 2026	Technical Report	January 2021 – June 2024

4. TITLE AND SUBTITLE
Human Factors Considerations for Hydrogen Rail Refueling and Maintenance

5a. CONTRACT NUMBER
693JJ620N000057

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Albuquerque, NM 87185

8. PERFORMING ORGANIZATION REPORT NUMBER
SAND2024-XXXXR

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
Office of Research, Development and Technology
Washington, DC 20590

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
DOT/FRA/ORD-26/17

12. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA website.

13. SUPPLEMENTARY NOTES
COR: Melissa Shurland

14. ABSTRACT
The Federal Railroad Administration contracted Sandia National Laboratories to review the risks introduced specifically through human interactions within hydrogen rail refueling and maintenance activities and present design and regulatory recommendations for future system development and implementation. The team developed 50 human factor design guidelines through analysis of human risk factors. This research was conducted between 2021 and 2024 at Sandia National Laboratories in Albuquerque, NM.

15. SUBJECT TERMS
Hydrogen, hydrogen fueled train, human factors, task analysis, failure modes and effects analysis

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**		32	**19b. TELEPHONE NUMBER** *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Acknowledgements

The authors thank the facilities that allowed researchers to conduct onsite observations of their refueling and maintenance activities, including Florida East Coast Rail, New Fortress Energy, and AC Transit. Additional thanks to CalTrans and Capitol Corridor for their assistance in conducting site observations and providing valuable expertise.

The team also acknowledge and appreciate technical reviews by Ethan Hecht, Ben Schroeder, and Michelle Pang at Sandia National Laboratories.[1]

[1] Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Executive Summary

System design and reliability analyses often show that humans are one of the greatest sources of variability in system performance. Within the rail industry, human error contributed to more than one third of train accidents in the United States (FRA, 2023). The rail industry uses human factors in rail systems to assess the likelihood of human error, but this is typically limited to train drivers, signalers, and controllers (i.e., rail controllers) while other stakeholders (e.g., maintainers) are not included in analyses. As the rail industry expands its fuel system to include hydrogen fuel, human interactions will become most common during refueling and maintenance operations.

The Federal Railroad Administration (FRA) contracted Sandia National Laboratories to review the risks introduced specifically through human interactions within hydrogen rail refueling and maintenance activities and present design and regulatory recommendations for future system development and implementation. The team developed 50 human factor design guidelines through analysis of human risk factors. This research was conducted between 2021 and 2024 at Sandia National Laboratories in Albuquerque, NM.

Due to the lack of domestic hydrogen-powered trains at the time of review, the research team visited four sites that use liquified natural gas (LNG) in their operations. The team studied the operations and maintenance of a LNG-powered train, an LNG tender refueling facility, a diesel-powered train refueling and maintenance facility, and a hydrogen-powered bus facility. The team also observed video footage of refueling operations for a hydrogen fuel cell road vehicle. Researchers collected observational data on these existing systems to consider various ways hydrogen might be implemented within future designs (e.g., gaseous or liquid hydrogen operations).

The team originally identified 47 human factors guidelines in a refueling task analysis; however, a follow-up Failure Modes and Effects Analysis of maintenance activities identified 3 additional human factors guidelines not previously identified in the refueling task analysis.

Because hydrogen rail systems are still in the early design stages of development, the resulting human factors guidelines represent general best practices and do not include specific design features. While the guidelines in this report were written to encompass a multitude of human actions and error opportunities, specific implementation of the guidelines will be dependent on actual system design features. The research team recommends design and regulatory agencies include a Human Factors Engineer in the design and review process to ensure the guidelines are appropriately implemented and verified.

While it is not possible to standardize most design aspects (e.g., facility layout, display design), emergency features and common components should be standardized to ensure users and maintainers can easily locate, identify, and interact with critical systems, such as standard operating buttons, standard safety signage, and/or a common nozzle size and shape. Future work should include identifying specific emergency features to be standardized across design. Additionally, the human factors guidelines developed in this research should be verified within conceptual design specifications submitted by designing agencies.

1. Introduction

The U.S. rail industry is exploring hydrogen as an alternative to current rail fuel types to reduce environmental impacts. While future applications of hydrogen fuel are promising, there are safety considerations associated with the use of hydrogen, including fire, explosion, and high-pressure and cryogenic fuel handling. As hydrogen fuel is implemented, human interactions have the potential to magnify or mitigate these risks, especially during refueling and maintenance operations, when human interaction is most likely present. The Federal Railroad Administration (FRA) contracted Sandia National Laboratories to review the risks introduced specifically through human interactions within hydrogen rail refueling and maintenance activities and present design and regulatory recommendations for future system development and implementation. The team developed 50 human factor design guidelines through analysis of human risk factors. This research was conducted between 2021 and 2024 at Sandia National Laboratories in Albuquerque, NM.

1.1 Background

More than one third of train accidents in the United States have been attributed to human error (FRA, 2023). Yet, the application of human factors in rail systems is typically limited to train drivers, signalers, and controllers (i.e., rail controllers) while other stakeholders, such as maintainers are excluded from analyses (Dhillon, 2007). There are several potential sources of human error within rail applications, including: communication errors such as miscommunication or misunderstanding between train operators, dispatchers, and other personnel can lead to errors in decision-making or actions; fatigue can arise from operators working long hours or shift work that can negatively affect cognitive performance and task vigilance; distraction can also lead to human error, for example personal electronic devices or other outside stimuli that removes a person's attention from their work. Training deficits such as inadequate knowledge about a person's job duties or how to respond in emergent events, and poor system or equipment design that can lead to confusing or difficult human interactions. Rail operators use a variety of strategies to address these potential sources of human error, such as implementing clear communication protocols, providing adequate training and resources, and designing equipment and systems that are easy to use and understand. Operators also may use safety management systems and other risk assessment tools, such as FRA's Confidential Close Call Reporting System, to identify and mitigate potential sources of human error (FRA, 2023).

Many of the same human failure situations may arise within rail maintenance and refueling operations, but on different systems. For example, fatigue may impact a maintainer's ability to safely conduct dangerous maintenance activities, such as operating heavy-duty equipment. Yet, since the physical system components encountered by maintainers and refueling personnel may differ from rail operators, the same human failure mitigations may not be adequate for maintenance and refueling systems. Within hydrogen rail operations, maintenance and refueling activities are potentially risky due to the potential for hydrogen leakage and possible ignition. Further, human interaction with highly pressurized or cryogenic fuel, such as the liquid hydrogen likely to be used for heavy rail operations, may introduce additional safety considerations for maintainers and refueling personnel. Thus, human tasks within rail refueling and maintenance should be evaluated for potential failures caused by human factors. The resulting task and failure analysis offer insight into mitigations that might reduce the risks associated with hydrogen.

