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Abstract

This research project investigated the application of remote driving technology for Truck Mounted Attenuator (TMA) operations. TMAs are necessary to protect the working crew from errant vehicles in support of various maintenance functions. The problem is that the driver of the TMA is susceptible to injury in high-speed crashes. The motivation is to mitigate injury potential for the driver by removing them from behind the wheel and into a remote driving station. This research study evaluated the existing state of commercially available remote driving technology and through a competitive bidding process acquired a system and tested it through several test scenarios designed in this research to evaluate its applicability for Caltrans TMA operations. The test results provided data indicating that remote driving is a viable option for Caltrans' TMA trucks in areas where the cellular network has a sound coverage, and the roadway lane width and geometry do not provide very tight and complex driving conditions.

Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Evaluation of remote operation of truck-mounted attenuator (TMA)-equipped shadow vehicles for use in Caltrans' operations

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Principal Investigator: Bahram Ravani

Report Number: CA25-4161
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California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

In Caltrans' highway operations, Truck-Mounted Attenuators (TMA) are necessary to protect the working crew from errant vehicles in support of various maintenance functions. This research investigated the application of new remote driving technology in TMA operations.

Problem, Need, and Purpose of Research

TMAs provide protection for the maintenance crew from errant vehicles, but the driver of the TMA is susceptible to injury in high-speed crashes. There is a need to mitigate injury potential for TMA drivers as well.

Alternative approaches to having a driver inside a TMA truck are needed to protect the TMA driver from high-speed crashes. Having the TMA follow the working crew autonomously has its own challenges, from complications regarding permits for autonomous operation and deployment to adding further reliability concerns because of all the sensors and actuators required for autonomous driving. As a more practical alternative, remote driving of the TMA will mover the driver to a location remote from the actual TMA providing driver protection in case of a crash while allowing the TMA to provide its intended traffic control function. The purpose of this research is to evaluate the state of remote driving technology for TMA applications.

Overview and Methodology

The available providers of remote-driving technology were investigated. A competitive bid process was used resulting in the selection of the remote driving technology by KRATOS (Micro Systems Inc.). A test plan was devised to account for Caltrans' safety and performance requirements for a remotely driven TMA in highway maintenance operations. A test track was designed in the shape for a loop for Remote-Control TMA (RCTMA) testing, such that completion of every loop in the test track would provide data for all testing scenarios entailed in the test plan.

KRATOS RCTMA technology, consisting of a truck with proper sensors and the remote driving station, was leased for testing. The actual testing was performed in a Caltrans facility. A total of 22 rounds of testing was conducted and 150 Giga Bytes (GB) worth of data was collected. The data was processed to produce objective results used in our evaluation of the potential of using the remote driving technology for TMA operations within Caltrans.

Major Results and Recommendations

The results of this research have provided data indicating that remote driving is a viable option for Caltrans' TMA trucks in areas where the cellular network has a sound coverage, and the roadway lane width and geometry do not provide very tight and complex driving conditions.

The test results showed that RCTMA was able to perform all the test scenarios with sufficient efficacy. Below is a brief description of the major test results across various test scenarios.

Communication

On AT&T network in Northern California, the communication latency was minimal, and remote driving was efficient and lag-free. Radio communication was maintained between the remote driver and on-site personnel for ensuring safety and proper execution of TMA duties.

Pause and Stop

The remote driver was able to pause the RCTMA motion and have it come to a full stop on demand.

Obstacle Avoiding

The remote driver was able to avoid the obstacle by negotiating around it at all test speeds (5, 10 and 15 MPH). However, obstacle-avoidance at higher speeds came with a more pronounced lateral offset.

Lane-Keeping

The RCTMA was able to keep its lane at typical 10 MPH and 15 MPH speeds with an average lateral offset below 2 feet while being driven remotely. Driver training proved essential to satisfactory lane-keeping. It was found that higher speeds and curved paths are more challenging for lane-keeping than low speeds and straight paths. The same challenges were observed when the driver was behind the wheel in such paths or at such speeds.

Gap maintaining

When instructed to maintain the gap with the lead vehicle, the remote driver was able to maintain a gap of 100 feet over a distance of 400 feet. Maintaining the gap while maintaining a speed proved challenging and requires extra training. Similar results are expected when the driver is behind the wheel.

Taking the Lane

The remote driver was able to take the lane by starting the RCTMA motion in the road's shoulder and joining the lane in minimal distance.

Acceleration/Deceleration

The remote driver was able to smoothly and rapidly accelerate or decelerate whenever necessary.

Driver Workload

Using NASA's Task Load Index method showed that remote driving had a 50% higher mental workload index as compared to behind the wheel driving. An inexperienced remote driver showed a further 40% increase in the mental workload. It was understood that remote driving is more demanding than behind the wheel driving. Therefore, in addition to training, the work schedule and the workload of the remote driver should be adjusted accordingly. Another thing that should be noted is that driver training is immensely important for the remote driving task and that good remote driving is not the same as good behind-the-wheel driving.

Driver Training

Finally, it was found that driver training is of utmost importance for remote driving and significantly affects the performance of the RCTMA across many test scenarios, such that inexperienced drivers did not perform as well as trained drivers for important features such as lane-keeping and gap-maintaining. Furthermore, trained drivers seemed to experience lower mental workloads for the remote driving task than inexperienced drivers.

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Acronyms and Abbreviations

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
DDT	Dynamic Driving Task
DMV	Department of Motor Vehicles
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
GB	Giga Bytes
GPS	Global Positioning System
INS	Inertial Navigation System
LiDAR	Light Detection And Ranging
LOC	Loss Of Communication
LTE	Long-Term Evolution
LV	Lead Vehicle
MASH	AASHTO Manual for Accessing Safety Hardware
MAZEEP	Maintenance Zone Enhanced Enforcement Program

Acronym	Definition
MPH	Miles Per Hour
META	Maintenance Equipment Training Academy
RCTMA	Remote-Control Truck-Mounted Attenuator
SAE	Society of Automotive Engineers
TLX	Task Load Index
TMA	Truck-Mounted Attenuator
WLAN	Wireless Local Area Network

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Chapter 1: Introduction

Problem

Part of the California Department of Transportation (Caltrans) operations is highway maintenance or repair. As the highways are rarely completely shut down for conducting these operations, the working crew must be protected from errant vehicles who might drive into the working site by accident. Therefore, these operations are often accompanied by a large truck that is equipped with a truck-mounted attenuator, usually referred to as a TMA. The TMA truck acts as a barrier between highway traffic and the working crew and provides the workers with protection from an impact by errant vehicles. The TMA truck that protects a highway work zone is known as a "Shadow Vehicle" in the Caltrans safety manual. Given that the shadow vehicles are primarily intended to brace the impact from the errant vehicles, their drivers are inherently susceptible to physical injury. In particular, the impact from fully-loaded semi-trucks driving at high speeds is significantly large and exceeds the standard impact limit specified in the American Association of State Highway and Transportation Officials' (AASHTO) Manual for Accessing Safety Hardware (MASH)[1]. Recent developments in vehicle teleoperation technology enable the TMA truck to be driven remotely with no driver behind-the-wheel, which eliminates the truck driver's risk of injury and provides just as adequate protection for the working crew.

Objectives

This research project aimed to identify a commercially available remote-control TMA (RCTMA) system, acquire their services for a proof-of-concept demonstration, develop a test plan for the RCTMA system according to Caltrans' requirements in terms of safety and performance, conduct an evaluation of the system according to the test plan and collect the data, and make objective deductions as to whether the use of RCTMA systems could meet Caltrans' needs in highway operations.

The evaluation intended to verify if the acquired RCTMA technology fulfills the Caltrans requirements, and if not, it should document how it can be augmented to accomplish that goal. Should the research identify an effective RCTMA system that meets all of Caltrans' safety and performance requirements, Caltrans could adopt the RCTMA system and deploy it for use at the Division of Maintenance.

Scope

This research project identified and acquired an operational remote-control shadow truck system that was recognized to fit Caltrans' needs from a notable manufacturer of teleoperation technologies for a proof-of-concept demonstration. The Advanced Highway Maintenance and Construction Technology Research Center (AHMCT) developed an RCTMA test plan to assess whether the RCTMA system can provide the same degree of safety as a standard Caltrans shadow vehicle, and whether it is as adequately functional. AHMCT executed the RCTMA test plan on closed roads while a safety rider was stationed inside the RCTMA to enhance safety measures. This final report presents the complete test results and recommendations of the RCTMA evaluation to Caltrans.

Background

Caltrans commonly uses conventional shadow trucks equipped with TMAs to protect the work zone in their highway operations. These shadow trucks are primarily intended to provide safety for the working crew and the passing motorists. However, they have other applications such as providing traffic control and maintenance support, where they can be placed off the shoulder on the highway, operated within the closed lane, or used to obstruct incoming traffic.

During a temporary highway lane closure for a routine maintenance task, a shadow truck is typically positioned near the work vehicle to shield the workers from any errant vehicles entering the work zone. The shadow vehicle is often driven by the lead worker overseeing the highway maintenance operation, as it provides the best vantage point for monitoring both the maintenance work ahead and the traffic control efforts behind, which includes the Highway Maintenance Zone Enhanced Enforcement Program (MAZEEP). This further enables a quick response to any imminent threat from an errant vehicle. Being the first line of defense, the shadow vehicle is inherently at the highest risk of being struck on the highway. TMAs are specifically designed to safely absorb and dissipate the impact energy from standard-sized cars and trucks. However, the TMA truck and its driver are susceptible to the great danger of a high-speed collision with a heavy vehicle, such as a large commercial semi-truck. Such a collision generates impact forces that far exceed the design limits of conventional TMAs. Figure 1.1 illustrates an example of a collision with a Caltrans shadow vehicle where the TMA has braced the impact.

Figure 1.1: Caltrans TMA impact on a highway

To eliminate the risk of injury for the shadow truck driver, autonomous TMA vehicles (ATMA) were designed. By removing the driver during highway operations, they would be protected against errant vehicle collisions. In collaboration, Royal Truck & Equipment (Royal) and KRATOS Unmanned Control Systems (KRATOS) had developed a leader-follower system that autonomously guided a TMA truck to follow a lead vehicle by tracking its trajectory at an adjustable gap distance.

The ATMA had been equipped with a variety of sensors that enabled the continuous monitoring of its following accuracy and the detection of any obstacles that may enter its path. In this case the shadow truck driver would remain in the lead vehicle to oversee the motion of the follower truck, serving as an additional safety measure to stop it immediately if necessary. The Caltrans ATMA shadow vehicle is shown in Figure 1.2.

Figure 1.2: Caltrans ATMA shadow vehicle

While the ATMA provides the required protection for the shadow vehicle's driver, it has certain shortcomings. As the ATMA is unoccupied during autonomous operation, its sole function in highway maintenance is to act as a barrier. Therefore, it cannot offer the additional operational advantages that conventional, human-driven shadow trucks provide, such as traffic control. It must be noted that deploying autonomous shadow trucks comes with extra cost and complexity as autonomous control introduces new potential risks that human-driven vehicles do not pose.

Furthermore, deploying the ATMA has its own regulatory challenges. The regulations for the operation of autonomous vehicles are relatively new and continuously evolving to keep up with technological advancements. For Caltrans to deploy the ATMA on California highways, a relevant agency must grant approval, primarily based on the ATMA's level of automation characteristics. The Society of Automotive Engineers (SAE) serves as the leading reference in categorizing levels of autonomous driving. Figure 1.3 shows the classification of autonomy according to the SAE J3016 standard [2].

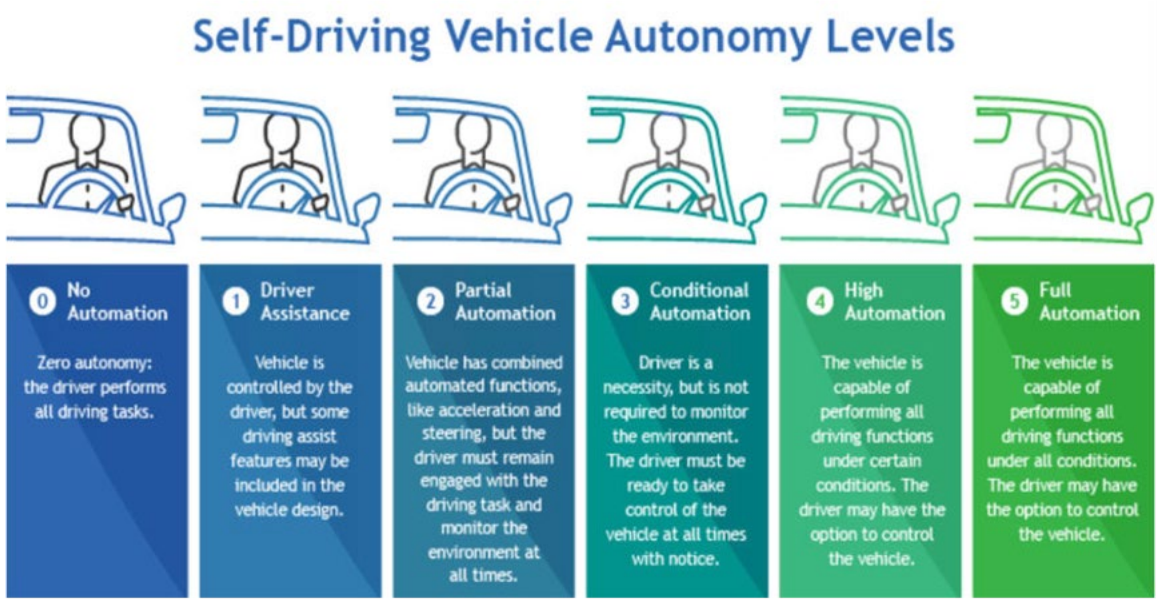

Figure 1.3: Classification of autonomous driving levels by SAE

While the ATMA's leader-follower system does not exactly conform to the SAE standard's model as it requires the presence of a driver inside the autonomous vehicle, its level of autonomy is considered to be between level 2 and level 3. The California Department of Motor Vehicles (DMV) requires specific permits for the operation of autonomous vehicles at SAE level 3 and above. Although the ATMA's operation does not exceed this threshold, it must be noted that California DMV regulations do not yet cover heavy-duty vehicles like the ATMA truck and therefore the deployment of the ATMA on highway operations has its own legal and regulatory complications.

Literature

Due to the above-mentioned shortcomings, the wide application and deployment of autonomous shadow vehicles is currently limited by practicality, safety, and regulatory concerns. To address the situations where the autonomous system faces uncertainty and could behave in unpredictable ways, some degree of human oversight is required for the foreseeable future[3]. Shadow vehicle teleoperation can be considered an alternative solution, such that the TMA truck could be remotely controlled, either at all times or simply during emergencies when the autonomous mode cannot safely operate itself[4].

The SAE J3016 standard recommends the use of the term remote driving instead of teleoperation, as the latter is viewed not to have been consistently defined in the literature. In the noted SAE standard, remote driving can be considered as part of levels 1 and 2 in terms of level of automation and is viewed as being in the category of remote support functions. Figure 1.4 shows a schematic of a remote driving situation for a shadow vehicle entailing the necessary network communications.

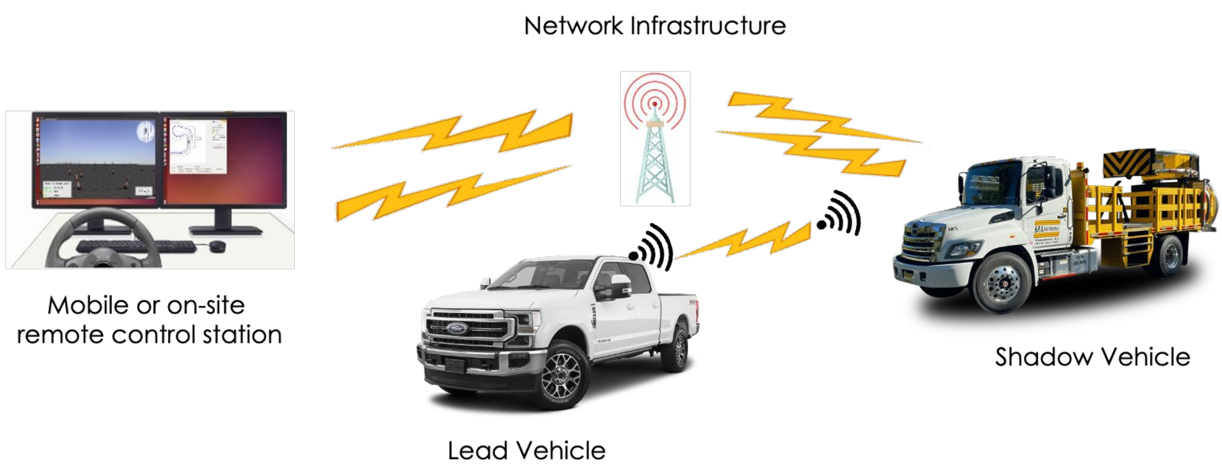

Figure 1.4: Schematic of remote driving for a TMA truck

Remote driving comes with numerous challenges present due to the physical disconnect between the vehicle and the operator. Upon an initial survey of the available literature on remote driving, it seems that remote driving as a research problem can be classified into three major categories: vehicle issues such as making it drive-by-wire, infrastructure considerations such as network latency, and operator concerns, such as the situational awareness of the remote driver.

