Explore the Use of Tele-operated or Autonomous Vehicles (TAVs) in Active Incident Management

FDOT Project BED31-977-19

Final Report

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June 2025

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Explore the Use of Tele-operated or Autonomous Vehicles (TAVs) in Active Incident Management		5. Report Date May 2025 6. Performing Organization Code
7. Author(s) Nithin Agarwal, Shraddha Sagar, Maynard Factor, Varshini Kateelu		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Florida 2100 NE Waldo Rd, Sta 106, Gainesville, FL 32609		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BED31-977-19
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32366-6580		13. Type of Report and Period Covered Final 04/24/2023-06/30/2025 14. Sponsoring Agency Code
15. Supplementary Notes Mr. Jeff Frost served as the Project Manager		

16. Abstract

This report documents the development, testing, and evaluation of a Remotely Controlled Truck-Mounted Attenuator (RCTMA) system designed to enhance roadside responder safety through tele-operated vehicle deployment. Built on Kratos's ATMA platform, the RCTMA integrates servo-controlled steering, throttle, and braking with 360° video monitoring and a Control Console (C2) for remote operation. Two rounds of field testing evaluated the system's functional reliability, communication latency, braking performance, visibility, and video quality under real-world conditions. Results demonstrated successful remote operation with consistent control and emergency stop performance, although video pixelation and occasional communication latency spikes were noted. The study found that while the RCTMA is viable as a proof-of-concept, full autonomy requires further integration of remote ignition, gear control, and active obstacle detection. Recommendations include pilot deployments, improved video bandwidth management, and hardware upgrades to move the system toward operational readiness.

17. Key Word		18. Distribution Statement	
Tele-operated Vehicle (TAV), Truck-Mounted Attenuator (TMA), Remote Vehicle Control, Incident Management			
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages 114	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Executive Summary

This report documents the development, deployment, and evaluation of a Remotely Controlled Truck-Mounted Attenuator (RCTMA), a tele-operated safety vehicle engineered to protect responders in high-risk roadside environments. Conducted by the University of Florida in collaboration with Kratos Defense & Security Solutions and sponsored by the Florida Department of Transportation (FDOT), this project explored whether autonomous and tele-operated vehicle technologies could support safer incident response operations across Florida's highway network.

System Overview

The RCTMA was developed by adapting Kratos's existing Autonomous Truck-Mounted Attenuator (ATMA) platform. Key modifications enabled remote operation of the vehicle via a dedicated Control Console (C2), replacing the leader-follower setup of the ATMA with full tele-operation. The system features:

- Servo-actuated throttle, brake, and steering mechanisms.
- A 5-camera wide-angle video system providing 360° situational awareness.
- A multi-router 4G/5G cellular communication architecture.
- A C2 console equipped with steering and pedal controls, three real-time video displays, and vehicle telemetry.
- An Emergency Stop (E-stop) system with four activation methods (console, onboard, external, and loss-of-connection).

Testing and Evaluation

Two structured rounds of field testing were conducted in Fort Walton Beach, Florida, evaluating both basic functionality and operational performance.

- **Round 1** verified core capabilities such as remote control, video feedback, latency, emergency stops, and maneuvering. It served as a proof-of-concept.
- **Round 2** introduced refined protocols, continuous latency monitoring, and quantitative measurements (e.g., braking distance, path deviation, image quality).

Key Findings

- **Steering, Throttle, and Braking:** Fully functional via tele-operation with consistent accuracy across multiple speeds. Stopping performance at 5, 10, and 15 mph met expected targets.

- **Communication Latency:** Average Round-Trip Time (RTT) was 150 ms, but 81 instances exceeded 500 ms, posing potential risks in emergency response situations.
- **Video Feed Quality:** Resolution was reduced to mitigate pixelation, which helped stabilize the feed but degraded object recognition, with SSIM values as low as 0.15.
- **Visibility and Obstacle Detection:** While camera coverage was largely sufficient, blind spots and limited resolution at close range hampered operational awareness. No radar/lidar systems were integrated.
- **System Autonomy:** Remote operation was successful; however, manual startup and gear shifting were still required, limiting true autonomy.

Lessons Learned

The testing highlighted several insights:

- **Latency spikes**, while infrequent, must be addressed through network redundancy and real-time monitoring to ensure safe tele-operation.
- **Video compression trade-offs** must balance bandwidth with the operator's need for high-resolution environmental feedback.
- **Human-in-the-loop testing protocols** must reflect real-world unpredictability beyond controlled test environments.
- **Operator interface design** should prioritize long-duration use, minimizing fatigue and improving responsiveness.
- **True autonomy requires additional integration**, including remote ignition, gear control, and onboard sensors for obstacle detection.

Deployment Readiness

Subsystem	Readiness	Notes
Communication	Partially Ready	Occasional latency spikes observed
Steering, Throttle, Brake	Ready	Responsive and accurate
Emergency Stop System	Ready	All triggers functioned as intended
Video Feed	Partially Ready	Stable but low-resolution; limits object recognition
Remote Startup & Gear	Not Ready	Requires on-site safety driver
Obstacle Detection	Not Ready	No lidar/radar or automated sensors
System Autonomy	Not Ready	Human intervention still required

Conclusion

The RCTMA successfully demonstrated the technical feasibility of a remotely operated attenuator vehicle for roadside incident response. While the system is not yet fully autonomous, it offers a viable, tested platform for enhancing responder safety. Future iterations should prioritize communication stability, higher-fidelity video, and integration of autonomous features to move toward broader operational deployment.

What This Report Tells You at a Glance

✅ **What Was Built**

- A **Remotely Controlled Truck-Mounted Attenuator (RCTMA)** system that can be driven entirely by a remote operator through a control console (C2).
- Based on an existing Autonomous Truck-Mounted Attenuator (ATMA), the RCTMA includes full remote control of **steering, throttle, braking, and emergency stop functions**.
- Equipped with **5 wide-angle cameras**, cellular communication hardware, and real-time video telemetry for incident response deployment without placing a human driver in harm's way.

🧪 **How We Tested It**

- Two rounds of field testing were conducted at **Fort Walton Beach, FL** in collaboration with **Kratos Defense & Security Solutions**.
- **Round 1**: Verified basic system functions—vehicle maneuvering, braking, E-stop response, visibility, latency, and operator control.
- **Round 2**: Conducted enhanced, data-driven assessments including:
  - **Latency monitoring** (RTT)
  - **Braking performance** at 5, 10, and 15 mph
  - **Pixelation/video clarity** using PSNR and SSIM analysis
  - **Stability testing** over bumps and narrow-lane navigation

⚠️ **What Needs to Be Improved**

- **Communication latency spikes** occasionally exceeded 500 ms, which could hinder performance in emergency scenarios.
- **Video feed resolution** was reduced to ensure stability, but this limits object detection and situational awareness.
- **Lack of full autonomy**:
  - Vehicle still requires **manual gear shifting and engine start** by a safety driver.
  - **No onboard obstacle detection** (e.g., lidar/radar) is currently integrated.
- **Console ergonomics and camera placement** can be optimized for better operator comfort and visibility in blind zones.

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Glossary of Definitions

C2 driver – The individual that operates the remote-control console and remotely drives the RCTMA.

Control console (C2) – An installation that includes a computer, computer monitors, steering wheel and foot pedals, and driver seating used by the C2 driver to operate the RCTMA remotely.

Console unit – Comprises the system control unit and the operator control unit in the RCTMA.

E-stop – An emergency stop of the RCTMA initiated by one of the three E-stop buttons on the RCTMA (two external, one internal) or from the control console (C2)

Graphical user interface (GUI) – The GUI is software that presents system status to the operator and includes physical controls for the operator to interact with the system. The GUI is at the C2 displays a variety of RCTMA vehicle status information and enables system operator commands for steering, throttle, and braking (more details in the Task 2 Report, Section 2.1.2.2).

Latency (lag time) – A time delay inherent in data transmission due to communication time and processing time within the various electronic devices in the chain of transmission. See Section 5.2.

Medium duty truck – A Class 6 or 7 truck generally defined by a gross weight of 19,501–33,000 lb (FHWA Classification).

Message Broker (MB) - A message broker is a software component that facilitates communication between different applications, systems, or services by translating messages and routing them appropriately.

Operator control unit (OCU) – The panel on the dashboard of the RCTMA cab that the operator can use for system boot-up, manual take-over control interface, and E-Stop (red) initiation.

Real time – Computation that occurs synchronously, within a reasonable time constraint, with a physical event, usually to collect data of the event. This can include video data that can be presented remotely and used to allow control of a device(s) in the physical event's environment. In this project, the device is the RCTMA, and the physical environment is the RCTMA's physical location.

Remote-control truck-mounted attenuator (RCTMA) – A medium duty vehicle that carries a crash attenuator unit and can be driven by remote control.

Safety driver – A trained driver that occupies the driver's seat of the RCTMA vehicle. The driver must at all times have an active role in monitoring the safe operation of the vehicle, and in case of emergency, they are in charge. For this testing, the safety driver remained in the vehicle for all safety testing,

System control unit (SCU) – The central computer processing system in the RCTMA vehicle includes navigation and power control modules. It interfaces with operator control unit (OCU), the cellular network communications systems, and servomechanisms, and the graphical user interface (GUI).

Tele-operated or autonomous vehicle (TAV) – A vehicle which contains the necessary servomechanisms, computer control, and communications to operate autonomously or by remote control, but not both. The vehicle in this project operates only by remote control.

Glossary of Acronyms

Acronym	Definition
ATMA	Autonomous Truck-Mounted Attenuator
RCTMA	Remotely Controlled Truck-Mounted Attenuator
TAV	Tele-operated Autonomous Vehicle
C2	Control Console (Remote Command and Control Station)
FDOT	Florida Department of Transportation
RRSP	Road Ranger Safety Patrol
RTT	Round-Trip Time (Latency)
PSNR	Peak Signal-to-Noise Ratio (Image Quality Metric)
SSIM	Structural Similarity Index (Image Similarity Metric)
LOC	Loss of Connection
OCU	Operator Control Unit
SCU	System Control Unit
E-Stop	Emergency Stop
V2V	Vehicle-to-Vehicle Communication
ADAS	Advanced Driver Assistance Systems
GVW/GCWR	Gross Vehicle Weight / Gross Combined Weight Rating

Chapter 1. Introduction

The primary objective of this research project is to customize existing autonomous vehicle technology to develop a tele-operated autonomous vehicle (TAV) capable of being remotely activated, operated, and deployed as an auxiliary support unit for Road Ranger Service Patrols. This initiative is intended to explore the feasibility and applicability of integrating remote-control and autonomous systems to enhance safety and operational efficiency in the field of active incident management across Florida.

The initial phase of the project involved coordination with the Florida Department of Transportation (FDOT) to identify a suitable subrecipient and establish a formal contractual agreement. The subrecipient selection process was conducted in accordance with the project's scope and technical requirements. This included a detailed evaluation of TAV system needs and performance specifications in order to identify the most capable partner for this research initiative.

Kratos Defense & Security Solutions (Kratos) was ultimately selected as the subrecipient due to their extensive expertise in Autonomous Truck-Mounted Attenuator (ATMA) systems. Their technical qualifications, prior successful collaborations, and in-house capabilities make them well-suited to adapt or customize the ATMA platform for TAV development. The project's primary use case involves deploying a Remotely Controlled Truck-Mounted Attenuator (RCTMA) vehicle to Road Ranger incident response locations.

Kratos also possesses the necessary resources and technical expertise to design and construct the TAV vehicle in full compliance with project specifications. In collaboration with Kratos, the project team developed a comprehensive specification document that outlines the vehicle's communication, hardware, and software requirements. That document is presented in this report, which also provides an overview of the first round of system testing conducted on April 15, 2024, followed by a second round on December 3, 2024, to assess and demonstrate the proof-of-concept functionality of the RCTMA system.

1.1. Project Goals and Requirements

The primary goal of this project is to tailor existing autonomous vehicle technologies to develop a TAV that supports full remote operation. The selected subrecipient was required to demonstrate subject-matter expertise in Autonomous Truck-Mounted Attenuator (ATMA) systems, as well as possess the technical capacity to adapt or reconfigure the ATMA platform into a fully functioning TAV or remotely operated ATMA unit.

In addition to vehicle design and fabrication, the subrecipient was responsible for developing a detailed specification document addressing all relevant aspects of communication systems, hardware components, and software infrastructure. This document serves as the technical blueprint guiding both the construction and testing phases of the RCTMA.

Moreover, the subrecipient was expected to collaborate with the University of Florida (UF) to support the execution of bench testing and closed-loop validation. These tests were aimed at evaluating the operational functionality and safety performance of the TAV system prior to and during field demonstrations.

1.2. Subconsultant Selection Process

To identify an appropriately qualified subrecipient, the project team conducted an extensive search for vendors and organizations with proven expertise in ATMA technologies and remote operation of autonomous vehicles. The search was carried out both within Florida and nationwide and included the review of prior work completed by potential vendors, as well as direct engagement with industry leaders at professional forums such as the ITS America Annual Meeting, the ITS World Congress, and the Transportation Research Board (TRB) Annual Meeting.

Despite exhaustive efforts, none of the potential vendors identified through this process fully met the specific technical and operational criteria established for this project. However, previous collaborations with Kratos Defense & Security Solutions, Inc. had demonstrated strong technical performance and alignment with the project's objectives. Given their successful track record and extensive experience, Kratos emerged as the sole and most qualified candidate.

In accordance with FDOT guidance and University of Florida procurement policy, a sole-source notice was formally issued through UF Procurement Services. The notice was published on the UF Procurement website and remained open for public comment. No objections or alternative submissions were received. Consequently, Kratos was officially selected as the project’s subrecipient based on their unmatched qualifications and specialized expertise in ATMA technology and autonomous vehicle operation.

1.3. Subconsultant Company Overview

Kratos Defense & Security Solutions, Inc. is a leading technology company operating in the defense, national security, and global markets. The organization specializes in developing and deploying affordable, transformative systems, products, and solutions to meet the needs of U.S. government agencies, allied defense forces, and global commercial partners.

With a workforce of over 3,000 employees located across more than 60 sites worldwide, Kratos maintains an expansive operational footprint. The company focuses on accelerating the deployment of breakthrough technologies by offering systems that are not only innovative but also cost-effective and deployment-ready.

Kratos emphasizes speed and agility in its business operations, ensuring that real-world solutions—not just theoretical models—are brought into service quickly and effectively. Their strategy prioritizes affordability at scale, factoring in variables such as cost, system quantity, user base, and lifecycle attrition. By leveraging next-generation technologies, Kratos aims to function as a force multiplier, dramatically enhancing the capabilities of the systems they develop. Their forward-leaning, adaptive culture reflects a deep commitment to innovation, mission effectiveness, and real-time responsiveness.

1.4. Capabilities to Fulfill the Project Requirements

The Uncrewed Systems Division at Kratos is responsible for supporting the FDOT-UF TAV development program. This effort draws on Kratos's considerable background in deploying autonomous and tele-operated systems for both defense and commercial sectors. Their field-tested technology base enables rapid configuration and deployment of proven solutions tailored for highway work zone and incident response scenarios.

Kratos first introduced its Autonomous Truck-Mounted Attenuator (ATMA) system in 2017. As shown in Figure 1, the ATMA platform consists of a two-vehicle system: a human-driven leader vehicle and a driverless follower vehicle. The leader vehicle transmits encrypted navigation data to the follower vehicle at a frequency of 10 times per second using vehicle-to-vehicle (V2V) communication. The follower vehicle processes this data and autonomously follows the leader, maintaining its trajectory and speed while keeping a fixed following distance.

This established ATMA system serves as the foundational architecture for the current RCTMA initiative. The project aims to convert the follower vehicle into a fully autonomous, remotely controlled unit—eliminating the need for a leader vehicle and enabling complete operation from a remote control console.

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Figure 1. ATMA system as used in the proof-of-concept project BDV 31-977-133. The autonomous follower vehicle (blue) is shown on the left with a crash attenuator deployed at the back (yellow). The white vehicle on the right is an FDOT truck retrofitted with the necessary equipment to act as a leader vehicle.

Chapter 2. RCTMA and C2 Specifications

Work zone safety is a significant concern in the State of Florida and among federal, state, and local agencies across the United States. Unfortunately, work zone-related incidents continue to rise. Based on crash data from 2017–2021, Florida experienced more than 53,000 work zone-related crashes, resulting in over 356 fatalities and more than 1,904 severe injuries. Nationally, work zone crashes increased by approximately 40% from 2020 to 2021, with work zone fatalities rising by more than 10% over the same period.

In Florida, work zones include areas where Road Ranger Safety Patrol (RRSP) personnel are often the first responders. These personnel are responsible for establishing temporary traffic control measures at incident scenes, placing them in high-risk situations. With a nationwide push to improve safety in work zones, Connected and Autonomous Vehicle (CAV) solutions—such as the ATMA and TAV platforms—have emerged as promising tools to enhance safety and operational effectiveness.

2.1. RCTMA Introduction

Incident management operations are inherently hazardous. A key objective of the TAV program is to evaluate the feasibility of the Remotely Controlled Truck-Mounted Attenuator (RCTMA) system as a critical safety tool that can be remotely deployed to incident locations. By serving as a mobile barrier, the RCTMA can provide added protection for RRSP personnel against errant vehicles, thereby improving the safety of incident response operations.

The RCTMA system is based on a conversion of the Autonomous Truck-Mounted Attenuator (ATMA) from a leader-follower platoon configuration to a fully remote-controlled platform. In the current ATMA setup, a multi-vehicle convoy includes a human-driven "leader" vehicle and a driverless "follower" vehicle, which is the ATMA itself (see *(*Source: Kratos Defense & Security Solutions)* Figure 2). The leader vehicle is equipped with onboard computers and navigation systems that transmit data to the follower vehicle at a frequency of 10 times per second over an encrypted Vehicle-to-Vehicle (V2V) communications link.

The ATMA follower vehicle is outfitted with computers, sensors for situational awareness, and actuators for steering, throttle, and braking. As the leader vehicle travels its route, it collects data such as position, speed, and heading. This data is transmitted to the follower vehicle in packets known as "eCrumbs". The follower vehicle receives these packets, processes the navigation data, and autonomously controls its steering, braking, and acceleration to replicate the leader's trajectory—without any onboard driver.

*(*Source: Kratos Defense & Security Solutions)*

*Figure 2. Leader-follower platoon ATMA**

In contrast, the RCTMA system is designed to operate as a standalone vehicle, controlled by a remote operator from a Command and Control (C2) station. The ATMA follower vehicle is retrofitted with video cameras and cellular network communications equipment, which eliminates the need for a leader vehicle. Instead, a human operator located at the C2 station remotely drives the vehicle using real-time video feedback and a command interface (see Figure 3).

The C2 station includes all necessary components to enable remote operation, including communication interfaces, video displays, computing equipment, and user control systems. During the TAV program, a safety rider will remain onboard the RCTMA during testing to monitor system performance and to take manual control of the vehicle if necessary.

Figure 3. Remote control TMA (RCTMA)

2.1.1. Hardware Specification

The RCTMA system is built upon a modified 2018 Hino 268 medium-duty truck, which serves as the base platform. This vehicle is equipped as a standard TMA follower unit and includes a deployable crash attenuator system, along with other typical highway maintenance features (see Figure 4). The 2018 Hino 268 has a Gross Vehicle Weight (GVW) of 25,900 lbs and a Gross Combined Weight Rating (GCWR) of 26,000 lbs. It is powered by a 7.6-liter inline 6-cylinder diesel engine.

There are no gross weight limitations specific to RCTMA operations, provided the vehicle operator is appropriately certified in accordance with state and federal guidelines.

Figure 4. Kratos autonomous truck-mounted attenuator (ATMA)

The RCTMA system integrates both existing components from the original ATMA platform and new components required to enable remote control functionality. The retained components from the ATMA include:

- **System Control Unit (SCU)**
- **Operator Control Unit (OCU)**
- **Actuators for steering, throttle, and braking**
- **Emergency Stop (E-Stop) controls**
- **Dual GPS antennas**
- **Associated linkages, brackets, and cabling**

To support remote operation, the following new components are added to the RCTMA platform:

- **Cellular network communication routers**
- **Cellular antennas**
- **Forward- and rear-facing video cameras**
- **Power and interface cabling**

- **Mounting hardware and brackets**

A notional block diagram of the full RCTMA hardware configuration is provided in Figure 5.