Relatedly, the aviation industry outlined human factors considerations for maintainers and identified critical human error types within maintenance operations (FAA, 2018). The Federal Aviation Administration (FAA)'s guidance also outlines specific human-system considerations for fueling and defueling aircraft. As with any fuel system, maintainers should be considered in the design of hydrogen refueling and maintenance infrastructure to minimize safety risks and human error potential. The FAA documentation incorporates guidance on identifying the correct fuel using color bands on piping, common contributors to fuel contamination, and fueling hazards, for example static electricity. The documentation also outlines procedures to safely fuel and defuel an aircraft, including specific procedural steps to minimize the likelihood of static electricity or fuel contaminants. However, the document does not prescribe how a system can inherently build human error mitigations into a system's design.

In this research, the team performed a human factors evaluation of refueling and maintenance activities for a variety of vehicles and projected findings to future hydrogen rail operations. A task analysis approach was used to outline refueling operations within contexts like hydrogen rail and identify the human error potential within those refueling activities. Since maintenance activities may include a variety of human interactions, a modified Failure Modes and Effects Analysis (FMEA) approach was used to identify hydrogen risks and system failures specifically due to human error in maintenance operations. The results of this study outline design requirements for human-system integration within hydrogen rail refueling and maintenance.

1.1.1 Human Factors Engineering

Human Factors Engineering (HFE) is the study of how people interact with products, systems, and environments. It is a multidisciplinary field that draws on principles from engineering, psychology, and design to optimize the relationship between people and the things they use. The goal of HFE is to design products, systems, and environments that are safe, efficient, and easy to use for interacting stakeholders. This includes considering factors such as human physical and cognitive capabilities, as well as cultural and social factors that may affect how people use a product or system. HFE is used in a wide range of industries, including transportation, healthcare, manufacturing, and technology. It is often applied in the design of products and systems that are used by people daily, such as cars, airplanes, computers, and medical equipment. By considering the needs and limitations of human stakeholders, HFE helps to ensure that products and systems are safe, efficient, and user-friendly.

HFE task analysis provides detailed analysis of tasks performed by different stakeholders within a system. That is, while error types might be similar between stakeholders within a domain, the manifestation of those errors may vary based on the system components with which the stakeholders interact. This difference in manifestation of error may lead to similar error mitigations but differing implementation of those mitigations within the system component design. From a regulatory perspective, general design guidelines can be used to verify the presence of error mitigations across a variety of component types, but implementation of mitigations may be difficult to regulate without standardization. Ultimately, HFE methods inform development of design guidelines and regulatory checks for overall system safety and performance.

System design and reliability analyses often show that humans are one of the greatest sources of variability in system performance. Variability in human performance becomes more noticeable when considering high-risk or high-consequence activities. Human reliability in high-risk activities can be reduced through intentional integration of human performance considerations within system design. Early in the design process, it is important to consider human limitations, for example anthropometric specifications, physical capabilities as well as how human activities might be best supported through integration of machine elements. Once the system has been developed, procedures, training, and work environment design such as workspace organization, tool availability, and more can be used to improve human interactions, but these later interventions should be considered secondary to a well-designed system.

1.2 Objectives

This work examined human performance impacts on safety during refueling and maintenance operations within applications and contexts comparable to hydrogen rail. The objective of this research was to develop recommendations on human performance to minimize human error potential in refueling and maintenance operations.

1.3 Overall Approach

The team primary used task analysis in this research. A task analysis can be used to identify error potential within tasks and establish mitigations to prevent those errors. The task-based approach allowed for definition of human-system integration design guidelines within specific activities expected to be incorporated within future hydrogen rail systems. Nominally, HFE helps define human-system integration requirements for use in technical system design specifications. However, given the uncertain design characteristics of future hydrogen systems for heavy and light rail applications, the team created high-level human-system integration design "guidelines." The recommended design guidelines can be used by rail stakeholders, such as designers, railroads, and regulatory entities, to inform future system design requirements and system evaluation.

To generate human-system integration guidelines, a series of activities were completed to collect pertinent information and then that information was used to complete a series of established systems analysis techniques: task analysis, failure analysis, and guideline definition (Figure 1)

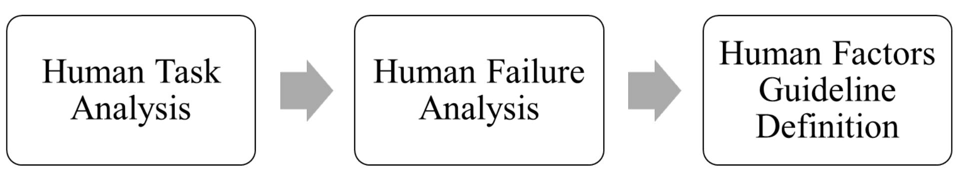

Figure 1. Overall research approach

1.3.1 Refueling Analysis Approach

For the refueling task analysis, the team examined the refueling of a hydrogen fuel cell road vehicle, a LNG tender system, and a diesel locomotive system. Additional observations of hydrogen bus refueling operations were performed and outcomes were compared to the hydrogen fuel cell car tasks. Results from these analyses were used to inform the subsequent failure analysis and guideline specification. The guidelines were combined for the fuel cell car, LNG, and diesel refueling tasks to identify the most pertinent information for mitigating hydrogen risks due to human error.

1.3.1.1 Task Analysis

A task analysis is a systematic and detailed examination of a specific task or set of tasks to understand the necessary steps, skills, and knowledge required to complete an activity within an operation (Rosala, 2020). A task analysis begins by identifying a high-level operation that should be decomposed, for example: "Complete maintenance." The high-level operation is then decomposed by breaking the task into manageable steps, or subtasks. See Figure 2 for a high-level visualization of a task analysis structure.

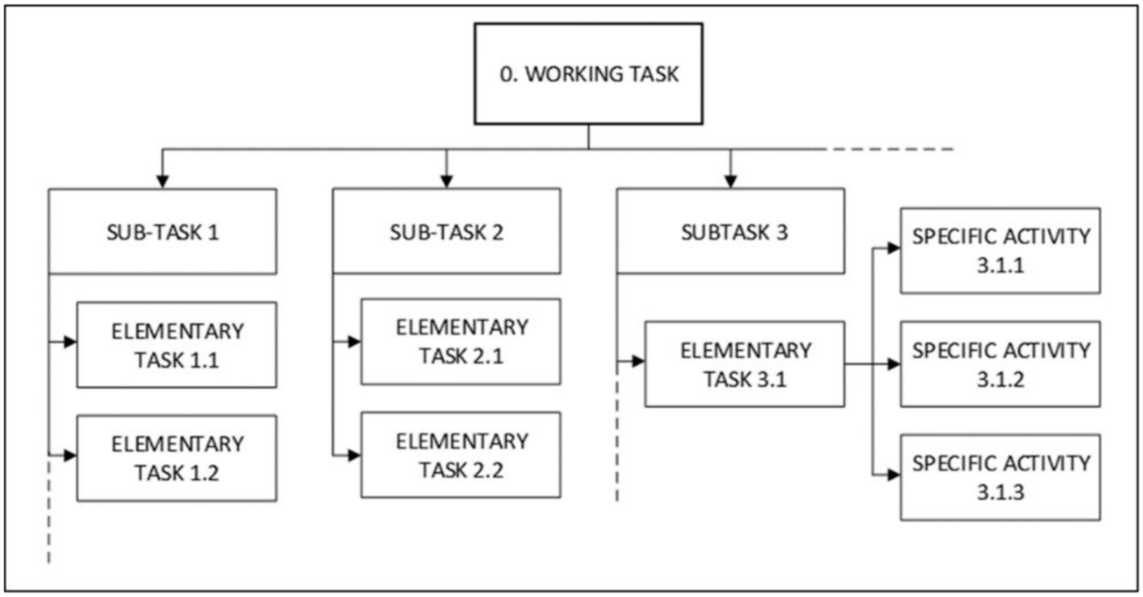

Figure 2. Task analysis structure (Fargnoli, Lombardi, & Puri, 2019)

