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NASA's Integrated Arrival Departure System/Airspace Technology Development-2: A Case Study for the Application of the Human Readiness Scale

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Acronyms and Definitions

AEFS....................................Advanced Electronic Flight Strip
ANSI....................................American National Standards Institute
ARC.....................................NASA Ames Research Center
ARTCC................................Air Route Traffic Control Center
ATC.....................................Air Traffic Control
ATCT...................................Air Traffic Control Tower
ATD-2..................................(NASA's) Airspace Technology Demonstration 2
ATM....................................Air Traffic Management
CLT......................................Charlotte Douglas International Airport (North Carolina)
ConUse................................Concept of Use
DAL.....................................Dallas Love Field Airport (Texas)
DFW....................................Dallas Fort Worth International Airport (Texas)
DoD......................................Department of Defense
EFD......................................Electronic Flight Data
FAA.....................................Federal Aviation Administration
FFC......................................(NASA's) Future Flight Central Simulator
HFES....................................Human Factors & Ergonomics Society
HRL.....................................Human Readiness Level
HSI.......................................Human Systems Integration
IADS....................................Integrated Arrival and Departure System
MIT......................................Miles-in-Trail
NASA..................................National Aviation and Space Administration
RTC/RMT............................Ramp Traffic Console/Ramp Manager Traffic Console
SARDA................................Spot and Runway Departure Advisor
STBO...................................Surface Trajectory Based Operations
SWIM..................................System Wide Information Management
TBFM.................................. Time Based Flow Management
TFDM..................................Terminal Flight Data Manager
TMC.....................................Traffic Management Coordinator
TMIs....................................Traffic Management Initiatives
TRACON..............................Terminal Radar Approach Control
TRL......................................Technology Readiness Level
TTP......................................TFDM Terminal Publication
ZTL......................................Atlanta Center

NASA's Integrated Arrival Departure System/Airspace Technology Development-2: A Case Study for the Application of the Human Readiness Scale

Sandy Lozito[1], Lucia Arsintescu[2]

Executive Summary

NASA formalized the use of the Technology Readiness Level (TRL) scale in 1989 to provide insight into the necessary tasks to define the maturity of a particular technology, but the scale does not directly assess the readiness of the technology for the users. A scale was introduced to mirror the TRLs with a human usability mapping as a measure to communicate the readiness of a system for use by human operators and maintainers, called the Human Readiness Levels (HRLs). (Acosta, 2010). Although NASA has not fully adopted the use of the HRLs, the Aeronautics Research Mission Directorate conducted a technical transfer of the Integrated Arrival and Departure System *(IADS) traffic management system to the FAA in 2021. The many activities supporting the technical transfer of IADS provide an opportunity to retrospectively assess the application of the goals and parameters from the HRL scale to the IADS technology. This paper addresses the HRL scale application to IADS research and development by discussing the research tasks at various scale levels. A brief background of the goals, methods, and expected benefits of IADS is presented, as well as a brief background of the development and usage of the HRL scale. The IADS research work is examined relative to the HRL levels. The analysis revealed that many of the tasks recommended as part of the HRL Scale were conducted during the IADS system development. Lessons learned from the application of the HRLs to the IADS work are discussed.*

1. Introduction/Background

As the United States organization that is responsible for space exploration, aeronautics research, and space and earth science, The National Aviation and Space Administration (NASA) has been developing, testing, and fielding complex technologies and systems that provide economic and safety benefits to the public. The development and evaluation of these systems require the application of systems engineering and integration principles and practices to ensure the mission objectives are met. The NASA Systems Engineering Handbook (NASA SP-2016-6105 Rev 2; 2016)

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is a comprehensive guide to systems engineering best practices at NASA, and provides guidance for the design, development, and operation of NASA systems.

NASA also created a method to assess the maturity of systems and technologies. NASA formalized the use of the Technology Readiness Level (TRL) scale in 1989 to provide insight into the necessary tasks to define and reach maturity of a particular technology (Figure 1; https://www.nasa.gov/directorates/somd/space-communications-navigationprogram/technology-readiness-levels). The TRLs measure the progress of new technologies from basic research to completion and have become common terminology in aerospace and defense to track product development. The TRL scale goes from Level 1 to Level 9, with Level 1 representing less mature (e.g., basic principles observed) to Level 9 representing the actual system "flight proven" through successful mission operations (Figure 1).

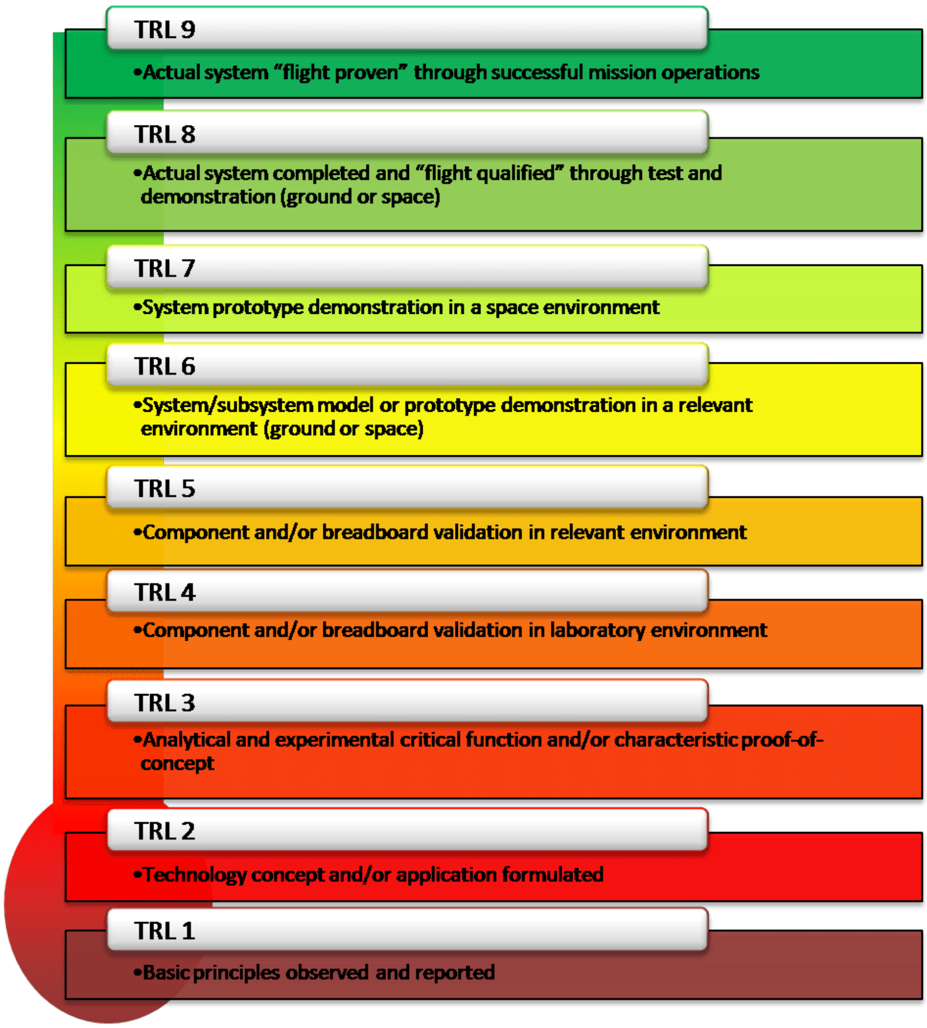

Figure 1. Technology Readiness Level Scale.
Retrieved from: https://www.nasa.gov/wp-content/uploads/2023/09/trl.png

A notable limitation of the TRL scale is its inability to capture the human-system interactions and usability elements of technology development (Kosnik & Acosta, 2010). In addition to technological maturity, it is essential that the systems engineering approaches for complex technologies include considerations of human performance and interaction. Accounting for the human interface and interactions as another aspect of integration is required to achieve full mission success and is as critical as the hardware and software. Human Systems Integration (HSI) means not only making certain that the systems we design are friendly to the end user, safe, and resilient, but also ensures that all phases of life-cycle development that involve humans are integrated in a manner that results in the highest probability for mission success. Accordingly, to complement the NASA System Engineering Handbook, NASA has also created the NASA Human Systems Integration Handbook (HSI, 2021) to address the full system including the human users. The NASA HSI Handbook discusses a broad range of topics including the relevant HSI domains, HSI tasks required for different developmental steps, and the role of HSI practitioners at the different levels during system development (Figure 2).