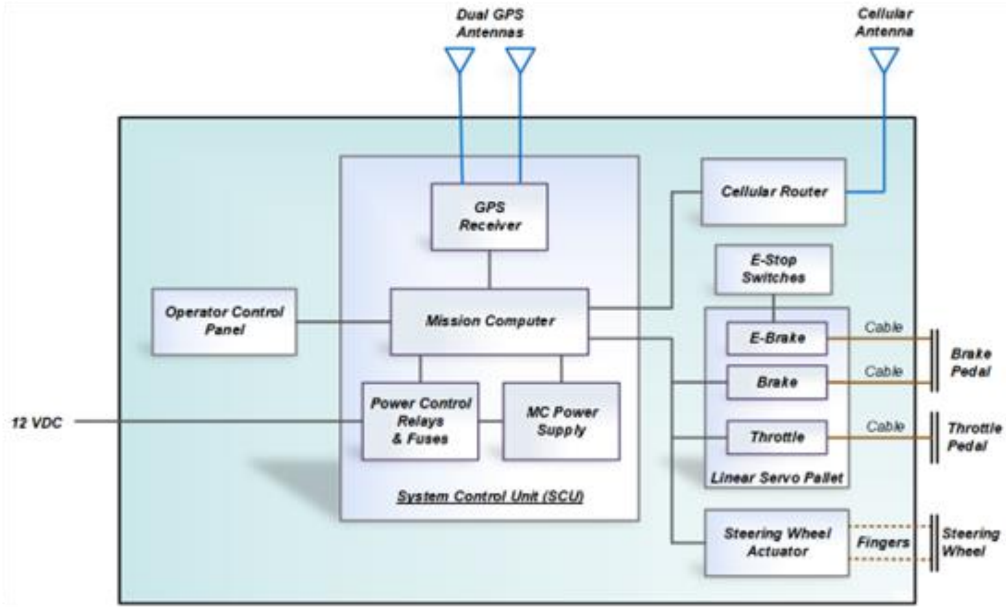


Figure 5. RCTMA system hardware (notional)

2.1.1.1. System Control Console (SCU)

The SCU shown in Figure 6 is the central computer processing system and includes navigation and power control modules. It shall interface to the Operator Control Unit, cellular network communications systems, actuators, and GUI.

Figure 6. System Control Unit (SCU)

2.1.1.2. Linear Servo Pallet

The linear servo pallet shall comprise three linear actuators that interface to the throttle and brake pedals using control linkages and steel cables as shown in Figure 7. The pallet includes one throttle actuator and primary and backup brake actuators.

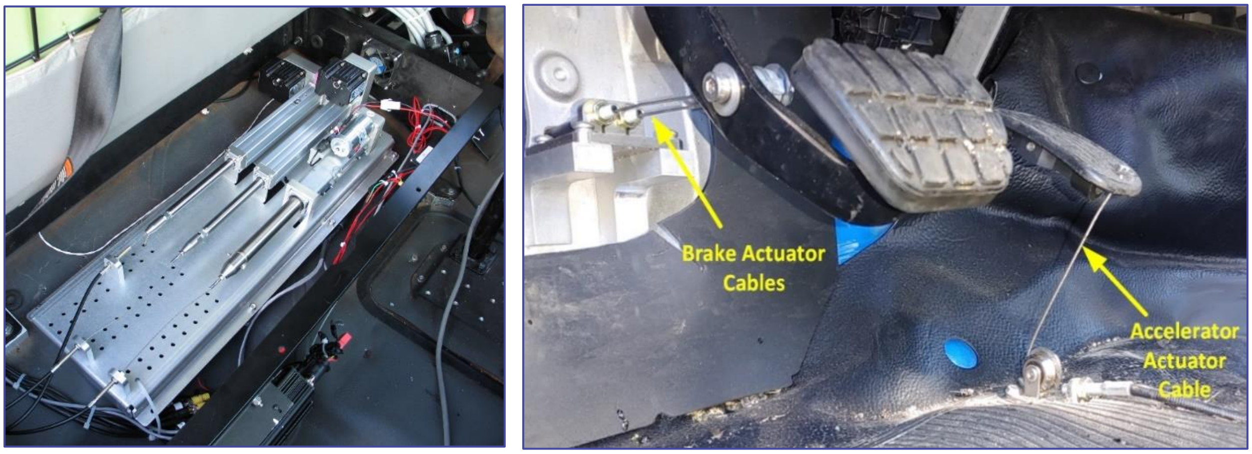


Figure 7. Linear Servo Pallet

2.1.1.3. Steering Actuator

The steering actuator (see Figure 8) shall interface to the spokes of the steering wheel using two removable finger-brackets to control left and right steering.

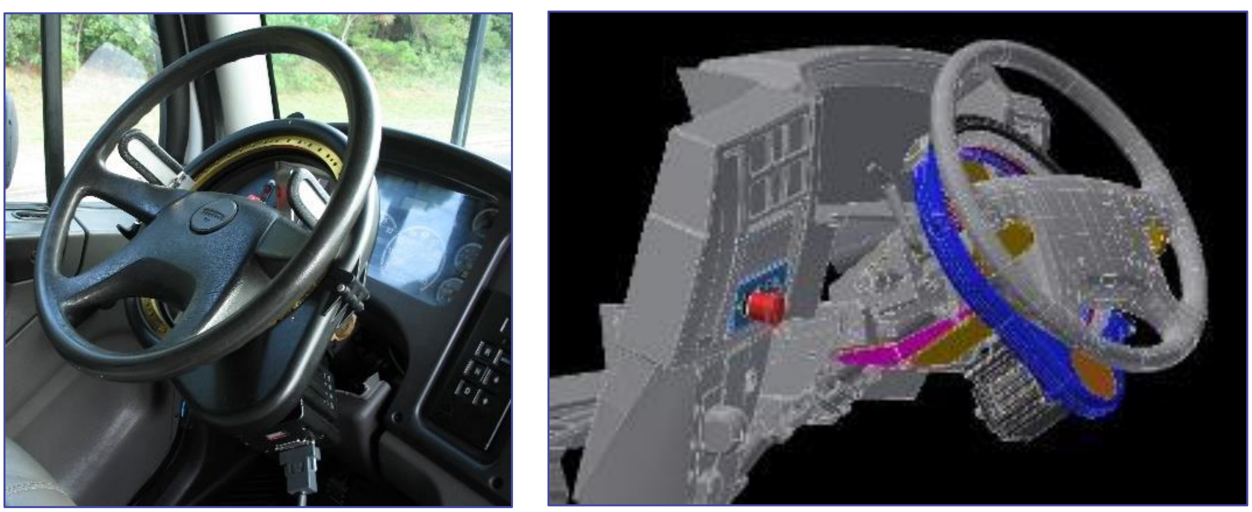


Figure 8. Steering Actuator

2.1.1.4. Emergency Stop

Emergency stop (E-Stop) switches as shown in Figure 9 shall be provided on the RCTMA to enable an operator inside or outside the vehicle to command the vehicle to an immediate stop when in remote control mode of operation. The RCTMA includes multiple E-Stop methods as follows:

- Remote Control Console E-Stop – This is an E-Stop switch at the Control Console that the system operator can initiate at any time. Once initiated, the vehicle system will engage brakes and release throttle.
- Auto E-Stop – If communication to the modem interfaced to the SCU goes down or there is loss of command signal, the RCTMA will automatically engage brakes and release throttle.
- External Vehicle E-Stop – When initiated on the vehicle, the RCTMA will automatically engage brakes and release throttle.
- Internal Vehicle E-Stop – When initiated on the vehicle, the RCTMA will automatically engage brakes and release throttle. This is applicable only when a safety rider is onboard the RCTMA.

When an E-Stop switch is activated, the engine's ignition shall be shut off and an independent brake servo actuator shall apply full force to the vehicle's brake pedal. The E-Stop switches shall apply 12-VDC power directly to the independent actuator from the vehicle's battery to prevent the system from interfering with the E-Stop function. The E-Stop 12-VDC signal shall be sent to the MPAK mission computer, telling it to return to an idle condition (if it is able to do so) and remain idle until the operator removes and reapplies power to the system.

Figure 9. E-Stop Switch

2.1.1.5. Operator Control Unit (OCU)

The operator control unit (OCU) as shown in *Figure 10* shall be the user interface for system boot-up, manual take-over control interface, and E-Stop (red) initiation from inside the RCTMA.

Figure 10. Operator Control Unit (OCU)

2.1.1.1.6. Cellular Network Communications Router

The cellular network communications router as shown in Figure 11 shall provide the communications link between the RCTMA and the remote C2. The routers used in the RCTMA shall be rated for operation over the temperature range of −22°F to +131°F and shall operate from a vehicle-supplied voltage source ranging from 10 VDC to 18 VDC. The routers shall accept local area network RJ-45 or RJ-49 connectors from the cameras and SCU.

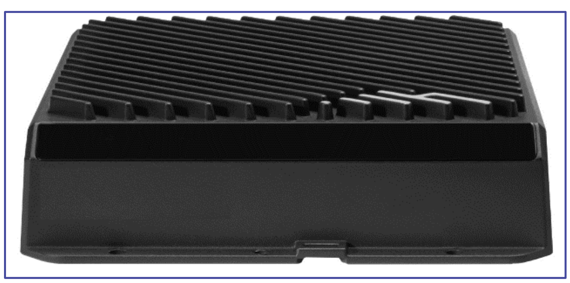


Figure 11. Cellular Network Communications Router

2.1.1.6. Cameras

The cameras as shown in Figure 12 shall be standard Internet protocol (IP) cameras and provide forward- and rear-facing video that is transmitted from the RCTMA to the remote C2. The RCTMA includes five cameras that provide a nearly 360° field of view.

Figure 12. IP Camera

2.1.1.6.1. Video Streaming

Each camera shall produce a digital Internet protocol (IP) output that shall be sent to the remote-control console via a 4G or 5G cellular network. All cameras shall use H.264 or H.265 video compression to reduce the bit rate of the IP signals that are transmitted to the remote-control console. Kratos recommends that all SIM card service plans provide a minimum UPLINK and DOWNLINK data rate of 50 megabits per second to ensure smooth transmission of video feeds.

2.1.1.6.2. Cellular Networks

The live video streams from all five cameras shall be simultaneously transmitted to the remote-control console over one or more 4G/5G cellular networks. Each cellular modem in the vehicle has a matching cellular modem at the remote-control console. The matching modems use the service provider's cellular network, and each modem has a unique static IP (Internet Protocol) address, such as '166.195.87.34' or '108.144.249.238'. The IP addresses are fixed on the SIM cards and cannot be changed. The modems use the IP addresses to find and communicate with each other for the transfer of data and video. For enhanced security, the video and data are hidden on the internet using a Virtual Private Network (VPN) and are fully encrypted using the highly secure AES-256 encryption method. Kratos-MSI shall acquire and maintain service contracts with AT&T, T-Mobile, and Verizon during the development and demonstration phases of the program. Figure 13 illustrates the system diagram showing the full network.

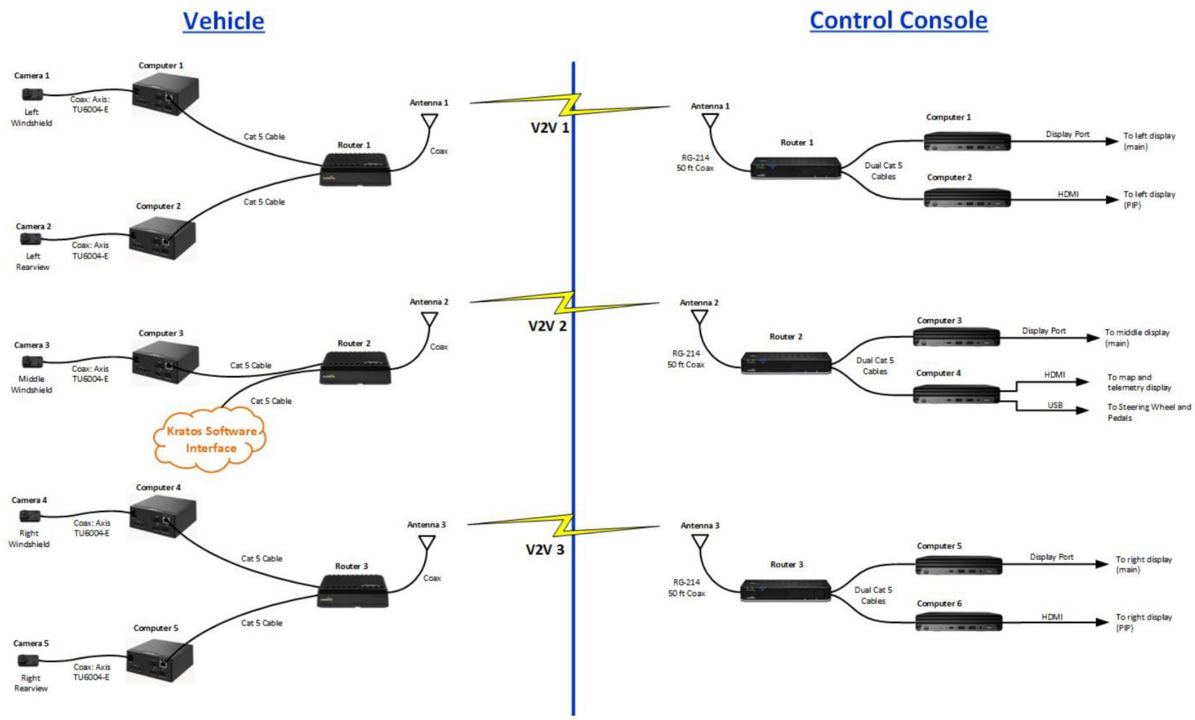


Figure 13. Full System Network Diagram

Each modem in the vehicle simultaneously holds 2 different SIM cards for using 2 different carriers. The system software can be reconfigured to use either SIM card. Switching between one service provider (SIM 1) to the other service provider (SIM 2) is a manual process that can be done by the system operator from the Control Console. This requires the system operator to initiate the switch and make adjustments to system configure to accommodate switching to the other service provider. This requires a service interruption that can take a few minutes to perform to transition from one carrier to the next. It should be noted that this is not something that can occur while the system operator is driving the RCTMA. The RCTMA needs to be parked as the switch from one service provider to the other is being performed. Further, the current system only supports 2 carriers per modem as described in the previous paragraph. If additional carriers are required, then 1 of 2 options can be used: 1) the operators can switch SIM cards in the field and change the modem software settings to reconfigure them for the different carriers, or 2) additional modems and control consoles could be added to the system with the different SIM cards pre-installed and pre-configured.

The mobile and ground-based IP routers shall have provisions for a primary and backup SIM card capability to provide backup cellular service in case the primary service becomes unavailable. The cellular service plans shall provide a minimum uplink data rate of 50 megabits per second (the actual uplink bit rate will vary depending on the distance to the cell towers, natural or manmade obstructions that degrade the cellular signals, excessive demand for cellular service in a local area, etc.). To mitigate these issues, multiple cellular routers may be used to minimize the data rate required by each cellular connection. If the local cellular services are determined to be inadequate for remotely controlling the TAV even with multiple routers, Kratos-MSI shall investigate using other satellite service providers such as HughesNet, ViaSat, Starlink, IntelSat, Iridium, etc. The results of these investigations shall be provided for the final report.

A monthly fee is required for each SIM card regardless of whether it is being used or not. However, there are no additional charges for minutes or data usage. The selection of the service provider can be done based on their ability to offer optimal performance within the coverage area, depending on the specific deployment location. A coverage analysis should be conducted across deployment locations to determine optimal service providers.

2.1.1.6.3. Encryption

The routers shall encrypt and decrypt the video streams using an IP-secure (IPSec) tunnel to authenticate and protect the video signals from unwanted eavesdropping, alteration, or interception. The encryption type shall be Advanced Encryption Standard (AES) 256 or AES 128. Kratos-MSI shall assign and maintain the encryption keys for the system.

2.1.1.6.4. Interference in communication

The study examines the impact of interference to the communications link between the Control Console and the RCTMA. Leveraging the expertise of Kratos in developing and fielding systems for the U.S. Department of Defense, Kratos takes into consideration and implements multiple mitigation techniques to harden communication links against interference and malicious hacking.

With regards to network congestion, if the network congestion initiates a loss of communication between the RCTMA and the Control Console, the RCTMA will initiate an auto E-Stop engaging the brakes and releasing the throttle. With regards to malicious injection of cellular data independent and/or in conjunction with network congestion, Kratos has hardened the communications link in multiple ways that include highly secure AES-256 encryption and implementation of a VPN as stated in a previous question response. Additionally, a checksum for the data transmitted over the cellular network is created and verified at the receiver. If the checksums do not match due to network interference, congestion, malicious hacking, etc., the data is dumped. If too much data is dumped, the RCTMA system will auto E-Stop and disengage.

2.1.1.7. C2 Hardware Specification

The C2 shall provide a realistic cockpit environment with the controls and displays required for a system operator to manually drive the RCTMA safely on state and federal roads as shown in the notional example of Figure 14.

Figure 14. RCTMA C2

2.1.1.7.1. C2 Operator Displays

Each of the three main operator displays on the console shall have a minimum diagonal viewing area of 27 inches. They shall provide a user-selectable resolution of up to 2560×1440 pixels in full color with an aspect ratio of 16:9. The displays shall have picture-in-picture (PIP) capability with DisplayPort and HDMI video inputs. The PIP function shall be used to display the rearview camera views on the left and right monitors. A smaller display (not shown) shall be provided beneath the 27-inch monitors. The smaller monitor shall display a combined moving digital map of the current RCTMA GPS position and shall display status and telemetry data from the RCTMA, including the vehicle speed, engine RPM, engine temperature, fuel remaining, transmission gear, and other vehicle status information that is required for safe operation. The monitor shall operate from standard 120 VAC.

2.1.1.7.2. C2 User Controls

The steering wheel and pedals used on the C2 shall be a Logitech model G920 Driving Force Steering Wheel with integrated hand controller and pedals or equivalent.

2.1.1.7.3. C2 Computers and Routers

The C2 shall include the computers and 4G/5G cellular network routers necessary to receive, decode, and display video signals from the RCTMA and transmit the driver's steering and braking commands to the vehicle. A notional diagram of the computers and routers layout, assuming that three separate 4G/5G networks will be required for the RCTMA application, is provided in Figure 15.

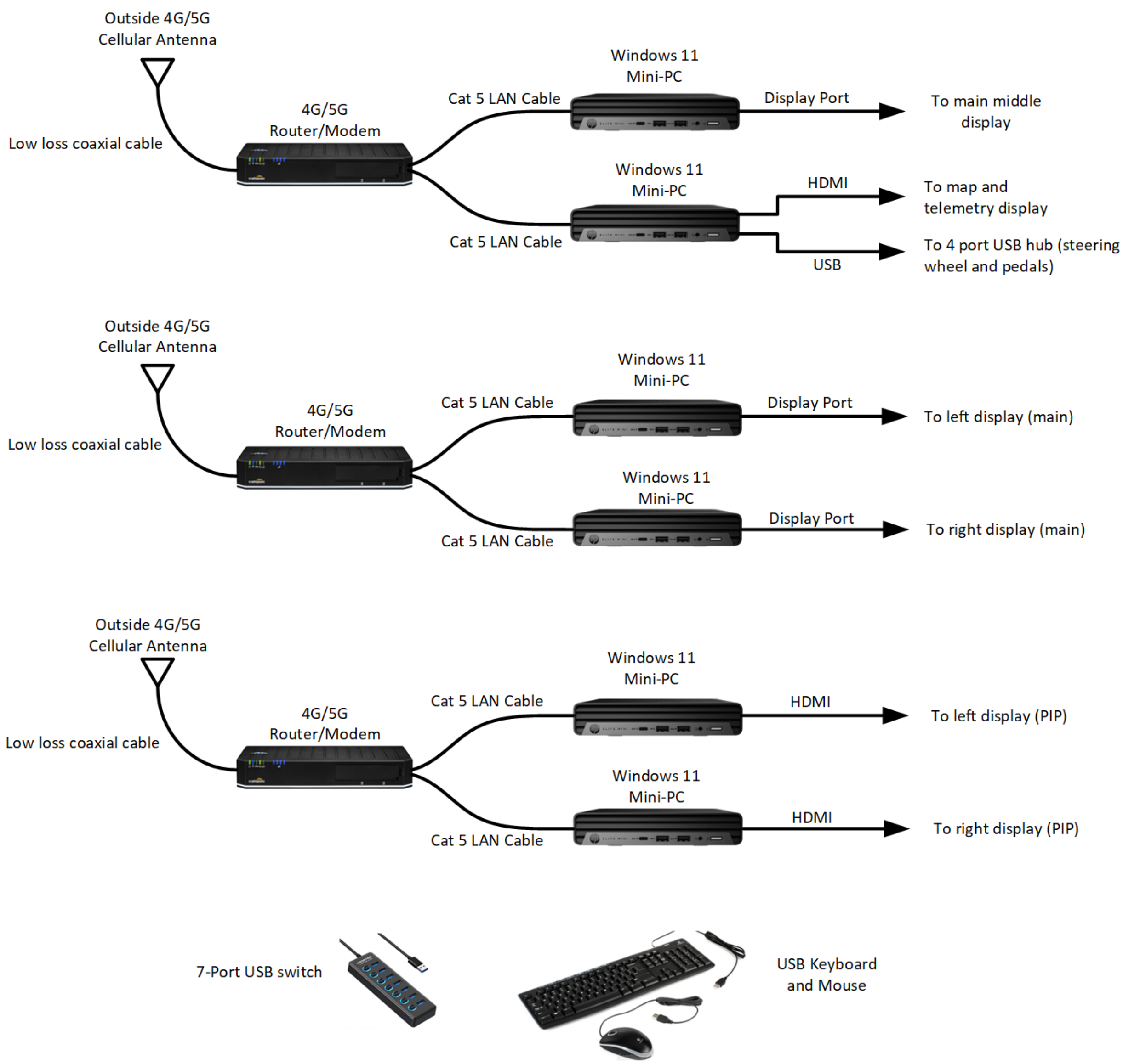


Figure 15. RCTMA C2 Computer and Router Configuration

2.1.1.7.4. Communication with Regional Traffic Management Center (RTMC)

As described in 2.1.1.1.6. Cellular Network Communications Router, the RCTMA communicates with the remote C2. For the proof-of-concept demonstration, the remote C2 is located at the Kratos facility. Status and remote control of RCTMA non-TAV equipment, such as signboard and TMA, are not included in the proof-of-concept demonstration; this capability can be supported in the next phase of the TAV program.