This task decomposition continues until a pre-defined stopping point, or level of detail, has been reached. The low-level tasks designated as "elementary task" or "specific activity" in Figure 2 are used to identify how failures might occur within the activity.

Task analyses are completed by studying documentation describing the activity, such as procedures or training materials, as well as by observing and interviewing stakeholders who perform the activity. For this work, the team first reviewed publicly available documentation and videos of refueling and maintenance activities within current rail systems and hydrogen-powered road vehicles. The initial analysis informed observations of and interviews with stakeholders performing current rail system refueling and maintenance operations.

1.3.1.2 Failure Modes and Effects Analysis

Outcomes of the task analysis were used to identify potential failures in the refueling and maintenance process. A FMEA is a widely used technique to identify potential failures within systems (Jet Propulsion Laboratory, 1990).

FMEA begins with the lowest-level tasks identified in the task analysis. For each of these tasks, the practitioner documents the different types of human errors or failure modes that can occur when completing the given task. After identifying the possible failure modes for each low-level task, the practitioner then documents the potential cause(s) and consequence(s) of each failure mode, should it occur. Lastly, understanding the potential cause(s) for each failure mode, the practitioner determines how each failure mode may be prevented or mitigated. These identified failure preventions/mitigations are used in the next step of the process, guideline definition.

1.3.1.3 Guideline Definition

To define the guidelines for the system under analysis, the mitigations identified for each failure mode during the failure analysis phase of the process are consolidated, as needed, and re-written to provide a set of general human factors design guidelines that are clear, concise, and verifiable. Proper incorporation of the guidelines into the design could reduce human error opportunities within the system because the guidelines directly address the potential human failures. While the guidelines in this report are written to encompass a multitude of human actions and error opportunities, specific implementation of the guidelines are dependent on system design. The team suggests that design and regulatory agencies include a Human Factors Engineer in design iterations to ensure the guidelines are appropriately implemented and verified.

1.3.2 Maintenance Analysis Approach

Due to the broad nature of maintenance activities, a slightly different approach was used for developing guidelines for maintenance, as depicted in Figure 3. In the modified approach, a system FMEA was performed by interviewing hydrogen safety subject matter experts (SMEs) at Sandia National Laboratories. Following the FMEA, potential human errors that would have led to each SME-identified system failure were identified. Those human errors were then compared to the refueling FMEA for similarities in guideline specification. Any human errors not initially included in the refueling guidelines were expanded to create maintenance-specific guidelines.

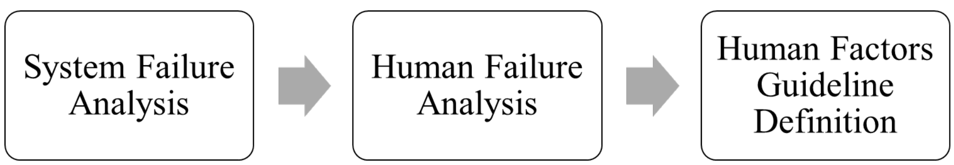

Figure 3. Research approach for analyzing maintenance tasks

1.4 Scope

Since hydrogen-powered trains are not yet designed, the team used a comparative analysis of gaseous hydrogen road vehicle refueling, LNG refueling, and liquid diesel refueling operations to identify design guidelines pertinent for both light and heavy rail refueling. The team also observed the refueling activities of a hydrogen fuel cell bus. Since a complete task decomposition was not available for the bus refueling, the hydrogen fuel cell road vehicle refueling activities were used as a baseline for gaseous refueling. Table 1 provides an overview of the various data sources and analysis incorporation.

Table 1. Overview of data sources and analysis

Vehicle Type	Data Type	Analysis Incorporation
Hydrogen Fuel Cell Road Vehicle	Video of Refueling	Task Analysis
Hydrogen Fuel Cell Bus	Observation	Comparison to hydrogen car tasks
LNG tender refueling	Observation	Task Analysis
Diesel locomotive	Observation	Task Analysis

Maintenance operations were also included in site observations; however, maintenance activities can incorporate broad task performance, so an FMEA was employed to capture broad error types not limited to a specific task. Once maintenance tasks are clearly defined in system specification, for example through component selection or maintenance schedule determination, a more detailed task analysis may be beneficial to pinpoint specific maintenance activities that are prone to human error or are critical for system safety.

The results of this work only consider the human performance and human error potential for design guideline recommendation. The described work does not consider technical faults or how requirements might be established to reduce system failure due to those technical faults.

1.5 Organization of the Report

Section 2 outlines the Refueling Task Analysis, including observation outcomes and human factors guidelines. Section 3 discusses the Maintenance Failure Analysis and additional human factors guidelines. Finally, Section 4 presents conclusions and describes the primary findings of this report.

2. Refueling Task Analysis and Human Factors Guidelines

Researchers performed a task analysis of three refueling activities to reveal a list of specific types of tasks. Subsequently, an FMEA was completed within critical task types. Using specific failure modes and human-driven causes, the team generated human factors guidelines to minimize the likelihood of failure due to human error within the critical task types.

The full task decomposition for the hydrogen fuel cell road vehicle, LNG tender, and diesel locomotive refueling activities are in Appendix A. Refueling Procedures for a Hydrogen Fuel Cell Road Vehicle, Appendix B. LNG Refueling Task Analysis, and Appendix C. Diesel Refueling Task Analysis.

2.1 Refueling Task and Failure Modes and Effects Analysis

The refueling tasks were categorized into general task types, or action types, within a subtask. These task types serve as the verb or activity being performed by the human. The task types were further limited to the most critical types, for example the types that likely introduce the most error potential resulting in 19 types for failure analysis. Potential human failures within each task type were then established, as well as the potential cause for that failure. Table 2 demonstrates the association of task type to potential human failure and potential causes.