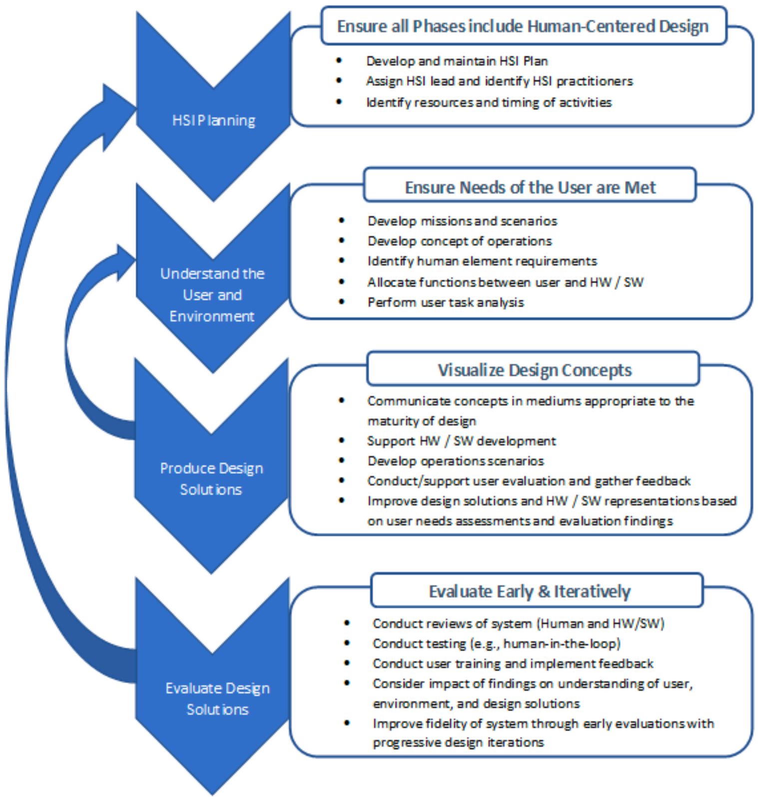

Figure 2. Systems Engineering – HSI Interaction: Human-Centered Approach. (Retrieved from: https://ntrs.nasa.gov/api/citations/20240003061/downloads/CLDP%20HSI%20TIM%20Human%20Centered%20Design%20Process.pdf.)

1.1. Human Readiness Levels

In 2010, a scale was introduced to mirror the TRLs with a human usability mapping proposed as a measure to communicate on the readiness of a system for use by human operators and maintainers (Acosta, 2010). Researchers began exploring the possibility of complementing the TRLs with a scale representing Human Readiness Levels (HRLs, Kosnik & Acosta, 2010). In 2021, the Human Factors & Ergonomics Society (HFES) and the American National Standards Institute (ANSI) approved the HFES/ANSI 400-2021 standard, "Human Readiness Level Scale in the System Development Process" to consider the readiness of the technology or system to support the human (See et al., 2019). The standard defines the nine levels of a HRL scale and provide guidance for their application (HFES/ANSI, 2021).

HRL1: Basic principles for human characteristics, performance, and behavior observed and reported

HRL2: Human-centered concepts, applications, and guidelines defined

HRL3: Human-centered requirements to support human performance and human-technology interactions established

HRL 4: Modeling, part-task testing, and trade studies of human systems design concepts and applications completed

HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design

HRL 6: Human systems design fully matured and demonstrated in a relevant high-fidelity, simulated environment or actual environment

HRL 7: Human systems design fully tested and verified in operational environment with system hardware and software and representative users

HRL 8: Human systems design fully tested, verified, and approved in mission operations, using completed system hardware and software and representative users

HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

The HRL scale was developed to evaluate, track, and communicate a system's readiness for human use and is intended to complement and supplement the TRL scale. The TRLs and the HRLs provide the steps for development and evaluation for the stages of technology development and user development, from less mature to more mature, including the overarching development stages of research and development, technology demonstration, and production and deployment. The application of the HRLs offers a systematic and consistent approach to measuring progress and incorporate the human element throughout the project life cycle. Use of the HRLs can also assist in communicating the status of the user development and provide guidance for crucial decision-making in the development cycle of new technologies. For example, in the early stages of development the HRLs guidance can help determine staffing requirements for system development based on the tasks expected to address the different levels.

Some researchers and engineers have begun applying the HRLs to their development (Salazar, G., 2020). In August 2025, the Department of Defense (DoD) formally adopted the HRLs standards (https://www.cto.mil/news/dod-hrl; 2025). Handley and Savage-Knepshield (2020) examined the suitability of HRLs use for an Army acquisition program while See, Craft, and Morris (2019) investigated the HRLs in applications of system engineering processes at Sandia National Laboratories. When applying HRLs to a U.S. Army software modernization, Handley, See, and Savage-Knepshield (2024) found that HRLs were useful, but the application of the scale needed to be applied in a way that is flexible and adaptable to the program needs.

Currently, there is very little application of the HRL Scale within NASA's formal systems engineering methods and metrics, possibly due to the recent formal publication of the HRL Scale by the Human Factors and Ergonomic Society/American National Standards Institute (HFES/ANSI; 2021). NASA has demonstrated expertise in human integration and performance and implements human-system interaction assessments for system development, as evidenced by the creation of the HIS Handbook (2021). The handbook references that the HRLs were in development at the time of the publication, stating that the HRLs should provide a familiar systematic and consistent approach to measuring progress and may more fully incorporate the human into the project life cycle of a mission.

Although there is currently little or no formal application of the HRLs for NASA's technology development, there is some evidence that the tasks described in the HRLs that accompany TRL maturation may have occurred in NASA-developed aeronautics tools. In particular, systems developed to support improvement in air traffic operations may provide relevant examples of informally addressing the HRL Scale tasks and metrics while the new technology matures. By investigating this possibility, there may be critical insight into the benefits and issues that may arise should NASA adopt a more formal HRL application while developing new technologies and systems.

Some of the more complex aeronautical technologies that NASA has developed have been systems created and tested in collaboration with the Federal Aviation Administration (FAA). There is a long-standing successful relationship between the two organizations in which NASA conducts research that will aid the FAA in meeting its regulatory obligations to manage a safe and efficient public air transportation system. (https://www.nasa.gov/aeronautics/nasa-and-federal-aviation-administration-sign-collaboration-agreements). In these cases, NASA typically intends to deliver the new technology to the FAA at a technology maturity level that is typically TRL 6 or 7. Technology transfer occurs after a large amount of research, development, and collaborative efforts have occurred between the two organizations.

A highly successful technology transfer from NASA's Aeronautical Research Mission Directorate to the FAA was the Integrated Arrival and Departure System (IADS) Traffic Management System. The IADS system extends integrated traffic sequencing from the gate to the overhead traffic stream and back again to handle multi-airport, metroplex operational environments. NASA's Airspace Technology Demonstration 2 (ATD-2) Project demonstrated the benefits of a IADS technology. The tools, tested at Charlotte Douglas International Airport (CLT) in North Carolina, and at Dallas Fort Worth International Airport (DFW) and Dallas Love Field Airport (DAL) in Texas, saved fuel, reduced carbon emissions, and increased information sharing between the FAA and industry. NASA provided the FAA with technology and knowledge from the demonstrations. The technologies were developed in close collaboration among NASA, the FAA, and industry stakeholders and were formally delivered from NASA to the FAA as part of a technology transfer that occurred in 2021 (https://www.prnewswire.com/news-releases/nasa-transfers-air-traffic-management-tool-updates-to-faa-301387009.html). IADS capabilities were developed under NASA's ATD-2 multi-year project, and had the goal of sharing data among controllers, flight operators, and airport operators to enhance coordination among the stakeholders and ultimately to improve the efficiency of the air traffic management systems and reduce fuel usage and emissions.

This paper examines the application of HSI tasks and metrics during the process of NASA's preparation of the ATD-2/IADS tool for technology transfer to the FAA. The goal of this document is to conduct a detailed analysis of the technical transfer documents to determine the degree to which the tasks associated with the HRL scale were performed during the TRL maturation of IADS. The work to prepare the IADS technology transfer occurred before the formal publication of the HRLS, so this analysis represents a retrospective assessment of the HRL scale application. Because of the complexity of the IADS technologies and the large amount of information provided as part of the technology transfer documents, a detailed assessment of the HRLs that were addressed as part of the technology demonstration provides a case study of how HRLs could be used to identify, communicate, and assess the technology's readiness for human users.

Note that this document does not intend to fully describe or represent the many tasks that were conducted over the years that the ATD-2 research tasks took place, but rather to explore that work in relation to how it may capture the human readiness levels. In addition, this paper will focus on the HRLs that occurred as part of the development and tasks associated with the FAA facilities and the FAA users. Industry stakeholders and users were a critical part of the years of development work by the ATD-2 Team, and their significant data and coordination contributions were invaluable to the success of system. Since this analysis focuses upon on the IADS system development in support of NASA's technical transfer to the FAA, only the HRL-related tasks associated with the FAA facilities and users are addressed.