Two major challenges that set remote driving apart from autonomous driving are the remote driver's situational awareness and the network latency. Much like behind-the-wheel driving, remote driving is a Dynamic Driving Task (DDT) which means "all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic"[1]. The DDT includes the following subtasks:

- Objects and event detection and response
- Lateral and Longitudinal motion control
- Maneuver planning

The detection of objects and events is part of situational awareness that requires many sensors and cameras and a network disseminating the input of these sensors to the remote operator. The data from these sensors and cameras need to be properly displayed to the remote operator so that the operator can have an adequate response to them, which is coupled with the operator's perceptual system. Tener and Lanir ran an experiment where remote operators were interviewed to discover the main challenges of teleoperation. They concluded that from an operator's perspective, teleoperation challenges include lack of physical sensing, human cognition and perception, video and communication quality, remote interaction with other humans, impaired visibility, and lack of sounds[5].

The other major issue with teleoperation is communication delay and latency [6]. When multiple components are involved, each one has its own individual delay. Some can be mitigated or accounted for, while others are inevitable. For the task of remote driving, there are additional latencies associated with human's perceptional and motor-control response.

Various communication networks have been studied for the purpose of vehicle teleoperation and their capabilities and limitations for remote and autonomous driving has been identified, from WLAN[6] to 5G LTE[7, 8]. The latency of the communication network can impact the driving performance. Commercial vehicle teleoperation companies have claimed communication latencies as low as 100 milliseconds, which allows for a rather seamless and smooth remote driving at speeds of about 50 miles per hour in urban settings [9, 10]. Since Caltrans TMA trucks are primarily used in highway maintenance operations, the application of remote driving

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[1] https://www.lawinsider.com/dictionary/dynamic-driving-task-ddt

technology is relatively more simplified, as state highway driving situation is not as complex as urban cities.

If the speed of the remote-driving operation is sufficiently small, higher values of latency would also be allowed. For Caltrans' highway maintenance purposes, the required speed for the shadow vehicle operation is usually low. Studies of remote driving operations for logistics applications have shown that latencies of the human remote driver and the network can be critical bottlenecks for highway-speed remote driving. However, smooth remote driving can be achievable at slow driving speeds which is applicable to the case of shadow vehicle applications in Caltrans' highway operations[4].

The Caltrans Division of Research, Innovation and System Information (DRISI) has also performed a preliminary investigation on tele-operated and automated vehicles. This study identifies some of the associated technologies and equipment as well as summarizes the experience of State Department of Transportations (DoTs) in utilizing some of such technologies[11].

It has been suggested that incorporating haptic feedback on the remote driver's end would help with smooth path planning and obstacle avoidance, as experimentally demonstrated by Coffey and Pierson[12]. Furthermore, the manual override capability must be retained as a protective measure against malicious intruders[13].

Research Methodology

The research methodology for the RCTMA study involved a background study on commercial providers of remote-driving technology, devising a test plan corresponding to Caltrans' safety and performance requirements for a shadow vehicle in Caltrans' highway operations, acquiring a standard configuration RCTMA system and executing the test plan scenarios with the acquired RCTMA equipment on a closed test track facility.

The safety scenarios verified the safe operation of the RCTMA and made sure the remote driver has the ability to prevent unexpected accidents. The safety scenarios check whether the remote driver has been in continuous communication with the working crew and in-field personnel, whether the remote driver can pause or stop the RCTMA motion at will, and whether the remote driver can avoid possible obstacles in the RCTMA path.

The performance scenarios check to see if a remotely driven shadow vehicle can function as well as a behind-the-wheel-driven shadow vehicle for Caltrans' highway maintenance operations. The performance scenarios check if the RCTMA has sufficiently accurate lane-keeping for both straight and curved paths, if the RCTMA can properly maintain its gap with the lead vehicle, if the RCTMA can smoothly roll out from the shoulder and take the lane at the start of a highway maintenance operation, and whether the RCTMA can seamlessly accelerate and decelerate when necessary.

The design of the test plan and the test track in the testing facility, and the evaluation of RCTMA performance were all conducted from the perspective of Caltrans operations, to see how the application of remote driving technology can be beneficial to Caltrans. Caltrans' highway maintenance operations include some of the riskiest tasks that need to occur daily, and this study verifies if Caltrans' shadow vehicles can benefit from remote driving.

Overview of Research Results and Benefits

This research project succeeded in acquiring and testing a remote-control TMA (RCTMA) vehicle suitable for application in Caltrans' highway maintenance operations. The results of the evaluation were satisfactory, and this research has found that the remote shadow vehicle has potential for deployment in the future. The RCTMA system tested to check both the safety and performance aspects of the remote-driving technology from the perspective of supporting Caltrans' highway maintenance operations. The study determined that the use of RCTMAs has potential beneficial applications for Caltrans operations that improve worker safety. The results of RCTMA testing indicated that the remotely driven shadow vehicle had sufficient performance and that it should satisfy Caltrans' operational accuracy requirements. While the RCTMA testing showed that a remotely driven TMA can have all the benefits of a behind-the-wheel-driven TMA with the bonus of keeping the driver safe, it also showed that training is crucial for remote drivers and that remote-driving has a higher workload than behind-the-wheel-driving.

The key deliverables of this project include:

- A report on remote-driving technology providers and the procedure of acquiring the required services
- A developed test plan and testing methodology for assessing the safety and performance of the acquired RCTMA technology
- The results and discussion on how the acquired RCTMA performed across the various test scenarios
- AHMCT's suggestion as to whether the RCTMA technology can suit Caltrans' needs.

Chapter 2:
RCTMA Procurement

To obtain a functional RCTMA system, multiple vendors with experience or interest in teleoperation technologies were contacted for this project. It was gathered that some are no longer in business and others did not show interest. In the end only three viable options remained. In this chapter a detailed description of vendor evaluation is given, including their background, and their response to AHMCT's inquiry.

Vendor Investigation

Below is a description of vendors who practice teleoperation technology with applications to remote driving, both inside and outside the US.

Designated Driver

Designated Driver is a Portland-based teleoperation company in Oregon, USA. They seem to be no longer in business as they neither responded to AHMCT's inquiries regarding collaboration, nor have they updated anything on their social media since 2020. Their main website is also inaccessible.

Kodiak Robotics

Kodiak Robotics are an autonomous truck company based in Mountain View, California. They offer software solutions for autonomous fleets of trucks. They did not respond to the multiple inquires via emails and phone calls from AHMCT and it is assumed they were not interested in collaboration.

Zoox

Zoox is a California-based company that develops autonomous vehicle solutions. They have merged with Amazon since 2020 and have their autonomous vehicle fleets operating on public roads.

They were also unresponsive to AHMCT inquiries and it is assumed that they were not interested in pursuing this project.

Waymo

Waymo is Google's autonomous vehicle company. They offer autonomous vehicle solutions and have an operational fleet of autonomous vehicles on the streets of San Francisco and in the Bay Area. Upon initial contact, they told the AHMCT representative that they would get back to AHMCT provided that they would be interested in further collaboration. However, AHMCT never heard back from them and upon a second inquiry did not receive a reply. It is assumed that they were not interested in collaboration.

Phantom Auto

Phantom Auto is a California-based artificial intelligence company that develops software solutions for both autonomous and remote driving. While they do have experience with vehicle teleoperation, upon contact they told AHMCT that they would not be taking in new ventures with commercial values below a million dollars. Therefore, they too were not available.

TORC Robotics

TORC Robotics are a Virginia-based robotics company that offer software solutions for autonomous trucks. Upon contact they told AHMCT that while they have been previously engaged in vehicle teleoperation, their current focus is exclusively on SAE level 4 of autonomy for trucks and they would not be taking on this project.

Ottopia

Ottopia is an Israel-based startup software company that offer software solutions for vehicle teleoperation. They have collaborated with the company Motional to deploy a fleet of autonomous taxis that have remote-control capabilities. They have demonstrated their vehicle teleoperation technology by driving a vehicle remotely on the streets of San Francisco from Tel Aviv at speeds of about 50 miles per hour. Upon initial contact, they claimed interest in collaboration on the project and gave a $200~300K price quote for a teleoperation proof-of-concept. However, they said that given that they are a startup company, they would require long-term commitment from Caltrans, for instance a 5-year contract. Upon further inquiry to obtain a bill of materials, they backed out of their initial position and stated that they would not be taking in academic projects and would proceed to pursue projects with commercially larger values.

DriveU.Auto

DriveU.Auto is an Israel-based company that provides software solutions for vehicle teleoperation. They are particularly known for their minimal communication latency attributed to their efficient encoding/decoding algorithms which they use to process the camera footage using high-computational-power, on-board, graphical processing units. They had demonstrated their vehicle teleoperation technology by driving a car remotely in San Francisco from Kfar-Saba, Israel with speeds as fast as 50 MPH. Their teleoperation solutions are vehicle-agnostic and can be adapted to any vehicle. When AHMCT reached out to them, they declared interest in taking on this project. They gave a bill of materials including the necessary hardware for signal processing and the remote-control station. Their price quote for the minimum package for a proof-of-concept demonstration of vehicle teleoperation was close to $80,000. However, their offered package was a software solution only and required AHMCT to already have a TMA truck with drive-by-wire capabilities. Their price quote was only for adapting their software solution to the drive-by-wire vehicle which AHMCT had to provide.

MIRA

MIRA is a Dusseldorf-based, German company that is a subsidiary of Rheinmetall, which is one of the largest European arms manufacturers. MIRA specializes in teleoperation technologies and have demonstrated their teleoperation technology by remote driving a vehicle on the streets of Berlin from Dusseldorf that is 350 miles away with speeds of almost 50 miles per hour. When AHMCT reached out to them, they agreed to collaborate. Their teleoperation solution was complete, meaning that they had both the software solution and the drive-by-wire vehicle to adapt it to. However, they said that because of their other engagements, it would take a year before they could do a proof-of-concept demonstration, and their suggested price tag was well over a million dollars.

KRATOS(Micro Systems, Inc.)

KRATOS is a San-Diego based company that develops transformative, and affordable technology, platforms, and systems for United States National Security-related customers, allies, and commercial enterprises. KRATOS specializes in unmanned systems, satellite communications, missile defense, cybersecurity/warfare, microwave electronics, hypersonic systems, training, and combat systems. They have previously collaborated with Caltrans and other DOTs several times in the past. Their subsidiary company, called MicroSystems, Inc. is in charge of developing teleoperation solutions for truck-sized vehicles. While they have not yet developed commercial teleoperation solutions, they have experience with vehicle teleoperation in military applications. They retrofit the vehicles of interest by placing actuators for steering, acceleration/braking, and transmission. Their teleoperation solutions pertain to speeds below 20 MPH where they claim that the effect of latency over Long Term Evolution (LTE) networks would be negligible (below 1 second).

Vendor Summary

Many possible vendors active in teleoperation were contacted as potential contenders for getting involved in this research project. Table 2.1 provides a listing of these companies.

Table 2.1: A List of teleoperation companies considered.

Vendor Name	Email
Kodiak Robotics	contact@kodiak.ai
Zoox	hello@zoox.com
Waymo	support@waymo.com
TORC Robotics	gwen@torc.ai
Ottopia	alexs@ottopia.tech
KRATOS (MicroSystems)	Maynard.Factor@ KRATOSdefense.com
MIRA	Marian.Meier-Andrae@mira-mobility.com
DriveU.Auto	dor@driveu.auto
Phantom Auto	shai@phantomauto.com

Vendor Selection

The University of California has a system to choose a potential vendor for collaborative projects. After the initial vendor research, in order to select one to collaborate with on the project, a bidding process was set up on the campus' website where potential vendors would make bids in terms of price and time of delivery. They would later be graded by a committee according to previously defined scoring criteria and the bidder with the highest score would be selected for collaboration and be offered a contract.

The bid went live on April 8th, 2024, and was open to take the bidders' offers for 30 days. After this period the bid was closed, and the bid packages were collected to be graded. A committee of 4 independent referees graded each bid according to predefined scoring criteria and MicroSystems, Inc. (KRATOS) was chosen to collaborate on this research project. They claimed they would be able to deliver proof of concept with Caltrans' TMA truck in a timeline of 4-6 months. Also, the teleoperation could take place from Caltrans' command center at a location of choice or their own command center in Florida. They also stated that if the proof-of-concept demonstration were to occur via their own remote-control TMA truck, they could deliver the proof-of-concept demonstration immediately. In a competitive bidding process, they came out on top and were selected for testing in this research project.

They were offered a contract and, after consulting with Caltrans, a test date was set for the week of June 3rd through June 7th, 2024.

Chapter 3:
Test Plan

AHMCT devised a test plan to enable an objective assessment of the performance of the remote-control TMA. In this chapter, the devised test plan is discussed.

AHMCT RCTMA Evaluation Objective

The objective of this research study is for AHMCT to independently verify the safety and performance of the remote-controlled TMA for Caltrans' highway use and to also assist Caltrans in acquiring the necessary authorizations to have the RCTMA deployed on highways.

The RCTMA would need to demonstrate functionality, driving reliability, and vehicle safety. For this purpose, validation test maneuvers are required to ensure the RCTMA is functional and safe to operate.

AHMCT partnered with KRATOS (MicroSystems, Inc.) in conducting these validation tests, which served to broaden both user training and testing plan development. AHMCT used this experience to devise and refine a Caltrans-specific RCTMA test plan.

The AHMCT test plan includes many of the KRATOS validation tests as well as specific, new tests that evaluate the Caltrans highway moving-lane-closure operation application. This resulted in a series of RCTMA test scenarios that are divided into safety and performance categories.

The safety test scenario trials evaluated RCTMA control in a variety of standard system and operator functions and conduct an operational failure mode analysis to ensure that the RCTMA always remains safely under the remote operator's control. The performance test trials evaluated the RCTMA's performance across the various aspects of TMA application to assess how the RCTMA would need to perform in a Caltrans highway moving closure maintenance operation, such as paint striping or sweeping.

AHMCT RCTMA Testing Practices

AHMCT followed a strict set of safety testing practices while operating the RCTMA in remote-control mode. The foremost of these practices is to always station a safety rider in the RCTMA while in remote-control mode. Despite not engaging in any of the RCTMA driving functions during remote-control testing, the safety rider sits behind the wheel of the RCTMA to ensure no accidents will occur on the off chance that the remote driver loses control of the RCTMA. The LV driver, the remote operator, and the RCTMA safety rider need to have direct, continuous radio communication using radio headsets while in remote-control mode. AHMCT performed RCTMA testing away from traffic on a series of test sites on a closed road. An AHMCT representative rode next to the safety rider inside the RCTMA to collect data and coordinate with the remote driver on test scenarios.

AHMCT RCTMA Test Sites

AHMCT identified an array of available test sites appropriate for conducting all of the RCTMA test scenarios. Caltrans requested that all AHMCT RCTMA testing be restricted to closed test sites until the legal aspects of operating a heavy truck in remote-control mode could be resolved within the State of California. This policy primarily affects the overcrossing test scenario, eliminating the Old Davis Road overcrossing testing site from further consideration. As a replacement, Caltrans could close a section of highway on State Route (SR) 905 that contains a suitable overcrossing for AHMCT to conduct the overcrossing validation test scenario. The test plan was designed for testing on a closed road and the Caltrans META facility located at 4304 Dudley Blvd, McClellan, CA 95652, was selected as a test site.

AHMCT Operational Safety Test Scenarios

The safety scenarios focus on exploring failure modes, errant hazards, and operator errors that could occur during normal RCTMA operations with Caltrans operators in highway operations. The test scenarios also seek to explore if any type of system failure while under remote control could ever result in the RCTMA driving out of control or being set adrift.

Safety Test Scenario 1: Error Recovery by the Remote Operator

Continuous links of radio communication must be maintained at all times between the remote operator and the LV and also between the RCTMA and the remote operator. If for any reason the communication link is disrupted, then the RCTMA should be able to respond to this incident safely.

There has to be a certain degree of redundancy in the number of radio channels used for communication to increase the possibility that at least one link will remain viable in case others might become momentarily inaccessible. Furthermore, switching between radio channels needs to be tested to ensure the switching would respond to signal loss promptly. The RCTMA should have the ability to come to an emergency stop if all signal links are lost and this should be demonstrated as a testing maneuver. Additionally, the method through which this stop action is communicated to the lead vehicle would need to be demonstrated as well.

Another possible error recovery would be in response to the loss of the GPS signal. The RCTMA would need to have at least two antennas, one for remote-control positioning and the other to determine the vehicle's heading. If the GPS signal is lost, the Inertial Navigation System (INS) should be able to take over. The INS would continue to drive the vehicle according to the last known trajectory until the GPS signal is restored. As this would make the vehicle susceptible to drifting apart from the designated heading, it needs to be verified how the RCTMA would respond if the GPS signal is not restored after a short while.

Safety Test Scenario 2: Pause-Mode Operation

The lead vehicle should have the ability to communicate a stop signal to the RCTMA. This would take place through the transmission of a stop signal from the lead vehicle to the remote operator who is controlling the RCTMA. After the RCTMA has come to a stop, the remote operator can resume its following mode by communicating to the RCTMA that the lead vehicle has restarted its motion. Therefore, it needs to be demonstrated that the remote operator could pause and resume the following motion of the RCTMA through communicating with the lead vehicle. Upon resumption, the remote operator may drive the RCTMA a little faster than the lead vehicle to maintain its designated gap distance.