Table 2. Association of task types from refueling procedures with potential human failures and the potential causes of those failures

Task type	Potential Human Failure(s)	Potential Cause(s)
Locate	Unable to quickly locate relevant system component Locates incorrect relevant system component	Improperly labeled relevant system component; multiple identical/similar system components in the same vicinity; system component visually identical when not functionally identical
Grasp	Unable to properly grasp relevant system component	Reach is too far; system component not designed for proper grasping (e.g., size, no obvious, standard way to grasp); not enough physical space surrounding system component to grasp
Align	Misalign relevant system component	Improper physical or visual alignment features
Pull	Unable to pull relevant system component away from another Unable to effectively pull relevant system component away from another	Force required to pull exceeds human strength capabilities; relevant system component not fully loosened; not enough physical space surrounding system component to pull it
Turn	Unable to turn relevant system component Do not turn relevant system component enough to fully loosen or tighten it Turn relevant system component in incorrect direction	Force required to turn exceeds human strength capabilities; system component not formed to allow proper leverage/torque to be applied by person; no clear indication of when the system component is sufficiently "loose" or "tight"; not enough physical space surrounding system component to turn; unclear which direction loosens versus tightens system component
Stow	Relevant system component not stored in appropriate location	No designated storage location for system component; system component not tethered
Lift	Unable to lift relevant system component	System component weight exceeds human strength capabilities

Task type	Potential Human Failure(s)	Potential Cause(s)
Carry	Trip, slip, fall, drop	Tripping hazards in the path of operator; relevant system component too bulky and blocks operator's ability to see; system component weight exceeds recommended weight limit for worker safety
Push	Unable to push relevant system component Don't push relevant system component far enough	Force required to push exceeds human strength capabilities; improper positive indication that the system component is fully inserted; system component misaligned
Squeeze	Unable to squeeze relevant system component Don't squeeze relevant system component far enough to 'lock'	Force required to squeeze exceeds human force capabilities; not enough physical space to squeeze system component; improper positive indication that system component is "locked"
Detect	Does not detect change in relevant system status	Improper indication that the relevant system status has changed
Monitor	Unable to properly monitor ongoing system processes	Improper visual access to ongoing system processes
Read	Misreads relevant system information	Text not properly contrasted with background; text not large enough to view from expected distance; text characteristics do not promote readability
Recall	Incorrectly recalls relevant system information	Limitations in recall abilities
Input data	Incorrect data entered in system display Data not entered in system display	Improper input method for the information being input; input features not sized/spaced appropriately; reliance on human input
Attach	Unable to attach relevant system component Doesn't properly attach relevant system component	Improper physical access; reach too far; mechanism is difficult to manipulate; improper feedback (visual or tactile) indicating proper attachment
Interpret	Incorrectly interprets system status information Unable to quickly interpret system status information	Presented information not in worker's language; words/colors used to present a certain status is similar to the words/colors used to present a different status; irrelevant status information co-located; cluttered display
Wait	Does not wait the pre-determined time (longer or shorter)	Loses track of time; timer not used; equipment designed to require worker to keep track of time
Stop	Does not stop relevant ongoing system process Unable to quickly stop relevant ongoing system process	Response time to stop ongoing system process not fast enough; forgets to stop ongoing system process

2.2 Refueling Human Factors Guidelines

From the identified task types and potential human failures in Table 2, the team generated specific mitigations or guidelines to minimize the likelihood of human error (see Table 3).

Table 3. Human factors guidelines resulting from the refueling task analysis

Task type		Potential Human Factors Guidelines
1. Locate	1.1	Provide labels for the relevant system components.
	1.2	Minimize the number of similar system components (e.g., visually similar valves and knobs) and physically separate similar system components as much as feasible.
	1.3	Visually distinguish similar system components.
2. Grasp	2.1	Place relevant system components so that they are within the arm's reach of the expected user position.
	2.2	Relevant system components should be sized in accordance with human factors standards to be grasped.
	2.3	Provide enough physical space around the relevant system components to allow for proper grasping.
3. Align	3.1	Relevant system components should have alignment features that prevent installation in the incorrect orientation.
4. Pull	4.1	The force required to pull a system component away from another should not exceed human strength capabilities.
	4.2	Provide enough physical space behind the relevant system components for them to be pulled.
5. Turn	5.1	Given the size and design of the system components, the turning force required to loosen components should not exceed human strength capabilities.
	5.2	Provide visual and/or tactile feedback for when the relevant system components are fully loosened/tightened.
	5.3	Relevant system components should follow standard convention of loosening and tightening directions. Include visual indicators of tightening/loosening directions.
	5.4	Provide enough physical space around relevant system components to turn it.
	5.5	If applicable, the edge(s) of relevant system components should be knurled or shaped to increase operator's ability to apply the necessary torque to turn.
	5.6	The motion required to turn a component should follow natural hand and wrist motions such that awkward, painful, or difficult body movements are not required.
6. Stow	6.1	Tether relevant system components that are temporarily removed, if feasible.
	6.2	Include a designated storage location for relevant system components that are temporarily removed.
7. Lift	7.1	The weight of the system components being lifted should not exceed human strength capabilities shown in the Revised NIOSH Lifting Equation (NIOSH, 1994) .
	7.2	Relevant system components should be able to withstand being dropped.
8. Carry	8.1	The weight of the system components being carried should not exceed human strength capabilities.
	8.2	Relevant system components should be able to withstand being dropped.
9. Push	9.1	The force required to push a relevant system component should not exceed human strength capabilities.
	9.2	Relevant system components should be able to withstand human force capabilities.
	9.3	Provide positive indication (ideally visual) that a relevant system component is pushed far enough.
10. Squeeze	10.1	The force required to squeeze the relevant system components should not exceed human strength capabilities.
	10.2	Provide positive indication (ideally visual) that the relevant system components are fully locked.
11. Detect	11.1	The system design should present information to the operator in a way that helps them detect a change in the system's status.
	11.2	Methods used to detect leaks in the system should be reliable and effective.

Task type		Potential Human Factors Guidelines
12. Monitor	12.1	Provide a way for the operator to visually monitor ongoing processes.
13. Read	13.1	If feasible, eliminate the need for an operator to read critical information through the use of a barcode/scanning-type technology.
	13.2	Otherwise, the text of the relevant information should be readable from the expected viewing distance (contrast, size, font)
14. Recall	14.1	If feasible, eliminate the need for the operator to recall critical information through the use of a barcode/scanning-type technology.
	14.2	Otherwise, place relevant information in immediate field of view so the operator can reference the information rather than recall it.
15. Input data	15.1	If feasible, eliminate the need for the operator to manually input critical information through the use of automation like a barcode/scanning-type technology.
	15.2	If feasible, automatically initiate critical operations at the required time without worker input.
	15.3	Otherwise, the input features of the display should be designed in accordance with HUMAN FACTORS standards.
16. Attach	16.1	Provide proper physical and visual access to attachments
	16.2	Attachments should be within the expected reach of the worker.
	16.3	Attachment locations should be properly labeled.
	16.4	Attachment mechanisms should be quick-release in nature.
	16.5	It should be visually and/or tacitly clear when components are properly attached.
17. Interpret	17.1	Status information should be provided using terms that are familiar to the workers.
	17.2	Status information (terms, colors, etc.) should be distinguishable from irrelevant status information.
	17.3	Status information should be appropriately separated on the display and only relevant information to the current status should be displayed at a time.
18. Wait	18.1	If feasible, have the system keep track of wait times and automatically initiate relevant operations once the wait time has lapsed.
19. Stop	19.1	Minimize the number of actions needed to stop a process or operation.
	19.2	If feasible, system equipment automatically stop a process or operation.