2.0 Integrated Arrival and Departure System (IADS): A Brief Overview

There are many inefficiencies in the busy terminal areas in the U.S. national airspace system. In the Airspace Technology Demonstration Closeout Report (2021), some of the barriers that led to the inefficiencies were airport surface and terminal airspace resources (e.g., taxiways, runways, departure/arrival fixes and routes) that are competed for by multiple users in an uncoordinated, first-come, first-served manner. (Airspace Technology Demonstration Closeout Report: Version 3, 2021). Concepts and technologies to manage arrival, departure, and surface operations have been under development by NASA, the FAA and industry to improve the flow of traffic into and out of the nation's busiest airports (Coupe et. al, 2019).

Working closely with the FAA and stakeholders, NASA investigated the information needs and the distribution of data among the air transportation stakeholders, including airlines, air traffic service providers, airport authorities, and technology vendors. The IADS/ATD-2 system was developed as an approach that integrated multiple data sources to address these inefficiencies in the US terminal airspace.

The primary goal of the NASA-FAA ATD-2 was to improve the predictability and operational efficiency of the air traffic system in terminal and metroplex environments through the development and integration of the nation's arrival, departure, and surface prediction, scheduling, and management systems. (ATD Project Closeout Report, 2021). The ATD-2 system, managed by NASA's Airspace Operations and Safety Program, included collaboration with users and stakeholders associated with American Airlines, Southwest Airlines, the National Air Traffic Controllers Association, Charlotte Douglas International Airport, Atlanta Air Route Traffic Control Center, Dallas/Ft. Worth International Airport, Dallas Love Field Airport, and the Fort Worth Air Route Traffic Control Center. These stakeholders partnered with NASA during the field demonstrations which involved the integration of data from independent systems to provide operators in multiple facilities with a shared situational awareness of traffic at the airport.

The ATD-2 field demonstration was conducted in three phases. The first baseline IADS phase commenced in September 2017 and demonstrated tactical surface departure metering at the American Airlines ramp tower and FAA's Air Traffic Control Tower at CLT, as well as overhead stream insertion at the Washington Air Route Traffic Control Center. CLT is characterized by some challenging operational conditions that restrict internal traffic flows that require coordination among the users, including limited ramp and holding space and some taxiways that permit only single direction traffic. The second phase of the ATD-2 demonstration began in 2018 and extended the surface departure metering time horizon with strategic planning tools, interfaces with tower controller electronic flight strips, and expanded the overhead stream insertion to Atlanta Air Route Traffic Control Center (Figure 3). The final phase demonstrated a Terminal Departure Scheduling capability that considered multiple airports and terminal boundary constraints and was conducted at DFW Terminal Radar Approach Control, Fort Worth Air Route Traffic Control Center, DFW and DAL Air Traffic Control Towers, and American and Southwest Airlines facilities at DFW and DAL airports, respectively (Figure 4).

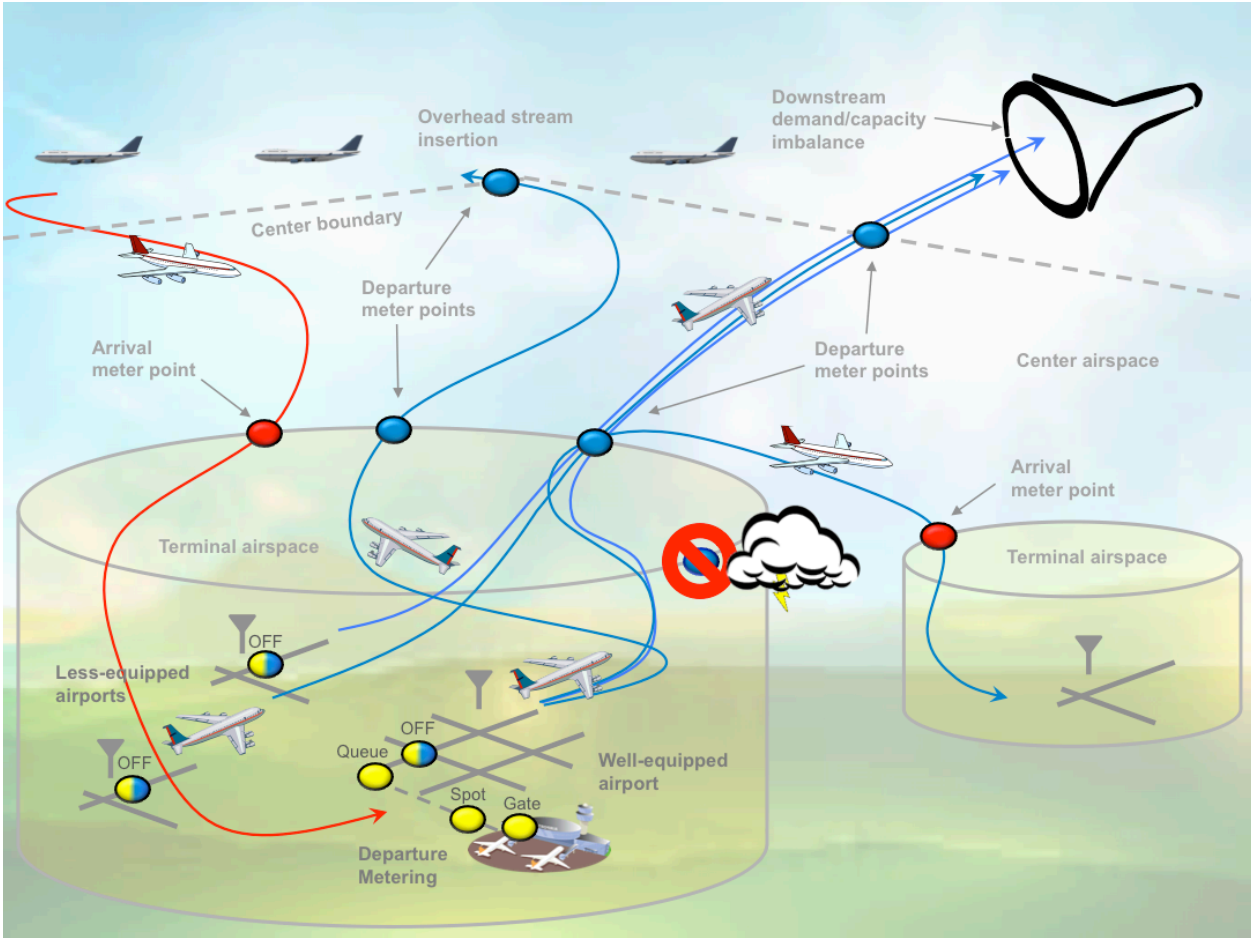

Figure 3. A simplified view of the ATD-2 project operational environment for the Phase 1 Baseline IADS Demonstration. There are several surface and airspace control points, plus constraints due to weather and downstream demand/capacity imbalances. (Retrieved from: [https://ntrs.nasa.gov/api/citations/20190002006/downloads/20190002006.pdf).](https://ntrs.nasa.gov/api/citations/20190002006/downloads/20190002006.pdf)

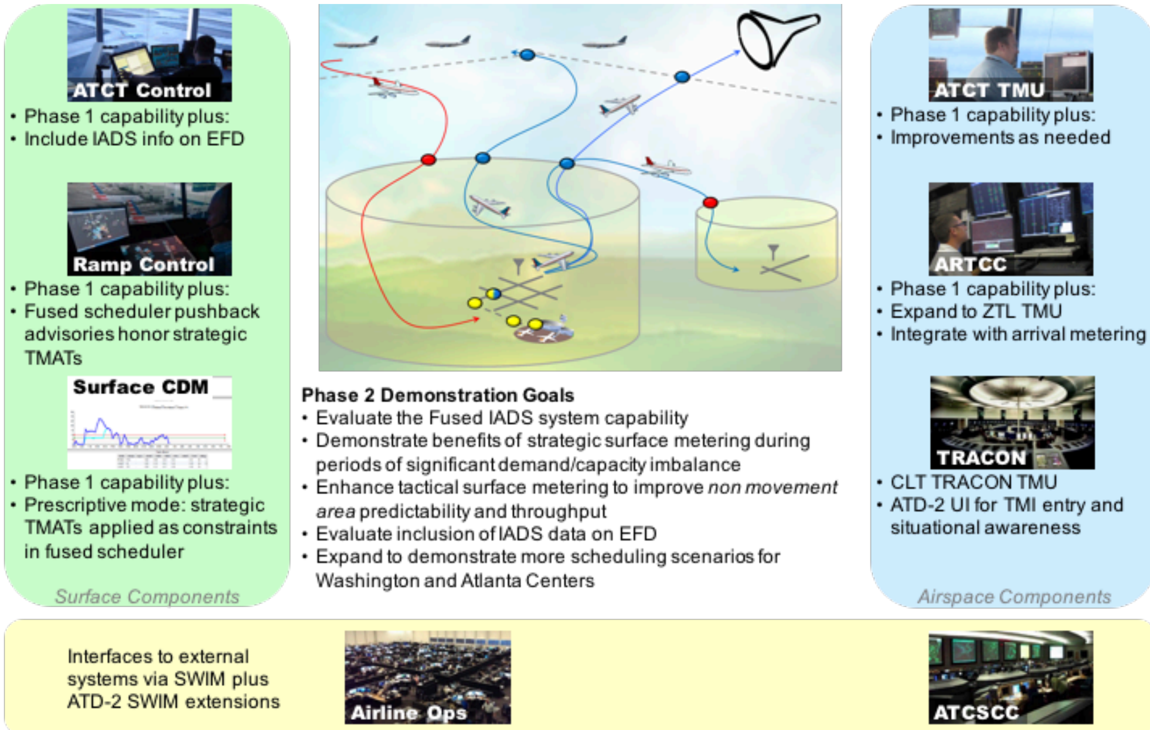

Figure 4. The enhanced operational overview of the IADS system that shows both the users at various facilities and the system improvements for the Phase 2 IADS Demonstration. (Retrieved from: https://ntrs.nasa.gov/api/citations/20190002006/downloads/20190002006.pdf).