Safety Test Scenario 3: Obstacle detection and avoidance

The situational awareness of the remote operator in terms of the surroundings of the remote-controlled RCTMA is of utmost importance for its safe operation. One of the critical scenarios for which the remote operator would need high situational awareness is when there are obstacles in the RCTMA's path. The remote driver should be able to identify potential obstacles along the path the RCTMA is taking in following the lead vehicle. The RCTMA recovery mechanism by the remote operator should be investigated, and its safe operation should be demonstrated for when such an obstacle is detected. In these cases, the remote operator would need to evaluate whether to stop the RCTMA or change its path to avoid the approaching obstacle. According to various parameters, such as the communication latency and human response time, there exists a safe window for active obstacle detection and decision-making. The size of this window needs to be investigated. Figure 3.1 shows a schematic of obstacle mapping. This test scenario is particularly important for the detection of errant vehicles that might come in between the RCTMA and the lead vehicle.

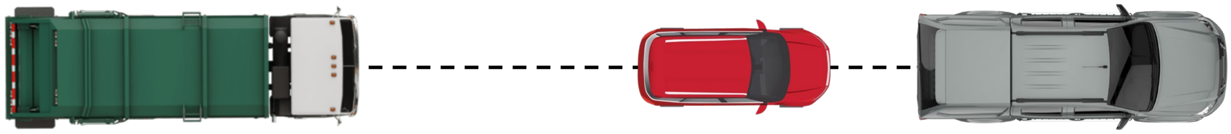

Figure 3.1: Schematic of obstacle in RCTMA path

Safety Test Scenario 4: Stop Operations

It might be necessary for the RCTMA to come to an emergency stop at the discretion of the remote operator. The lead vehicle driver, and an in-field personnel member who is aware of the situation should also be able to communicate a necessary stop to the remote operator. In all cases, the safe stopping maneuver needs to be investigated and demonstrated by repeated trials. When the remote operator stops the RCTMA, this should be communicated to the lead vehicle and the working crew on the radio channel.

AHMCT RCTMA Performance Test Scenarios

The following RCTMA performance test scenarios are specifically developed to evaluate how the RCTMA would perform in Caltrans highway maintenance operations. The RCTMA is supposed to provide extra safety by removing the TMA driver and delegating the driving task to the remote operator in moving highway work zones. Therefore, the performance test scenarios are intended to represent common Caltrans moving closure highway maintenance applications and maneuvers. These performance test scenarios assess various possible RCTMA system operational errors while in remote-control mode and describe the necessary procedures to safely address the error.

Performance Test Scenario 1: Path-following accuracy

One of the most important features to ensure in the operation of the RCTMA is maintaining sufficient accuracy in path following, also known as lane-keeping. This would require the RCTMA to be within a designated, allowed threshold of lateral offset with respect to the lane. In order to evaluate the RCTMA's lane-keeping performance, the RCTMA's position can be videotaped and by locating landmark points on the road and the RCTMA, the RCTMA's relative position with respect to the lane can be determined. Lane-keeping is particularly important in cornering maneuvers. To assess the path-following accuracy while cornering, various speeds of 5, 10, 15, and 20 MPH need to be tested while making turns to make sure the RCTMA can track the lead vehicle's trajectory with sufficient accuracy in its operational speed range. It is noted that the smallest turn radius for the RCTMA according to its size and steering capabilities would be 65 feet.

Another maneuver where accurate path-following is essential is a lane change. In order to simulate a lane-change maneuver, a slalom course would be used. The design of the slalom course would be such that the maximum lateral acceleration in traversing the slalom course would not exceed a certain threshold. The width of the slalom course would be that of a typical lane. Figure 3.2 shows a schematic of the designed slalom course and its dimensions.

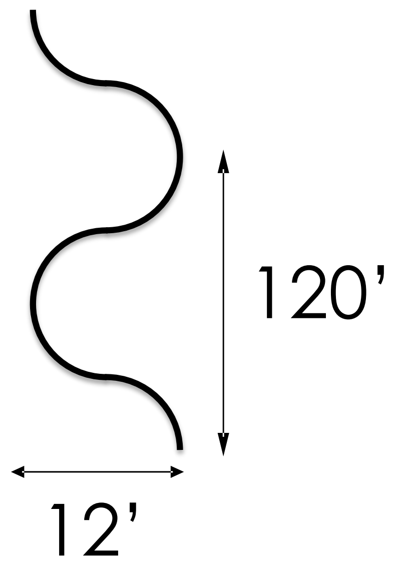

Figure 3.2: Slalom course dimensions

Performance Test Scenario 2: Following gap distance accuracy

In addition to the RCTMA staying within the allowable lateral offset, it also needs to be ensured that it remains within a certain longitudinal gap distance from the lead vehicle. In this regard, the RCTMA would need to be able to both maintain and transition from various values of prescribed gap distances. Given the RCTMA’s typical deployment objectives, values of 50, 100, and 150 feet are suggested for testing gap distances and maintaining longitudinal distance. Laser rangefinder tools can be used by the data collector inside the RCTMA to measure the real-time longitudinal distance between the RCTMA and the lead vehicle and therefore enable assessing the RCTMA’s performance in maintaining the gap distance. The remote operator would ensure that the RCTMA maintains the gap distance or transitions between different prescribed values in a steady, smooth, and safe manner.

Performance Test Scenario 3: Roll-out maneuver

The roll-out maneuver or taking the lane is probably the most important operational feature of the RCTMA. It typically begins from a stopped position on a road shoulder where the RCTMA takes the lane and starts to follow the lead vehicle's trajectory. Figure 3.3 shows a schematic of the RCTMA position at the beginning of the roll-out maneuver.

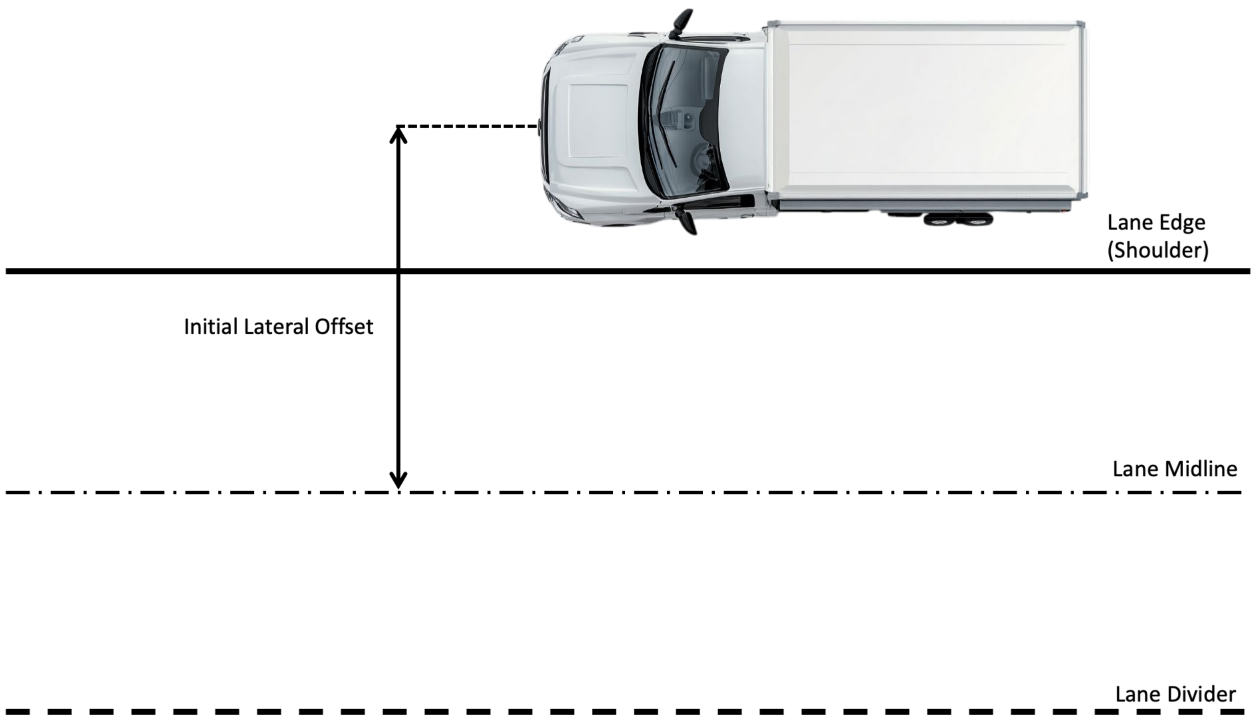

Figure 3.3: Schematic of the RCTMA roll-out maneuver

It needs to be investigated whether the roll-out maneuver can take place while not falling too far behind the lead vehicle such that an allowable gap distance is maintained during rollout. Furthermore, the lane-keeping accuracy while performing the roll-out maneuver must be assessed to ensure excessive lateral offsets do not occur during roll-out. This test scenario needs to be repeated until certain limits are found for lane-keeping offset and longitudinal gap distance.

Performance Test Scenario 4: Acceleration/Deceleration

While the majority of the RCTMA's operation would be to follow the lead vehicle in a steady motion with constant speed, it might be occasionally required for the lead vehicle to decelerate to a stop or accelerate to a designated speed. The ability of the RCTMA to safely accommodate these maneuvers needs to be investigated. Although the safe exertion of said maneuvers by the RCTMA significantly depends on the skills of the remote operator, the communication mechanism between the remote operator and the lead vehicle needs to be verified to ensure that the remote operator's response would be in a timely manner.

Effect of Communication Latency

Given that there will be some amount of communication latency between the RCTMA and the remote operator, and between the lead vehicle and the remote operator, this latency might affect all the aforementioned testing scenarios. It needs to be investigated how significant this effect is for each scenario.

Repetition and Statistical Significance

To ensure that the results and observations from each testing trial are not random or due to human errors, it is essential that every testing trial be conducted quite a few times to ensure that the testing results would be statistically significant.

Conclusion

A detailed test plan including multiple safety and performance scenarios has been devised to ensure the safety of the operation of the RCTMA, as well as assessing the RCTMA's performance in typical highway maintenance applications.

Chapter 4: Preparations and Testing Methodology

In this chapter, we discuss how the test site and how the truck were prepared for the testing day. This includes the efforts by the AHMCT team in developing a test track in the testing site and installing cameras on the RCTMA truck to ensure proper data collection. We further discuss how the KRATOS team set up an on-site remote-control station and performed some tests to establish steady remote control.

Test Plan Review

A review of the developed test plan is given before the design of the test track is discussed.

Safety Scenarios

- S1: Error recovery by remote operator: check 3-way radio communication
- S2: Pause mode operation: remote operator pauses RCTMA motion
- S3: Obstacle avoidance and negotiating around the obstacle.
- S4: Stop mode operation: remote operator brings RCTMA to full stop

Performance Scenarios

- S5: Path-following accuracy: Lane-keeping, lateral offset
  - Straight Path
  - Curved Path
- S6: Following gap distance accuracy: Maintaining gap with LV
- S7: Roll-out alignment: Taking the lane

- S8: Acceleration/Deceleration

Test Track Design

The test track for the remote-controlled TMA was set up at the Caltrans META site located at 4304 Dudley Blvd, McClellan, CA 95652. Figure 4.1 shows the selected location for the test track in an aerial view of META taken from Google Earth.

Figure 4.1: Aerial view of the META site from Google Earth

Considering the test scenarios, the test track was designed in the form of a loop, such that all test scenarios would be investigated every time a loop is completed. The test track was set up by placing cones that separated different scenario sections introduced in the test plan as well as placing adhesive tapes in place to mark a slalom course to investigate the curved path-following capabilities of the RCTMA. Figure 4.2 shows where landmark points were designated with cones to separate various test plan scenarios in an aerial view of the test track.

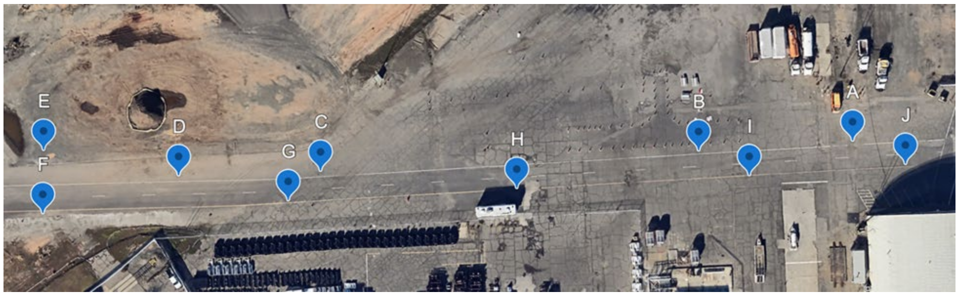

Figure 4.2: The designated landmark points on the test track

As noticed in Figure 4.2, the test track comprises two lanes. The right lane is southbound and includes landmark points A through E and the left lane is northbound and features landmark points F through J. In observation of investigating all test scenarios with the completion of each loop, the test track was designed as follows.

In the first section of the track, the RCTMA takes the right lane from landmark A towards landmark E, during which the RCTMA follows the lead vehicle and tries to maintain its gap distance. Then in the second section of the track, the RCTMA no longer follows the lead vehicle which takes another path to return to the initial landmark A, but rather makes a U-turn and takes the path in the left lane from landmark F towards landmark J.

Here is a breakdown of the RCTMA motion as it goes through the test track's loop as depicted in Figure 4.2:

- Accelerate from zero velocity, take the lane at A (scenario 7)
- Accelerate to designated speed by B (scenario 8)
- Follow Lead Vehicle on straight path, maintain gap until C (scenarios 5,6)
- Negotiate slalom course until D (scenario 5)
- Decelerate to E, turn around and stop at F (scenario 8, 2)
- Accelerate from zero velocity at F (scenario 8)
- Obstacle is brought into RCTMA path as it crosses G and avoided at H (scenario 3)
- Going straight until I and confirming radio communication (scenario 1)

- Decelerate to a full stop at J (scenario 8)
- Turn around and stop before A to finish the loop

Hence, each loop enables investigation of all previously devised scenarios, as well as returning to the track's starting point.

To assess RCTMA's performance in following curved paths, a slalom course was designed. The profile of the slalom course was selected to be sinusoidal and represent a double lane change motion. The amplitude of the profile was selected to be 12 feet which is the width of a typical lane on a standard road. The wavelength of the profile was selected according to the condition that if the slalom course was to be traveled at a maximum speed of 20 MPH, the lateral acceleration would not exceed 0.1 g's. This creates a constraint for the minimum radius of curvature which would mathematically lend itself to a threshold value for the wavelength. Knowledge of the amplitude and the wavelength gives the course's midline profile. To obtain the edge profiles, half of the width of the lane is added to the midline profile perpendicular to it in either direction. Adhesive tape was placed on the ground along the established edges and cones were placed 1 foot outside the edge to ensure tape visibility and marking a strict boundary for the slalom course. Figure 4.3 shows the designed slalom course.

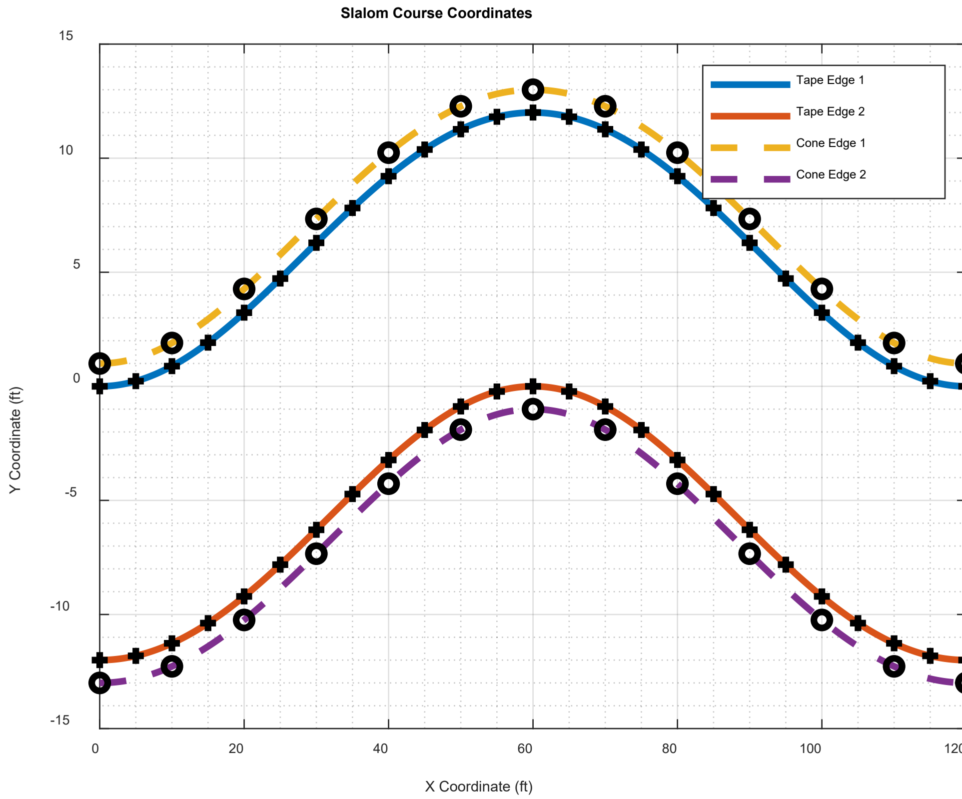

Figure 4.3: Designed slalom course and its designated coordinates

Figure 4.4 shows how the slalom course was marked on the test track with adhesive tape and cones.