Many of the guidelines that resulted from the refueling task analysis can be partnered with human factors standards documentation. Human factors standards offer varying levels of detail around expected or required system design characteristics and human interactions within the system (Green, 2018). Some published human factors standards are rigid requirements that must be incorporated within a system design to meet regulatory guidance, while other standards offer flexible guidelines and best practices for reliable system design and use. Military Standard 1472 is the most relevant standard for most of the human factors guidelines in Table 3, but other standards documents provide insight specific to how those guidelines might be implemented (Department of Defense Design Criteria Standard: Human Engineering, 2020).

The team found evidence of the application of existing human factors guidelines and standards in the designs of the LNG tender, diesel locomotives, hydrogen fuel cell cars, and hydrogen bus refueling operations, many of which directly relate to the guidelines in Table 3. The refueling dispensers for the hydrogen bus (Figure 4) and diesel fuel train (Figure 5) showed clearly visible stowage receptacles (Human Factors Guideline 6.2). Additionally, in both removing and replacing the dispensers, it was easy for operators to reach the stowage receptacle (Human Factors Guideline 2.1), required little force or pressure to remove and replace (Human Factors

Guidelines 4.1, 5.1, and 7.1), and involved natural hand movements with no awkward twisting of the hands or wrists to replace the dispenser (Human Factors Guideline 5.6). Within the diesel refueling system, the dispenser's shape was further improved to help human grasping by adding a large ring around the dispenser (Human Factors Guidelines 2.2, 2.3, and 5.5). A display was used in all contexts to confirm when refueling had been completed (Human Factors Guideline 17.3). For future hydrogen train systems, an indication might be provided when the dispenser has been appropriately stored to prevent any inadvertent misplacement or dropping (Human Factors Guideline 9.3 and 11.1).

Figure 4. Example refueling receptacle for hydrogen buses

Figure 5. Example refueling receptacle diesel locomotives

For the hydrogen refueling facilities, if there are other types of tenders or locomotives also refueling at that facility, it will be important that the differing fuel types be kept separate and clearly marked with the fuel type. Within aviation, system designers use specific color bands on piping and nozzles to denote the various fuel types. For hydrogen refueling systems, the nozzle shape and size can also be distinct from other fuel types to prevent using the wrong nozzle on a vehicle.

3. Maintenance Failure Analysis and Guidelines

As discussed in the Introduction, due to the broad nature of maintenance activities, a slightly different approach was used for developing guidelines for maintenance (see Figure 3). In the modified approach, a system FMEA was performed by interviewing hydrogen safety SMEs at Sandia National Laboratories. Following the FMEA, potential human errors that would have led to the SME-identified system failures were identified. Those human errors were then compared to the refueling FMEA to find similarities and differences from the initial human factors guideline specification. Any human errors not initially included in the refueling guidelines were expanded to include maintenance-specific guidelines. The previously discussed human factors guidelines developed using refueling operations should be considered for how their implementation might differ within maintenance contexts.

3.1 Maintenance Failure Modes and Effects Analysis

For the FMEA, three primary modes were examined that could lead to an explosion or jet flame: 1) hydrogen mixing with air, 2) an accumulation of hydrogen, and 3) an ignition source nearby the hydrogen accumulation (Figure 6). Each branch was further decomposed to identify how a human might contribute to those errors (Figure 7, Figure 8, and Figure 9). This activity was meant to simulate how errors might occur within a maintenance environment and how those errors might contribute to hydrogen-specific risks. Thus, the decomposition does not include every failure potential for the hydrogen rail maintenance, which have been analyzed elsewhere.

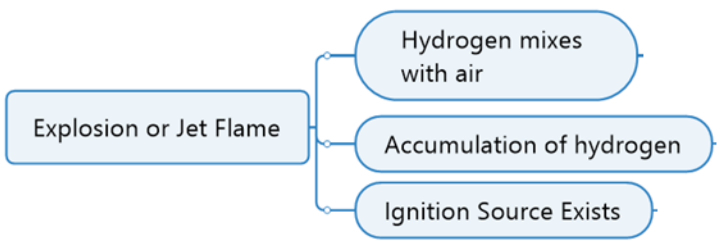

Figure 6. Failure scenarios for hydrogen maintenance activities which could lead to an explosion or jet flame

Within the failure mode "Hydrogen mixes with air" (Figure 7) many of the human errors are associated with missing requirements, inadequate equipment feedback, or failures going undetected by the human (either due to inappropriate inspection or due to system faults being hard to detect).

In the failure mode "Accumulation of hydrogen" (Figure 8), human errors again are attributable to humans not detecting conditions that lead to the failure, either due to inadequate inspection or due to the system fault being difficult to detect. Other errors are attributable to space design, such as missing or inadequate venting systems.

Finally, for the failure mode "Ignition source exists" (Figure 9), many of the errors are due to the ignition source being introduced by a human. This may be attributable to humans being unaware of the risks due to lack of signage or because the human was not appropriately trained to recognize the risks.