Phase 1 provided a demonstration of the integrated system of strategic and tactical scheduling, collaborative tactical surface metering, tactical departure scheduling to an en route meter point and overhead stream insertion, initial integration of a Terminal Flight Data Manager (TFDM) System Wide Information Management (SWIM) prototype feed, and an early implementation prototype of a TFDM Electronic Flight Data (EFD) system. The Phase 2 Fused IADS system provided substantial updates to baseline IADS demonstration capabilities, including improvements to the IADS modeler; tactical surface scheduling, and metering; tactical departure scheduling for overhead stream insertion; EFD and the integration with the FAA Advanced Electronic Flight Strip (AEFS); Ramp Traffic Console/Ramp Manager Traffic Console (RTC/RMT), and departure trajectories. New capabilities included a TFDM SWIM prototype feed and delivery of IADS data via the TFDM Terminal Publication (TTP) service of the FAA's SWIM system; strategic surface scheduling and metering as well as fusion with tactical surface metering; integration and ingestion of data from TTP-connected Mobile App and texting industry. The Phase 3 Field Evaluation extended the capabilities to a Metroplex environment where multiple airports are interacting and sharing resources along the terminal boundary (Coupe et. al, 2020).

The IADS tool provided some clear operational benefits and savings made possible by reducing jet engine run time. During the period of September 2017 to September 2021, the tools saved more than one million gallons of jet fuel and spared passengers 933 hours of flight delay. Airlines also saved an estimated $1.4 million in flight crew costs (Figure 5). The FAA committed to deploying IADS capabilities to 27 airports beginning in 2022 as part of their TFDM program (retrieved from https://www.nasa.gov/ames/core-area-of-expertise-air-traffic-management).

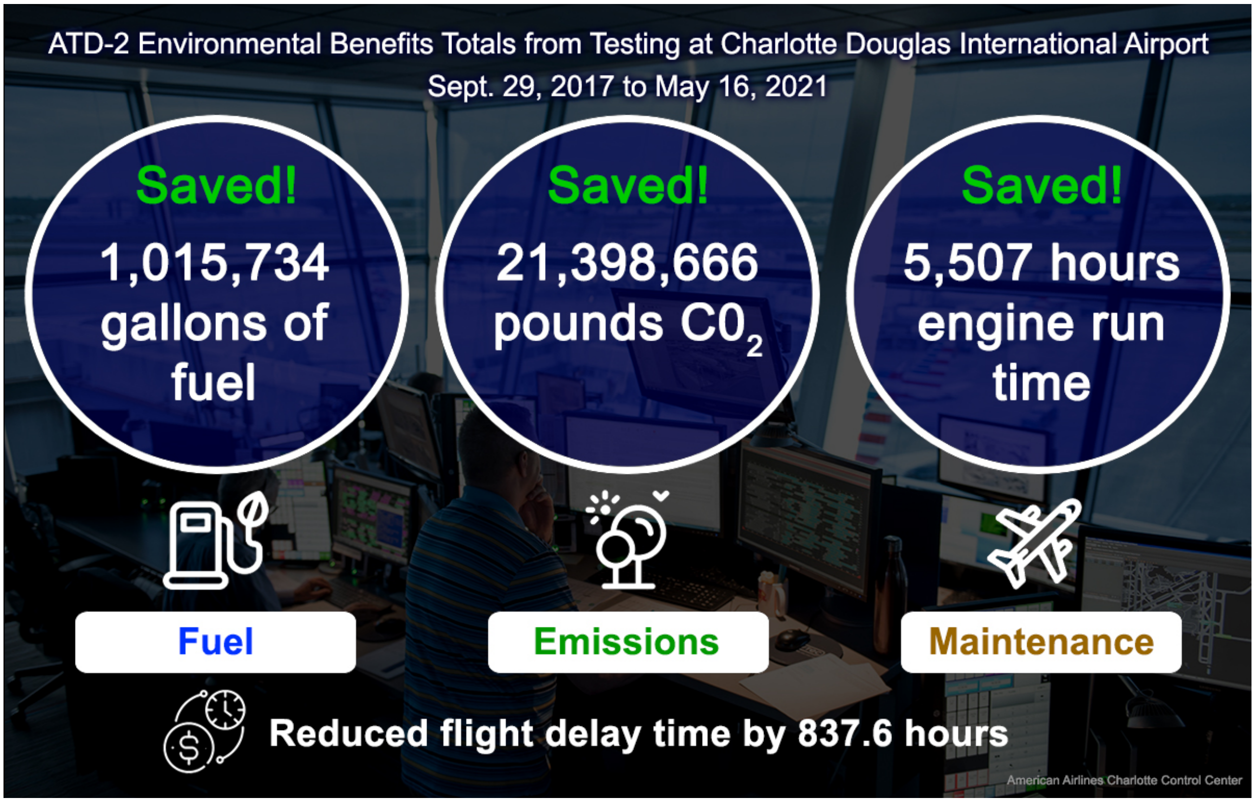

Figure 5. ATD-2 Environmental Benefits Totals from Testing at Charlotte Douglas International Airport from September 29, 2017, to May 16, 2021. (Retrieved from https://www.nasa.gov/centers-and-facilities/ames/nasa-testing-saves-airlines-one-million-gallons-of-jet-fuel).

For more details about the IADS/ATD-2 System and evaluations, there are several project documents and papers available (Bhadoria et al, 2021; Talebi et al., 2019; Jung et al, 2018; Coupe et al. 2022; Coupe et al., 2020).

3.0 Human Readiness Levels and ATD-2/IADS Technical Transfer Document Assessment

Similar to the TRLs, the HRLs are organized around three broad phases of system development: basic research and development; technology demonstration; and production and deployment. As the development of the technology matures, the development of the human user requirements and implications should also mature so that human-centered usability considerations are addressed. In the basic research and development phase, the emphasis of the work attempts to understand constraints and limitations of the environment and define the human concepts and requirements. During the technology development phase, the human interfaces and interactions are defined, and simulation evaluations begin. In the final phase of production and deployment, field assessments are conducted with the more mature interface design and procedures. As the research changes with the more mature system development phases, the user-related risks associated with the stages of development can be more easily identified and mitigated in a timely manner.

The work that was conducted in support of the development of IADS/ATD-2 was largely performed in the field, including FAA and airline ramp environments. The collaboration among the many partners was critical to every aspect of ATD-2 and allowed for the broad access that enabled the user input and other essential data that defined the steps for the creation and evaluation of the concepts and technologies. Because of that access, many of the early human user aspects were investigated in the field rather than a laboratory setting, thus creating a more realistic context for study and assessment. This means that the ATD-2 work in the earlier HRL levels (HRL 1-4) was sometimes explored in a more operationally relevant environment.

In addition, because access to the FAA facilities was provided over the span of a few years, the HRL tasks were often repeated to account for the increasing maturity of the IADS system. For example, as the characteristics of IADS were modified based on testing and user feedback, additional evaluations were performed to make sure that the user-centered requirements and guidelines were addressed with system updates.

This paper is organized by the corresponding TRL and HRL. Since NASA is not responsible for final implementation decisions at FAA facilities, NASA's IADS-related development and research did not go beyond TRL 7 and HRL 7. Starting from TRL 1 and HRL 1, the ATD-2 work that captures the efforts at each level (from TRL 1/HRL 1 to TRL 7/HRL 7) will be discussed in separate sections. In addition, at the end of sections describing each of the HRL/TRL levels, evaluation activities are provided to offer some examples of the tasks and assessments that can be used at each level. These examples are taken from Appendix C: HRL Guidance in the HFES/ANSI document (HFES/ANSI, 2021) and include the activity reference number provided in Appendix C to allow for cross-reference to the document. Table 1 provides a summary of examples of IADS research and development tasks that were conducted in support of each of the HRLs from HRL 1 to 7.