Enabling communication between the vehicle and C2 regarding response events, such as when the TAV parks next to the RRSP vehicle, activates its lights and/or arrow board, deploys its attenuator, or detects impact using its sensors, if feasible. The vehicle's system would require sufficient input-output or serial (RS-232, CAN, etc.) interfaces to facilitate this communication effectively. Consequently, software updates would be necessary to manage these components and transmit status information to the C2. Additionally, essential modifications to the GUI software at the C2 would be required to facilitate the display and control of these components.

2.2.1. Software Specification

The software specification includes RCTMA and C2 components.

2.2.1.1. RCTMA Software Specification

The RCTMA includes graphical user interface (GUI) software for system operator control and configuration and embedded software operating control algorithms and peripheral interfaces. The GUI software architecture shall be a modular configuration using a Windows OS. The embedded software architecture shall be implemented using an industry standard ROS 2.0 framework and modular software nodes hosted on a processing system using the Linux operating system (OS). A notional block diagram of the RCTMA software architecture is provided in *Figure 16*.

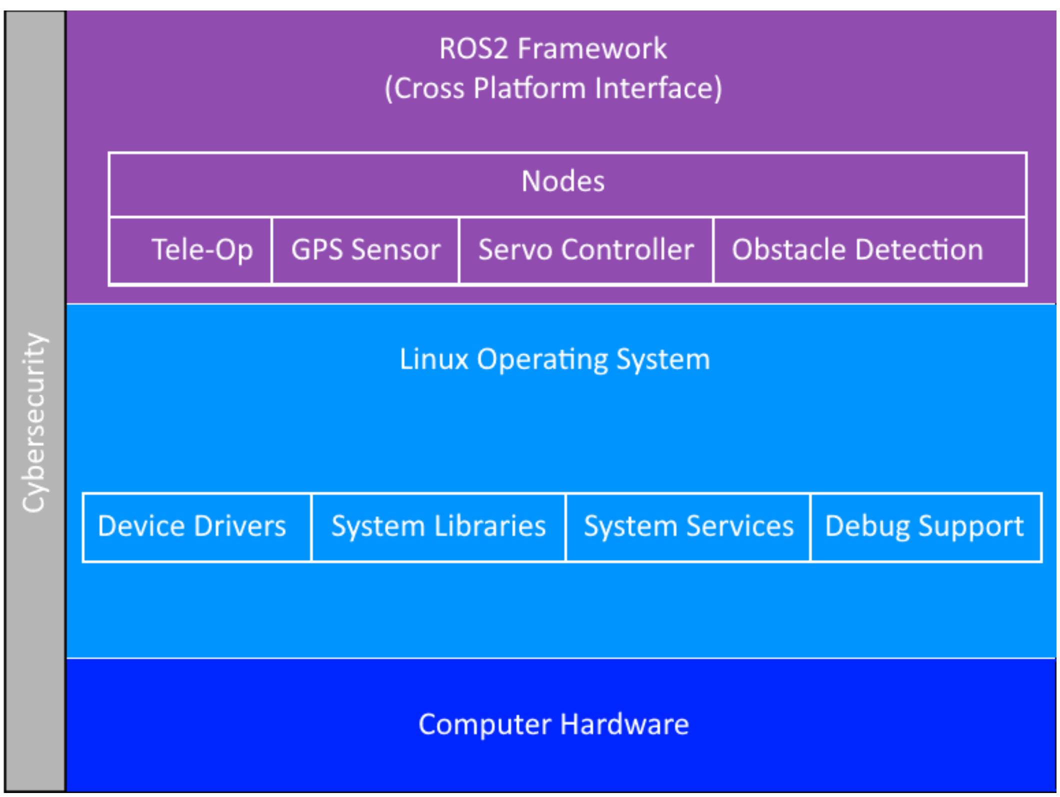


Figure 16. RCTMA Software Architecture

2.2.1.2. ROS 2.0 Framework

ROS 2 (Robotics Operating System 2.0) framework shall be used to provide the following benefits for the RCTMA:

- Modularize software components for robust operation and testing
- Support cross-platform operation
- Allow collaboration of software running on multiple computer systems
- Allow easy replacements of sensor interface software and application algorithms
- Limit software errors to a single software module

2.2.1.3. Modular Software Nodes

RCTMA software shall be designed as modular software nodes running under ROS 2 application framework. The software shall separate operational concerns for safety. For example, an application error triggered in the sensor interface node shall not fail the main control system node.

Software modules shall be divided into their main concerns such as sensor interface nodes, control system node, navigation system node, etc. Each node shall only implement the task relating to the node and delegate the unrelated tasks to other nodes in the ROS 2 ecosystem.

2.2.1.4. Linux Operating System

A customized Linux operating system shall be used for running ROS 2 ecosystem and RCTMA application nodes. Linux OS shall support automatic starting of the RCTMA application on power-up. The Linux OS shall provide runtime debugging support. The Linux OS shall support cybersecurity applications and configuration as required.

2.2.2. C2 Software Specification

The C2 software architecture shall be adapted from an existing Kratos C2 software architecture currently supporting military remote control vehicle applications. The software architecture will be a modular configuration using a Windows OS, with cybersecurity best practices applied. A GUI shall also be provided to display RCTMA vehicle status information and enable system operator commands for steering, throttle, and braking, as shown in the notional concept in *Figure 17*.

Figure 17. C2 GUI Display

2.2.2.1. Cybersecurity Specification

Cybersecurity precautions shall include a combination of technologies, processes, and practices protecting the network, computers, and data from attack, damage, or unauthorized access. The C2 system computers and communications are prevented from accessing any internal/external vehicle hardware interfaces directly. Additionally, there shall be no Wi-Fi or Bluetooth interfaces installed on the C2 system, completely isolating the Windows OS from external wireless networks to minimize cyber-attack vulnerabilities. Cybersecurity risks shall be further mitigated by limited physical access, vulnerability management, and system hardening techniques.

Kratos implements secure coding practices to establish a standard "Coding Guideline" for software development. Kratos has a "Software Practices & Guidelines for C++ Development" that is used as our guideline for software development. This provides guidance to Kratos Software engineers with good C++ programming practices and C++ coding recommendations common in the C++ community. Additionally, we run our software through a "Static Code Analyzer" tool called CCPCheck. This provides unique code analysis to detect bugs and focuses on detecting undefined behavior and dangerous coding constructs. The CCPCheck tool that we are currently using statically tests code to the MISRA C/C++ standard (C 2004, 2012, amendment 1, 2, 3; and C++ 2008, 2023).

The GUI software shall use secure coding practices and with Windows 11 providing a stable OS with support for the latest security updates to be maintained. Other maintenance activities and vulnerability management shall be a consideration to provide limited administration access using strict password controls managed by a designated system administrator. The following 'baseline' cybersecurity posture shall be implemented on the C2 system:

- Update the OS with the most recent security patches
- Update Basic Input/Output System (BIOS) Version
- Update system drivers
- Implement 'basic' security controls to include:
    - Password policy
    - Firewall rules
    - Updating antivirus definitions
    - Configure Audit Rules
    - AppLocker (as necessary)
    - Enable BitLocker Drive encryption (as necessary)
- Clean-up or remove unnecessary applications like:
    - Xbox application
    - Calendar and Mail
    - Weather
    - Desktop App Installer
    - Photos
    - Feedback Hub
    - Store and Store Purchase App
    - Groove Music
    - Alarms & Clock
    - Movies & TV
    - Sticky Notes
    - People
    - Microsoft Solitaire Collection
    - Get Office
- Minimize background processes to increase performance
- Customize background, start-up menu, taskbar, and screen lockout

2.2.2.2. Operator Control Interface (OCI) Specification

The C2 software architecture includes an operator control interface (OCI), which will be the main user interface for controlling RCTMA. Commands to control the RCTMA initiated through the OCI and telemetry from the vehicle are displayed on the OCI. The OCI provides a "Tele-Op" mode of operation which allows the operator to manually drive an RCTMA via remote control. The OCI shall provide the following remote-control capabilities:

- Remote start of the RCTMA
- Indicators showing current status of RPM, fuel remaining, throttle, brake, steering input, engine temperature, and transmission gear

- Commanding transmission positions: Park, Neutral, Reverse, Drive
- Map display with topology, geographical data (e.g., roads, buildings, barriers, boundaries, emergency locations) and satellite imagery (e.g., OpenStreetMap, MapQuest, MapBoxSat), all while showing the current RCTMA position
- Indicators for RCTMA Warnings from OBD vehicle interface: (N*ot included in proof-of-concept demonstration, due to limited CAN bus interfaces in current hardware design)*
- Status of communication link between the C2 Software and the RCTMA
- Emergency stop (E-Stop)

The OCI shall provide the capability to record all command and telemetry values for post-processing and playback of the operational event.

2.2.2.3. Video Streaming Software Specification

Kratos shall research commercially available video player programs that run on Windows 11 and determine which ones will meet the requirements for the RCTMA. The selected video player shall meet the latency requirements specified in this document as a minimum. The rationale for either recommending a player or not recommending it shall be provided in the final report.

2.2.3. Operational Specification

The RCTMA and associated C2 shall include all necessary computers, communications interfaces, and user controls to enable a proof-of-concept bench-top demonstration of the remote control system. Key operational specifications include:

- Maximum Speed: 20 mph
- Communications: Cellular network
- Navigation: Remote control
- E-Stops: 2 cab-external
- Independent E-Stop: Remote E-Stop
- System Redundancy: Braking
- Forward View Cameras: 3
- Rear View Cameras: 2
- Mobility: Forward *(Reverse not included in proof-of-concept demonstration)*
- Ignition: Manual control
- Transmission: Manual control
- GPS-Denied Operation: Via Remote Control
- Operational Modes: Manual and Remote Control modes of driving
- Vehicle: Maintains normal ability to perform non-AV functions
- Interface for initialization: Tablet PC

Additionally, GPS is only used to display the vehicle's position on the remote-control console map display. Control of the vehicle is not affected if the vehicle loses GPS signal, and the operator still has full situational awareness and secure vehicle control as long as the cellular service is capable of transmitting video back to the control console.

2.2.3. Customization

The RCTMA shall be customized with a combination of legacy ATMA components and new components enabling remote control operation. The legacy components are already integrated into the ATMA vehicle, establishing the base RCTMA configuration. The new components include the cellular network communications routers and the forward- and rear-facing cameras.

2.2.3.1. Cameras

The cameras used for remote control shall be capable of producing full color video streams with a minimum resolution of 800×450 pixels at an aspect ratio of 16:9. Five cameras shall be installed on the vehicle to provide maximum visibility in all directions with minimal image distortion. Three of the cameras shall face forward to provide a horizontal field of view (FOV) of 180°. The other two cameras shall provide a minimum horizontal FOV of 90° each to provide rearview images on both sides of the vehicle. The minimum vertical FOV of all cameras shall be 45°. The cameras shall be rated for operation over the temperature range of −22°F to +131°F and shall be waterproof to the levels specified by IP66 and IP76 for electronic enclosures. The cameras shall operate from any vehicle-supplied voltage source, ranging from 10 to 18 VDC.

Accommodating remote control capability for pan/tilt/zoom (PTZ) cameras from the C2 is indeed feasible. However, the current POV navigation cameras lack PTZ functionality. To implement this feature, additional hardware and software are necessary to establish an interface between the controller and the C2, facilitating the transmission of commands to the vehicle.

2.2.3.1.1. Forward-Facing Cameras

The three forward-facing cameras shall be installed in locations that provide the same FOV that a human driver would have while driving the vehicle. As shown in *Figure 18* the right-facing camera (camera 1) shall be mounted on the passenger side of the vehicle, the front-facing camera (camera 2) shall be mounted directly in front of the driver, and the left-facing camera (camera 3) shall be mounted to the left of the driver. All three cameras shall be mounted near the top of the windshield to avoid blocking the view of the driver.

Figure 18. RCTMA Three Front-Facing Camera Locations

2.2.3.1.2. Rear-Facing Cameras

The two rearview cameras shall be installed in locations that provide 90° horizontal views from the two sides of the vehicle without blocking the rearview mirrors from a human driver. As shown in *Figure 19*, the driver's side rearview camera (camera 4) shall be mounted on the steel bar rising from the flat bed of the vehicle. The passenger side rearview camera (camera 5) shall be located in a similar location on the passenger side as shown in *Figure 19*.

Figure 19. RCTMA Rear-Facing Camera Locations

2.2.3.1.3. Video Latency

The video latency from the cameras to the C2 displays shall be less than 0.5 second. The latency shall be measured using a system similar to the one shown in *Figure 20*. To measure the latency, the operator shall place a timer in front of the display and then point a RCTMA IP camera directly at the display to create a "hall-of-mirrors" effect. Each mirror image on the display will be one cycle of latency ahead of the image behind it. The operator shall take a screen snapshot to freeze the image and make the measurement. An example measurement is shown in *Figure 21* with a latency of (02:07:50.92 – 02:07:50.73) = 0.19 second.

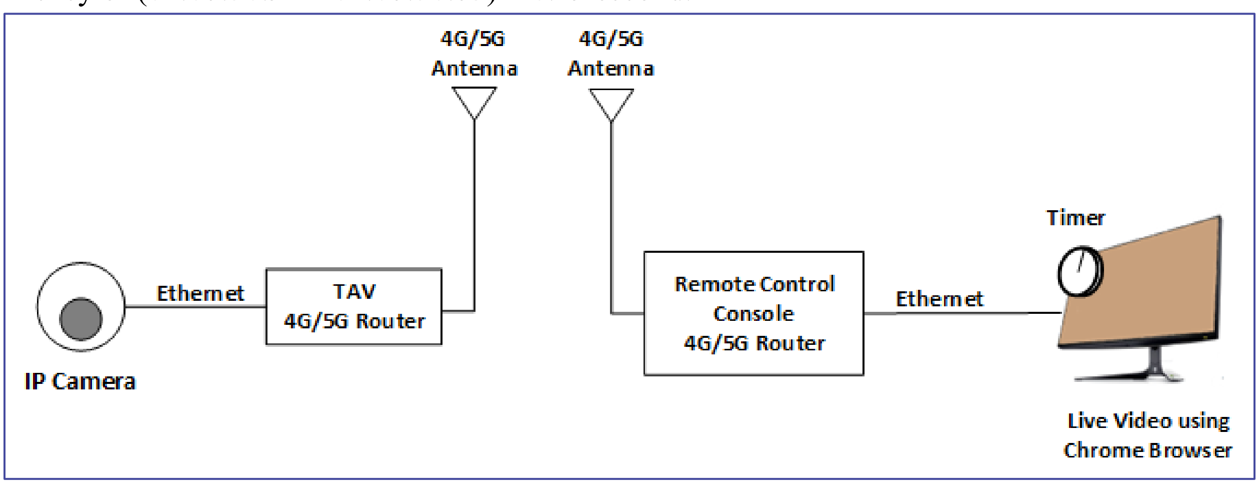


Figure 20. Measuring Video Latency

Figure 21. Video Latency Measurement Example

2.2.3.1.4. Data Collection and Analysis

During the development of the RCTMA, Kratos shall document the equipment evaluations and the test methods that are performed to verify the system requirements defined in this document are met. In particular, Kratos shall define the minimum operational conditions required for safe operation of the RCTMA and develop the test methods and operational instructions to ensure that those conditions are met during the proof-of-concept demonstration.

2.2.3.1.5. Cameras

Kratos shall research commercially available IP cameras to determine which ones will meet the video requirements for the RCTMA. The rationale for either recommending a camera or not recommending it shall be provided in the final report.

2.2.3.1.6. Cellular Communications Network Routers

Kratos shall research commercially available cellular routers to determine which ones meet the requirements for the RCTMA. The rationale for either recommending a router or not recommending it shall be provided in the final report.

2.2.3.1.7. Network Configuration

Kratos shall configure and document the RCTMA IP network for video and vehicle control. Kratos shall document the configuration of the IPSec tunnel and its encryption settings, the network addresses used in the system (both static and dynamic), and configurations for other functions such as port forwarding and Real-Time Streaming Protocol (RTSP).

2.2.3.1.8. Network Performance

The network performance of each cellular provider shall be evaluated while manually driving the RCTMA along a fixed course in the Fort Walton Beach area. Any video anomalies such as screen freeze-ups, erratic pixelation, blurring, loss of video, etc. shall be documented in terms of the length of time, time of day, and physical location of each occurrence. From these data, Kratos shall make recommendations for the number of cellular networks required, the preferred service provider for the Fort Walton Beach area, and the maximum number of anomalies that are acceptable for safe driving at speeds up to 20 mph.

Chapter 3. Description of Functional RCTMA System

The functional configuration of the Remotely Controlled Truck-Mounted Attenuator (RCTMA) system comprises two main components:

1. **RCTMA Vehicle** – A modified Class 6/7 medium-duty truck equipped with critical onboard systems, including sensors, servos, cameras, actuators, modems, computing units, and crash attenuation equipment.
2. **Control Console (C2)** – A remote control console that allows a trained operator to maneuver the RCTMA using real-time video feeds, telemetry, and standard driving controls (steering wheel, brake, throttle, etc.) via cellular network communication.

3.1. RCTMA Vehicle and Associated Equipment

Kratos Defense & Security Solutions (Kratos) modified a 2018 Hino 268 medium-duty truck to serve as the base platform for the RCTMA. The truck, with a GVW of 25,900 lbs and a 7.6L L6 diesel engine, is outfitted with air brakes and a deployable crash attenuator. The vehicle retained many elements from its original ATMA follower configuration, while integrating new components to enable full tele-operation. A picture of the RCTMA is shown in Figure 22. Table 1 shows the dimensions of the vehicle.

Figure 22. Overview of the RCTMA.

Table 1. RCTMA dimensions

RCTMA Dimension	Measurement
Overall length with the attenuator closed	31 ft 6 in
Overall length with the attenuator open	44 ft 8 in
Length of the cab	9 ft 2 in
Length of the bed	18 ft 2 in
Length of attenuator (open)	17 ft 0 in
Length of attenuator (closed)	3 ft 10 in
Length from windshield to back of cab (inside)	4 ft 0 in
Width of the cab	6 ft 6 in
Width of the bed	8 ft 0 in
Width of the attenuator	7 ft 10 in
Height of the cab	8 ft 7 in
Height of the bed (at antenna rack, excluding rack)	8 ft 9 in
Height of antenna rack	1 ft 0 in
Height of the bed with antenna rack	9 ft 9 in
Height of the actual bed	4 ft 0 in
Height of the attenuator when open	1 ft 10 in
Height of the attenuator when closed (on top of bed)	10 ft 8 in

3.2 Core Components and Configuration

Key Retained Components:

- **System Control Unit (SCU)** – Central processing for navigation, power distribution, and communication with other components.
- **Operator Control Unit (OCU)** – In-cab interface for startup, manual override, and emergency stop (E-stop).
- **Servo actuators** – For throttle, brake (primary and backup), and steering.
- **Mechanical linkages and mounting hardware** – For secure integration of servos and controls.
- **GPS antennas** – Primary and backup for location tracking.

Newly Integrated Components for Tele-Operation:

- **4G/5G Cellular routers and antennas** – For bi-directional communication.
- **Five wide-angle cameras** – Three front-facing, two rear-facing, enabling 360° visual awareness.
- **Power and data interface cabling** – Supports video and command signals.
- **External E-stop buttons** – Located at front and rear of the vehicle.

Figure 23 and Figure 24 shows the physical components: E-stop buttons (a, b); modems/cable harness (c); steering actuator (d); and camera placements (e).

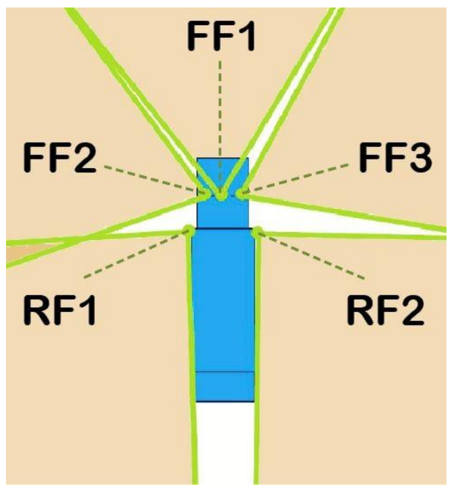
a) E-stop button front b) E-stop button rear c) Modems and cable harness

d) Left – Side view of steering actuator; right – mechanical coupling: steel "fingers" (arrows) and ring

e) The RCTMA dash (left) showing OCU (detail, right)

Figure 23. RCTMA Components

e) The camera placement inside and above the RCTMA



f) The test model RCTMA includes five cameras, each with a horizontal FOV of 180° and a vertical FOV of 90° (top left): three front-facing cameras ("FF"), mounted at the top of the windshield, and two rear-facing cameras ("RF"), mounted at the top corners of the communications frame just behind the cab (top right). The diagram (bottom) shows the direction in which each camera is pointed (dashed lines) and the FOV that appears on the C2 driver's monitors.(orange areas) as determined from video footage. The C2 driver has an almost 360° view. The views are seamless at 20-30 ft from the RTMA. The narrow white triangles show areas near the RCTMA that are not visible on the C2 monitors. For reference, the upper right triangle appears to be about 1 ft at its base.