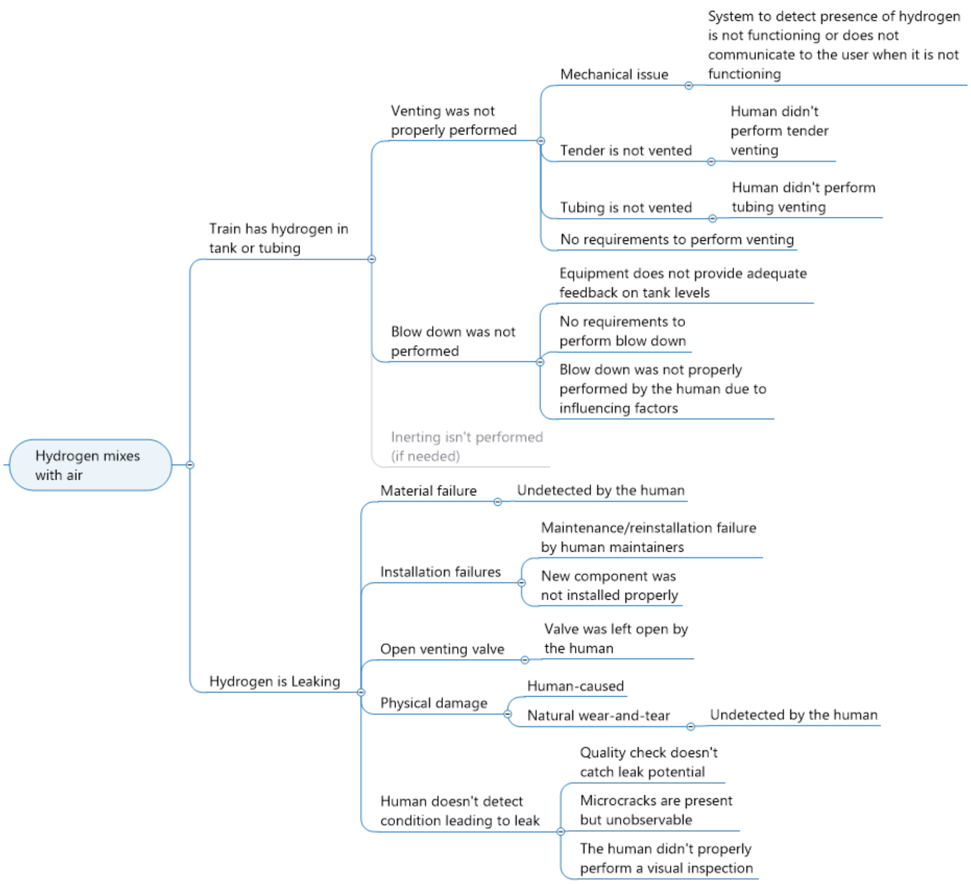

Figure 7. Failure decomposition for the failure branch "Hydrogen mixes with air"

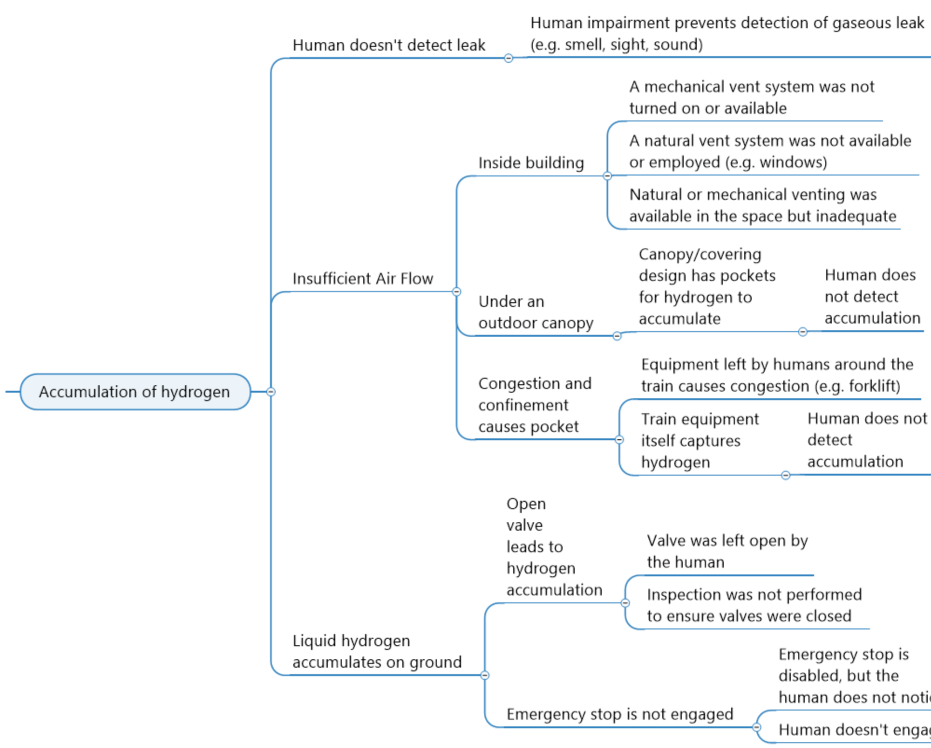

Figure 8. Failure decomposition for the failure branch "Accumulation of hydrogen"

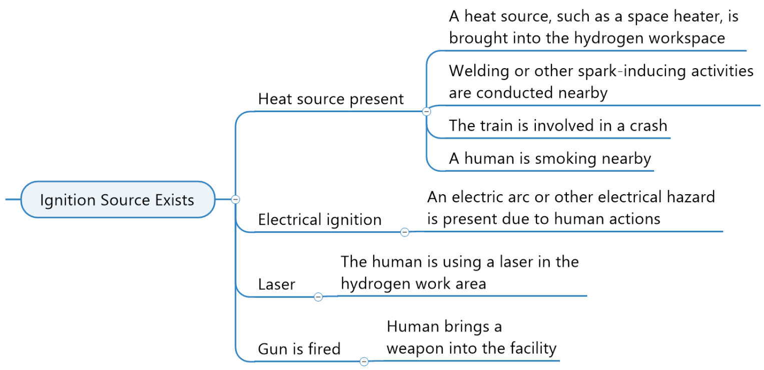

Figure 9. Failure decomposition for the failure branch "Ignition source exists"

From the failure decomposition, human tasks were identified that might lead to that failure. Subsequently, the task type for the failure was associated to the same task types identified in the refueling task analysis (Table 4).

Table 4. Association of human failures within maintenance activities with potential causes and task types

Tasks	Potential Failure(s)	Potential Cause(s)	Relevant Task Types
Vent tank	• Did not properly vent tank	• System components/equipment not designed to detect fuel leftover in tank • Equipment design is not intuitive • Improper feedback mechanisms for when venting is done • Improper training • Improper procedures	Detect; interpret
Vent tube(s)	• Did not properly vent tube	• System components/equipment not designed to detect fuel leftover in tube • Equipment design is not intuitive • Improper feedback mechanisms for when venting is done • Improper training • Improper procedures	Detect
Close relevant valve(s)	• Does not close vent valve all the way • Forgets to close vent valve Closes irrelevant valve	• Locating relevant valve is difficult • Grasping valve is difficult • Turning valve is difficult; no feedback when valve is fully closed • Improper training • Improper procedures	Locate; grasp; turn
Blow down	• Did not properly perform blow down operation	• Equipment not designed to provide feedback of fuel levels in tank • Improper training • Improper procedures • Miscommunication • No requirement to perform operation	Detect