Table 1. Examples of Research and Development Tasks for the Integrated Arrival Departure System (IADS) and the Human Readiness Levels (HRLs)	
Human Readiness Levels (HRLs)	*Integrated Arrival and Departure System (IADS) Research and Development Tasks*
HRL 1: Basic principles for human characteristics, performance, and behavior observed and reported.	• Worked with subject matter experts from FAA to understand current FAA system characteristics, issues, and constraints. • Gained understanding of users' tasks and goals. • Developed a concept of use document.
HRL 2: Human-centered concepts, applications, and guidelines defined.	• Formulated user-centered requirements and guidelines formulated. • Formulated initial designs and procedures. • Defined initial human performance metrics.
HRL 3: Human-centered requirements to support human performance and human-technology interactions established.	• Continued development of interface design and procedures. • Gained broader understanding of users' tasks and goals. • Gained broader understanding of users' interactions and metrics.
HRL 4: Modeling, part-task testing, and trade studies of human systems design concepts and applications completed.	• Conduct simulation assessment to test interface, interactions, and procedures using the Future Flight Central Simulator, an air traffic control tower simulation environment. • Conduct simulation assessment to test usability and workload using the Future Flight Central Simulator, an air traffic control tower simulation environment.
HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design.	• Conduct further simulation assessment to continue to test interface, interactions, and procedures using the Future Flight Central Simulator, an air traffic control tower simulation environment. • Conduct further field assessment to test interface, interactions, and procedures with FAA participants in Charlotte airspace facilities.
HRL 6: Human systems design fully matured and demonstrated in a relevant high-fidelity, simulated environment or actual environment.	• Conduct further field assessment to test interface, interactions, and procedures with FAA participants in Charlotte airspace facilities and Dallas-Fort Worth airspace facilities to continue. • Conduct further field assessment of workload, situation awareness, and usability of IADS system assessment with FAA participants in Charlotte airspace facilities and Dallas-Fort Worth airspace facilities.
HRL 7: Human systems design fully tested and verified in operational environment with system hardware and software and representative users.	• Conduct further field assessment to test the most mature IADS' interface, interactions, and procedures at CLT ATC Tower, Terminal Radar Approach Control (TRACON), and Air Route Traffic Control Center (ARTCC). • Conduct further field assessment of workload, situation awareness, and usability of the most mature IADS system at CLT ATC Tower, TRACON, and ARTCC)

4.0 IADS and the TRL and HRL Research

4.1 Basic Research and Development Phase: TRL 1–3 and HRL 1–3

The Basic Research and Development Phase refers to the earliest work supporting a new technology. The goals of the work are defined, and concept definition is being developed through research, analyses, and working with subject matter expertise and potential users. This phase also marks the beginning of human user guidelines and requirements development. Addressing human performance in the initial development phase enables early identification of possible human performance issues and may provide mitigation strategies that may support the usability and safety of future concepts and systems.

4.1.1 Technology Readiness Level One (TRL 1) and Human Readiness Level One (HRL 1) for IADS

4.1.1.1 Technology Readiness Level One (TRL 1)

TRL 1 is intended to establish the basic principles of a particular environment through observation and reporting. NASA conducted work for TRL 1 on IADS/ATD-2 over many years through research investigating the relevant airspace and airline environment and through discussions and interviews with various experts and stakeholders.

NASA has been investigating the terminal area inefficiencies for decades. Working closely with the FAA and industry partners, NASA researchers identified the existing operations, limitations, and constraints associated with the airport and terminal environment. Much of this foundational work was conducted as part of the development of an airport surface tool called Spot and Runway Departure Advisor (SARDA), a NASA-developed research tool that focused on addressing inefficiencies in airport surface management. Initial assessments of SARDA were conducted in 2012-2013 to study the potential success of NASA technologies in addressing these inefficiencies (Gupta et al., 2013; Windhorst, 2012).

4.1.1.2 Human Readiness Level One (HRL 1)

HRL 1 has the goal of observing and reporting the basic human characteristics and behaviors for the users in the relevant environment. This includes identifying user tasks, issues, and limitations and capabilities within the operational environment. Interactions with other users and with technologies and systems are also defined, including general tasks and communication requirements that may be required.

The NASA researchers observed and gathered much of the data required to address HRL 1. In preparation for early development of surface and terminal technologies, they conducted many interviews and hours of observations and created much documentation within the airline ramp towers and air traffic control facilities around the CLT. They also held several meetings with senior leaders within the FAA and airlines to gather their guidance and feedback.

The information about the CLT system and user limitations was derived from discussions and interviews with FAA, industry users and stakeholders as well as direct observations of the airline ramp operators and Air Traffic Control (ATC) users at multiple facilities. The NASA Team also conducted an assessment based on interviews and collected data of the various users, which indicated the challenges associated with the data-sharing and limited integration of data among the different systems. The ATD-2 Concept of Use (ConUse) document (Jung, 2018) lists several examples of the existing issues for the system users and stakeholders. For example, for the CLT

ATC Tower Control users, there is limited awareness of the intended trajectory and the sequence of departures in the aircraft queue, and the schedule departure times for the departures are conducted verbally over the phone which can limit timeliness and add to workload. There a great deal of uncertainty associated with the use of Traffic Management Initiatives (TMIs), and Inefficiencies in the way TMIs are planned, coordinated and complied. Complying with Miles-in-Trail (MIT) restrictions is challenging; controllers must rely on experience and best practices to stage departures for takeoff and translate spacing off the runway to desired spacing in the airspace and they are limited in their application and execution. Both pilots and ramp controllers can be unaware of TMI restrictions prior to pushback. These limitations and constraints, described in the ATD-2 ConUse provided further insight into how decision-making is conducted by stakeholders and some details about user roles and how they are affected by existing data and interaction tasks (Jung et. al, 2018).

The HRL1 Evaluation Activities that were conducted as part of the IADS research include:

- Identified human behaviors, capabilities, and limitations (C.1.1.1).
- Identified usage scenarios (C.1.1.2).
- Identified key human performance issues and risks (C.1.1.3).
- Conducted basic human research relevant to the concept (C.1.1.4).

4.1.2 Technology Readiness Level Two (TRL 2) and Human Readiness Level Two (HRL 2)

4.1.2.1 Technology Readiness Level Two (TRL 2)

TRL 2 refers to the work to formulate the system concept and application. In the case of IADS/ATD-2, the system concept and application were formulated while the NASA researchers collaborated with the FAA and industry partners to study the issues in existing operations at CLT. The ATD-2 ConUse helps explain the formulation and the plans for the systems and how it might address the constraints and limitations in the FAA and airline environments. There are additional documents provided in the technology transfer to the FAA that describe details about the functions, tools, and applications. A list of these documents can be found on the NASA Technical Report Server (https://ntrs.nasa.gov/citations/20205006383).

4.1.2.2 Human Readiness Level Two (HRL 2)

HRL 2 suggests that human-centered concepts, applications, and guidelines be developed as part of the creation of the broader concept and applications. This includes consideration of human design principles that are essential to help address the early stages of usability. Preliminary human concept designs are addressed, and definitions of human performance metrics are defined, including usability metrics, workload, and situational awareness.

The detailed development work conducted by the NASA ATD-2 Team and the various stakeholders is described in the ATD-2 ConUse (Jung et al, 2018). It involved exhaustive work with a number of stakeholders from the FAA and industry. Several interviews with subject matter experts combined with many hours of observations in their operational environments provided information about requirements, procedures, and information necessary to conduct their jobs.

An assessment of information requirements was conducted for airline ramp operators and tower controllers. Some examples of information requirements identified for both FAA and industry users include awareness of the pushback sequence of the aircraft, better TMI planning, and improved information about departure demand forecasts. In addition, user operational scenarios were created to help illustrate the existing environment limitations and suggest targets of opportunity that may demonstrate ATD-2 benefits. The scenarios also reflected the interactions required among the users for both the current environment and with use of ATD-2 tools. Interactions between the users and ATD-2 functions were observed and noted.

Several potential ATD-2 benefits were identified during the observations and discussion, including improved predictability for airspace and airport operations and more efficient surface operations. Potential human performance benefit mechanisms that were determined as part of ATD-2 technologies include situational awareness improvements due to broader sharing of data among the stakeholders. In addition, reduction in workload was expected due to increased predictability, better information exchange, and a reduced dependence upon voice communications for coordination. Due to increased automated data entry, fewer user errors were also predicted.