Figure 24. RCTMA Components (continued)

The steering actuator uses removable "finger" brackets to grip the wheel spokes, while the throttle and brake servos operate via steel cables mounted behind the pedals—ensuring safe manual override by the safety driver if needed.

The **E-stop system** can be triggered:

- Manually (from the cab, vehicle exterior, or C2)
- Automatically (if communication is lost)
- Via the OCU's "Idle" button (manual override mode)

3.1.1. A-Stop Capability (Not Enabled)

Although the ATMA includes an automatic stop (A-stop) triggered by obstacle detection sensors (lidar/radar), this functionality was not enabled in the RCTMA configuration. The current software architecture mirrors Kratos's military tele-op systems, which do not utilize A-stop. Future integration is feasible if obstacle detection is prioritized.

3.1.2. Control Console (C2) and Operator Environment

The Control Console (C2) (Figure 25) is a mobile command station equipped for full tele-operation of the RCTMA vehicle.

Figure 25. Control Console (C2)

C2 Hardware Configuration:

- **Laptop monitor** – Displays map location, gear, speed, throttle, steering, and engine telemetry (Figure 26).
- **Three 27-inch monitors** – Provide 180° forward view with PIP rear views (Figure 27). Max resolution: 2560x1440 px.
- **Logitech G920 Driving Force** steering wheel and pedal set – Mimics traditional vehicle controls.
- **Communication Routers:**
    - **1 outbound router/antenna** – C2 to RCTMA commands.

- **3 inbound routers/antennas** – Receives video from 5 onboard cameras:
    - Router 1: Left windshield & left rear
    - Router 2: Center windshield
    - Router 3: Right windshield & right rear
- Note: Video streams are not time-synchronized across routers. The video feeds are received from the vehicle's five cameras and each transmitted through separate cellular routers which may not be perfectly aligned in time. This can result in slight delays or mismatched frames between camera views. This is noteworthy because it may affect the operator's perception of real-time situational awareness, particularly when monitoring fast-moving events or navigating tight spaces.

3.1.3. RCTMA Operations and Functional Testing

Each session begins with a pre-operation protocol to validate communication links, control responses, and servo functionality. Full remote control of steering, throttle, and braking is enabled. However, engine ignition and gear selection are still performed by the onboard safety driver.

Roles:

- **Safety Driver**: Ensures servo linkage, powers on vehicle systems.
- **C2 Driver**: Establishes connection, enters tele-op mode, activates servo control.

3.3.1 Functional Test Procedures:

Each functional test procedure (steering calibration, brake, and throttle tests) was repeated at the start of every test session to ensure system readiness and safety. The full pre-operation protocol, including all three procedures and system checks, typically required approximately 15 to 20 minutes per session.

Steering Calibration Test:

- Servo rotates to full right → sets position 0
- Rotates full left → calculates midpoint → centers automatically
- C2 driver issues full right/left/center commands; safety driver confirms alignment.
- Repeat calibration if deviation detected.

Brake Test:

- C2 driver applies full brake → safety driver verifies pedal press.

- C2 releases brake → safety driver verifies release.

Throttle Test:

- Servo calibration sets 0–100% range.
- C2 driver applies 25% throttle → safety driver verifies position.
- C2 releases throttle → confirm return to idle.

Figure 26 *and* Figure 27 *illustrate visual feedback and control data available to the C2 driver.*

Figure 26. The C2 driver is provided with readouts for the RCTMA's functions on the laptop shown in Figure 10. From left to right, the readouts are gear, brakes, mph and rpm, steering, throttle, coolant and engine oil temperatures, engine oil and transmission oil

Figure 27. C2 monitors: three 27-inch monitors provide the C2 driver with a more than 180-degree forward view and rear views (PIP insets) along either side of the RCTMA.

The RCTMA system integrates advanced components into a robust tele-operation platform. While current configuration limits full autonomy (e.g., no remote start or gear change), the architecture supports safe and responsive vehicle control for field operations under test conditions. Future enhancements such as sensor-based A-stop and full drivetrain control will enable wider deployment potential.

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Chapter 4. RCTMA Testing Program

Accurate vehicle control and reliable emergency stop (E-stop) capabilities are essential for the RCTMA to serve its intended purpose—protecting work sites and removing the need for a human driver in hazardous roadside environments.

To evaluate these functions, the RCTMA was subjected to a comprehensive series of field tests. The vehicle was assessed for its ability to maintain proper lane heading, accelerate to target speeds, and execute maneuvers such as turning and parking. Safety protocols were also evaluated, including E-stop functionality (both from the vehicle and the C2 console) and the C2 driver's capacity to detect obstacles and promptly stop the RCTMA.

Additional testing was performed to verify the system's reliability and accuracy when the RCTMA encountered disturbances, such as significant bumps, while operating in both forward and reverse directions. The vehicle was also tested under various acceleration scenarios to determine its responsiveness and stability.

The RCTMA's E-stop function allows for emergency shutdown of operations by locking out the throttle, stopping the engine, and applying full brakes. This feature can be triggered by:

- Pressing external E-stop buttons located on both sides of the RCTMA
- Activating an internal dash-mounted button (via the Operator Control Unit, or OCU)
- Issuing a command from the C2 console
- Automatic engagement following a communication loss between the RCTMA and C2

The following sections describe the test environment, personnel roles, and the specific test procedures used to evaluate the RCTMA system.

4.1. Locations and Test Personnel

Figure 28 shows the venues used for RCTMA testing and the connecting roadways in Fort Walton Beach, Florida. Testing took place at two primary locations:

- **Kratos 2 Facility**: Located at 65 Hill Ave NW, this site housed the C2 operations console for all tests.
- **Santa Rosa Mall**: Located at 300 Mary Esther Blvd, this site served as the physical test area for RCTMA driving operations.

The majority of RCTMA maneuvers were conducted in the Santa Rosa Mall's vacant parking lot, which measures approximately 450 feet by 600 feet. This lot was unused during the tests, allowing for flexible course setup. Most motion-based tests were performed along a designated straight-line track on the west side of the lot, although additional course layouts were configured as needed.

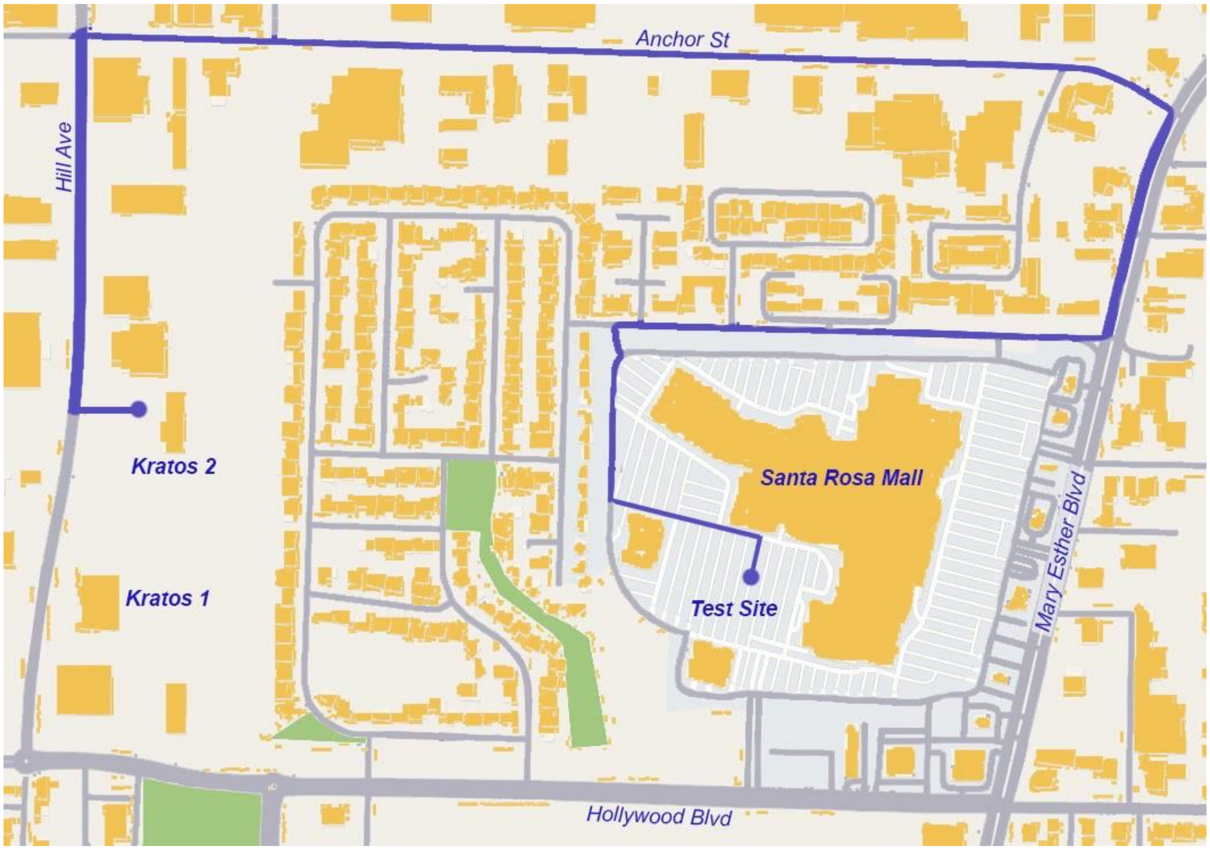

Figure 28. Venues for RCTMA testing in Ft. Walton Beach, FL. Note the Kratos 2 facility on the left and the Santa Rosa Mall test site on the right.

Test Personnel included:

- At Kratos 2: The C2 operator, Kratos engineers providing technical support, and UF research team members recording video and observing the C2 displays and driver actions.
- At the field site (Santa Rosa Mall): The RCTMA's onboard safety driver, Kratos engineers, and UF field operatives executing, observing, and documenting test procedures. In some cases, a field team member accompanied the safety driver in the passenger seat for additional observation and documentation.

Table 2 shows the list of tests, test locations and course.

Table 2. Tests, location, and course for RCTMA testing

No.	Test Name	RCTMA Location	Course Type
1	Pixelation Demonstration	Kratos facility & roads	-----
2	Latency Test 1	Mall	N/A
3	Servo Test	Mall	N/A
4	Visibility Test	Mall	N/A
5	Braking Test in Motion	Mall	Straight-line track
6	Throttle Test in Motion	Mall	Straight-line track
7	Straight-line Test	Mall	Straight cone course
8	Reverse Test	Mall	Straight cone course
9	Object Detection and Braking Test	Mall	Straight-line track
10	Person Detection and Braking Test	Mall	Straight-line track
11	Right- and Left-Turn Test	Mall	Turn course
12	Bump Test	Mall	Straight-line track
13	Maneuverability Test	Mall	Turn course
14	Parking Test	Mall	Marked parking space
15	Loss-of-connection E-stop Test	Mall	Straight-line track
16	Latency Test 2	Mall	N/A
17	Human Driver-Initiated E-stop Test	Mall	Straight-line track
18	External E-stop Test	Mall	Straight-line track
19	C2-Initiated E-stop Test	Mall	Straight-line track

Course Descriptions:

- **Straight-line Track**: Used for most motion-based tests. Defined by one of the existing driving lanes in the parking lot.
- **Straight Cone Course**: A 12-foot-wide lane created with 10 cones (five per side), spaced 12 feet apart. An inner line of orange markers was placed 1 foot inside the cones to provide greater visual reference for alignment precision.
- **Turn Course**: Comprised of two semicircular arrays of cones, spaced approximately 30 feet apart, with a central barrel between them. Each semicircle was used independently for the left- and right-turn tests. Combined, the two semicircles formed a figure-eight layout for maneuverability testing. The layout of the turn course is shown in Figure 29.

All tests were conducted at 5 or 10 mph, unless otherwise specified.

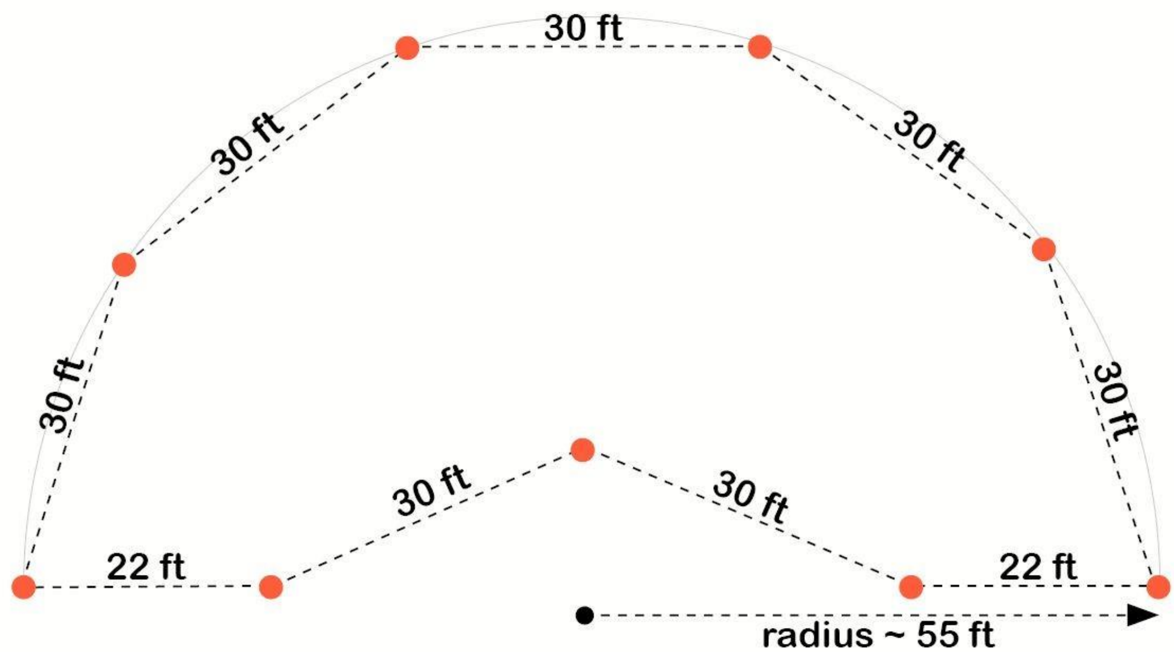

Figure 29. Nominal spacings of the cones that defined the semicircular course were used to demonstrate left and right turns and the figure-eight maneuver.

4.2. Test Program

The RCTMA system underwent two rounds of field testing to evaluate its performance and functionality.

- **Round 1** focused on demonstrating the RCTMA's ability to perform basic tele-operation functions such as remote steering, braking, throttle control, and real-time video transmission. This phase was intended to confirm baseline system functionality —defined as reliable remote vehicle control, stable communication, real-time visual feedback, and proper Emergency Stop (E-Stop) activation—through qualitative assessments in a controlled test environment.
- **Round 2** focused on a more detailed and quantitative evaluation of selected performance parameters. Test procedures were enhanced to collect measurable data on critical operational characteristics such as latency, braking response, vehicle visibility, and video quality.

The test programs and corresponding results from these two rounds are described in **Chapter 5 (Round 1)** and **Chapter 6 (Round 2)** of this report.

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Chapter 5. First Round Test Program

The first round of testing for the Remotely Controlled Truck-Mounted Attenuator (RCTMA) system was conducted to establish preliminary system validation through a sequence of structured and regulated field demonstrations. Prior to these evaluations, the RCTMA underwent comprehensive bench testing that verified system communications, hardware integration, and baseline functional performance. These initial tests confirmed that the RCTMA met fundamental performance specifications outlined in the project design. The primary focus of this phase was to validate proof-of-concept operations under stable, controlled conditions rather than real-world dynamic scenarios. Test procedures were standardized, with clear acceptance criteria and observational checkpoints to assess system performance and guide future iterations. The insights obtained in this phase informed and refined the methodology for the more advanced second round of data-driven testing.

5.1 Pixelation Demonstration

This demonstration addressed a cellular connection issue identified during preliminary evaluations by Kratos staff. The issue manifested as stuttering or pixelation in video streams transmitted from the RCTMA's onboard cameras to the C2 monitors. Typically, the video streams provide uninterrupted real-time views from five cameras. However, during vehicle operation near the Kratos 2 site, stutters occurred as brief frame freezes (lasting fractions of a second to over one second), while occasional pixelation events significantly degraded image resolution—with resolution degrading by more than 75%, rendering features unrecognizable.

Test Procedure:

- Conduct standard system startup protocols to confirm operational readiness.
- A safety driver drove the RCTMA from Kratos 2 to the Santa Rosa Mall via Hollywood Blvd (Figure 28).
- Pixelation events were documented using a GoPro camera pointed at the C2 monitors.

Observations:

- The central camera experienced minor stuttering during the drive, notably at Hill Ave NW and Hollywood Blvd and again upon turning into the mall's internal road.
- Left and right cameras also displayed stuttering but no pixelation, as shown in console video C112.
- A significant pixelation incident was captured in video C212 (Figure 30) from 6:45 to 7:12, where a scene became dominated by light gray pixels during a turn, with resolution recovery taking several seconds.

- Signal strength remained optimal (green status) throughout testing. Kratos-provided signal graphs for parameters RSRP, RSRQ, and SINR (Figure 31) were representative, though not recorded during the April 15 test.

Figure 30. Example of pixelation from video C112

Figure 31. Graphs showing signal parameters RSRP, RSRQ, and SINR for the C2-RCTMA connection. This data is representative; they were not available from the April 15 testing session.

5.2 Latency Test 1

Latency, the time delay in video signal transmission from the RCTMA to the C2, was measured using an infinity mirror technique. A stopwatch app displayed on a phone was placed in front of a camera whose output looped through the C2 system and reappeared on the monitor. Each image reflected a time difference equal to the latency. Figure 32 shows the schematic diagram of the setup used for the test.

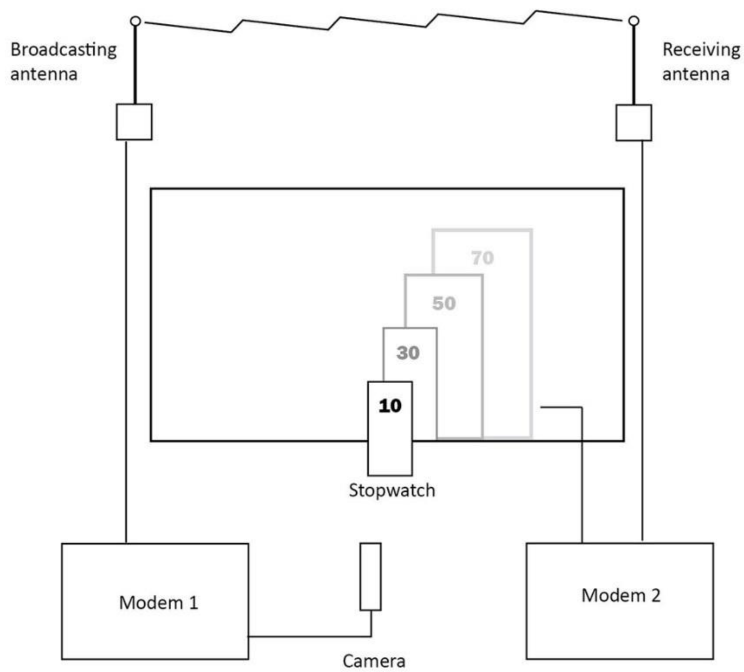

Figure 32. Schematic diagram of the setup used for Latency Test 1. Stopwatch times are for illustration only, and do not represent actual times in the test.

Test Procedure:

- Connect a camera to a modem and antenna in the C2 area.
- Position a phone with a running stopwatch app between the camera and monitor.
- Capture screenshots showing successive reflections of the stopwatch.
- Calculate latency as the time difference between adjacent reflected stopwatch images.

Figure 33 shows the test set up showing multiple images in the C2 monitor used for comparison of stopwatch times.

Figure 33. Latency Test 1, showing multiple images in the C2 monitor used for comparison of stopwatch times

Observation:

- Latency was consistently measured around 300 ms. Kratos engineers reported performing this test over 50 times with similar results. Variability under field conditions remains unknown due to unavailability of real-time latency monitoring equipment during testing.

5.3 Servo Test

This test verified the C2 driver's ability to control RCTMA servos (steering, braking, throttle) while the vehicle was stationary with the parking brake engaged.

Test Procedure:

- Engage parking brake.
- Enter Teleop mode and activate motion control.
- Command full right, center, and full left steering, verifying responses with the safety driver.
- Repeat for full brake and throttle application.