Tasks	Potential Failure(s)	Potential Cause(s)	Relevant Task Types
Install system components	• Improperly installed components (misaligned, incorrect orientation, not secured) • Equipment/tools impact system components	• System components not designed to only be installed one way • Improper physical and visual access to operation • Improper visual/tactile feedback for when components are properly secured • Improper training • Improper procedures	Align; push; attach; turn; grasp; locate
Detect improper installation of system components	• Unable to detect improper installation of components • System tests not performed/required • Quality checks not performed/required	• Quality checks not required/performed • Quality of installation using non-hazardous substance not performed • Improper training • Improper procedures	Detect
Detect hydrogen fuel leak	• Unable to detect fuel leak	• Methods used to detect fuel leak are not appropriate for human detection	Detect
Turn building vent system on	• Does not properly turn vent system on	• Improper training • Improper procedures • Relies on human intervention to turn vent system on • Improper feedback of vent system status	Locate; input data
Clear equipment from train vicinity	• Does not clear equipment from train vicinity	• Checks not performed/required • Equipment does not have a designated storage place outside a "keep out" zone • Improper training; improper procedures	--
Engage emergency stop button	• Does not engage emergency stop quickly enough • Does not engage emergency stop	• E-stop button design does not follow industry standards	Locate; push
Do not introduce ignition source to area	• Introduces ignition source to area	• Improper signage; improper training • Improperly marked "keep out" zones to certain activities (e.g., welding, smoking)	--

3.2 Maintenance Human-System Guidelines

For maintenance, the guidelines that were developed for refueling can be reused for maintenance activities for the same task types (Section 2.2). While many of the refueling human factors guidelines were repeated for maintenance, there were two potential failures that were not previously identified. The team created additional guidelines for those potential failures to supplement the earlier list, as shown in Table 5.

Within maintenance activities, it is critical that risks and boundaries be clearly marked for workers, without excessive signage. Human Factors Guidelines 20.2 and 21.1 shown in Table 5 denote the need to clearly mark keep out zones for equipment and people. These zones could be marked using red tape on the ground as well as signs clearly stating the specific risk displayed near the boundary of that zone. While it is important to inform humans of keep out zones and the risks to entering or bringing equipment into those zones, excessive signage could be distracting and remove the overall impact of the warnings (i.e., sign fatigue). Thus, signs should be poignant and minimal. Further, trainings and pre-work briefings could reiterate the importance of abiding by signage.

Table 5. Additional human factors guidelines resulting from the maintenance FMEA, in addition to the refueling guidelines previously identified

Task	Potential Human Factors Guidelines	
20. Clear equipment from train vicinity	20.1	All maintenance equipment should have a designated storage area
	20.2	Keep out zones should be clearly marked for operations involving hydrogen fuel
21. Do not introduce ignition sources	21.1	Keep out zones should be clearly marked for operations/activities that can introduce a fuel ignition source.

Additional applications of the guidelines can be taken from this table. For example, the best way to prevent equipment from entering keep out zones is to create appropriate storage areas (Human Factors Guideline 20.1). This storage area would hold equipment and tooling in clearly marked bins, including any warnings about using the equipment in undesignated areas or without appropriate checks. This guideline is also connected with Human Factors Guideline 6.2 ("Include a designated storage location for relevant system components that are temporarily removed"). However, Human Factors Guideline 20.1 is specific to maintenance tooling and equipment that may be used outside of the fuel system.

Human Factors Guidelines for detection (11.1 and 11.2) are critical within maintenance operations. For example, a system could be implemented to help maintainers detect when hydrogen has accumulated in their workspace, leading to increased risk of ignition.

4. Conclusion

The research team used analyses of fuel cell vehicles, LNG tenders, and diesel locomotive refueling operations to project and identify design guidelines pertinent for future hydrogen rail refueling operations. A task analysis and FMEA of relevant context refueling activities resulted in the identification of 47 human factors guidelines for hydrogen refueling operations. Additionally, since maintenance operations can incorporate broad task performance, an FMEA was employed to capture broad error types not limited to a specific task. The resulting FMEA identified three additional unique human factors guidelines not previously identified in the refueling task analysis.

Due to the early design stages of hydrogen rail systems, the resulting human factors guidelines represent best practices but do not include specific design features. While the guidelines in this report are written to include a multitude of human actions and error opportunities, specific implementation of the guidelines are dependent on system design. The team recommends that design and regulatory agencies include a Human Factors Engineer in the design and review process to ensure the guidelines are appropriately implemented and verified.

While many of the human factors guidelines are intuitive, designers may omit specific design considerations without appropriate encouragement and verification from human factors professionals. Unfortunately, the guidelines cannot be standardized across all possible designs. Thus, the guidelines are important to highlight for future referencing by designers, human factors professionals, and regulators.

While most design aspects cannot be standardized (e.g., facility layout, display design), emergency features should be standardized to ensure maintainers can easily locate, identify, and interact with emergency systems. This might include a standard emergency stop button, standard signage for keep out zones and high-risk work areas, and a standard nozzle shape/size. Future work could include the verification of human factors guidelines within conceptual design specifications and identifying specific emergency features which should be standardized across designs.

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Appendix A.
Refueling Procedures for a Hydrogen Fuel Cell Road Vehicle

The below procedures were obtained by watching video footage of an individual refueling a Toyota Mirai vehicle.

1. Select available dispenser
    a. Locate an “online” dispensing station
    b. Navigate to dispensing station
    c. Identify an open dispenser
    d. Pull car up to identified dispenser
2. Prepare car and dispenser for fueling
    a. Turn car off
        i. Put car into park
        ii. Press ignition button
    b. Open fuel door
        i. Press “fuel” button on interior of car
        ii. Exit car
        iii. Walk to fuel door on exterior of car
        iv. Press on right side of fuel door so that door pops open
        v. Swing door into fully open position
        vi. Remove dust cap from receptacle
            1. Grasp dust cap
            2. Pull dust cap away from receptacle
            3. Align dust cap with storage holder
            4. Place dust cap on storage holder
    c. Activate dispenser
        i. Read on-screen prompts
        ii. Provide input when prompted (on screen or keypad)
        iii. Watch training (if needed)
        iv. Insert payment card
        v. Read on-screen prompts
        vi. Provide input when prompted (on screen or keypad)
3. Complete re-fueling process
    a. Remove nozzle from dispenser
        i. Grasp nozzle handle
        ii. Pull nozzle up until clear from lever
        iii. Pull nozzle away from dispenser until free from storage port
    b. Secure nozzle onto receptacle
        i. Face receptacle on car
        ii. Align nozzle with receptacle
        iii. Push nozzle onto receptacle until seated
        iv. Grasp hand grip and nozzle handle
        v. Squeeze hand grip and nozzle handle together until hand grip is latched
        vi. Pull on nozzle handle to ensure nozzle is properly secured (being careful to not depress latch release mechanism)

c. Start flow of fuel
    i. Lift nozzle lever on dispenser
    ii. Select fuel pressure (H70 or H35)
        1. Determine if H70 or H35 should be used
        2. Locate selected fuel pressure button
        3. Press selected fuel pressure button
d. Verify fueling is in process
    i. Observe fuel amount and cost increase on dispenser screen
    ii. Listen for sounds of fueling (e.g., hissing, pump noises)
e. Stop fueling process or wait for fueling to stop
    i. Determine when fueling should be stopped
    ii. Monitor dispenser screen until stopping threshold is reached
    iii. Lower nozzle lever on dispenser OR
    iv. Observe fueling process has stopped
    v. Lower nozzle lever on dispenser