The HRL 2 Evaluation Activities that were conducted as part of the IADS research include:

- Knowledge of relevant human characteristics, capabilities, and limitations been refined (C.2.1.1).
- Key human-centered design principles, standards, and guidance were established (C.2.1.2).
- Usage scenarios were updated to include basic task descriptions for user roles (C.2.1.3).
- Human performance on legacy systems were analyzed to understand human-technology interactions, human behavior, and human performance issues (C.2.1.4).
- Potential human error and misuse sources were identified (C.2.1.5).
- Metrics for performance were identified (C 2.1.6).

4.1.3 Technology Readiness Level Three (TRL 3) and Human Readiness Level Three (HRL 3)

4.1.3.1 Technology Readiness Level Three (TRL 3)

TRL 3 is when the concept is demonstrated analytically and/or experimentally. Several analyses of the ATD-2 functions and technologies were conducted to investigate the expected benefits during the project lifetime of ATD-2 (Amblard et. al, 2021; Bhadoria et. al, 2021; Churchill et. al, 2021; Coupe et. al., 2020). The fast-time simulations examined the critical functions of the ATD-2 system and included evaluations of CLT and the DAL airspace environments to capture the functions of the ATD-2 technologies as they were developed over the y ears. Some examples of these analyses include assessments of taxi out times, terminal operations restricting, and Metroplex airspace operations.

4.1.3.2 Human Readiness Level Three (HRL 3)

Human-center requirements to support human performance and human-technology interactions are established as part of HRL 3. The requirements should be able to trace back to the concepts and guidelines from HRL1 and 2 and are mapped to the operational expectations and demands in the system to help create human-centered requirements for new technologies and operations.

The ATD-2 ConUse document provided an overview of the IADS concept and development and provided detailed descriptions of how each group of users interacted with the proposed system, focusing on the conceptual elements for the ATD-2 Phase 1 Baseline IADS Demonstration at CLT (Jung et. al, 2018). As development of the ATD-2 technologies continued, updated ATD-2 documents were provided to reflect the new tools, functions, and user tasks and procedures (Talebi et. al., 2019). These documents also describe the assessment of the current problems and conditions in the CLT airspace environment, as well as many of the tasks and assessments that were conducted to support the analysis of the existing challenges, technologies, and procedures.

Using the technologies and tools designed for ATD-2, NASA worked with FAA and industry partners to modify the various user information requirements based on the new tools. Both FAA and industry users were the relevant users considered for these assessments. Interface design was conducted and the expected human-computer interactions were defined. Through interviews and discussions with users, subject matter experts, and senior FAA and industry leaders, initial human user roles were established to help identify information exchange and interactions (Jung et al, 2018). Preliminary issues and benefits of usability were also addressed in some of these evaluations. Candidate procedures were defined so that the development and testing could continue to mature and be evaluated in draft scenarios, including departure scheduling procedures and metering procedures (Verma et. al, 2018).

The HRL3 Evaluation Activities that were conducted as part of the IADS research include:

- Assigned human factors experts to support design and development (C.3.1.1).
- Usage scenarios were updated based on human needs (C.3.1.2).
- Situation awareness flows and requirements for human-team and automation were identified (C.3.1.5).
- Initial environment conditions and impacts were analyzed (C.3.1.8).
- Relevant human performance data were collected and evaluated to determine the feasibility of metrics for human performance (C.3.1.13).
- Preliminary design features to accommodate human capabilities, limitations, and needs were investigated and recommended (C.3.1.14).
- Requirements to support human performance were identified and included in system requirements (C.3.1.15).

4.1.4 Technology Demonstration Phase: TRL 4–6 and HRL 4–6

The Technology Demonstration Phase refers to the phase during which the concept is mature enough to conduct more formal assessments of the system. Evaluations occur in more relevant and representative environments, allowing for experimental data about the various concept parameters, including human performance characteristics. During this phase, many of the same functions and characteristics of the concept are investigated as the TRL and HRL stages progress, but the methods used during the stages become more operationally realistic as concept and user development matures.

The research team was able to evaluate IADS human performance parameters using the NASA's Future Flight Central (FFC) Simulator, a national ATC/Air Traffic Management (ATC/ATM) simulation facility dedicated to solving the present and emerging capacity problems of the nation's airspace (Figure 6). The FCC simulator offers a 360-degree full-scale, real-time simulation of an airport, where controllers, pilots and airport personnel participate to create and evaluate plans, procedures, and new technologies (https://www.nasa.gov.future-flight-central).

Figure 6. Picture from inside the Future Flight Central Tower Simulator. (Retrieved from: https://ntrs.nasa.gov/api/citations/20190031933/downloads/20190031933.pdf)

Because the development of the IADS technologies was accomplished in close collaboration with FAA and industry partners, the researchers were also able to conduct much of the work during the technology phase in the field environment, allowing for assessment of some of the HRL 4–6 parameters within both simulation and field environments. In September 2017, the ATD-2 RTC and the RMTC were installed in the CLT ramp tower with the goal of improving information exchange with the ATC Tower and to provide surface metering information to the Ramp Controllers (Parke et. al, 2019). The Surface Trajectory Based Operations (STBO) Client tool was installed in the Air Traffic Control Tower (ATCT) as the primary Traffic Management Coordinator (TMC) display, and the RMTC in Observer Mode was also made available there. The STBO Client and RMTC in Observer Mode were also placed in the CLT TRACON. In addition, the STBO Client in Observer Mode was placed at the Air Route Traffic Control Center (ARTCC or Center). Prior to this, the data exchange of information was often conveyed via phone calls between facilities.

4.1.5 Technology Readiness Level Four (TRL 4) and Human Readiness Level Four (HRL 4)

4.1.5.1 Technology Readiness Level Four (TRL 4)

TRL 4 involves demonstrating key system elements in a laboratory environment. Many of the functions, features, and procedures of ATD-2 were tested in the FFC Simulator with both FAA and airline users as participants.

4.1.5.2 Human Readiness Level Four (HRL 4)

HRL 4 involves developing and evaluating human user aspects of a system through the use of modeling, part-task testing, and trade studies of human systems design concepts and applications completed. These concepts are analyzed via trade studies and evaluated in laboratory environments to identify viable options.

The HRL 4 methods involved assessments in laboratory settings using the FFC Simulator located at NASA Ames Research Center (ARC). The research team gathered data about existing FAA and airline functions, procedures, communications, and interactions, as well as data collected using the new ATD-2 tools. These simulations were conducted with both airline ramp users and air traffic control personnel as study participants and helped prepare the research team for field evaluations.

Using the FFC ATC Tower simulator at NASA ARC, the ATD-2 Team was able to evaluate several characteristics of the tools that had been developed in the early HRL stages. Different interface features were compared and evaluated in this highly realistic tower environment (Figure 7). Candidate procedures were matured, tested, and fine-tuned with the various users. In addition, communications and interactions among users were assessed to help prepare for demonstrations in the field (Stevens et. al., 2017). Initial human user roles were established to identify information exchange and interactions (Jung et al, 2018; Stevens et. al., 2017). Additional preliminary issues and benefits of usability were also addressed in some of these evaluations.