Observation:

- All servo functions performed according to specification. Occasional recalibration was required for steering limits, particularly after system power cycles, extended periods of inactivity, or when test personnel observed slight misalignment between the steering command issued from the C2 and the actual front wheel position.

5.4 Visibility Test

The objective of the Visibility Test was to evaluate the effectiveness and coverage of the onboard camera configuration. A technician walked 360 degrees around the RCTMA at a 50-foot distance, with visibility monitored via the C2 display. Figure 34 and Figure 35 shows the test set up from C2 and field.

Figure 34. Monitor view during visibility test

Figure 35. Field view during visibility measurements

Test Procedure:

- Position technician behind RCTMA at 50 feet.
- Walk counterclockwise around the vehicle.
- Technician and console operator communicate visibility transitions.

- Measure lowest visible stick height from C2 monitor at various positions.

Observation:

- Blind spots exist within five feet of the cab. No rear camera was installed, resulting in no rearward view. Results displayed in **Error! Not a valid bookmark self-reference.** show minimum visible heights around the vehicle. Kratos later lowered camera positions to reduce unsurveyed areas. Figure 36 illusrtrate the visibility measurements in a diagram.

Table 3. Visibility measurements

Location	Distance from truck (ft)	Minimum height at which stick is visible (ft)
In front of the driver seat	5	3.1
	9.1	0
In front of the passenger seat	1	4.7
	5	3.1
	9.9	0
At the right of the passenger seat	1	7.6
	5	5.3
	8.2*	0
At the rear axle	1	0
	7.5	0
At the left of the driver seat	1	4.1
	5	3.1
	17.4*	0

** Value based on linear extrapolation.*

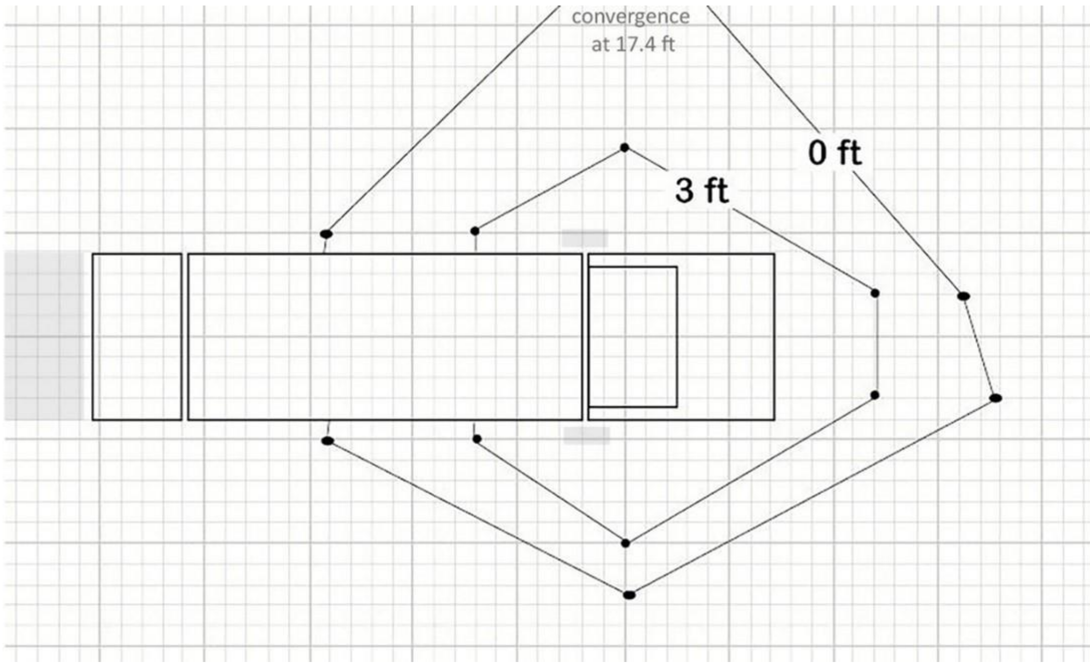

Figure 36. Visibility measurements show approximate boundaries at which the C2 driver can see objects of the indicated height. Gray areas where the C2 driver has no visibility below 10 ft.

Note: In response to the visibility testing, Kratos has lowered the position of all cameras to reduce Un-surveilled areas. The adjustment improved the downward field of view and minimized blind spots, particularly near the front and rear bumpers.

5.5 Braking Test

This test assessed RCTMA braking capability while in motion using a barrel marker. Figure 37 shows the test set up in the field.

Test Procedure:

- Line up vehicle; place barrel to side.
- Drive at 5 mph and 11 mph.
- Apply brakes as the vehicle reaches the barrel.

Observation:

- Stopping distances were 7.7 ft and 7.6 ft beyond the marker, respectively. Estimated 2-second delay included latency and driver response time.

Figure 37. RCTMA positioned to begin the braking test in motion

5.6 Throttle Test in Motion

This test evaluated the vehicle's ability to accelerate to and maintain target speeds.

Test Procedure:

- Accelerate to 10 mph, hold for 3 seconds, then brake.
- Repeat at 15 mph.
- Include bump test to evaluate course correction after impact.

Observation:

- RCTMA met acceleration targets. Bump test showed effective heading maintenance post-impact.

5.7 Straight-Line Test

This test confirmed RCTMA's ability to maintain straight heading through a cone-defined lane.

Test Procedure:

- Drive through cone lane without deviating or displacing cones.
- Repeat test multiple times.

Observation:

- First run showed slight deviation from the intended path, which was delineated using cones. The RCTMA drifted slightly to the left of center during its approach. The second run was more precise (Figure 38).

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Figure 38. Straight-line test in progress

5.8 Reverse Test

This test evaluated the RCTMA's reverse driving capabilities through a defined lane.

Test Procedure:

- Enter and exit cone lane in forward gear.
- Switch to reverse; reenter cone lane without disturbing cones.
- Repeat.

Observation:

- RCTMA successfully navigated reverse cone lane with precision (Figure 39).

Figure 39. Reverse test in progress

5.9 Object Detection and Braking Test

This test assessed the C2 operator's ability to detect an obstacle vehicle entering the RCTMA's path and apply brakes to prevent a collision.

Test Procedure:

- Operate vehicle at constant speed.
- Introduce another vehicle into the RCTMA's path.
- C2 operator initiates emergency braking.

Observation:

- C2 operator detected vehicle and braked successfully. (Note: RCTMA was not equipped with automated lidar/radar detection.)

5.10 Person Detection and Braking Test

This test demonstrated the system's response to human presence in its path.

Test Procedure:

- Drive vehicle at steady pace.
- Have a person enter vehicle path.
- C2 operator observes and brakes.

Observation:

- RCTMA stopped effectively after person entered its path (Figure 40).

Figure 40. Monitor view during obstacle detection and braking test

5.11. Right- and Left-Turn Test

The Right- and Left-Turn Test evaluated the RCTMA's ability to perform controlled, accurate turns in both directions. Cones were arranged in a U-shaped lane to simulate a turn path. The operator executed a right turn by entering the lane from the right and repeated the test by entering from the left for a left turn. The test confirmed the vehicle's turning radius, steering responsiveness, and ability to maneuver within confined paths.

Test Procedure:

- Engage full brake from the console.
- Safety driver releases the parking brake.
- Release the console brake.
- Navigate the RCTMA into the turn lane from the right and perform a right turn.
- Repeat by entering from the left and executing a left turn.
- Repeat the right turn.
- Engage full brake and reapply the parking brake.

Observation: The C2 driver successfully completed both left and right turns without disturbing any cones, demonstrating precise vehicle control. Figure 41 presents the C2 monitor view during testing. The turning movements were conducted using a semicircular cone layout designed to evaluate maneuverability within confined spaces, ensuring consistent path geometry for both directions.

Figure 41. Monitor view during turn test

5.12 Bump Test

The Bump Test assessed the RCTMA's ability to maintain heading and stability after encountering a physical obstacle. A 4x4 wooden beam was placed in the vehicle's path within the same cone layout used for turn testing. The operator repeated left and right turns, ensuring that at least one tire passed over the bump each time.

Test Procedure:

- Place the 4x4 bump on the driver-side path.
- Engage full brake, release parking brake, release console brake.
- Execute right and left turn maneuvers through the cone lane, ensuring wheel travels over the bump.

- Repeat right turn.
- Engage full brake, reapply parking brake, remove the bump.

Observation: The RCTMA maintained heading and directional control during and after contact with the obstacle, in both forward and reverse motion. Figure 42 illustrates the RCTMA approaching the bump.

Figure 42. The bump test is in progress. The 4x4 bump can be seen immediately in front of the RCTMA's left front tire (indicated by a yellow arrow).

5.13 Maneuverability Test

The Maneuverability Test assessed the RCTMA's ability to handle complex paths using a figure-eight cone layout. The test evaluated steering accuracy, path tracking, and overall responsiveness.

Test Procedure:

- Apply full brake, set parking brake, release console brake.
- Enter the cone lane and execute a figure-eight pattern around a center barrel.
- Repeat the figure-eight maneuver three times.
- After exiting, engage brake and apply parking brake.

Observation: The RCTMA completed all iterations of the figure-eight course smoothly, validating its maneuverability in confined spaces.

5.14 Parking Test

This test evaluated the RCTMA's ability to park accurately within a designated space using only camera feedback.

Test Procedure:

- Create a parking spot using cones if lines are not present.
- Engage brake, release parking brake, release console brake.
- Designate a parking space.
- Navigate the vehicle into the space.
- Engage full brake and reapply parking brake.
- Safety driver verifies final position.

Observation: The C2 driver successfully parked the RCTMA within the defined boundaries using camera input. The maneuver was completed with precision.

5.15 Loss-of-Connection (LOC) E-Stop Test

This test simulated a loss of telecommunication link between the C2 and the RCTMA to evaluate the automatic E-stop response.

If a loss of connection (LOC) in communications between the C2 and the RCTMA lasts more than 2 seconds, the RCTMA automatically executes an E-stop. (During those 2 seconds, the RCTMA continues to move along the commanded heading.) The test is part of evaluating the system's safety features, emergency response capabilities, and risk mitigation.

Test Procedure:

- Line up vehicle, apply full brake, release parking brake and console brake.
- Drive straight at 5 mph and initiate LOC.
- Observe automatic braking and E-stop state.
- Clear LOC and E-stop, repeat test at 10 mph.

Observation: The RCTMA successfully detected the LOC event and automatically entered E-stop mode 2 seconds after disconnection, as specified in the system design. The vehicle came to a stop without operator intervention and remained in E-stop until manually reset. This was a **qualitative test**, and precise measurements of the time and distance to full stop after E-stop initiation were **not collected**. Field personnel visually confirmed the stop in both test runs. Quantitative data (e.g., braking distance and deceleration time) will be collected in future testing phases once additional logging instrumentation is integrated into the system.

5.16 Latency Test 2 (Two Phones Test)

This test compared time displays on two phones accessing time.gov to measure latency.

Test Procedure:

- Both test technicians access time.gov on phones.
- One technician holds phone near C2 camera; the other near RCTMA front camera.
- Observe and compare displayed times.

Observation: No measurable difference was observed, confirming latency remained under 1 second, consistent with earlier 300 ms measurements.

5.17 Internal E-Stop Test

This test validated the RCTMA's response to an internal E-stop initiated manually by the safety driver using the in-cab E-stop button. The objective was to confirm that the system promptly shut down upon command and safely brought the vehicle to a stop.

Test Procedure:

- Drive vehicle at 10 mph.
- Instruct safety driver to press internal E-stop when approaching a designated barrel marker.
- Observe shutdown.

Observation: The RCTMA responded as designed: upon pressing the internal E-stop, all systems—including throttle, brake servos, and engine—shut down immediately. The vehicle safely came to a stop without further input from either the C2 or safety driver. This was a qualitative validation, and precise time-to-stop and stopping distance were not measured during this test. Visual confirmation by field staff verified that the E-stop was executed effectively. Quantitative stop metrics will be incorporated into future test phases once enhanced data collection tools are available.

5.18 External E-Stop Test

This test assessed the RCTMA's response to an external E-stop button activation.

Test Procedure:

- Operate vehicle at 5 mph.
- A field technician stationed along the test course was instructed to press the external E-stop button as the RCTMA passed by. The technician was positioned on the passenger side of the vehicle near the rear quarter panel, allowing safe access to the E-stop control without entering the vehicle's path of travel.
- Repeat from both sides.

Observation: Vehicle stopped within 3 seconds on both sides. Test confirmed successful external E-stop activation.

5.19 Console Driver-Initiated E-Stop Test

This test evaluated E-stop response from the console during forward movement.

Test Procedure:

- Set up a barrel 100 ft ahead of vehicle.
- Drive vehicle toward the barrel at 10 mph.
- Execute console E-stop as RCTMA passes barrel.
- Verify lockout of all motion controls.

Observation: E-stop functioned as intended: vehicle stopped, controls were locked out, and engine shut down completely.

Chapter 6. Second Round Test Program

The second round of testing expanded upon the foundational results of the first round, shifting from controlled, lab-based environments to enhanced field-based evaluations. While the first round focused on initial system validation, including communication, hardware integration, and basic operational functionality, this phase prioritized practical, real-world scenarios to validate deployment readiness and system responsiveness under more dynamic conditions.

A notable advancement in this round was the integration of a new latency monitoring tool that records Round-Trip Time (RTT) during each test, allowing for precise communication delay tracking. Procedural refinements also included synchronized time standards, enhanced braking markers, and improvements in the course setup to allow for accurate quantitative data collection.

The goal was to quantify the RCTMA's operational maturity by measuring metrics such as braking performance, maneuverability, and latency consistency while reducing the repetition of previously validated tests.

6.1 Overview of Second-Round Testing Methodologies

The second-round methodology emphasized field-based assessments to gather robust quantitative data. Key enhancements included:

- **Latency Measurement Integration**: A new software tool recorded RTT timestamps to enable real-time latency analysis.
- **Quantifiable Metrics**: Tests were designed to capture specific operational data including braking distance, deviation from centerline, and RTT statistics.

The list of tests conducted is second round in given in Table 4 and the location of the tests is shows in Table 5**.**

Table 4. List of tests performed in the second round

No.	Test	Included in 2nd Round	Classification
1	Pixelation Demonstration	Y	Demonstrative/Quantitative
2	Latency Test 1	Y	Quantitative
3	Servo Test	N	Unlikely to Yield New Insights
4	Visibility Test	Y	Quantitative
5	Braking Test in Motion	Y	Quantitative
6	Throttle Test in Motion	N	Unlikely to Yield New Insights
7	Straight-line Test	Y	Quantitative
8	Reverse Test	N	Unlikely to Yield New Insights
9	Object Detection and Braking Test	N	Qualitative
10	Person Detection and Braking Test	N	Qualitative

Table 4. List of tests performed in the second round (continued)

No.	Test	Included in Second Round	Classification
11	Right- and Left-Turn Test	N	Unlikely to Yield New Insights
12	Bump Test	Y	Quantitative
13	Maneuverability Test	N	Qualitative
14	Parking Test	N	Qualitative
15	Loss-of-connection E-stop Test	N	Unlikely to Yield New Insights
16	Latency Test 2	N	Unlikely to Yield New Insights
17	Human Driver-initiated E-stop Test	N	Unlikely to Yield New Insights
18	External E-stop Test	N	Unlikely to Yield New Insights
19	C2-initiated E-stop	N	Unlikely to Yield New Insights

Table 5. Tests and locations for RCTMA testing

No.	Test	RCTMA Location
1	Latency Test 1	Mall
2	Visibility Test	Mall
3	Braking Test in Motion	Mall
4	Straight-line Test	Mall
5	Bump Test	Mall
6	Pixelation Demonstration	Kratos facility and local roads

6.2. Test Program for Second Round

6.2.1 Latency Measurement Test

The latency test measured the communication delay (RTT) between the control console (C2) and the RCTMA. Unlike previous stand-alone latency tests, this test was embedded within every operational trial. A newly integrated tool recorded timestamps for all message transactions to compute RTT values.

A recent update in the RCTMA system was able to generate timestamps of the signals sent from the console to the RCTMA and back. These data were used to estimate the round-trip time (RTT), offering a more reliable means of evaluating system latency. Given the relevance and accuracy of this new tool, we decided not to repeat the latency tests using previous methods.

Integrating latency measurements directly into the testing process approach allowed for continuous performance monitoring. This method provided a clear and ongoing assessment of the RCTMA's responsiveness, which is essential for smooth teleoperation and effective incident response operations.

Quantifiable Measures:

- Average Round-Trip Time (RTT): Measured in milliseconds (ms) to determine the typical communication delay between the C2 and the RCTMA.
- Standard Deviation of RTT: To assess the variability of RTT, providing insight into the consistency of system latency.
- Maximum and Minimum RTT: Captures the range of RTT values during testing, highlighting any extreme delays that may affect teleoperation.

Acceptance Criteria: RTT must not exceed 500 milliseconds. This limit was established in accordance with Kratos's operational guidelines for optimal teleoperation performance.

Communication Process:

1. C2 to MB (Message Broker) (timestamped)
2. MB to RCTMA (timestamped)
3. RCTMA to MB (timestamped)
4. MB to C2 (final timestamp)

RTT = Final timestamp - Initial timestamp

Test Results:

Timestamps were recorded continuously, and RTT was averaged every 5 seconds. Table 6 shows the latency results.

Table 6. Results of latency test

Metric	Value	Unit
Average RTT	150	milliseconds
Maximum RTT	1963	milliseconds
Minimum RTT	98	milliseconds
Std Dev of RTT	59	milliseconds
Variance of RTT	0.003	$seconds^2$
RTT > 500 ms	81	counts
RTT > 300 ms	503	counts
Total Observations	21,693	counts

The average RTT was estimated to be 150 milliseconds, which was lower than the recommended latency threshold of 500 milliseconds. The highest observed RTT was 1963 milliseconds. These values are often linked to temporary network congestion and processing delays that cause disruptions in the communication pathway.

On the other end of the scale, the shortest RTT was 98 milliseconds, which reflected the system's best-case performance under ideal conditions. This low latency indicated an optimal state of communication where delays are minimal, allowing for rapid data transfer between the C2 and RCTMA.

The variability of RTT is reflected in the standard deviation of 59 milliseconds and a variance of 0.003 s^2. These values indicate that the majority of RTT measurements are tightly clustered around the mean, suggesting consistent system performance for most observations. Low standard deviation and variance are positive indicators of system stability, showing that most messages experience similar levels of delay with only a small number of deviations.

Out of 21,693 total observations, RTT exceeded 500 ms in 81 instances, which accounted for approximately 0.37% of all measured RTTs. While these occurrences were infrequent, they represented critical delays that could disrupt teleoperation, particularly during tasks requiring quick responsiveness. RTT exceeded 300 ms in 503 instances (about 2.32% of the total observations). While these delays were less severe than those exceeding 500 ms, they still reflected moments where system responsiveness may be reduced.

Overall, the RTT results demonstrated that the system maintained consistent performance for the majority of operations, with most RTTs falling well below the 500-ms threshold. Additionally, while the tests were conducted at various speeds (5, 10 and 15mph), the data measurements were not specifically designed to analyze how speed impacts latency. It is theoretically possible that higher speeds could result in increased data transmission per unit time. However, the current dataset does not provide direct evidence to confirm or quantify any relationship between speed and latency.

In summary - despite rare spikes, RTT was consistently below the threshold in 99.63% of cases, indicating stable communications and acceptable responsiveness.

6.2.2 Visibility Test

The Visibility Test was conducted to evaluate the C2 driver's field of view using the updated RCTMA camera system. Following the initial test round, the camera positions were lowered to improve coverage and reduce blind spots, especially near the vehicle's front and rear (explained in 5.4 Visibility Test). The goal was to assess visibility around critical areas of the vehicle—especially the corners, axles, and blind spots—at both close (1 ft) and extended (5 ft) distances using a calibrated surveying stick. This test verified whether visual feedback provided through the C2 monitor was adequate for safe operation.

Test Procedure:

- Position a surveying stick at nine predefined locations around the RCTMA: front centerline, front corners, rear corners, and at both front and rear axles.

- At each location, the C2 driver identified the lowest visible portion of the stick visible on-screen.
- Repeat the procedure with the stick 5 ft from the vehicle.
- Record video of the entire session and review for final analysis.

Quantifiable Measures:

- Minimum visible stick height at 1 ft and 5 ft from the vehicle.
- Measurement location and relative orientation.

Acceptance Criteria:

- C2 driver must maintain an uninterrupted view of all immediate areas surrounding the RCTMA.

Test Results:

The measuring tool used in the visibility test was a level rod. The level rod features graduated markings in feet, where each foot is divided into 10 equal increments. A picture of the level rod is given in Figure 43.

The visibility test was conducted to evaluate the C2 driver's ability to perceive critical areas around the RCTMA, particularly at key points along its perimeter. The test involved using a level rod at specified positions around the RCTMA to identify the minimum visible height that could be seen by the C2 driver through the video feed. Measurements were taken at two distances from the RCTMA: within 1 ft and at 5 ft from the vehicle. Table 7 shows the measurements from the test.