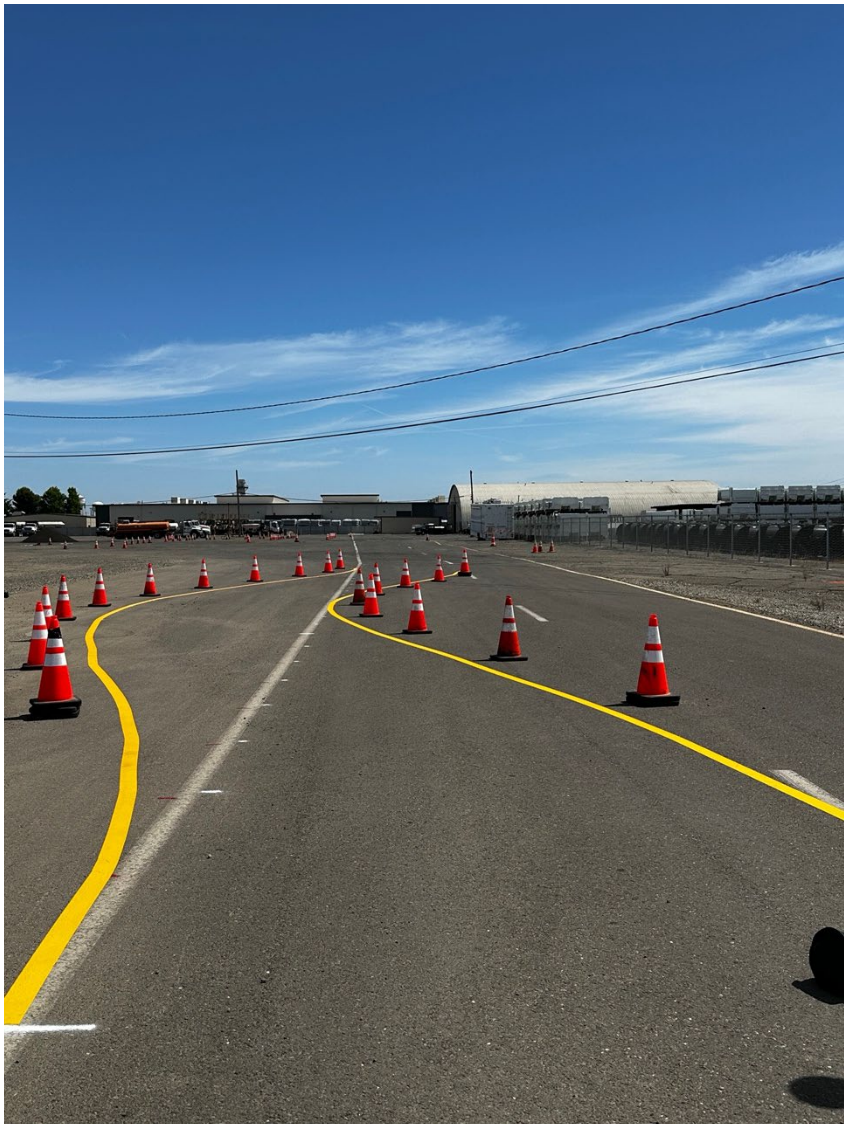

Figure 4.4: Marking the slalom course with adhesive tape and cones

Installing Cameras

To collect data on RCTMA's lane-keeping and gap-maintaining performance, cameras were installed on the truck. Two Go-Pro 12 cameras were installed on the RCTMA's side poles to record footage on the ground as the RCTMA goes through the test track. This footage would be analyzed to obtain the RCTMA's lateral offset from the lane edge which is a measure of its lane-keeping performance. Furthermore, a Go-Pro 8 camera was installed in the middle of the truck's cab facing forward to record the gap distance measurements made by the data-collector riding in the RCTMA during testing.

KRATOS Preparations

The KRATOS team did their own testing and set up to prepare the RCTMA for remote driving. Their efforts primarily included setting up the remote-control station, the communication antennas, and the remote driving sensors on the truck. To make sure all equipment was delivered safely, the truck had arrived unassembled and LIDAR/GPS/camera sensors had to be installed on it prior to remote driving. Once the hardware set up had been completed on both the remote-control station and the RCTMA, the KRATOS team tested the multiple features of remote driving such as the correct operation of sensors and actuators and communication latency. For safety purposes, the remote-driving software had been configured to stop the RCTMA if at any point there was a Loss Of Communication (LOC) for longer than two seconds. This kept happening on the first attempts at remote driving. Upon inspection it was gathered that the Verizon cellular network and its coverage in the testing site was not suitable for remote driving because of high communication latency and therefore the set up was reconfigured to work with AT&T cellular network. Once this change took effect, no LOC-stop was reported, and remote driving re-commenced without disruption.

A side view of the RCTMA with the sensors in place is given in Figure 4.5. The remote-control station showing the remote driver's field of view is given in Figure 4.6.

Figure 4.5: Side view of the RCTMA equipped with all sensors

Figure 4.6: The remote-control station

On the day of testing, a total of 22 testing rounds were performed that included the following:

- 4*4 speed rounds with 5, 10, 15, 20 MPH velocity
- 2 rounds with the driver sitting behind the wheel
- 2 rounds with an inexperienced remote driver
- 2 rounds aiming to maintain the RCTMA-LV gap distance

Nearly 150 GB of data was collected from these 22 rounds of testing. The collected data includes the following.

- GPS surveying geospatial data collected from the track. (~15 GB)
- Go-Pro camera footage for lateral offset measurement (~100 GB)
- Go-Pro camera footage for gap distance measurement (~30 GB)
- Driver workload data, obtained from questionnaire responses.

This collection of raw data is processed to acquire performance results for the following categories:

- Lane Keeping (Lateral offset)
    - Via GPS
    - Via Camera footage and length calibration
- Gap Distance Maintaining
- Driver workload: NASA TLX
- Performance assessment for other designated test scenarios
    - 3-way communication
    - Obstacle avoidance
    - Remote pause and stop

Conclusion

A test track was designed in the shape of a loop to enable the investigation of all test scenarios with the completion of each loop. A total of 22 loop-tests were conducted with different speeds and driving conditions and the corresponding test data was collected.

Chapter 5:
Results and Discussion

The collected data from the RCTMA testing were analyzed and their corresponding findings and subsequent discussions are given in this chapter. Additionally, AHMCT asked every driver of the RCTMA, whether remotely or behind the wheel, to participate in a driver-workload study by filling a questionnaire that rates the workload in different aspects of a task. The processed results of driver workload are presented at the end of this chapter.

As many of the test scenarios pertain to specific sections of the test track that are designated with certain landmark points, the aerial view of the test track with its landmark points are given in Figure 5.1.

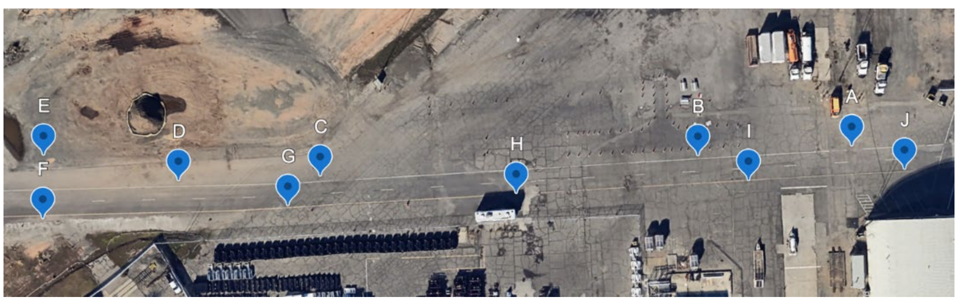

Figure 5.1: Aerial view of the test track and designated landmark points

Scenario 1: Communication Check

A five-way radio connection was always maintained during testing. The 5 radio operators were the remote driver, the safety rider inside the RCTMA, the test conductor/data collector inside the RCTMA, the driver of the LV, and a ground agent who performed safety checks before each test round and brought the obstacle into the RCTMA's path. Wireless radio headsets were used with a range of 2000 feet that covered the entire test track. The test conductor and the remote driver were in constant contact during the test by conveying commands such as accelerating, coming to a stop, negotiate the obstacle, decelerate, etc. However, section IJ of the track had entirely been dedicated to checking radio communication. As the RCTMA passed landmark I, the test conductor would ask for verbal confirmation of radio communication from each of the other radio holders i.e., the remote driver, the safety rider, and the ground agent. In this part of the maneuver the driver of the LV is no longer present as the LV only plays a role in the first half of the test track (right lane), however, communication with the driver of the lead vehicle has also been checked as the speeds of each round were communicated to the LV driver via radio. In all test rounds radio communication was maintained with sufficient clarity. To ensure the wireless radio headsets would not run out of batteries, freshly charged batteries were replaced twice between some of the test rounds.

Conclusion

Maintaining a continuous link of verbal communication is essential for remote driving to ensure the safety of the working crew and proper execution of remote driving tasks. In the tests conducted with the RCTMA, wireless radio was selected that had a range of 2000 feet. In highway applications of the RCTMA, different means of communication with wider ranges such as cellular connection might be more suitable. In the RCTMA test rounds a clear line of radio communication was kept during every test round and was tested each time with 5 radio operators to ensure the safety of everyone on the test site and make sure test scenarios are performed adequately.

Scenario 2: Pause Mode Operation

In each of the test rounds, at the end of the right lane, the RCTMA turned around and at the queue of the test conductor came to a halt at landmark point F to start its motion down the left lane.

Conclusion

The remote driver was able to pause the RCTMA motion on demand.

Scenario 3: Obstacle detection and avoidance

Part of the test track and each test round had been dedicated to avoiding an obstacle in the RCTMA's path to confirm the possibility of avoiding obstacles and assess its performance when driving remotely. It was decided to negotiate around the obstacle in order to avoid it instead of coming to a full stop (which had been assessed under another test scenario). For this purpose, the obstacle, which was a cardboard, life-size mannequin, would be brought into the RCTMA path at a certain moment and the driver would react to the presence of the obstacle in their path after crossing a certain landmark point. Figure 5.1 should be referenced for the aerial view of the test track which features the locations of the obstacle and the reaction landmark.

The obstacle-avoiding part of the test occurs when the RCTMA has finished its course of the right lane, has turned around and has begun moving back towards the starting point along the left lane. To replicate a realistic obstacle-avoidance case study, the obstacle had to be hidden from view until a certain time or otherwise the driver could react to its presence early on and not face a challenge in negotiating the obstacle. For this purpose, the obstacle was hidden behind the trailer at point H. The driver was asked only to react to the presence of the obstacle in their path once they had crossed landmark point G. This would be reminded to them in every test round by the rider inside the RCTMA. Point G was selected to be 120 feet prior to arriving at the obstacle location at point H. The reason this distance was selected was to give the driver a total of 4 second reaction time with a maximal speed of 20 MPH which corresponds to roughly 30 feet per seconds. Once the RCTMA crossed landmark point G, the driver would steer to the left and negotiate around the obstacle and subsequently return to their original path along the left lane.

The results of obstacle avoidance were that in all test-rounds the obstacle was negotiated around with no impact and the RCTMA returned to the lane after maneuvering around the obstacle. However, the obstacle-avoiding performance has not been the same in all test rounds. In the case of the inexperienced driver driving remotely, the driver began the obstacle negotiation prematurely (well before crossing landmark point G) which resulted in significant lateral deviation from the designated path despite maneuvering around the obstacle successfully. Additionally, in the case of 20 MPH, the driver's steering command would often take the RCTMA into the opposite lane which would not be acceptable in usual highway operations.

Conclusion

Every test round had a successful trial of obstacle-avoidance. In order to replicate a realistic scenario in which an obstacle is to be avoided, the driver was instructed to only start negotiating the obstacle when there would be a maximum of 4 seconds time to react to the presence of the obstacle that was brought into RCTMA path. Some scenarios deviated further than others from the lane when negotiating around the obstacle which stresses how essential training is in remote driving tasks.

Scenario 4: Stop Mode Operation

At the end of the test loop the RCTMA came to a full stop on the test conductor's queue when it arrived at point J. In all test rounds the operation was executed smoothly and immediately after receiving the signal from the test conductor.

Conclusion

On-demand stopping of the RCTMA motion is achievable via remote driving in a seamless and smooth fashion.

Scenario 5: Path-following accuracy via GPS

In order to assess RCTMA's lane-keeping performance via GPS, the coordinates of the test track and the real-time coordinates of the truck in the same, two-dimensional coordinate system were required. Details of how these two sets of coordinates were obtained follows.

Obtaining Track and Truck Coordinates

In order to calculate the GPS lateral offset of the vehicle in lane keeping, the track coordinates needed to be updated. These track coordinates were obtained during the initial test track surveying. They were transformed from a point cloud representation in the global 3D coordinate system of the Earth to a local 2D coordinate system of the track. The corner of the hanger building towards the eastern end of the META facility was used as a designated landmark as the origin of the coordinate system and the track's coordinates were obtained in an XY frame.

. Figure 5.2 shows the track's point cloud obtained from GPS surveying and Figure 5.3 gives the transformed coordinates of the test track in the local 2D frame.

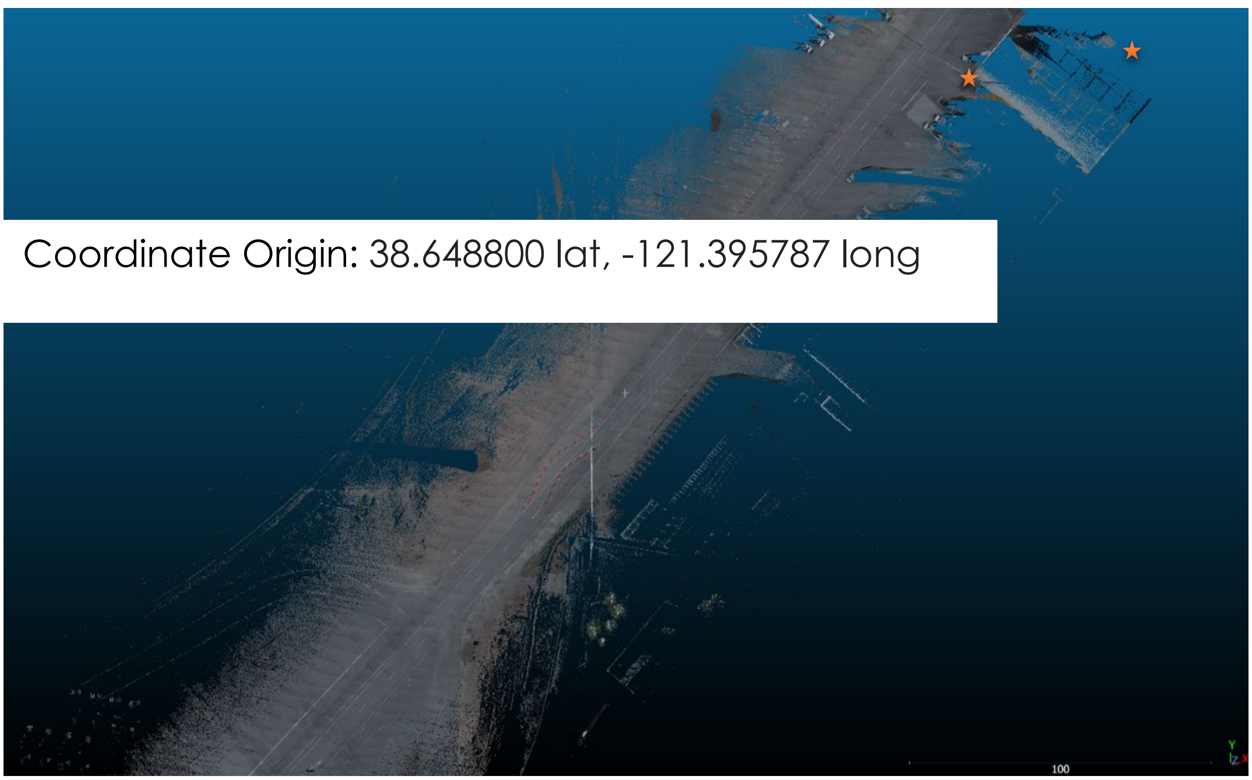

Figure 5.2: Test track point cloud obtained from GPS surveying

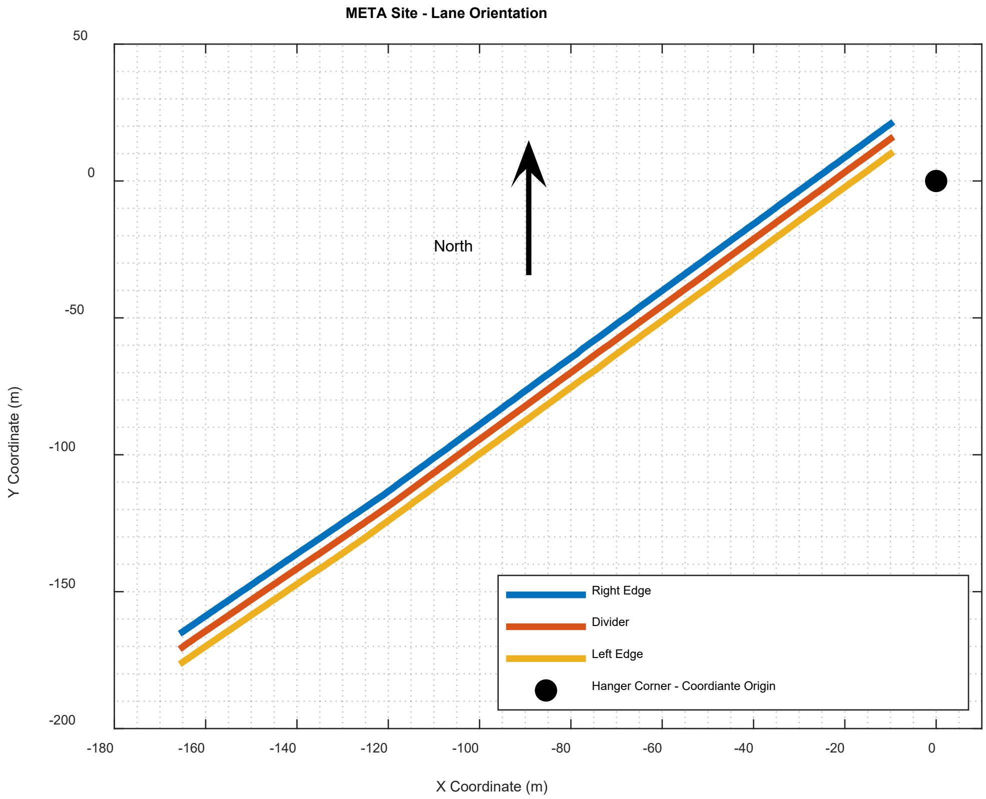

Figure 5.3: Testing site's lane coordinates in the local 2D frame

Given that the GPS data obtained from the installed sensors by KRATOS is a single set of latitude and longitude coordinates (an average of the two antennas place on either side of the RCTMA), the lanes' midline coordinates were calculated by averaging the middle divider and the edges of each lane. Figure 5.4 shows the midline coordinates for both lanes. Henceforth, the southbound lane is known as the right lane and the northbound lane is known as the left lane.