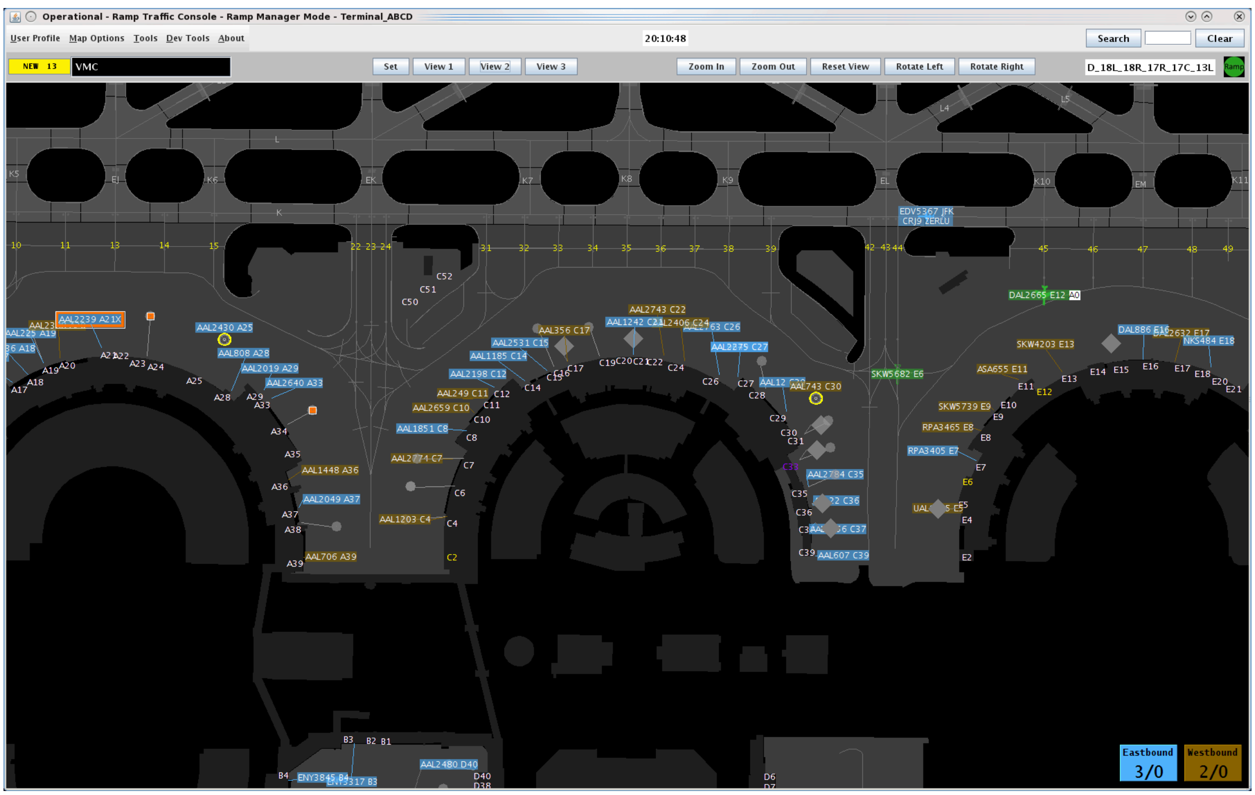

Figure 7. The ATD-2 Ramp Traffic Console (RTC) used in the simulation in the Future Flight Central Simulator in 2018. Note: This simulation used the Dallas Fort Worth International Airport as the test environment. ("Assessment of Ramp Times-4 (ART-4) Human-in-the-Loop Simulation Final Results", September 2019. (Retrieved from: https://ntrs.nasa.gov/api/citations/20190031933/downloads/20190031933.pdf.)

The HRL4 Evaluation Activities that were conducted as part of the IADS research include:

- Prototypes for human systems design concepts were developed for users to support assessment of critical human performance issues (C.4.1.1).
- Usage scenarios were updated based on part-task testing (C.4.1.2).
- Requirements for human-machine teaming and automation were identified and initially assessed in part-task testing (C.4.1.4).
- Strategies for addressing environment impacts were identified and recommended (C.4.1.7).
- Procedures were designed for human use through the lifecycle using part-task testing (C.4.1.10).
- Human performance data were collected and evaluated using part-task analyses to determine whether human performance metrics were successfully met (C.4.1.12).
- Strategies to support human use were identified and recommended based on part-task testing (C.4.1.13).

4.1.6 Technology Readiness Level Five (TRL 5) and Human Readiness Level Five (HRL 5)

4.1.6.1 Technology Readiness Level Five (TRL 5)

TRL 5 involves demonstrating key system elements in a relevant environment. In the case of IADS, many of the same functions and characteristics that were tested and matured in the FFC Simulator were then tested in operational environments of the FAA and airline users to continue their development and assessment. The methods used to examine user characteristics sometimes overlapped between simulation and field testing so there is some redundancy between HRL 5 and HRL 6 methods applied for the ATD-2 development and evaluations. Workload, situation awareness, and acceptability were investigated in most simulations and demonstrations for both HRL 5 and HRL 6.

4.1.6.2 Human Readiness Level Five (HRL 5)

HRL 5 refers to the point human-centered evaluations of prototypes in mission-relevant part-task simulations that are used to help inform the continuing design of the tools. The maturity of many of the core elements has increased significantly, so the users participating in the evaluations are representative of the users in the actual intended concept environment.

Due to a strong collaborative relationship with both the FAA and industry partners, NASA was able to investigate many of the functions for the ATD-2 tools in airline ramp and air traffic control operational environments. As the ATD-2 technologies and procedures continue to mature, many of the human performance parameters were assessed in the field demonstrations. Some of these parameters included usability, situation awareness, and workload. Procedures were also assessed and adjusted based on feedback and data from field observations. Because these data are based on actual field operations in the ATC or ramp environment, the information reflects observations and questionnaires of the users. For example, one study examined that impact of ATD-2 on workload and situation awareness for the CLT airline ramp users, ramp managers, and traffic management coordinators at CLT Tower and TRACON (Parke et. al., 2020 - DASC). The same investigation also explored the usability of the functions and tools of ATD-2.

The HRL5 Evaluation Activities that were conducted as part of the IADS research include:

- Functional prototypes for human-system interface and simulation of mission tasks and conditions were updated to support assessment of critical human performance issues (C.5.1.1).
- Usage scenarios were updated based on high-fidelity part-task testing and field testing (C.5.1.2).
- Human-machine teaming and human-machine strategies have been updated based on part-task testing and field testing (C.5.1.4).
- Strategies for addressing environment impacts were updated based on part-task testing and field testing (C.5.1.7).
- Prototyping was used in mission-relevant part-task testing and field testing to update human user roles (C.5.1.10).
- Relevant human performance data were collected to determine whether human performance metrics were successfully met, based on field testing (C.5.1.12).
- Updated strategies to support human use were identified and recommended based on part-task testing and field testing (C 5.1.13).

4.1.7 Technology Readiness Level Six (TRL 6) and Human Readiness Level Six (HRL 6)

4.1.7.1 Technology Readiness Level Six (TRL 6)

TRL 6 is representative of the deliverable demonstrated in realistic operational environments. Many of the IADS function and procedures were tested as part of field demonstrations in ATC and airline environments, allowing for a highly realistic context with participants who are actual intended users of the IADS tool.

4.1.7.2 Human Readiness Level Six (HRL 6)

HRL 6 refers to the stage when the human system design is fully matured, and the concept is demonstrated in a relevant high fidelity simulated environment or actual environment. For IADS tools, this would include ATC and/or airline ramp environments and the actual users in those locations as participants.

HRL 6 involved many human user evaluations in the field with actual ATC and airline users. These evaluations examined many of the same user parameters that were investigated during earlier HRL stages but in a more fully realistic environment. In addition, the concept and technologies continued to mature and were more representative of the intended technology deliverable. Continuing field evaluations allowed the ongoing development and refinement of ATD-2 and thorough assessments of tools and procedures.

Another benefit from the strong ATD-2 collaborations with the FAA and industry was the ability to conduct field tests in multiple sites with a variety of users. During the ATD-2 Phase 1 demonstration from 2017–2018, there were many capabilities that were developed and deployed to the Charlotte International Airport air traffic control facilities, including Tower and Ramp, as well as Washington ARTCC for field evaluation. Phase 2, which occurred from 2018–2019, included expansion of airspace deployments to include adjacent Center automation, in particular interface with the Atlanta Center (ZTL) arrival metering system to evaluate pre-scheduling of flights. Phase 3 was conducted at DFW Terminal Radar Approach Control, Fort Worth ARTCC, DFW, and DAL ATC Towers, and American and Southwest Airlines facilities at DFW and DAL airports, respectively. The Phase 3 formal data collection period included real time, operational participation by seven field facilities including American, Envoy and Southwest Airlines, DFW ATC Tower, DAL ATC Tower, DFW Terminal Radar Approach Control and Fort Worth Center. This extensive field demonstration deployment allowed for critical input from a variety of users and provided diverse user input about the many capabilities.

The HRL6 Evaluation Activities that were conducted as part of the IADS research include:

- Functional prototypes for human-system interface and simulation of mission tasks and conditions were fully developed to support assessment of critical human performance issues (C.6.1.1).
- A broad range of usage scenarios were updated based on field testing (C.6.1.2).
- Human-machine and human-machine strategies have been updated based on field testing (C.6.1.4).
- Strategies for addressing environment impacts were updated based on field testing (C.6.1.8).
- Prototyping was used in mission-relevant part-task testing and field testing to update human user roles (C.6.1.10).
- Testing in high-fidelity field testing was used to finalize procedures for human user roles throughout the lifecycle (C.6.1.11).
- Relevant human performance data were collected to determine whether human performance metrics were successfully met, based on field testing (C.6.1.12).
- Updated strategies to support human use were identified and recommended based on field testing (C 6.1.13).

5.0 Production/Deployment Phase: TRL 7–9 and HRL 7–9

The last development phase involves the final production of the technology and its deployment in the intended environment for which it was developed. This also involves final adaptation and integration with the existing environment and infrastructure.

5.1 Technology Readiness Level Seven (TRL 7) and Human Readiness Level Seven (HRL 7)

5.1.1 Technology Readiness Level Seven (TRL 7)

TRL 7 occurs when the final development version of the deliverable is demonstrated in an operational environment. For the IADS capabilities in the field at CLT, the NASA IADS system was integrated with the operational FAA systems at CLT (AEFS) and with Time Based Flow Management (TBFM) at Washington and Atlanta ARTCs.