The minimum visible height recorded represents the lowest point on the level rod that was visible in the C2 video feed from different positions around the RCTMA. Any portion of the rod below this height was obstructed and could not be seen by the C2 driver. Figure 43 provides a visual reference, where the position of the hand on the rod indicates the minimum visible height which means everything below that point was not visible in the video feed. Figure 44 illustrates visibility boundaries from Testing Round 1 vs. Round 2.

Figure 43. Level Rod used for visibility test

Table 7. Visibility measurements

Location	Minimum Visible Height on Surveying Stick (ft)	
	Within 1 ft	At 5 ft
Front centerline	4.5	3.2
Front corner (left)	4.2	3.0
Front corner (right)	4.6	3.3
Rear corner (left)	0.0	0.0
Rear corner (right)	0.0	0.0
Front axle (left)	5.4	3.0
Front axle (right)	5.4	3.7
Rear axle (left)	0.0	0.0
Rear axle (right)	0.0	0.0

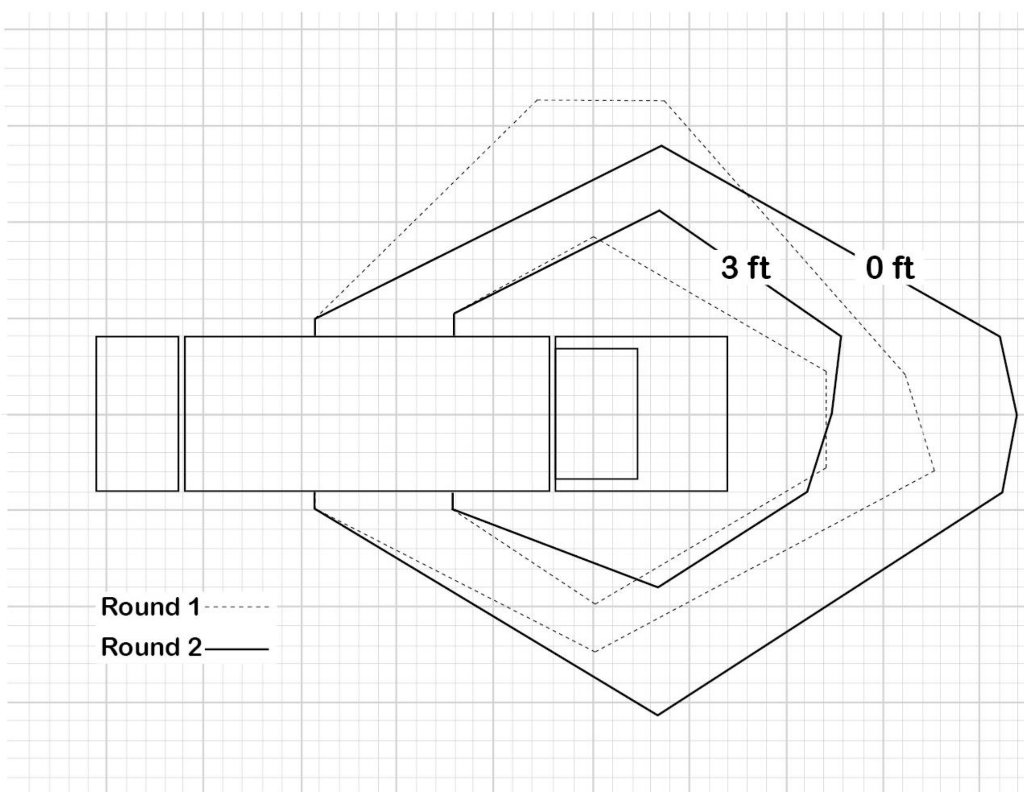

Figure 44. Visibility measurements show approximate boundaries at which the C2 driver can see objects of the indicated height – Testing Round 1 vs. Round 2.

The visibility measurements revealed that the minimum visible height at the front centerline was 4.5 ft at 1 ft from the vehicle and 3.2 ft at 5 ft. At the front corners, the visibility ranged from 4.2

to 4.6 ft at 1 ft and 3.0 to 3.3 ft at 5 ft, indicating a slight improvement in visibility at the corners compared to the centerline. The highest minimum visible height was recorded at the front axles, with 5.4 ft at 1 ft and 3.0 to 3.7 ft at 5 ft, indicating that objects positioned near the front axles were less visible at close distances but became more visible as they moved farther away.

In contrast, the rear corners and rear axles had a minimum visible height of 0.0 ft, meaning the entire level rod was visible at these positions, suggesting full visibility coverage. However, visibility directly behind the vehicle was more limited. Objects became visible at 11.0 ft behind the rear camera on the left side and 13.5 ft behind the rear camera on the right side, indicating that obstacles close to the rear of the vehicle may not be detected until they are at a greater distance.

Overall, the front of the RCTMA, including the front centerline, front corners, and front axles, provided sufficient visibility for detecting objects with minimum heights ranging from 3.0 to 5.4 ft, indicating that larger objects such as vehicles, equipment, and people are likely to be visible to the C2 driver. The rear corners and rear axles offered maximum visibility, with the entire level rod visible at both 1 ft and 5 ft distances, ensuring that objects at ground level were fully detectable in these areas. However, limited rear visibility suggests potential challenges during reversing or navigating confined spaces. The visibility measurements also demonstrated that as distance from the vehicle increased, more of the rod became visible, indicating improved visibility at farther distances.

A blind spot was identified along the side of the RCTMA, extending 42 inches from 2 inches in front of the rear camera to 10 inches behind the front camera. This visibility gap could hinder the detection of obstacles or personnel adjacent to the vehicle, likely due to camera positioning or obstructions caused by the vehicle's body structure.

To summarize, visibility was highest near the axles and rear corners, with full stick visibility (0.0 ft minimum height) indicating no obstructions. At the front corners and centerline, visibility began at 3.0–4.6 ft. Blind spot analysis revealed a 42-inch visibility gap along the side, from 2 inches ahead of the rear camera to 10 inches behind the front camera. Objects directly behind the RCTMA were not visible until they were more than 11–13.5 ft away from the rear cameras.

6.2.3 Braking Test in Motion

This test assessed the RCTMA's braking response across speeds of 5, 10, and 15 mph. The evaluation compared manual and teleoperated performance.

Test Procedure:

- A barrel was placed 100 ft ahead of the starting point.
- Upon passing the barrel, the C2 driver initiated full braking.
- Time and distance to full stop were measured.

- Each test was repeated three times for each speed.

Quantifiable Measures:

- Stopping distance and time for 5, 10, and 15 mph.
- Results compared against calculated thresholds (shown in Table 8 and the calculation is shown in Appendix A. Explanation of Stopping Distance and Time Calculations).

Table 8. Calculated stopping times and distances for C2 braking

Speed (mph)	Stopping Distance (ft)	Stopping Time (s)
5	9.13	1.49
10	21.84	1.98
15	38.13	2.47

Test Results:

The braking test was conducted to evaluate the stopping performance of the RCTMA under manual operation and teleoperation control. The test was performed at three different speeds — 5 mph, 10 mph, and 15 mph — with multiple test runs conducted for each speed. In each test, a hard brake was applied to assess the vehicle's ability to come to a complete stop as quickly as possible. The results are presented in terms of time to full stop and distance to full stop, with averages and variability calculated to assess consistency across runs. Table 9 shows the results of the braking test.

Table 9. Manual vs. teleoperation braking results

Speed	Mode	Run	Time (s)	Avg Time ± SD	Distance (ft)	Avg Distance ± SD
5 mph	Manual	1–4	0.58–1.37	0.69 ± 0.09 s	4′4″–6′8″	4′4″ ± 2′0″
5 mph	Teleop	1–3	0.68–0.99	0.80 ± 0.17 s	1′10″–2′10″	2′5″ ± 0′6″
10 mph	Manual	1–3	0.61–0.98	0.84 ± 0.20 s	8′1″–8′7″	8′3″ ± 0′4″
10 mph	Teleop	1–3	1.29–2.17	1.60 ± 0.49 s	15′0″–19′0″	16′11″ ± 2′0″
15 mph	Manual	1–3	0.58–1.23	0.84 ± 0.34 s	10′8″–15′9″	13′9″ ± 2′0″
15 mph	Teleop	1–4	1.59–3.5	2.00 ± 0.37 s	24′1″–54′3″	31′11″ ± 8′0″

The results for manual operation at 5 mph showed stopping times ranging from 0.58 seconds to 0.74 seconds, with an average of 0.69 ± 0.09 seconds (±14%). The stopping distances ranged from 2 feet 1 inch to 6 feet 8 inches, with an average of 4 feet 4 inches ± 2 feet (±53%). The variability in stopping distances at this speed is relatively high, which could be influenced by differences in operator input, such as reaction time and braking technique. At 10 mph, the time to full stop ranged from 0.61 seconds to 0.98 seconds, with an average of 0.84 ± 0.20 seconds (±24%), while the stopping distances ranged from 8 feet 1 inch to 8 feet 7 inches, with an average of 8 feet 3 inches ± 3 inches (±3.2%). For 15 mph, stopping times ranged from 0.58 seconds to 1.23 seconds, with an average of 0.84 ± 0.34 seconds (±41%), and the stopping distances ranged from 10 feet 8 inches to 15 feet 9 inches, with an average of 13 feet 9 inches ± 2 feet (±20%). For all manual operation, the stopping distance and stopping time are within the estimated threshold limits.

For teleoperation, at 5 mph, stopping times ranged from 0.68 seconds to 0.99 seconds, with an average of 0.8 ± 0.17 seconds (±21%), and stopping distances ranged from 1 foot 10 inches to 2 feet 10 inches, with an average of 2 feet 5 inches ± 5 inches (±22%). The system demonstrated stable performance at this speed, with no stopping times or distances exceeding the thresholds of 1.49 seconds for time and 9.13 feet for distance. At 10 mph, stopping times ranged from 1.29 seconds to 2.17 seconds, with an average of 1.6 ± 0.49 seconds (±31%), while stopping distances ranged from 15 feet 0 inches to 19 feet 0 inches, with an average of 16 feet 11 inches ± 2 feet (±3.2%). The system demonstrated stable performance at this speed, with no stopping times or distances exceeding the thresholds of 2.98s for time and 36.50ft for distance. At 15 mph, stopping times ranged from 1.59 seconds to 2.32 seconds, with an average of 2.0 ± 0.37 seconds (±19%), while stopping distances ranged from 24 feet 1 inch to 54 feet 3 inches, with an average of 31 feet 11 inches ± 8 feet (±26.6%). For stopping times, only one test run (3.5 seconds) exceeded the threshold of 3.47 seconds.

The braking test revealed notable differences between manual and teleoperation control. Manual operation consistently produced shorter stopping times across all speeds compared to teleoperation, which exhibited higher variability, particularly at higher speeds. Across both manual and teleoperation control, stopping times and distances increased as vehicle speed increased, which is consistent with the principles of deceleration. Higher speeds require longer stopping distances due to the higher kinetic energy that must be dissipated. Additionally, variability in both time and distance increased as speed increased, especially for teleoperation at 15 mph, where external factors like latency could influence the C2 operator's braking response.

In summary (Table 10), most exceedances occurred at 15 mph, indicating increased difficulty for teleoperation at higher speeds. The worst performance was recorded at 15 mph Run 3, where both time and distance thresholds were exceeded.

Table 10. Exceedances in stopping thresholds

Speed	Run	Time (s)	Time Limit	Exceeds?	Distance (ft)	Distance Limit	Exceeds?
10 mph	3	2.17	1.98	Yes	19.0	21.84	No
15 mph	3	3.50	2.47	Yes	54.25	38.13	Yes
15 mph	1	2.10	2.47	No	40.92	38.13	Yes

6.2.4 Straight-line Test

This test evaluated the RCTMA's ability to maintain a centered path within a 10-ft lane bordered by tennis balls, using visual analysis from camera footage.

Test Procedure:

- Create a 10-ft-wide lane using tennis balls inside a 12-ft cone-defined lane.
- Operate RCTMA at 5, 10, and 15 mph.
- Record and analyze video to determine path deviation from centerline.

Quantifiable Measures:

- Maximum and average deviation from lane center.

Acceptance Criteria:

- The RCTMA must navigate through both wide and narrow lanes without knocking over or making contact with cones or lane markers. The acceptance criteria were conservatively set to ensure the RCTMA maintains a straight track and navigates both wide and narrow lanes without making contact with cones or lane markers. The half-cut tennis balls at 10-foot intervals serve as reference points to confirm that the vehicle stays within the designated path and does not deviate beyond them.

Test Results:

Table 11 presents the measured deviations of the truck's center from the centerline of the 10-ft lane during testing at speeds of 5 mph, 10 mph, and 15 mph. These deviations were calculated through an image analysis methodology, where the lane's centerline was determined as the midpoint between the tennis balls marking its boundaries. *Appendix B. Deviation Calculation* provides a detailed explanation of the procedures used to estimate these deviations.

Table 11. Deviation from centerline

Speed (mph)	Deviation (ft)
5	0.30, 0.34, 1.74
10	0.41, 0.87, 1.38
15	1.46, 1.50, 1.54

Figure 45 shows vehicle deviation paths. The yellow line marks the lane center; red lines represent tire paths. The RCTMA's tire width of 88 inches provided reference boundaries.

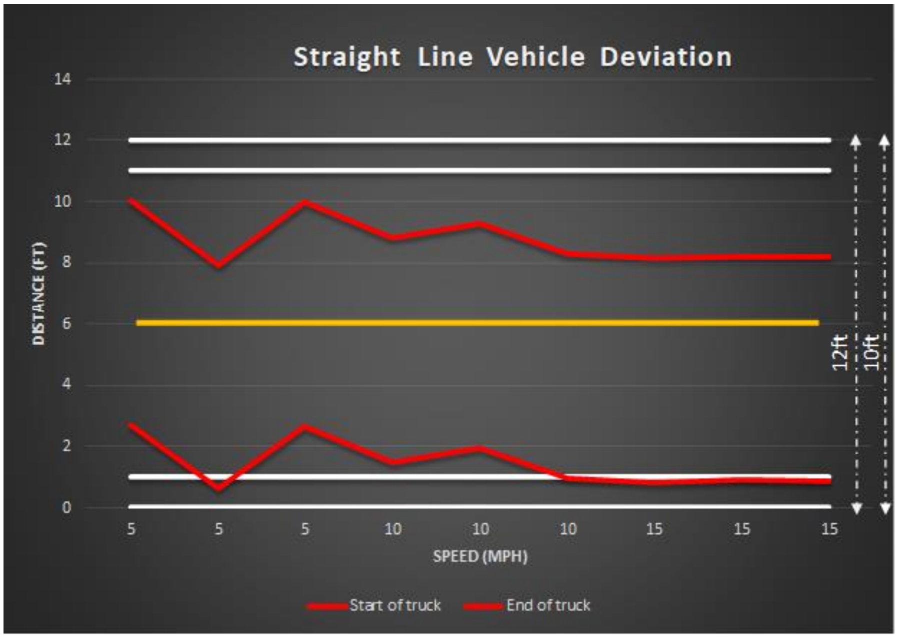

Figure 45. Graph showing deviation of vehicle path during straight-line test

At 5 mph, the deviations ranged from 0.30 ft to 1.74 ft, with smaller deviations observed in most runs, except for one instance where the truck touched the lane boundary. At 10 mph, the deviations were more consistent, ranging between 0.41 ft and 1.38 ft, demonstrating stable performance without any contact with the lane boundaries. At 15 mph, the deviations increased slightly, ranging from 1.46 ft to 1.54 ft, indicating greater variability at higher speeds.

At higher speeds, deviation increased slightly but remained within the 10-ft limit. While some trials appeared to touch lane markers, field observations and video review confirmed no cones were knocked over. Reduced camera resolution contributed to minor alignment errors, particularly at higher speeds or when minor course corrections were needed.

Higher deviations were recorded in certain tests, where the truck's path approached the edge of the 10-ft lane and, in some cases, appeared to cross the defined limits. However, both video footage and field observations confirmed that the truck never fully left the 10-ft lane and consistently remained within the broader 12-ft lane.

There were instances where a tire appeared to briefly touch or nearly contact the 10-ft lane marking. While the data and graph suggest minor crossings, these discrepancies may result from slight inaccuracies in the manual video analysis process, as outlined in Appendix B, rather than an actual deviation beyond acceptable limits.

A contributing factor to the observed deviations was the reduced resolution of the cameras. The lower image quality made it difficult for the C2 driver to clearly identify the half-cut tennis balls marking the 10-ft lane boundaries, particularly given their low height. This reduced visibility likely impacted the driver’s ability to maintain precise alignment, especially at higher speeds or when making minor course corrections. Combined with minor measurement errors during video analysis, this challenge could explain the instances where the vehicle appeared to approach or touch the lane boundaries.

Overall, the results indicate acceptable precision and steering control under the constraints of narrow-lane operation. The consistent containment within the 12-ft outer lane boundaries supports the vehicle's suitability for remote operation in constrained environments. However, additional improvement in visual resolution could enhance performance at higher speeds and in environments requiring finer lateral control.

6.2.5 Bump Test

The Bump Test is designed to evaluate the RCTMA's ability to maintain its heading and stability after encountering a significant bump along its path. The test aims to assess the system's robustness in handling minor road obstacles without significant deviation from its intended course.

Test Procedures:

- Use the same setup as the straight-line test to define the 10-ft and 12-ft lanes.
- Place a 4x4 wooden log at a designated point so the driver-side wheels roll directly over it.
- Operate the RCTMA at 5, 10, and 15 mph, repeating the test three times at each speed.
- Record the RCTMA's movement from a front-mounted camera.
- Analyze video to measure deviation before and after the bump.

Quantifiable Measures:

- Max deviation from centerline after the bump.
- Average deviation for each speed tier.

Acceptance Criteria:

- RCTMA must return to its path within 10 ft of the bump.
- No erratic behavior or control loss observed.

Test Results:

During the test, deviations of the truck's center from the lane's centerline were measured at two key points: immediately before and immediately after the truck passed over the bump. This allowed for a comparative analysis of the truck's alignment to determine the impact of the bump on its trajectory. Appendix B provides a detailed explanation of the procedures used to estimate these deviations. Table 12 shows the results from the bump test.

Table 12. Deviation in path after bump

Speed (mph)	Before Bump (ft)	After Bump (ft)	Change (ft)
5	0.21	0.16	0.05
5	0.18	0.09	0.09
5	0.23	0.40	0.17
10	0.42	0.27	0.15
10	0.21	0.26	0.05
10	0.25	0.27	0.02
15	0.27	0.40	0.13
15	0.22	0.27	0.05
15	0.28	0.42	0.14

At 5 mph, the deviations before the bump ranged from 0.18 ft to 0.23 ft, while deviations after the bump varied slightly more, between 0.09 ft and 0.4 ft. The change in path ranged from 0.05 ft to 0.17 ft, indicating minimal disruption to the truck's trajectory. At 10 mph, the deviations before the bump ranged from 0.21 ft to 0.42 ft, while the deviations after the bump ranged between 0.26 ft and 0.27 ft. The change in path was generally small, ranging from 0.02 ft to 0.15 ft. At 15 mph, deviations before the bump ranged between 0.22 ft and 0.28 ft, while deviations after the bump increased slightly, ranging from 0.27 ft to 0.42 ft. The change in path at this speed was slightly larger, ranging from 0.05 ft to 0.14 ft, reflecting a greater impact of the bump on the truck’s trajectory at higher speeds.

Figure 46 shows vehicle deviation paths. The orange line marks tire path of the vehicle before passing through the bump and purple line marks tire path of vehicle after passing through the bump. The RCTMA’s tire width of 88 inches provided reference boundaries.