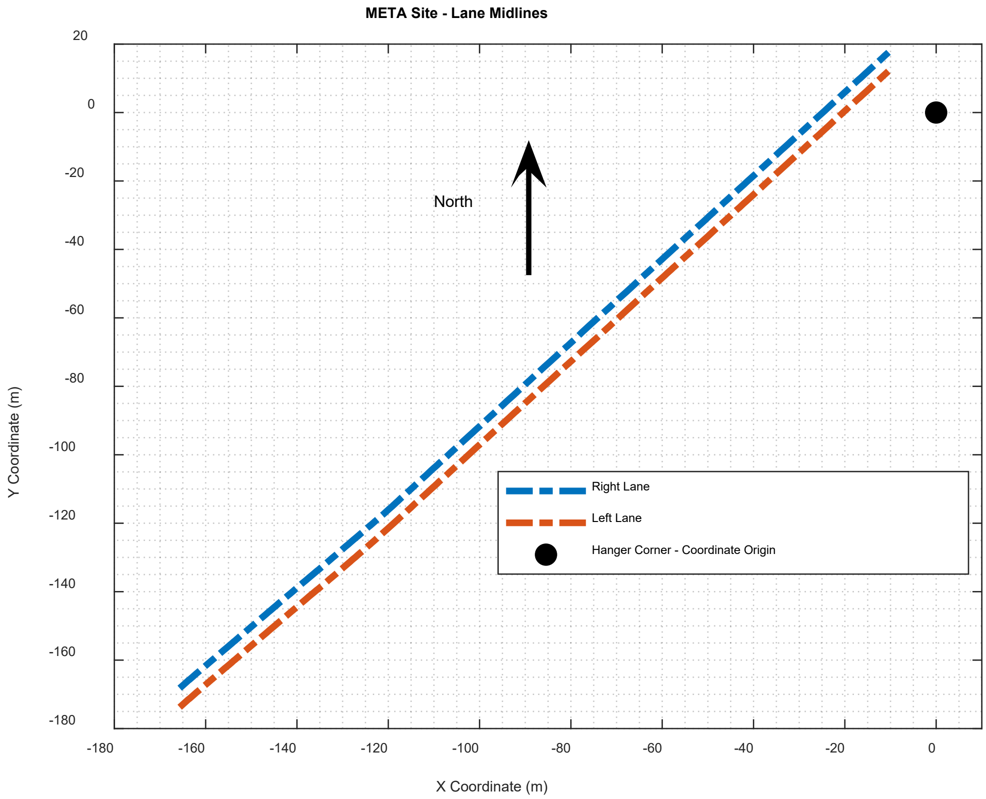

Figure 5.4: Midline coordinates for the test track lanes

Before we can proceed to mapping out the RCTMA's trajectory in the multiple testing rounds, it should be noted that the track must be modified to account for the slalom course and the obstacle-avoiding section. The slalom course has its own respective lanes defined (that are different than the straight lanes designated on the road), and the obstacle-avoiding section does not comply with regular lane-keeping since by negotiating around the obstacle the truck would deviate significantly from the designated lane and including the obstacle-avoiding section in lane-keeping assessment would significantly increase lane-keeping error. Consequently, the track is modified accordingly, and the lane-keeping portion of the track would look a bit different than the one presented in Figure 5.3. Therefore, the slalom section is added to the right (southbound) lane and the obstacle-avoiding section is removed from the left (northbound) lane. Figure 5.4 depicts the modified track that is used for lane-keeping analysis.

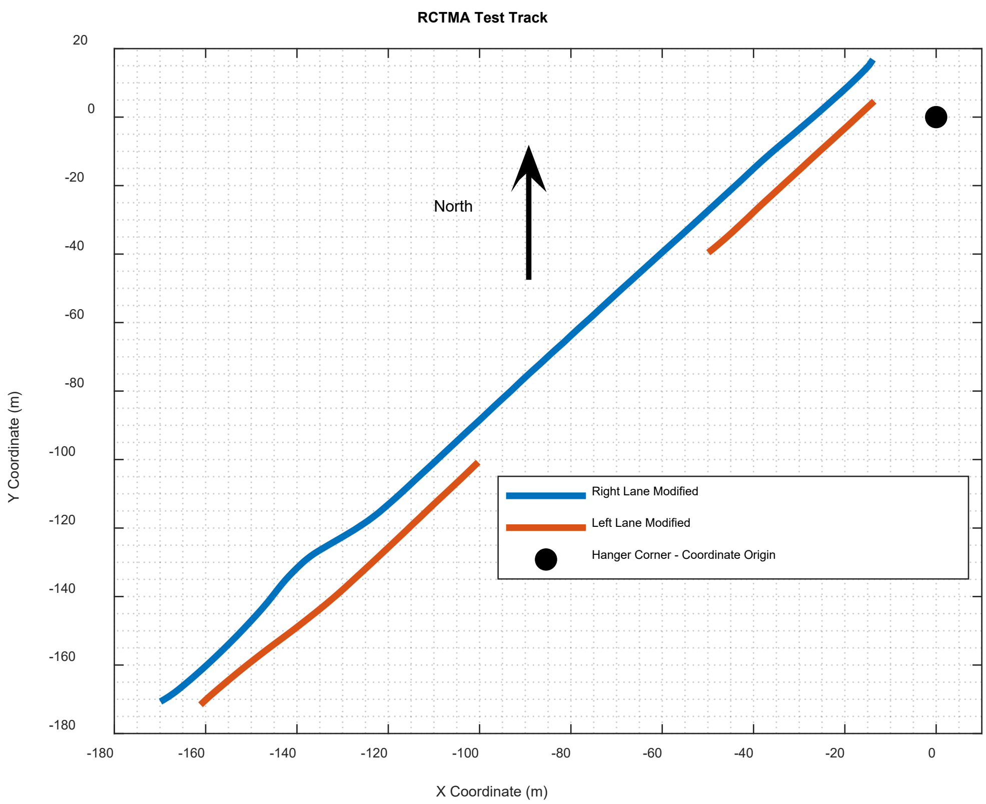

Figure 5.5: Modified test track for GPS lane-keeping analysis

Next, the real-time coordinates of the truck as reported by KRATOS had to be transformed into the same local frame. However, given that the raw data from KRATOS included many duplicate data points and featured a wider range of time that pertained to each of the testing rounds, the KRATOS data first had to be pruned so that the processed data would only include the information pertaining to the particular time interval of each test round and did not include duplicates. Then the truck coordinates would be transformed into the same local frame as the track. Once both track's and truck's coordinates are in the same frame, they would be trimmed to have the same beginning and endpoints and interpolated according to one another such that they would have the same number of data points. At this point the coordinates are ready for the calculation of lane keeping error which simply becomes the difference between the corresponding points' y-coordinate. To facilitate the comparison of lane-keeping performance in multiple test rounds, the RMS (Root Mean Square) of the error is calculated for each round.

With the lane-keeping test track ready, the lateral offset can now be assessed for all22 test rounds, including 16 speed rounds, 2 rounds with novice remote driver, 2 rounds with the professional driver behind the wheel, and 2 rounds for the purpose of maintaining the gap distance.

Speed Rounds

The bulk of the testing pertains to the RCTMA going through the track in a series of speed rounds, with 5, 10, 15, and 20 MPH speeds. Each speed was tested 4 times to provide better statistical significance. Figure 5.6 shows the lane-keeping performance for the 5-MPH speed in the combined track (both straight and curved sections) for an average of four rounds of going through the track at that speed.

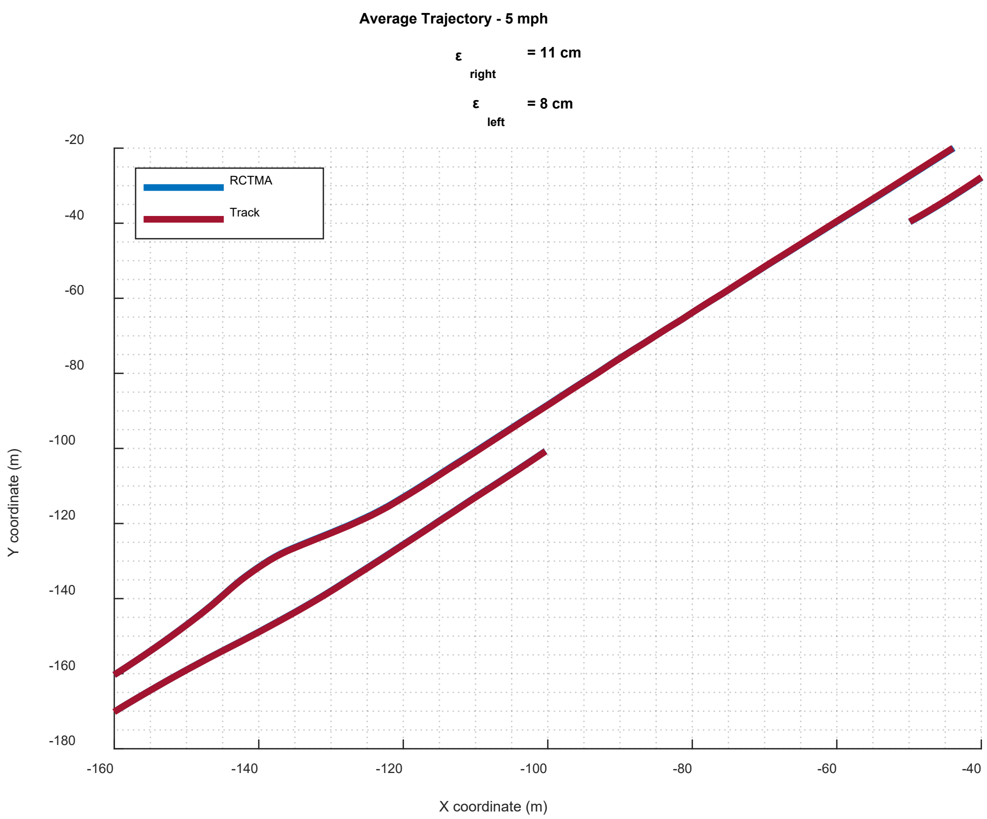

Figure 5.6: Lane-keeping performance at 5 MPH

As can be seen in Figure 5.6, the RCTMA has had virtually perfect lane-keeping at 5 MPH with an average lateral offset of 11 cm for the right lane and 8 cm for the left lane. The RCTMA has had relatively better lane-keeping in the left lane which features only straight sections than the right lane which includes the slalom section. The lane-keeping performance has been more or less similar in all 4 rounds of 5 MPH speed which certifies statistical significance.

Continuing with lane-keeping analysis, Figure 5.7 shows the lane-keeping performance for an average of 4 rounds with the RCTMA being driven at 10 MPH.

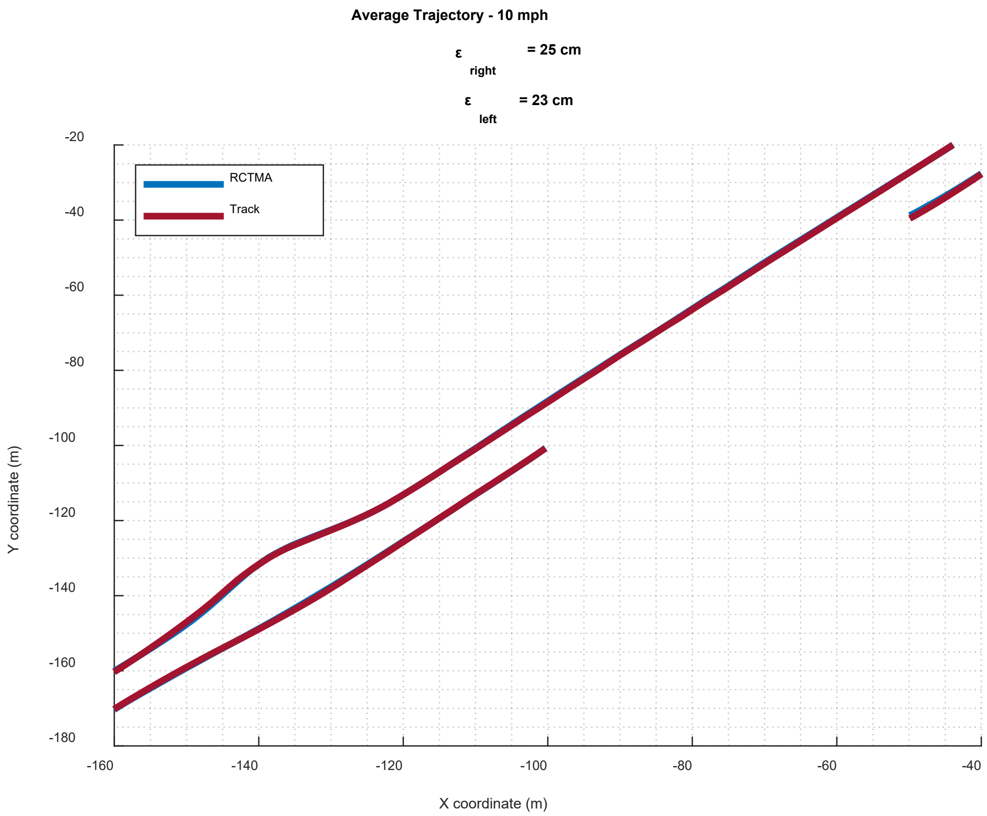

Figure 5.7: Lane-keeping performance at 10 MPH

As it can be seen in Figure 5.7, the 10-MPH lane-keeping performance has slightly deteriorated compared to 5 MPH with an average lateral offset of 25 cm for the right lane and 23 cm for the left lane, where the right lane lateral offset is again slightly larger due to featuring curved sections. Once more, statistical significance has been ascertained as the 4 rounds yielded somewhat similar lane-keeping performance.

Figure 5.8 depicts the lane-keeping performance for the 15-MPH speed for an average of 4 rounds of the RCTMA being driven through the test track.

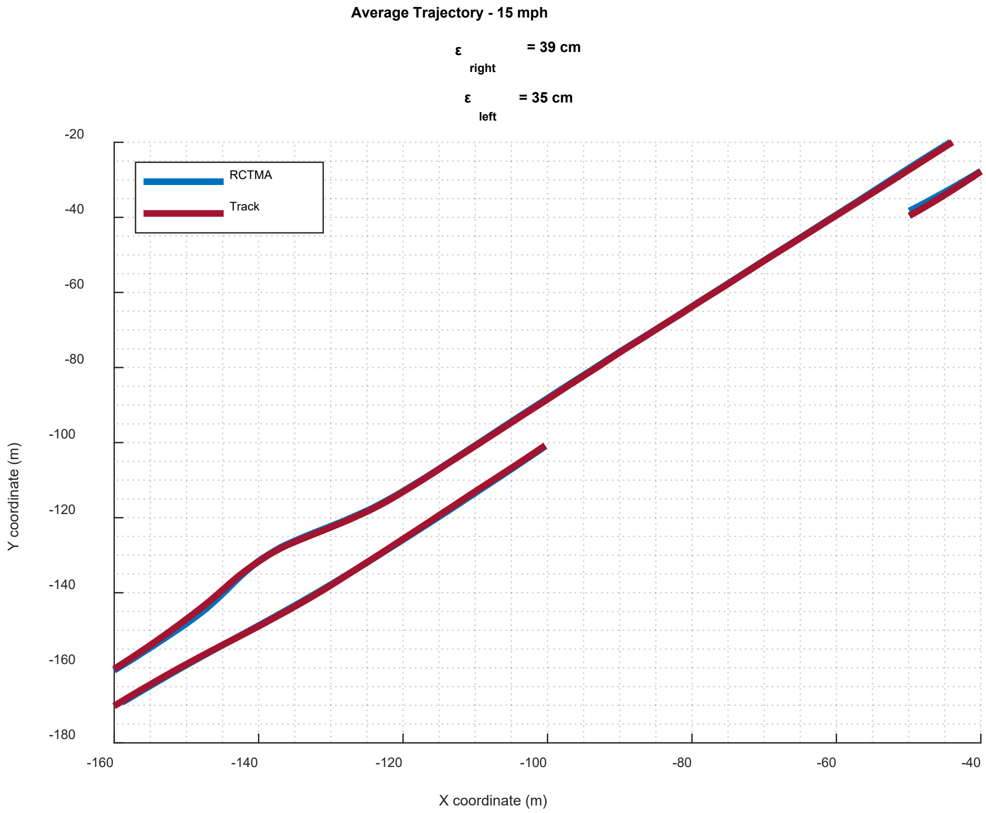

Figure 5.8: Lane-keeping performance at 15 MPH

As we can see in Figure 5.8, the lateral offsets for 15 MPH are relatively larger than those of 10 MPH, with a 39 cm average lane-keeping error for the right lane and 35 cm for the left lane. It is noted that the right lane has had slightly poorer performance due to featuring curved trajectories. Additionally, statistical significance of the data has been established as the 4 different rounds have produced relatively similar results.