5.1.2 Human Readiness Level Seven (HRL 7)

HRL 7 occurs when the human systems design is fully tested and verified in operational environment with system hardware and software and with representative users. Human performance is evaluated for the full range of usage scenarios and tasks with the final development system in an operational environment. As the IADS tools continued to be demonstrated in the field, they were integrated with the existing FAA AEFS and TBFM tools to more fully reflect the operational environment.

With the integration of the AEFS and TBFM operational system for CLT, the field data and user interface reflected even more realism for the FAA operational users that were part of the IADS demonstration. TBFM is a computer-based tool for air traffic controllers that schedules aircraft to arrive at specific points at specific times, creating a more efficient flow by reducing delays and unnecessary holding patterns. AEFS is a system designed to provide air traffic controllers with an electronic alternative to traditional paper flight strips. As the field testing of ATD-2 continued in operational environments, ongoing assessments of human performance metrics such as usability, situation awareness, and workload were conducted.

Another aspect that is a characteristic of higher HRL levels is the development of training. As the IADS technologies matured, the IADS teams developed many training documents that were provided in the technical transfer documents from NASA to the FAA. The training manuals were developed collaboratively with operators and other stakeholders and were frequently updated based on their feedback. The training was focused on the procedures and tasks related to those new ATD-2 features rather than the fully integrated system, although prior to final deployment the training provided by the NASA Team should offer valuable insight into a training plan.

The HRL6 Evaluation Activities that were conducted as part of the IADS research include:

- A broad range of usage scenarios and tasks were tested in an operational environment (C.7.1.1).
- Human-machine and human-machine strategies were evaluated in an operational environment (C.7.1.3).
- Strategies for addressing environment constraint and impacts were evaluated in an operational environment (C.7.1.7).
- Human user roles and procedures were tested in an operational environment. (C.7.1.10).
- Testing in high-fidelity field testing was used to finalize procedures for human user roles throughout the lifecycle (C.6.1.11).
- Relevant human performance data were collected to determine whether human performance metrics were successfully met in an operational environment (C.7.1.11).
- Recommended strategies to support human use were incorporated into the operational environment (C 7.1.12).

5.1.3 Technology Readiness Levels Eight (TRL 8) and Nine (TRL 9) and Human Readiness Levels Eight (HRL 8) and Nine (HRL 9) for IADS

5.1.3.1 Technology Readiness Levels Eight (TRL 8) and Nine (TRL 9)

TRL 8 refers to an actual deliverable qualified through test and demonstration. The IADS capabilities were not provided as a system that was fully complete and ready for implementation into an FAA operational environment, since additional steps towards possible implementation were always intended after NASA made the technical transition of IADS to the FAA.

TRL 9 refers to the actual operational use of a system. The FAA is responsible for the fielding of a new tool or procedures within their facilities. While NASA provides research, expertise, and data that intends to facilitate that decision-making process, the FAA makes all decisions regarding implementation. For these reasons, NASA did not participate in TRL 8 or 9 for the IADS system during the activities that led to the technical transfer.

5.1.3.2 Human Readiness Levels Eight (HRL 8) and Nine (HRL 9)

HRL 8 occurs when the human systems design is fully tested, verified, and approved in mission operations, using completed system hardware and software and representative users. Human performance is verified with production system in a representative environment before full-rate production and final system fielding.

HRL 9 occurs when the system is successfully used in operations across the operational envelope with systematic monitoring of human system performance. That is, the qualified system is fielded in the operational environment and operated by intended users.

NASA's ATD-2 tools were developed and evaluated for both FAA air traffic control and airline ramp users. The FAA is ultimately responsible for the safety, efficiency, and maintenance of the air traffic control systems within its facilities in the United States. The FAA also conducts the final integration, evaluation, and deployment steps of the candidate new technologies, and ultimately makes the decision to use any or all the developed technologies within their facilities. In addition, there are steps that the FAA takes that must occur before a final deployment decision is made to help complete the comprehensive evaluation of the new tools. Some of these steps include detailed cost assessments and risk evaluations.

The distinctions among the technology readiness levels are not always clear. Similarly, the human readiness levels have some overlap among them, including some overlapping requirements and methods applied among the different levels. Because of NASA's focus on air traffic management research and development rather than operational deployment, the ATD-2 team provided the technical transfer to the FAA of IADS at TRL 7/HRL 7. Although NASA conducted years of field demonstrations in a variety of FAA facilities, the IADS technology development conducted by NASA and its collaborators did not continue past TRL 7.

For this reason, this document does not include an assessment of the human user tasks at the HRL 8 or HRL 9 for the IADS technical transfer to the FAA.

6.0 Lessons Learned from the Application of the Human Readiness Levels to NASA's Technical Transfer of the Integrated Arrival and Departure System to the FAA

While investigating the IADS technical transfer activities, some common themes arose when exploring the application of HRL tasks during the system development. These are primarily based on aspects of the IADS technical transfer that either were issues that the ATD-2 Team encountered or appeared to lead to the success of the research outcomes.

1. As indicated in the suggested application of the HRLs, it is beneficial to assign human factors specialists to the team early in the development process and to integrate them into the entire team to share insights among all team members and across the technical areas, including human factors. This will ensure early consideration and integration of human factors issues and tasks and allows the human factors team to identify critical issues that may affect their research and development tasks.
2. Keep human factors specialists on the team throughout the project, including after the implementation of the system. This provides consistent application of the human

factors' principles/tasks, and allows the tracking of unexpected uses, benefits, and possible errors that users may uncover over time.

3. Establish strong collaboration with development partners and other stakeholders. This creates the essential foundation for critical information sharing and buy-in from users and stakeholders and allow for the early identification of technical or procedural issues when they arise.
4. The organizational culture of the users of the new system should be accounted for when considering TRL and HRL tasks. This culture may impact critical assumptions for the system. For example, the FAA selection and training of their staff were required to be considered when creating the procedures and interface for the tools used in the ATD-2 field demonstrations.
5. The application of the HRLs to the IADS technical transfer work led to some confusion and apparent overlap of work in different levels in the scale. This was related to the fact that the IADS research team had access to the field environment (i.e., FAA facilities and airline operations environments) early in the development process, leading to HRL tasks at the lower levels being conducted while performing higher HRL activities. For example, many human centered requirements (corresponding to HRL 2) were developed and refined while conducting workload and user satisfaction assessments in the operational field (corresponding to HRL 5). Rather than a constraint, this application should be seen as part of the flexibility of the implementation of the HRLs, and as a reminder that the many HRL steps should be revisited as the maturity of the system develops and new benefits and constraints are uncovered.
6. As with the integration of any tool into an existing system, there are existing constraints that must be considered when developing and adapting new technology. Many of the IADS tools were intended to be fielded in FAA environments that are fully operational with existing tools and procedures that were developed by and implemented over many years. There are physical and environmental constraints present in those facilities that are part of the operational requirements, as well as the expertise and characteristics of the user group(s). For example, in an FAA tower facility, the ATC staff heavily depend upon an out-the-window view to allow the controller to identify, monitor, and control airport surface traffic. The existing environmental and user requirements must be adhered to when developing and implementing new tools. It's critical to have a broad and deep understanding of these characteristics when conducting TRL and HRL tasks.

7.0 Summary and Conclusions

The development and use of HRLs is intended to complement the use of TRLs with a focus on the development and assessment of the systems or tools for human use. There has been some research and application of HRLs (Kosnik & Acosta, 2010; Salazar, G., 2020; Handley & Savage-Knepshield, 2020; Handley, See, & Savage-Knepshield, 2024), but very little application of the scale to development work in support of FAA operational systems. This document discussed the use of HRL-related tasks by the NASA research team who conducted the development and research of NASA's IADS as part of the technology transfer of the tool to the FAA in 2021. Since the HRLs were not formalized during most of the IADS development work, this was a retrospective analysis using the many documents provided as part of the transfer.

The analysis conducted revealed that many of the tasks recommended as part of the HRL Scale were conducted during the IADS system development. The NASA team included strong expertise in surface and terminal area operations. In addition, the critical broad collaboration with FAA and industry partners further added to the operational expertise and permitted extensive access to FAA and airline personnel and facilities to ensure a solid understanding of the operational and organizational constraints. The research team had human factors specialists directly involved in the design and evaluation of the tools and procedures. In the early HRL tasks, the skills and expertise of the team and subject matter experts permitted concept and requirements development. As IADS matured, simulation and fielding evaluations were conducted to assess interface characteristics, workload, user acceptance, and situation awareness. The successful transfer of IADS to the FAA is almost certainly related to the attention paid to the users when developing and assessing the tools and procedures.

The application of HRLs to IADS led to some insights regarding lessons learned, the most notable being that the scale should be applied in a flexible manner rather than assuming distinct activities at each level and the requirement for sequential progression through the scale.

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