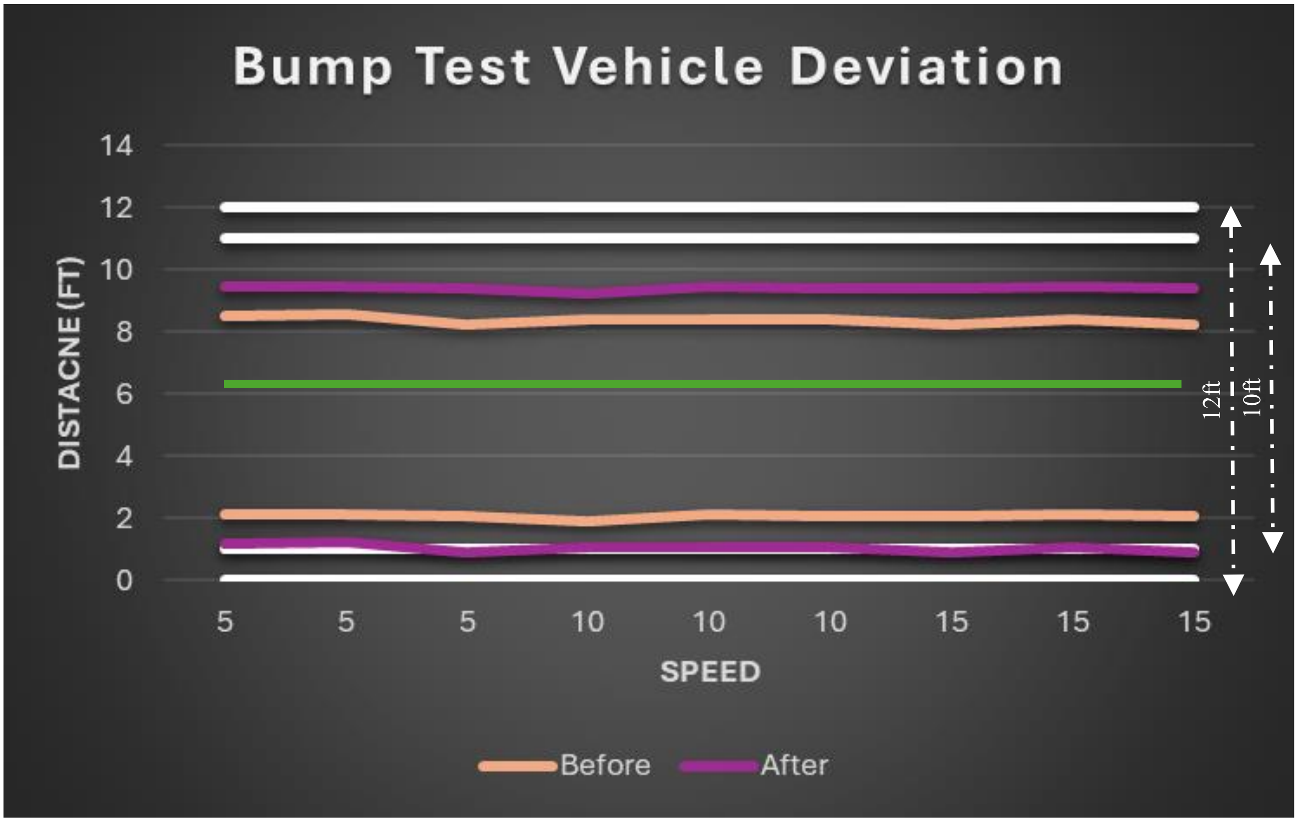

Figure 46. Graph showing deviation of vehicle path during bump test

The results confirm RCTMA's stability post-bump. Deviations remained minimal, with no erratic behavior observed. Even at 15 mph, the system returned to its trajectory within acceptable bounds.

6.2.6 Pixelation and Video Quality Test

The pixelation and video quality test was designed to evaluate the quality of the video feed from the RCTMA under realistic operating conditions. The test focused on identifying and measuring instances of pixelation and stuttering that may occur in the video feeds displayed at C2. These issues can impact the effectiveness of remote operation, making it critical to assess video quality in a systematic and objective manner. Unlike preliminary testing, which relied primarily on visual observations, this enhanced test incorporated quantitative measures to provide objective and consistent evaluations of video quality. Specifically, two key metrics were used:

1. Peak Signal-to-Noise Ratio (PSNR):
    - PSNR quantified the level of signal degradation in the video feed.
    - A higher PSNR value indicated better video quality because it reflected less noise and clearer imagery.
2. Structural Similarity Index (SSIM):
    - SSIM measured the structural similarity between the original (reference) image and the test image.

- A higher SSIM value indicated that the visual structure and details of the video feed remain intact.

Additionally, the test used homography techniques to align the test images with a reference image. Homography was essential for ensuring that any perspective differences caused by camera movement or positional shifts did not interfere with the analysis. By transforming the test frame to match the reference image, homography enabled accurate pixel-to-pixel comparisons for PSNR and SSIM calculations.

Test Procedure:

- Capture a high-quality frame (reference.png).
- Record the RCTMA feed from the C2 monitor during a drive.
- Save pixelated instances as test_frame.png.
- Align test images to the reference using homography.
- Calculate PSNR and SSIM for each comparison.

Quantifiable Measures:

- PSNR: Measures image noise levels.
- SSIM: Measures structural similarity.

Acceptance Criteria:

- PSNR ≥ 30 dB, SSIM ≥ 0.7 (There are no formally established industry-wide thresholds for PSNR and SSIM specific to remote vehicle operation. The suggested thresholds were derived from research studies in video compression, telecommunications, and visual quality assessment in related fields [1, 2].)

The Pixelation and Video Quality Test aimed to assess the quality of the video feed from the RCTMA under realistic operating conditions. Two key metrics were used for this analysis: peak signal-to-noise ratio (PSNR) and structural similarity index (SSIM). PSNR measures signal degradation, with higher values indicating better image quality, while SSIM assesses structural integrity, focusing on the similarity of shapes, textures, and edges between two images. To establish a baseline, comparisons were made between a high-quality reference image (Base 1) and another non-pixelated image (Base 2). Pixelated test images (Pix 1 to Pix 7) were then compared against Base 1 to measure the extent of pixelation-related degradation. Homography

[1] Wang, Z., Bovik, A. C., Sheikh, H. R., & Simoncelli, E. P. (2004). Image quality assessment: From error visibility to structural similarity. *IEEE Transactions on Image Processing*, 13(4), 600–612. https://doi.org/10.1109/TIP.2003.819861

[2] Sara, U., Akter, M., & Uddin, M. S. (2019). Image quality assessment through FSIM, SSIM, MSE, and PSNR—A comparative study. *Journal of Computer and Communications*, 7(3), 8–14. https://doi.org/10.4236/jcc.2019.73002

techniques were employed to align images, ensuring accurate pixel-to-pixel comparisons, even with variations in camera position or perspective. This alignment process ensured that pixelation effects could be accurately identified and measured.

The results of the pixelation analysis are shown in Table 13, which highlights the PSNR and SSIM values for the comparison of Base 1 with Base 2 and Base 1 with the pixelated test images.

Table 13. PSNR and SSIM results

Baseline	Test Image	PSNR (dB)	SSIM
Base 1	Base 2	28.6	0.27
Base 1	Pixelated 1	28.0	0.25
Base 1	Pixelated 2	28.2	0.31
Base 1	Pixelated 3	28.1	0.25
Base 1	Pixelated 4	28.2	0.37
Base 1	Pixelated 5	27.9	0.23
Base 1	Pixelated 6	27.9	0.26
Base 1	Pixelated 7	28.0	0.15

The comparison between Base 1 and Base 2 yielded a PSNR of 28.6 dB and an SSIM of 0.27. This establishes the level of "natural" variability between two high-quality, non-pixelated images. The PSNR value of 28.6 dB indicates minimal noise, while the SSIM of 0.27 suggests moderate structural differences between the two images. These differences could be attributed to slight changes in lighting, camera position, or natural image variability. This analysis provides a critical reference point for evaluating the impact of pixelation on the other images.

When Base 1 was compared with pixelated images (Pix 1 to Pix 7), the PSNR values ranged from 27.9 dB to 28.2 dB, which is only slightly lower than the PSNR for the Base 1 vs. Base 2 comparison. This result suggests that pixelation did not significantly increase noise levels relative to the natural variability observed between two high-quality images. However, SSIM values exhibited more significant variation, ranging from 0.15 to 0.37. The SSIM of 0.15 for Pixelated 7 indicates significant structural degradation, while Pixelated 4 had an SSIM of 0.37, suggesting minimal pixelation effects in this frame. The differences in SSIM highlight the loss of key structural information, such as object edges, textures, and finer details, which are crucial for clear video feeds.

The observed PSNR and SSIM values for pixelated images did not meet the commonly recommended thresholds for high-quality video feeds. In general, PSNR values above 30 dB are considered sufficient for clear and distinguishable video, while SSIM values above 0.6 are typically associated with acceptable image quality. The baseline images also failed to meet these thresholds, with a PSNR of 28.6 dB and an SSIM of 0.27. This indicates that even the best-quality images had noticeable noise and structural variability.

To summarize, baseline-to-baseline variation (28.6 dB, SSIM 0.27) set a standard for natural variability. Pixelated images showed similar PSNR (27.9–28.2 dB), but wider SSIM variation (0.15–0.37). The lowest SSIM (Pixelated 7) indicated significant structural degradation. No test images met the suggested SSIM or PSNR thresholds, including the best-quality images, suggesting consistent moderate video quality under current settings.

Chapter 7. Lessons Learned and Conclusion

This project demonstrated the feasibility of developing and deploying a Remotely Controlled Truck-Mounted Attenuator (RCTMA) to enhance safety during active incident management in Florida. By modifying an existing Autonomous Truck-Mounted Attenuator (ATMA) platform, the team integrated remote control capabilities—including steering, throttle, braking, and emergency stop—operated via a centralized control console (C2). The RCTMA system was designed to reduce the need for an onboard human driver in high-risk roadside environments, particularly during Road Ranger Safety Patrol (RRSP) operations.

Two rounds of field testing (listed in Table 14) were conducted in Fort Walton Beach, Florida, with the C2 system housed at the Kratos facility and the vehicle operated in a nearby test area at Santa Rosa Mall. Led by the University of Florida in partnership with Kratos engineers, the testing program evaluated core system capabilities such as latency, braking, visibility, maneuverability, path tracking, obstacle response, and video feed quality. Round 1 provided a qualitative assessment of system functionality, while Round 2 introduced refined procedures to collect quantitative performance data and identify critical areas for system improvement.

Table 14. Summary of tests

No.	Test	Test Round
1	Pixelation Demonstration	Round 1 and Round 2
2	Latency Test 1	Round 1 and Round 2
3	Servo Test	Round 1
4	Visibility Test	Round 1 and Round 2
5	Braking Test in Motion	Round 1 and Round 2
6	Throttle Test in Motion	Round 1
7	Straight-line Test	Round 1 and Round 2
8	Reverse Test	Round 1
9	Object Detection and Braking Test	Round 1
10	Person Detection and Braking Test	Round 1
11	Right- and Left-Turn Test	Round 1
12	Bump Test	Round 1 and Round 2
13	Maneuverability Test	Round 1
14	Parking Test	Round 1
15	Loss-of-connection E-stop Test	Round 1
16	Latency Test 2	Round 1
17	Human Driver-initiated E-stop Test	Round 1
18	External E-stop Test	Round 1
19	C2-initiated E-stop	Round 1

The qualitative tests conducted during the first round of field evaluation demonstrated that the RCTMA system was generally capable of performing the core functions required for remote operation. Basic vehicle control, such as steering, braking, throttle response, and emergency stop activation, was successfully demonstrated. However, several performance limitations were identified that could affect operational reliability. Most notably, issues related to communication latency and video feed interruptions were observed. During operation near the Kratos facility and along the route to the Santa Rosa Mall, video feeds experienced brief but recurring stuttering and pixelation. These disruptions were linked to cell tower transitions and areas of weak signal strength. At times, this led to temporary degradation in the C2 operator's visibility, raising concerns about situational awareness and the potential impact on safe maneuvering in more complex or time-sensitive situations.

Latency was further evaluated using a stopwatch-based method that measured the delay between an input event and its display at the C2 console. The observed delay, while acceptable for routine driving tasks, confirmed that the system was not operating in true real-time. Although this level of latency did not prevent basic operation, it introduced uncertainty for scenarios that require quicker reaction times, such as emergency braking or obstacle avoidance.

To better quantify these concerns, the second round of testing introduced improved tools for measuring system performance, including continuous monitoring of round-trip time (RTT). On average, RTT remained well within the acceptable 500-millisecond threshold, hovering around 150 milliseconds. However, there were 81 recorded instances where RTT exceeded 500 milliseconds, and over 500 instances where it exceeded 300 milliseconds. While these spikes were not frequent, they revealed a lack of consistency in latency performance that could potentially impact vehicle responsiveness during critical maneuvers. The low standard deviation and variance in the RTT data suggested a relatively stable system, but one that still requires attention to ensure reliability under all operating conditions.

To reduce the burden on the communication network and minimize pixelation, the resolution of the video feeds was intentionally lowered before the second round of testing. This adjustment effectively reduced the frequency and severity of video disruptions. However, it also introduced a trade-off: lower-resolution video made it more difficult for the C2 driver to identify smaller objects, read signs, or detect fine details in the driving environment. This limitation was particularly evident during visibility testing. Although overall coverage was acceptable, reduced clarity could present operational risks in scenarios that require high visual precision.

Other challenges noted across both testing rounds included limited visibility in close proximity to the vehicle despite the multi-camera setup, absence of active obstacle detection systems, and the need for manual startup and gear shifting by the on-site safety driver. These issues restrict the RCTMA's autonomy and limit its ability to function independently in a real-world deployment without close human support.

Lessons Learned

Throughout the development and evaluation of the RCTMA system, several critical lessons were identified that will inform future iterations of tele-operated vehicle technologies for incident management applications:

1. **System Latency Must Be Continuously Monitored and Managed**
   While average latency values remained well within operational thresholds, occasional spikes in Round-Trip Time (RTT) due to network handoffs or signal degradation introduced variability. These findings underscore the importance of real-time monitoring tools and redundant communication pathways to preserve responsiveness during mission-critical maneuvers.

2. **Trade-offs Between Video Quality and Network Stability Require Careful Balancing**
   Reducing video feed resolution improved communication reliability and minimized pixelation; however, this also reduced the operator's ability to interpret fine environmental details. Future systems should explore adaptive resolution encoding and dedicated bandwidth to preserve video integrity without compromising system responsiveness.

3. **Testing Protocols Must Account for Operator Anticipation and Human-in-the-Loop Factors**
   Manual interventions by safety drivers and the inherent anticipation of commands in structured test environments influenced performance metrics such as reaction time. Future testing should incorporate blind trials and scenario variability to better replicate real-world unpredictability.

4. **System Interfaces and Controls Require Optimization for Extended Use**
   The C2 console interface was functional but could benefit from ergonomic refinements and customizable controls for long-duration use. These changes would improve operator comfort and reduce fatigue during real deployments.

5. **Full Autonomy Will Require More Than Remote Control Integration**
   While the RCTMA successfully demonstrated teleoperation capabilities, full deployment readiness will depend on integrating autonomous features such as obstacle detection, automated gear control, and remote ignition. These elements are critical for eliminating the need for an on-board safety driver.

7.1. Deployment Readiness Summary

Table 15 summarizes the deployment readiness level for each subsystem. Readiness levels were assigned based on whether the subsystem met expected performance criteria under test conditions and whether it would require further development or modification for full deployment.

Table 15. Deployment readiness summary

Subsystem	Readiness Level	Notes
Communication	Partially Ready	Reliable under most conditions; occasional latency spikes
Steering/Control	Ready	Remote control precise and stable across all test speeds
Braking	Ready	Consistently met time/distance targets
Throttle	Ready	Responsive acceleration; speed targets maintained
Emergency Stop System	Ready	All inputs functioned, including LOC-triggered shutoff
Video Feed	Partially Ready	Stable but resolution limits detail recognition
Autonomy	Not Ready	No onboard autonomy; requires manual start/gear selection
Obstacle Detection	Not Ready	No active sensors integrated (e.g., lidar/radar)
Remote Startup & Gear Ctrl	Not Ready	Requires on-site intervention by safety driver

7.2. Safety Implications

Safety Implications for Work Zone Operations

The RCTMA project offers significant implications for improving roadside responder safety, particularly for Road Ranger Safety Patrol (RRSP) teams. Key safety benefits observed through this effort include:

- Reduced Human Exposure: By enabling remote control of the attenuator vehicle, the need for an onboard driver in high-risk response areas is minimized, directly reducing exposure to live traffic.

- Controlled Emergency Responses: The fully functional E-stop system ensures that operators can halt the vehicle immediately from multiple trigger points, adding a vital layer of operational safety.
- Predictable Maneuverability: The system consistently demonstrated stable path tracking and braking, improving the reliability of mobile barrier positioning in dynamic work zones.

While not fully autonomous, the RCTMA prototype has laid the groundwork for safer incident response workflows, and it provides a scalable model for future deployments that prioritize responder protection.

7.3. Future Recommendations and Path Forward

7.3.1. Path Forward: Pilot Testing and System Enhancements

To support broader implementation and move toward operational readiness, the following next steps are recommended:

1. **Live Highway Pilot Testing**
   - Conduct tests on live roadways during active RRSP deployments under FDOT supervision.
   - Evaluate system responsiveness under real-world traffic dynamics, weather, and lighting conditions.

2. **Hardware Integration**
   - Incorporate active obstacle detection sensors (e.g., lidar, radar) to enhance situational awareness and support partial autonomy.
   - Enable remote engine start and gear shifting to eliminate dependency on an onboard safety driver.

3. **Adaptive Communication Strategy**
   - Implement multi-carrier failover or edge-based decision support to minimize latency spikes and ensure uninterrupted control.

4. **Operator Training and Interface Refinement**
   - Introduce usability studies to refine the C2 console for long-duration use, reduce fatigue, and improve intuitive controls for diverse operator backgrounds.

5. **Scalability and Deployment Roadmap**
   - Begin phased rollout across select RRSP regions, supported by data collection, evaluation metrics, and continuous feedback to iterate system enhancements.

This roadmap provides a clear progression from proof-of-concept to deployable safety innovation, aligning with FDOT's strategic objectives in connected and autonomous vehicle integration.

7.4. Conclusion

Both rounds of field testing confirmed the basic feasibility of remotely operating the RCTMA under controlled conditions. The system performed reliably in several areas and met most functional requirements, validating its potential as a proof-of-concept. At the same time, the tests revealed critical areas for improvement, particularly in the consistency of communication latency, video clarity, and remote operability. The enhanced testing conducted in the second round provided deeper insight into these challenges and helped establish a foundation for further system refinement and future testing under more demanding operational scenarios.

Appendix A. Explanation of Stopping Distance and Time Calculations

The stopping distance and stopping time were calculated based on physics principles of motion under constant deceleration. The total stopping distance is the sum of the reaction distance and braking distance, while the total stopping time is the sum of the driver reaction time and the braking time.

A.1. Definitions

- Reaction Distance: The distance travelled by the RCTMA from the moment the C2 driver initiates the braking command to when the brakes are physically engaged.
- Braking Distance: The distance travelled while the RCTMA is actively decelerating to a full stop.
- Stopping Distance: The total distance from when the C2 driver issues the braking command to when the vehicle comes to a complete stop.
- Stopping Time: The total time it takes for the RCTMA to stop, including reaction time and braking time.

A.2. Calculation Equations

Reaction Distance = Speed (ft/s) × Reaction Time (s)

Braking Distance = ($Speed^2$) / (2 × Deceleration (ft/s^2))

Total Stopping Distance = Reaction Distance + Braking Distance

Braking Time = Speed (ft/s) / Deceleration (ft/s^2)

Total Stopping Time = Reaction Time + Braking Time

A.3. Example Calculation for 10 mph

Speed (mph to ft/s): 10 mph × 1.46667 = 14.6667 ft/s

Reaction Distance: 14.6667 ft/s × 2 s = 29.3333 ft

Braking Distance: Braking Distance = $(14.6667\ ft/s)^2$ / (2 × 15 ft/s^2) = 7.17 ft

Total Stopping Distance: 29.3333 ft + 7.17 ft = 36.50 ft

Braking Time: Braking Time = 14.6667 ft/s / 15 ft/s^2 = 0.9778 seconds

Total Stopping Time: 2 s + 0.9778 s = 2.9778 seconds

A.4. Summary of Calculations for 5, 10, and 15 mph

Similarly, the stopping distance and stopping time are estimated for each speed.

Speed (mph)	Stopping Distance (ft)	Stopping Time (s)

5 mph	16.46 impf	2.49 s
10 mph	36.50 ft	2.98 s
15 mph	60.13 ft	3.47 s

A.5. Assumptions Made in Stopping Distance and Time Calculations

- Reaction Time: The reaction time for the C2 driver to initiate a braking command is set to 1 second. This assumption is based on guidance from the AASHTO Green Book (2018) and Wickens et al. (2004), which suggest reaction times range from 0.7 to 2.5 seconds, depending on driving conditions. For this analysis, a reaction time of 2 seconds was chosen based on the specific conditions of the testing environment. The tests are conducted in a controlled setting, where the driver is already anticipating the braking command as part of the structured test plan. Given this anticipation, the reaction time is set at 2s to account for any slight delays in execution while maintaining a realistic yet conservative estimate for the braking response.
- Deceleration Rate: The deceleration rate is assumed to be 15 ft/s². This rate is supported by the AASHTO Green Book (2018) and studies from Fambro et al. (1997) on stopping sight distance. NHTSA standards for Advanced Driver Assistance Systems (ADAS) also support the use of this value in performance evaluations.
- Kinematic Equations for Braking Distance: The braking distance is calculated using the kinematic equation: where ___ is the speed and ___ is the deceleration rate. This equation is standard in classical mechanics and transportation engineering. It is cited in the AASHTO Green Book (2018) and physics textbooks, such as Serwa & Jewett (2013).
- Stopping Distance and Time Calculation: The total stopping distance and stopping time are calculated as the sum of the reaction distance and braking distance and the sum of the reaction time and braking time, respectively. This method is standard practice in transportation safety analysis and is referenced in the AASHTO Green Book (2018).

A6. References

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Appendix B. Deviation Calculation

The purpose of this analysis was to evaluate the truck's ability to maintain alignment within narrow lanes. The deviation from the centerline of the lane defined during the testing is a critical parameter that indicates how effectively the truck remains within its intended path. To quantify this deviation, an image-based methodology was developed using selected frames from video footage recorded during testing. This approach allowed for precise measurement of the truck's position relative to the lane's centerline, providing valuable insights into its alignment performance.