Figure 5.9 shows the average lane-keeping performance for the 20-MPH speed tests as the RCTMA has gone through the test track 4 times at that speed.

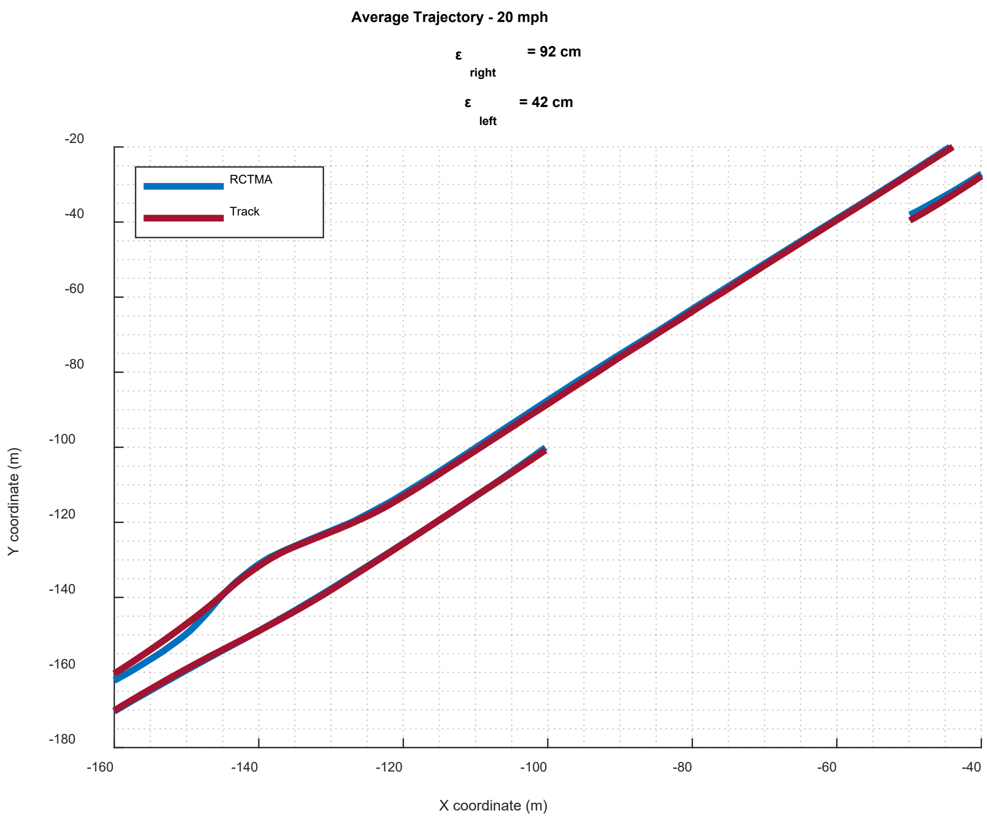

Figure 5.9: Lane-keeping performance at 20 MPH

As can be noted from Figure 5.9, the 20-MPH speed has had the worst lane-keeping performance amidst all tested speeds. The exacerbation of lane-keeping error compared to that of 15 MPH is proportionally expected for 20 MPH for the left lane with an average lateral offset of 42 cm, however, lane-keeping performance has severely deteriorated for the right lane at 20 MPH with a lateral offset of 92 cm. This can be attributed to the fact that the RCTMA has a large inertia and therefore at the relatively large speed of 20 MPH it will have a large amount of momentum. Therefore, changing its direction of travel as it is required to negotiate the slalom course would also require a significant amount of steering torque. Since the remote-control station does not provide torque feedback from the steering rack to the steering wheel (as the remote-control station is not mechanically attached to the steering rack), the necessary amount of torque can only be estimated by visual tracing of the trajectory.

The communication latency in receiving the camera footage from the RCTMA was negligible at a lower speed of 5 MPH and therefore did not interfere with steering. As the speed of operation was increased to 20MPH, the effect became significant. At 20 MPH, the delay in receiving the camera feed resulted in an over-correction of the steering command as the truck negotiated the slalom course. This overcorrection resulted in the RCTMA trajectory falling significantly below the test track at the end of the slalom course.

Figure 5.10 shows the average lateral offset for each speed for both right and left lanes.

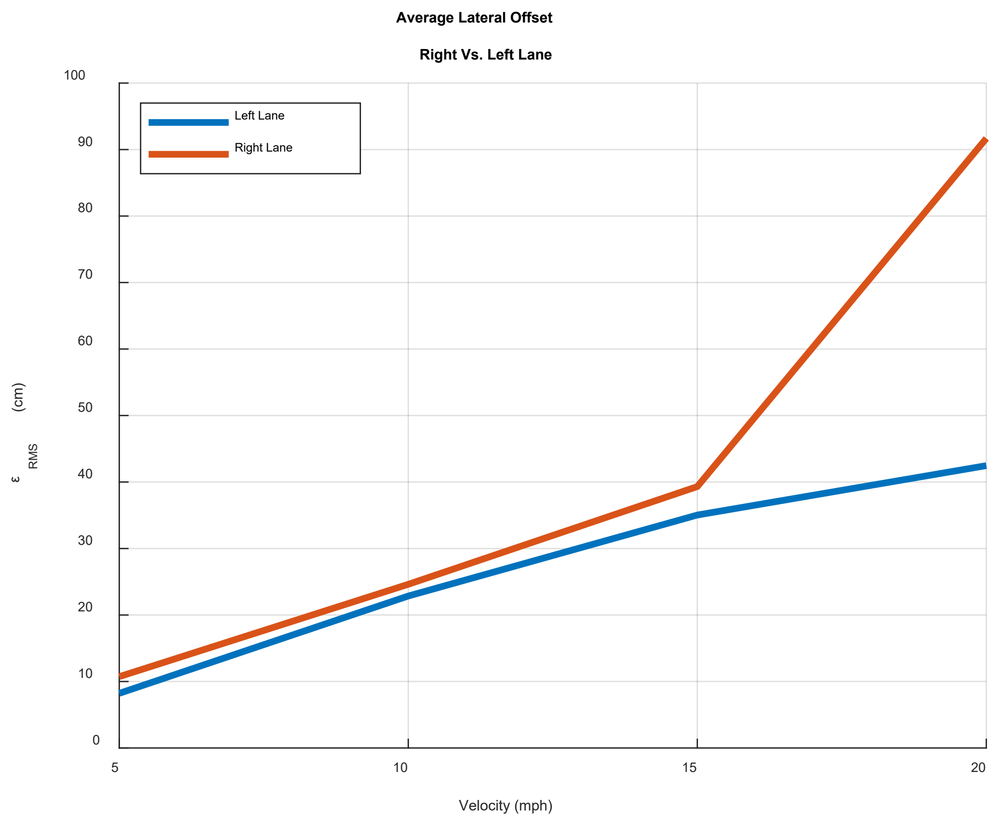

Figure 5.10: Effect of traveling speed on average lateral offset

We observe from Figure 5.10 that lane keeping errors have steadily increased with increasing speed. We notice that the most severe effect of speed on lane-keeping can be observed at 20 MPH where the lateral offset abruptly increases for both the left lane and the right lane. This has been addressed above by how latency effects become prominent in 20 MPH and the slight delays in receiving the camera footage can translate to significant lateral offsets that result in insufficient or excessive steering.

Furthermore, it is evident from Figure 5.10 that lane-keeping performance has been better for the left lane compared to the right lane. This can be attributed to how the right lane features the slalom section of the track where the RCTMA had to follow a curved trajectory as opposed to the left track where the RCTMA was following a straight path. To test this hypothesis, the right-lane lateral offset data has been collected for all speeds and the straight and the curved sections of it have been separated and given in Figure 5.11.

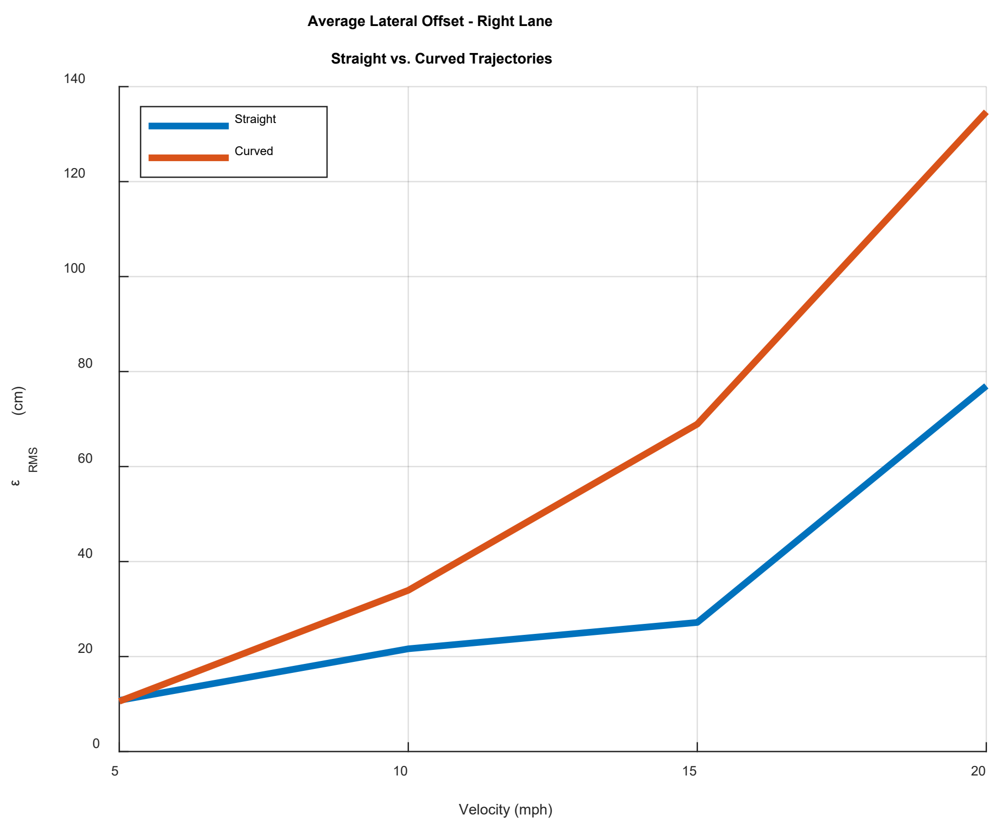

Figure 5.11: Lane-keeping performance for straight and curved trajectories

Figure 5.11 shows that although lateral offset steadily increases with traveling speed for both paths, this increase has a larger slope for curved paths than straight paths which indicates the increasing difficulty of steering in curved trajectories. Both curved and straight paths show a sudden increase in the lateral offset when it comes to the 20-MPH speed which indicates the significance of latency in higher velocities of travel. Figure 5.11 shows that as long as traveling speed is kept below 15 MPH, the lateral offset is less than 2.5 feet for curved paths and less than 1 foot for straight paths. However, when traveling at 20 MPH, curved-path lane-keeping can have errors as large as 5 feet while the straight-path lane-keeping error is about 3 feet.

This concludes the study of the effect of curvature and speed on the lane-keeping performance of the RCTMA. Other parameters can affect lane-keeping such as the driver's skill, whether the RCTMA is being driven remotely, and whether the RCTMA's gap distance with the lead vehicle is being maintained. The effect of these variables will be studied next.

Behind-the-Wheel Rounds

So far, the lane-keeping performance of the RCTMA when it was driven remotely has been investigated. In this section, we study the lane-keeping performance when the same driver is behind the wheel instead of driving the RCTMA remotely. For this purpose, two test rounds with the speeds of 10 and 15 MPH were conducted, given that the majority of the application of the RCTMA would be in this speed range.

Figure 5.12 depicts the RCTMA trajectory with the driver behind the wheel driving it at 10 MPH.

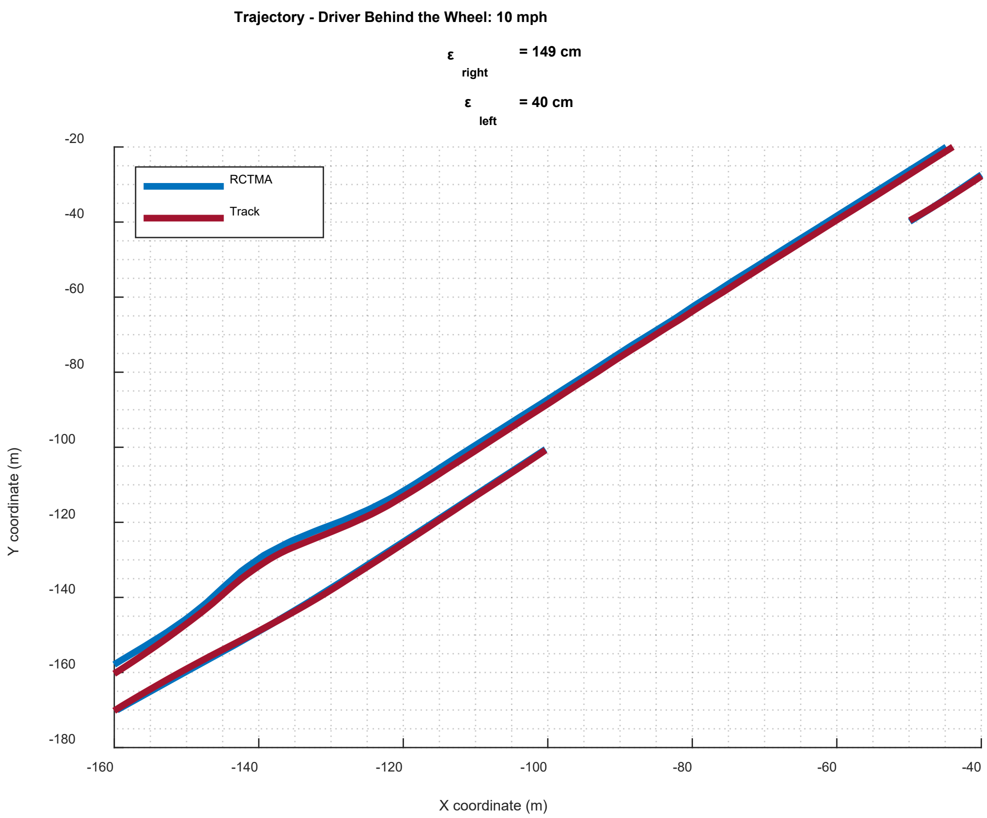

Figure 5.12: Driven trajectory with the driver behind the wheel, 10 MPH

Figure 5.12 shows that the lateral offset is significantly higher when the driver is behind the wheel, with a lateral offset of 40 cm for the left lane and a relatively large lateral offset of 149 cm for the right lane. Figure 5.13 depicts the trajectory when the driver is behind the wheel and driving the RCTMA at 15 MPH.