4. Detach dispenser equipment from car
    a. Remove nozzle from receptacle
        i. Depress latch on nozzle handle
        ii. Grasp nozzle handle
        iii. Pull nozzle away from receptacle (if nozzle is "frozen" to receptacle, wait for nozzle to "thaw" before reattempting)
    b. Place nozzle back on dispenser
        i. Align nozzle with storage port on dispenser
        ii. Place nozzle into storage port
        iii. Lower nozzle into lever until resting
    c. Close fuel door
        i. Replace dust cap on receptacle
            1. Grasp dust cap
            2. Pull away from storage holder
            3. Align dust cap with receptacle
            4. Push dust cap onto receptacle
        ii. Push door closed until locked

Appendix B.
LNG Tender Refueling Task Analysis

I. Prepare for fueling
  a. Ground fuel tender
    i. Locate grounding wire
    ii. Grasp grounding wire
    iii. Locate grounding location on tender
    iv. Attach grounding wire to tender grounding location
  b. Don PPE
  c. Perform visual check of tender
    i. Visually check for leaks
    ii. Verify valves are closed
      1. Grasp valve
      2. Turn valve clockwise
  d. Collect status information from display
    i. Locate status information on display
    ii. Read status information
    iii. Interpret status information
  e. Vent tender
    i. Remove vapor fuel port cover on tender
      1. Locate vapor fuel port on tender
      2. Grasp vapor fuel port cover
      3. Turn vapor fuel port cover counterclockwise until loose
      4. Pull vapor port cover away from fuel port
      5. Stow vapor fuel port cover
    ii. Connect liquid hose nozzle to vapor port
      1. Locate liquid hose
      2. Grasp liquid hose nozzle
      3. Lift liquid hose nozzle
      4. Carry liquid hose nozzle to port
      5. Align liquid hose nozzle with port
      6. Push liquid hose nozzle into port
      7. Turn liquid hose nozzle “handles” clockwise until loose
    iii. Open vent valve
      1. Locate vent valve
      2. Grasp vent valve
      3. Turn vent valve counterclockwise until “open”
    iv. Monitor pressure gauge
    v. Disconnect liquid hose from vapor port
      1. Grasp handles on nozzle
      2. Turn handles counterclockwise until loose
      3. Pull nozzle away from fuel port

f. Remove liquid fuel port cover on tender
    i. Locate liquid fuel port on tender
    ii. Grasp liquid fuel port cover
    iii. Turn liquid fuel port cover counterclockwise until loose
    iv. Pull liquid port cover away from fuel port
    v. Stow liquid fuel port cover
g. Connect liquid hose to liquid port
    i. Align liquid nozzle with liquid port
    ii. Push nozzle into port
    iii. Turn nozzle handles clockwise until locked
h. Connect vapor hose nozzle to vapor port
    i. Locate vapor hose
    ii. Grasp vapor hose nozzle
    iii. Lift vapor hose nozzle
    iv. Carry vapor hose nozzle to port
    v. Align vapor hose nozzle with port
    vi. Push vapor hose nozzle into port
    vii. Turn vapor hose nozzle handles clockwise until locked
i. Open fill and vapor
    i. Locate toggle
    ii. Grasp toggle
    iii. Pull/Push toggle to new position

II. Re-fuel
  a. Start fuel flow
    i. Set up short circulation (input data) on display
    ii. Set stopping weight (input data) on display
  b. Monitor fuel flow
  c. Detect when fuel automatically stops
  d. Purge line
    i. Wait pre-determined amount of time
  e. Send nitrogen
    i. Locate control to send nitrogen on display
    ii. Actuate control (input data) to send nitrogen on display
    iii. Monitor nitrogen flow
    iv. Stop nitrogen flow on display
  f. Close fill and vapor
    i. Locate toggle
    ii. Grasp toggle
    iii. Push/Pull toggle to new position

III. Clean up

a. Close liquid valve
    i. Locate liquid valve
    ii. Grasp liquid valve
    iii. Turn liquid valve clockwise until closed
b. Close vapor valve
    i. Locate vapor valve
    ii. Grasp vapor valve
    iii. Turn vapor valve clockwise until closed
c. Disconnect vapor hose
    i. Grasp handles on vapor hose nozzle
    ii. Turn handles counterclockwise until loose
    iii. Pull vapor hose nozzle away from port
    iv. Place vapor hose nozzle in storage hanger
d. Disconnect liquid hose
    i. Grasp handles on liquid hose nozzle
    ii. Turn handles counterclockwise until loose
    iii. Pull liquid hose nozzle away from port
    iv. Place liquid hose nozzle in storage hanger
e. Install liquid fuel port cover on liquid port
    i. Locate liquid fuel port cover
    ii. Grasp liquid fuel port cover
    iii. Align liquid fuel port cover with port
    iv. Push cover onto port
    v. Turn cover clockwise until secured
f. Install vapor fuel port cover on vapor port
    i. Locate vapor fuel port cover
    ii. Grasp vapor fuel port cover
    iii. Align vapor fuel port cover with port
    iv. Push cover onto port
    v. Turn cover clockwise until secured

Appendix C.
Diesel Locomotive Refueling Task Analysis

I. Prepare for fueling
  a. Remove fuel port cover on locomotive
    i. Locate fuel port cover on locomotive
    ii. Grasp fuel port cover
    iii. Turn port cover counterclockwise until loose
    iv. Pull port cover away from fuel port
    v. Stow fuel port cover
  b. Install nozzle in fuel port
    i. Locate nozzle
    ii. Grasp nozzle
    iii. Lift nozzle
    iv. Carry nozzle to port
    v. Align nozzle with port
  c. Log train info on digital display
    i. Locate train number
    ii. Read train number
    iii. Recall train number
    iv. Input train number in display

II. Re-fuel
  a. Start fuel flow
    i. Grasp hand lever
    ii. Squeeze hand lever until locked
  b. Monitor fuel flow and level
    i. Watch fuel level in gauge
    ii. Detect leaks
  c. Detect stopped fuel flow

III. Clean up
  a. Remove nozzle from fuel port
    i. Locate nozzle
    ii. Grasp nozzle
    iii. Turn nozzle handles counterclockwise until loose
    iv. Pull nozzle away from fuel port
    v. Carry nozzle to storage area
    vi. Align nozzle with storage port
    vii. Place nozzle on storage port

b. Install fuel port cover on locomotive
    i. Locate fuel port cover
    ii. Grasp fuel port cover
    iii. Lift fuel port cover
    iv. Align fuel port cover with fuel port
    v. Turn fuel port cover clockwise until secured

Abbreviations and Acronyms

ACRONYM	DEFINITION
FAA	Federal Aviation Administration
FMEA	Failure Modes and Effects Analysis
FRA	Federal Rail Administration
HFE	Human Factors Engineering
LNG	Liquid Natural Gas
NIOSH	National Institute for Occupational Safety & Health
SME	Subject Matter Expert