B.1. Analysis Procedure

To estimate the deviation of the truck from the centerline of the 10-ft lane defined by tennis balls, the video footage was carefully reviewed to identify frames where the truck's tire was closest to the lane boundaries. Screenshots of these frames were captured for analysis. In each selected frame, the two tennis balls marking the left and right edges of the lane were identified, and a white line was drawn between them to represent the full width of the lane, known to be 10 ft. The length of this white line was measured in pixels using image analysis tools, serving as the reference scale for converting pixel measurements into real-world units.

Next, the centerline of the lane was calculated as the midpoint of the white line. This centerline, representing the ideal path for the truck, was visually marked using a yellow dashed line. The center of the truck was then identified by determining the midpoint between the left and right tires, which was marked with a green dashed line. The deviation of the truck from the lane centerline was measured as the distance, in pixels, between the yellow dashed line (lane centerline) and the green dashed line (truck center).

To convert the measured deviation from pixels to feet, the ratio of the white line length in pixels to the known lane width (10 ft) was used. The deviation in pixels was multiplied by this ratio to yield the corresponding distance in feet. This process was repeated for all selected frames to evaluate the truck's alignment within the lane. The results provide a clear indication of how well the truck maintained its position relative to the centerline during testing.

B.2. Formula

The deviation of the truck from the centerline in feet is calculated using the following formula:

$$\text{Deviation (ft)} = \frac{\text{Deviation}_{VM} \times 10}{\text{White Line Length}_{VM}}$$

where:

- Deviation$_{VM}$: The perpendicular distance between the truck's center (green dashed line) and the lane centerline (yellow dashed line).This indicates the virtual measurement taken from the frames.
- White Line Length (pixels): The length of the white line connecting the two tennis balls

marking the lane boundaries, measured in pixels.

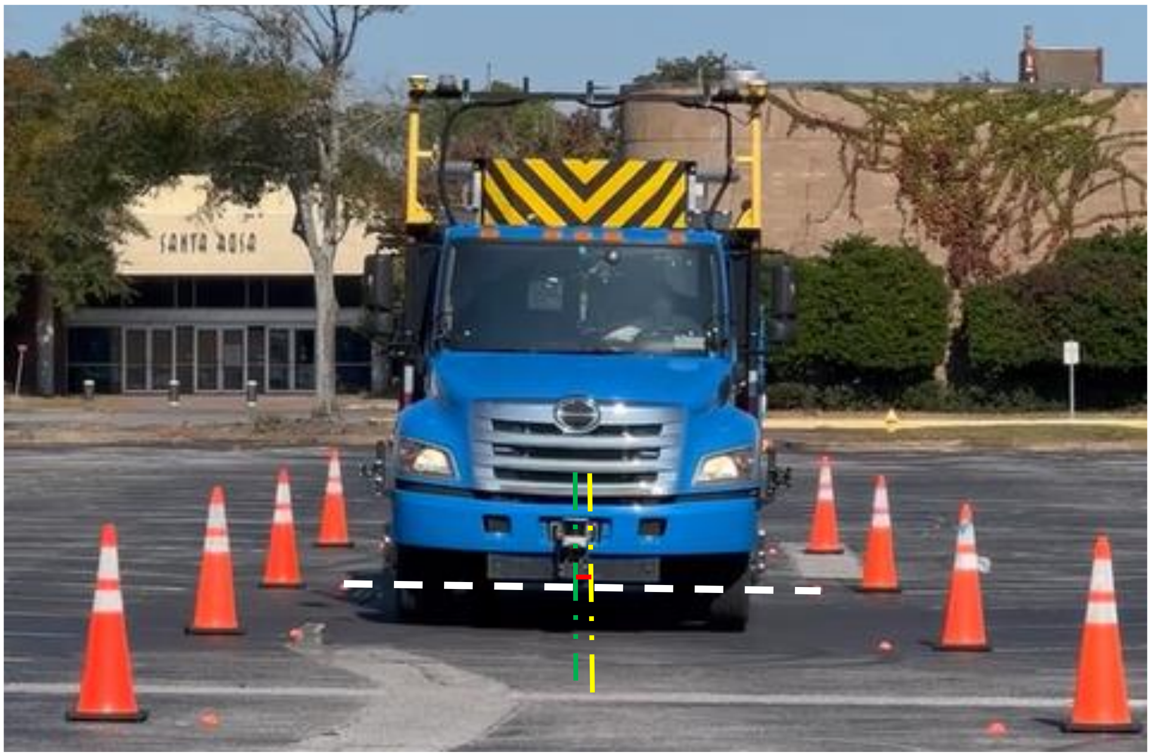
- 10 ft: The known width of the lane defined using the tennis balls.

The same procedure is followed for both straight-line test and the bump test.

B.3. Straight-line Test Analysis

Analysis for 5-mph Speed

Test 1

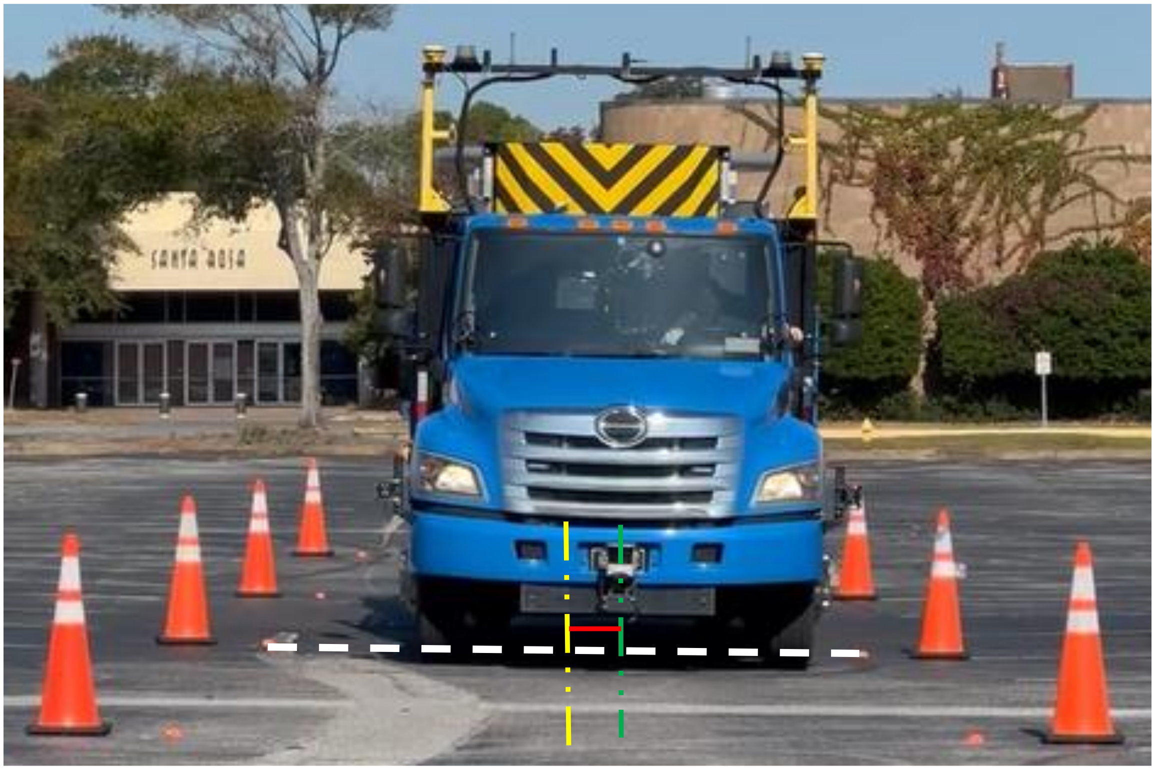


Test 2

Test 3

Analysis for 10-mph Speed

Test 1



Test 2

Test 3

Analysis for 15-mph Speed

Test 1

Test 2

Test 3

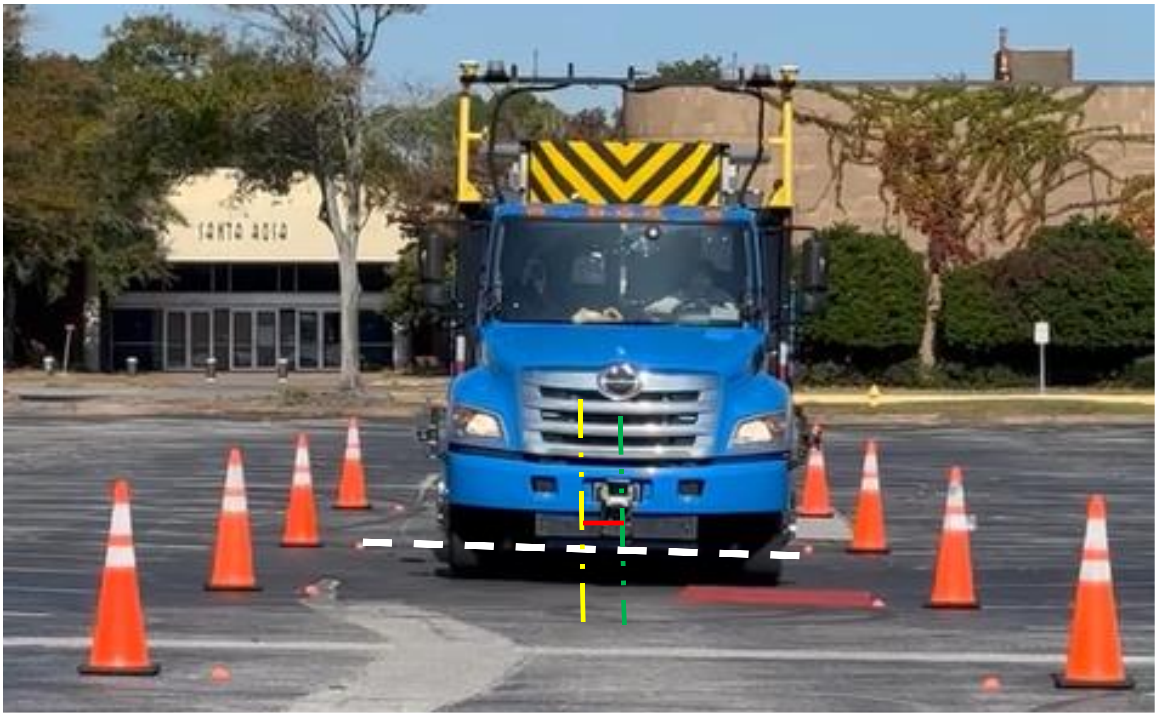
B.4. Bump Test Analysis

Analysis for 5-mph Speed

Test 1 – Before Bump

Test 1 – After Bump

5-mph: Test 2 – Before Bump



Test 2 – After Bump

5-mph: Test 3 – Before Bump

Test 3 – After Bump

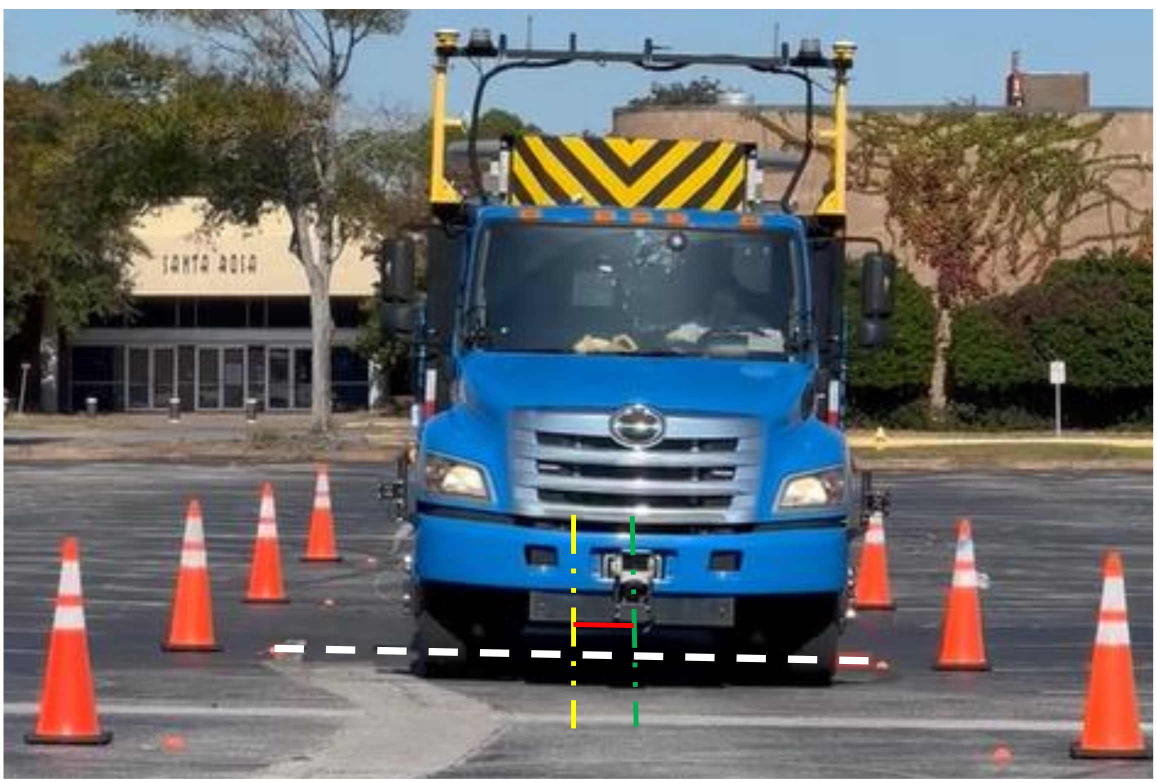
Analysis for 10-mph Speed

Test 1 – Before Bump

Test 1 – After Bump

10 mph: Test 2 – Before Bump

Test 2 – After Bump



10-mph: Test 3 – Before Bump

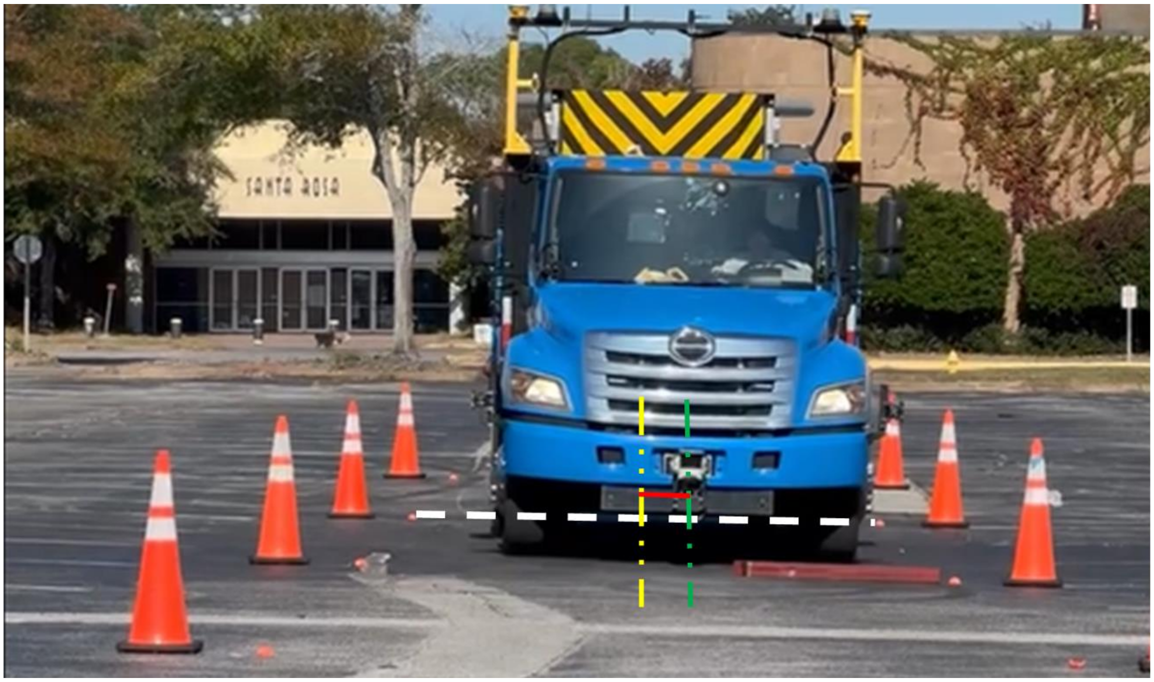
Test 3 – After Bump

Analysis for 15-mph Speed

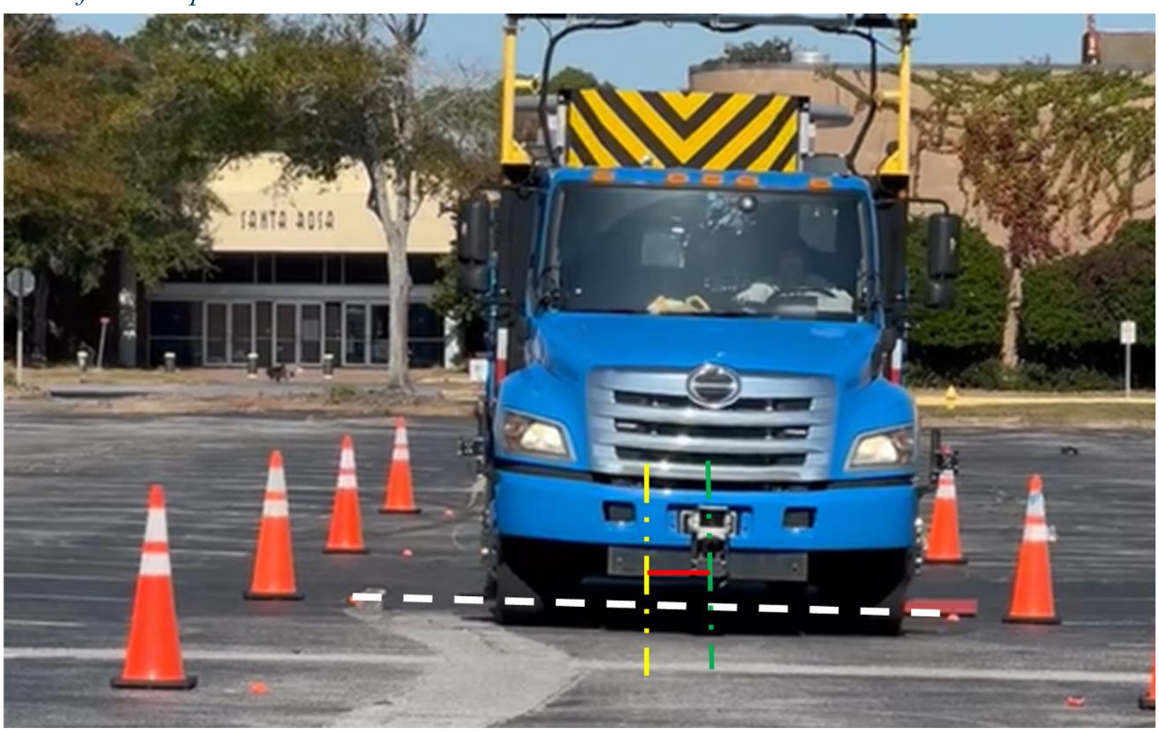
Test 1 – Before Bump

Test 1 – After Bump

15 mph: Test 2 – Before Bump



Test 2 – After Bump



15 mph: Test 3 – Before Bump

Test 3 – After Bump

Appendix C. Pixelation Test

Python code used for the analysis is given below.

```
import cv2
import numpy as np
from skimage.metrics import structural_similarity as ssim
import os
import pandas as pd

# File paths
image_folder = r'C:\Users\ssagar\UFL Dropbox\Shraddha
Sagar\TAV\Phase2\Deliverables\Deliverable 4\Pixelation\Test images'
file_paths = {f"Pix {i}": os.path.join(image_folder, f"Pix {i}.png") for i in range(1, 8)}
file_paths.update({
    "Base 1": os.path.join(image_folder, "Base 1.png"),
    "Base 2": os.path.join(image_folder, "Base 2.png")
})

# Load images
images = {name: cv2.imread(path) for name, path in file_paths.items()}
for name, img in images.items():
    if img is None:
        print(f"Failed to load: {name}, path: {file_paths[name]}")
        exit()

# Convert Base 1 to grayscale
base_1_gray = cv2.cvtColor(images["Base 1"], cv2.COLOR_BGR2GRAY)
height, width = base_1_gray.shape
```

```
# PSNR function
def calculate_psnr(img1, img2):
    mse = np.mean((img1 - img2) ** 2)
    return 20 * np.log10(255 / np.sqrt(mse)) if mse > 0 else 100

# Compare Base 1 with all other images
results = []
for name, img in images.items():
    if name == "Base 1":
        continue
    img_gray = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)
    img_resized = cv2.resize(img_gray, (width, height), interpolation=cv2.INTER_AREA)
    psnr_value = calculate_psnr(base_1_gray, img_resized)
    ssim_value, _ = ssim(base_1_gray, img_resized, data_range=255, full=True)
    results.append({"Comparison": f"Base 1 vs {name}", "PSNR (dB)": psnr_value, "SSIM":
ssim_value})

# Results
results_df = pd.DataFrame(results)
print(results_df)
```

The pictures used are given below.

Baseline image 1

Baseline image 2

Pixelated images