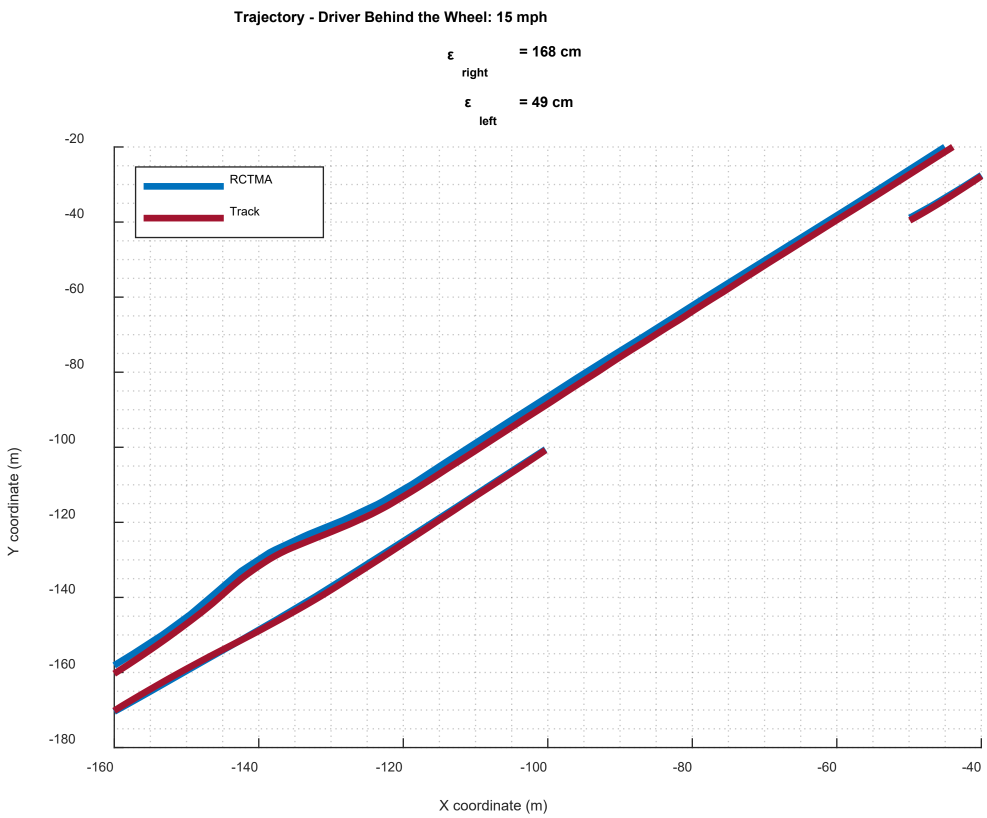

Figure 5.13: Driven trajectory with the driver behind the wheel, 15 MPH

We see from Figure 5.13 that similar to the speed rounds, the same deterioration effect was observed for the lane-keeping performance with increasing speed. For the case when the driver is behind the wheel, the right lane lateral offset has increased from 149 to 168 cm and the left lane lateral offset has increased from 40 to 49 cm when the speed has increased from 10 to 15 MPH. Furthermore, we notice that the right lane lateral offsets are much larger than that of the left when the driver is behind the wheel which corroborates our previous observation that lane-keeping is generally more difficult when traversing curved paths.

To study how lane-keeping performance compares between the two cases when the same driver once drives the RCTMA remotely and once behind-the-wheel, average lateral offsets are given for both the left and the right lane. Figure 5.14 shows the lateral offset comparison between these two cases for the left lane.

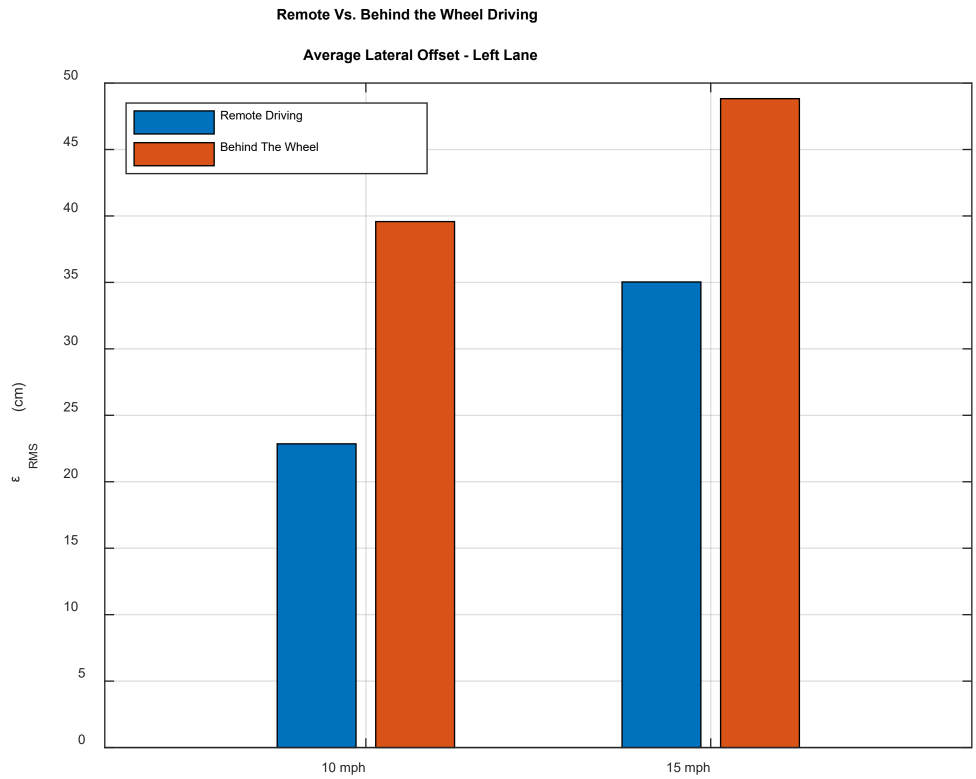

Figure 5.14: Lateral offset: Remote Driving vs. Behind the Wheel – left lane

It is observed from Figure 5.14 that lane-keeping performance for the left lane when the same driver was driving the RCTMA behind the wheel is not as good as the usual remote driving case, albeit the lateral offsets are somewhat close to one another. The left-lane lateral offsets for the behind-the-wheel case have increased from 23 to 40 cm for 10 MPH and from 35 to 49 cm for 15 MPH.

Figure 5.15 depicts the lateral offset comparison for behind-the-wheel and remote driving for the right lane.

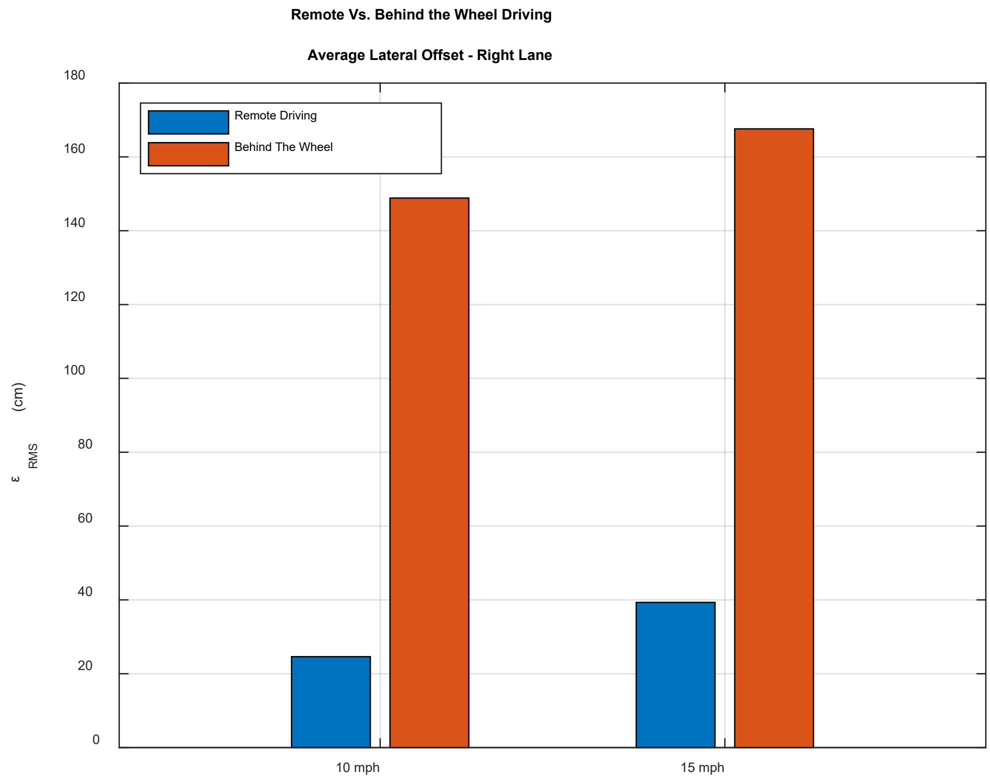

Figure 5.15: Lateral offset: Remote Driving vs. Behind the Wheel – Right lane

We notice in Figure 5.15 that lane-keeping has severely deteriorated in the right lane which includes the curved sections of the path, as the lateral offset has exacerbated from 25 cm to 149 cm for 10 MPH and from 39 cm to 169 cm for 15 MPH. It might seem counter-intuitive for the behind-the-wheel case to have worse lane-keeping performance than the remote-driving case. However, we must note that the driver had been trained for remote driving only. Given that the RCTMA is a heavy-duty medium-sized truck, its efficient driving requires experience and is different than driving usual sedans. The driver's lack of experience with behind-the-wheel driving of the RCTMA, and the fact that the remote driving station did not provide torque feedback on the steering wheel seem to have contributed to the behind-the-wheel cases having much larger lateral offsets. When driving a vehicle with mechanical steering (as opposed to steer-by-wire) behind the wheel, steering exerts torque feedback from the steering rack on the steering wheel. Given that negotiating the slalom course of the test track's right lane requires significant steering, it will exert a relatively large torque on the driver's hands if driven manually. It appears the driver could not adapt to the torque requirements of manual steering as quickly as necessary and therefore the lateral offset is much higher when driving behind the wheel on a curved path.

Inexperienced Driver Rounds

To highlight the importance of driver training for remote driving purposes, two test rounds were conducted with an inexperienced driver at 10 MPH, which is the typical speed the RCTMA will be driven at. Figure 5.16 shows the average lane-keeping performance for these two rounds with the inexperienced remote driver.

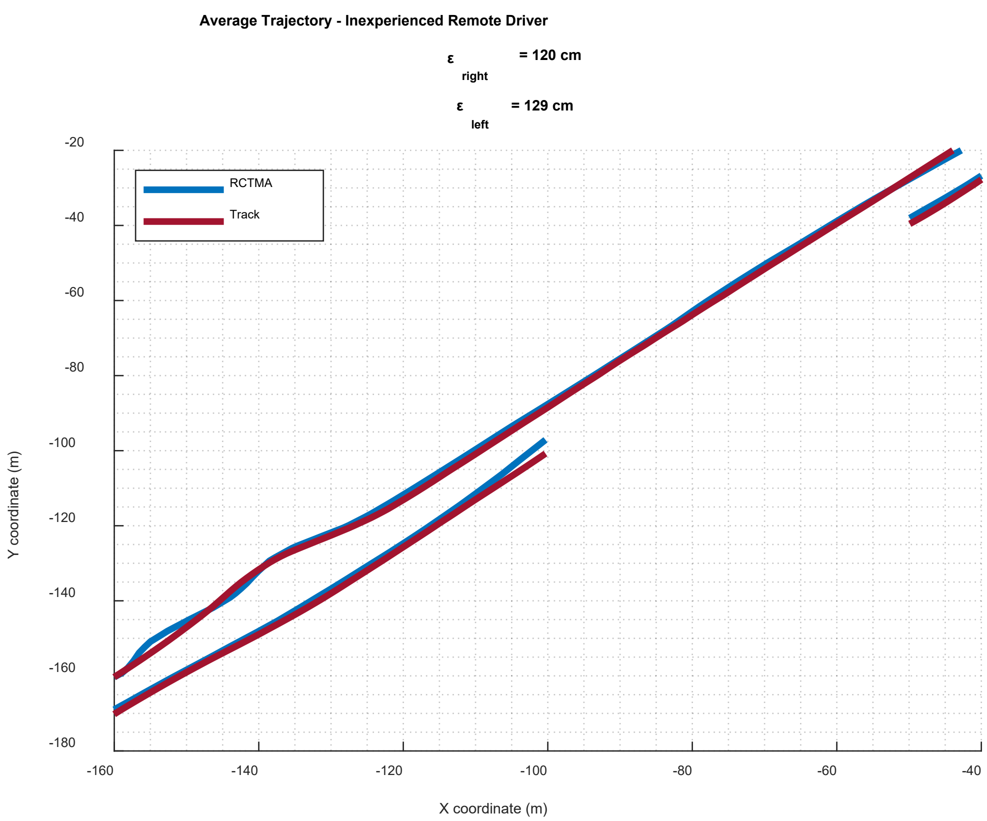

Figure 5.16: Lane-keeping performance with inexperienced remote driver

As it is noticed in Figure 5.16, the average lateral offset for the inexperienced driver is rather significant, with a right-lane lateral offset of 120 cm and a left-lane lateral offset of 129 cm. In contrast to the previous examples, lane-keeping performance has been worse for the left lane compared to the right lane. This is because the inexperienced driver started negotiating around the obstacle prematurely and thus deviated from the lane's course before crossing the mark where drivers were supposed to start maneuvering around the obstacle in order to avoid it. This has caused a rather significant departure from the straight path in the left lane and has caused lane-keeping to exacerbate.

In order to better grasp the importance of driver training for remote driving purposes, the average lateral offsets for the same speed have been given in Figure 5.17 for both trained and inexperienced drivers as they drove the RCTMA remotely through the test track.

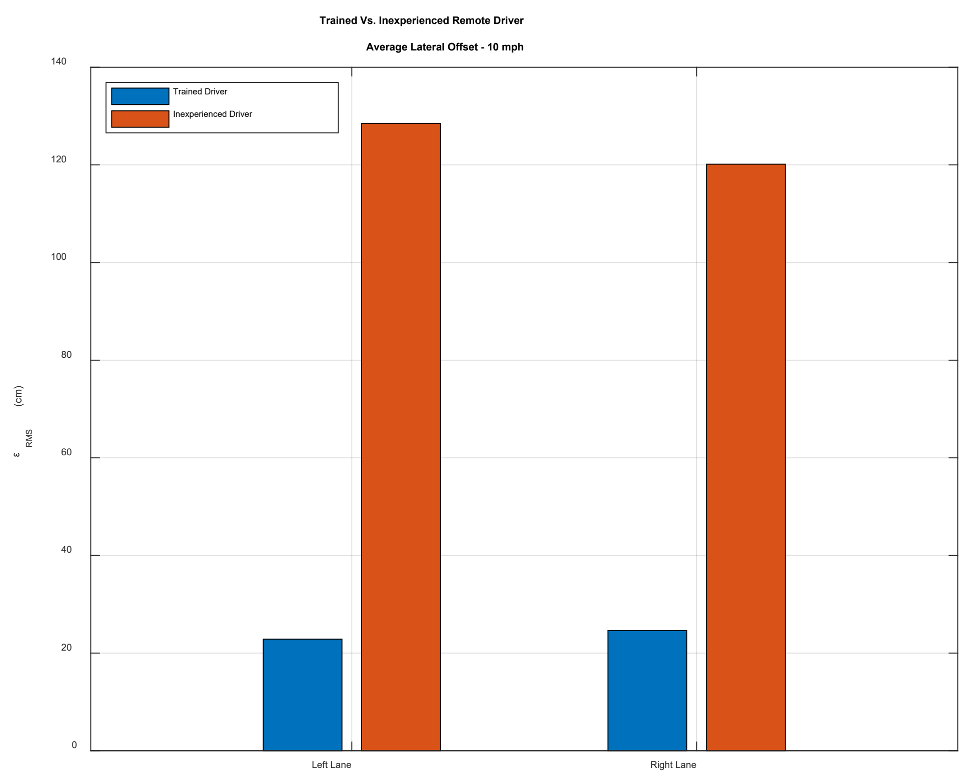

Figure 5.17: Lane-keeping comparison: trained driver vs. inexperienced driver

It is observed from Figure 5.17 that lane-keeping performance with the inexperienced remote driver has severely deteriorated for both left and right lanes as the average lateral offsets for the inexperienced remote driver are nearly 5 times larger than that of the trained remote driver. This can be attributed to the inexperienced driver not having an adequate grasp of remotely steering the RCTMA. It further highlights the importance of driver training for the remote operation of the RCTMA so that they would be comfortable and oriented with the remote driving station and how its commands take effect in the RCTMA.

Gap-Maintaining Rounds

The last two rounds of testing pertained to maintaining the gap distance between the RCTMA and the lead vehicle. In all previous tests there was a designated speed between 5 MPH and 20 MPH where the RCTMA proceeded through the test track, but for these two rounds the target had been to maintain a gap distance of about 100 feet with the lead vehicle while staying in-lane. Figure 5.18 shows the average lateral offset for the gap-maintaining rounds.

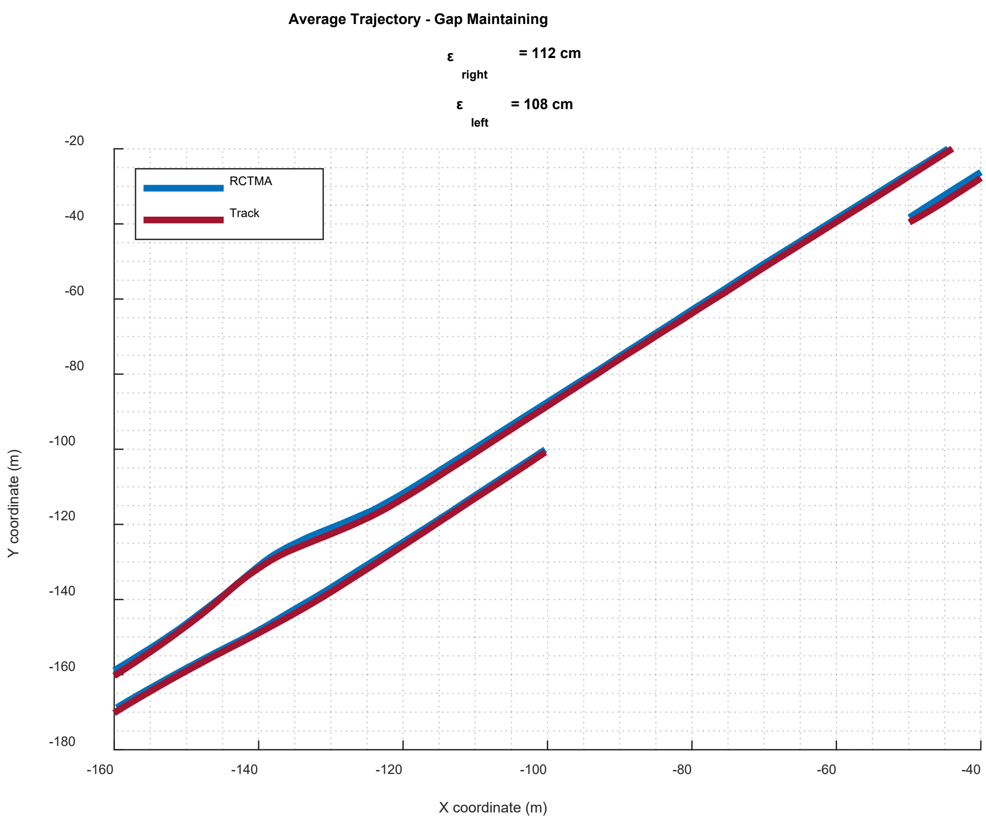

Figure 5.18: Lane-keeping performance for gap-maintaining rounds

It is observed from Figure 5.18 that the gap-maintaining rounds have had a rather significant average lateral offset, with an average lane-keeping error of 112 cm for the right lane and 108 cm for the left lane. Figure 5.19 shows how lane-keeping performance in gap-maintaining rounds compares to those with the driver driving the RCTMA at a designated speed of 10 MPH and 15. Although the target for the gap-maintaining rounds was not to maintain a steady speed, later study of RCTMA kinematic data showed that the vehicle's speed had been between 10 and 15 MPH for these test rounds and therefore the lane-keeping data for these rounds has been compared to those of 10 MPH and 15 MPH test rounds.

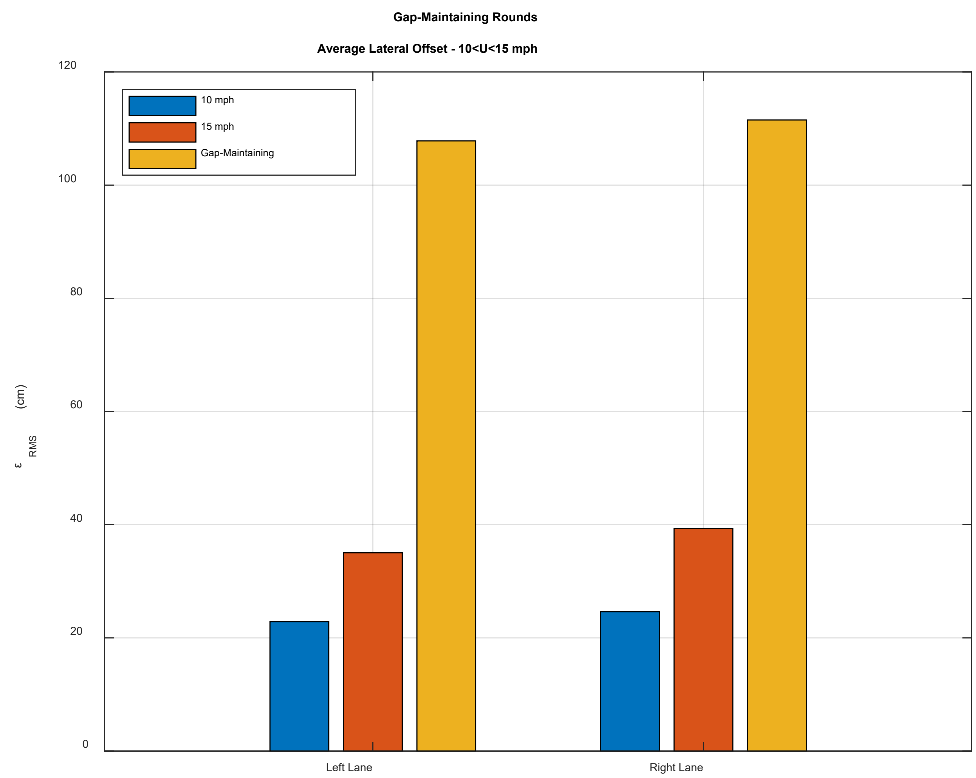

Figure 5.19: Comparing average lateral offsets for the gap-maintaining rounds

It is noticed from Figure 5.19 that lane-keeping in the gap-maintaining rounds have been significantly worse than when the remote driver aimed to maintain a constant speed. However, given that the goal for those rounds had been to maintain a constant gap between the RCTMA and the lead vehicle, lane-keeping had not been prioritized in these rounds.

Conclusion

22 rounds of testing with various scenarios were ran and lane-keeping performance was studied across all of them. It is gathered that lane-keeping performance deteriorates with increasing speed. Also tracking a curved trajectory has produced poorer lane-keeping results than tracking straight paths. Furthermore, it was noticed that an inexperienced driver could not keep the same levels of lane-keeping as a trained remote driver, and to highlight the importance of training for remote drivers it must be noted that the remote driver himself did not perform as well when sitting behind the wheel rather than driving remotely. This further separates remote driving from hands-on driving and signifies the importance of training for remote drivers with a goal of sufficient lane-keeping performance.

Scenario 5: Path-following accuracy via Camera

The camera footage captured from the sides of the RCTMA as it went through the test track was investigated in evaluating the lane-keeping performance. This provided a second method for such as evaluation as the first method was based on using the GPS data.

For this purpose, a total of 11 rulers with known lengths had already been placed across the test track, 9 on the right lane which featured most of the test scenarios and 2 on the left lane that featured obstacle avoidance and communication check scenarios. Also, GoPro12 cameras were installed on the RCTMA side poles, perpendicular to the pole and parallel to the ground, and set to have a linear field of view. This way, the rulers once caught on camera footage will represent their own true length which enables the calibration of a video analysis software for length measurement. Figure 5.20 shows an example of a frame in the video analysis software that allows for length calibration and measurement of lateral offset from side-camera footage.

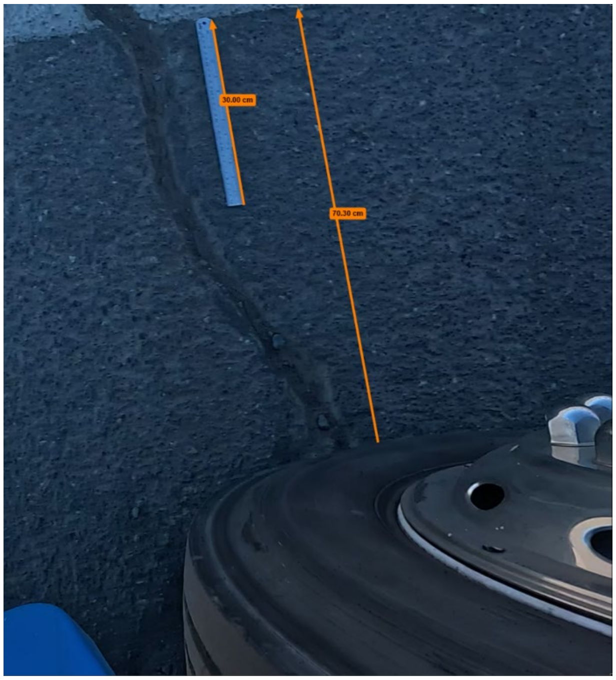

Figure 5.20: A frame of side-camera footage with taped ruler and lateral offset

Anytime a new ruler is caught on tape, a new length calibration is performed. Given the orientation and the installment location of the side cameras, the outer edge of the RCTMA front tires and the lane's edge line are caught on camera footage. The distance between them is obtained as a measure of lateral offset, using the length calibration procedure described.

It must be noted that not all rulers are caught on camera footage for every test round and the measurements of the lateral offset are not ruler exclusive. Therefore, an average lateral offset is calculated to compare the measured lateral offset via camera to the calculated lateral offset via GPS.

The measured lateral offsets for all test rounds are presented as follows.

Speed Rounds

Tables 5.1 through 5.5 give the measured lateral offset data for the speed rounds with speeds of respectively 5, 10, 15, and 20 miles per hour.

Table 5.1: Measured lateral offset: 5 MPH

5 MPH - Lateral Offset (cm)																			$\bar{\varepsilon}$
Round 1	**Right**	96	116	69	57	22	49	46	60	76	63	24	78	80	53	6			**60**
	Left	123																	**123**
Round 2	**Right**	46	55	41	27	13	37	76	27	63	23	3	55	72	72				**44**
	Left	42																	**42**
Round 3	**Right**	29	70	77	68	50	49	51	48	71	93	39	67	61	0	77	62	67	**58**
	Left	81																	**81**
Round 4	**Right**	131	75	47	29	30	56	54	55	66	84	81	76	66	0	44	82	108	**64**
	Left	70																	**70**

Table 5.2: Measured lateral offset: 10 MPH

10 MPH - Lateral Offset (cm)																				$\bar{\varepsilon}$
Round 1	**Right**	135	69	42	42	53	66	51	22	27	75	108	175	34	93	30	72	60	53	106	**69**
	Left	46	125																		**86**
Round 2	**Right**	131	160	72	32	20	3	0	17	20	47	110	32	30	0	47	64	77	78		**52**
	Left	67	92																		**80**
Round 3	**Right**	56	48	42	32	28	34	44	57	60	155	99	100	31	81	47	69	57	105		**64**
	Left	46																			**46**
Round 4	**Right**	140	71	55	42	41	32	34	31	62	76	75	107	69	43	8	63	76	102		**63**
	Left	84																			**84**

Table 5.3: Measured lateral offset: 15 MPH

15 MPH - Lateral Offset (cm)																			$\bar{\varepsilon}$
Round 1	**Right**	141	68	38	48	42	0	14	58	57	59	52	64	53	71	54	65	89	42	**56**
	Left	35	147	97																**93**
Round 2	**Right**	127	69	43	12	28	59	41	44	55	96	35	74	68	61	42	39	57	0	**53**
	Left	69																		**69**
Round 3	**Right**	112	82	69	40	37	48	54	26	9	33	65	96	94	11	53	0	82	54	**54**
	Left	59																		**59**
Round 4	**Right**	120	63	51	41	31	49	66	58	50	74	99	9	72	36	50	70	111	17	**59**
	Left	72																		**72**

Table 5.4: Measured lateral offset: 20 MPH

20 MPH - Lateral Offset (cm)																			$\bar{\varepsilon}$
Round 1	**Right**	139	58	31	65	73	64	0	0	28	30	39	14	69	65	45	42	40		**56**
	Left	104	69	77																**93**
Round 2	**Right**	134	42	0	14	0	11	20	31	70	158	91	93	37	0	26	89	51	78	**53**
	Left	58																		**69**
Round 3	**Right**	111	77	37	12	32	0	0	18	63	93	66	12	56	36	48	38	68	20	**54**
	Left	90																		**59**
Round 4	**Right**	143	74	8	32	43	50	73	76	54	37	92	64	27	78	69	65	104	26	**59**
	Left	85																		**72**

Behind the Wheel

Table 5.5 gives the measured lateral offset data for the driver behind-the-wheel rounds.

Table 5.5: Measured lateral offset: Behind the Wheel

		Behind-the-Wheel Lateral Offset (cm)																	$\bar{\varepsilon}$
10 MPH	**Right**	9	46	43	27	49	50	46	38	57	79	61	45	13	36	10	26	54		**41**
	Left																			
15 MPH	**Right**	36	55	44	24	13	18	38	49	70	90	80	33	0	7	3	22	22	52	**36**
	Left																			

Inexperienced Remote Driver

Tables 5.6 gives the measured lateral offset data for the inexperienced remote driver rounds.

Table 5.6: Measured lateral offset: Inexperienced Remote Driver

		Inexperienced Driver Lateral Offset (cm)																	$\bar{\varepsilon}$
Round 1	**Right**	34	40	32	29	123	47	59	29	10	38	73	71	68	84	97	0			**52**
	Left	97																		**97**
Round 2	**Right**	107	69	81	95	82	50	74	74	67	11	51	47	71	79	81				**69**
	Left	37	10																	**24**

Gap-Maintaining

Table 5.7 shows the measured lateral offset data for the gap-maintaining rounds.

Table 5.7: Measured lateral offset: Gap-Maintaining

		Gap-Maintaining Lateral Offset (cm)																	$\bar{\varepsilon}$
Round 1	**Right**	80	84	72	78	62	68	72	68	67	77	79	68	53	14	67	81	72	63	**52**
	Left	4																		**97**
Round 2	**Right**	74	76	68	91	70	43	53	74	74	61	62	29	28	34	87	75	77	83	**69**
	Left	21																		**24**

Scenario 5: Cross Referencing GPS with Camera

To verify the calculated lateral offsets from GPS data with the measured lateral offsets from camera footage, they have both been averaged out and brought together in Table 5.8. Before we can proceed with the comparison of the two methods, it must be noted that only the measured lateral offsets for the right lane have been given in Table 5.8, as too few measurements, if any, were caught on camera for the left lane. The reason for this is that the left lane primarily was intended to complete the track's loop and return the RCTMA to the starting point as well as featuring test scenarios like obstacle avoidance (which caused significant deviation from the lane and disrupted lane-keeping), and radio communication check. Because of this, most of the rulers were placed on the right lane and therefore many more data points were obtained for the right lane than the left, which would enable a comparison with the GPS data.

Table 5.8: Comparison of GPS lateral offsets to camera lateral offsets

	ε_G GPS offset (cm)	ε_C Camera offset (cm)	Relative Error (%)	$\frac{\lvert\varepsilon_G - \varepsilon_C\rvert}{w_L - w_T}$	$\frac{\sigma_{camera}}{\varepsilon_{camera}}$ (%)
5 MPH	11	57	418	1.01	45
10 MPH	25	62	148	0.81	60
15 MPH	39	56	44	0.37	52
20 MPH	92	51	45	0.9	69
Behind the Wheel	158	39	75	2.6	57
Inexperienced Driver	120	61	49	1.29	46
Gap Maintaining	112	67	40	0.98	26

It is observed from Table 5.8 that the lateral offsets obtained from GPS tracking and camera footage analysis seem to have a rather significant difference. This can be attributed to two facts:

First, it must be noted that data acquisition for the camera footage has occurred in few, sporadic positions along the track with rulers being often 50 to 100 feet apart and not all of them were caught on camera and the instances where the rulers actually were caught on camera would not necessarily correspond to a lateral offset that is a good representation of the lane-keeping performance of the RCTMA along the track. Therefore, compared to the GPS data that is available every few feet (a total of 200 data points for each lane), the camera data would have a sampling bias. This can be further noted in the last column of Table 5.8 where the ratio of the standard deviation of the camera lateral offsets to their average value is given. It is seen that these values are rather significant which indicates the lateral offsets obtained from video footage are not uniformly distributed and do not necessarily represent the average lane-keeping behavior of the RCTMA.

Second, another issue that must be addressed is that the camera lateral offset represents the distance between the side of the RCTMA and the edge of the lane which will be noted as the camera, whereas the GPS lateral offset represents the distance between the middle of the truck (as two RTK antennas on either side of the truck produce an average position for the middle of the truck) and the middle of the lane.

Depending on which side of the lane midline (towards the edge or towards the divider) the RCTMA was leaning, the two mentioned lateral offsets would be different by a relatively considerable amount. Figures 5.21 and 5.22 depict a schematic of the two lateral offsets in both scenarios.

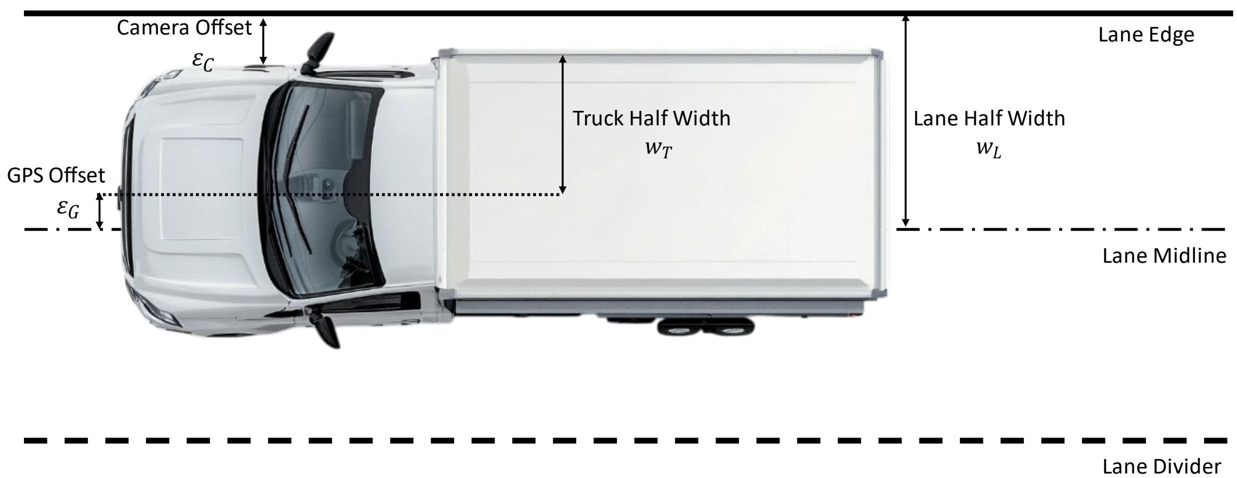

Figure 5.21: GPS and camera offset when RCTMA is above lane midline

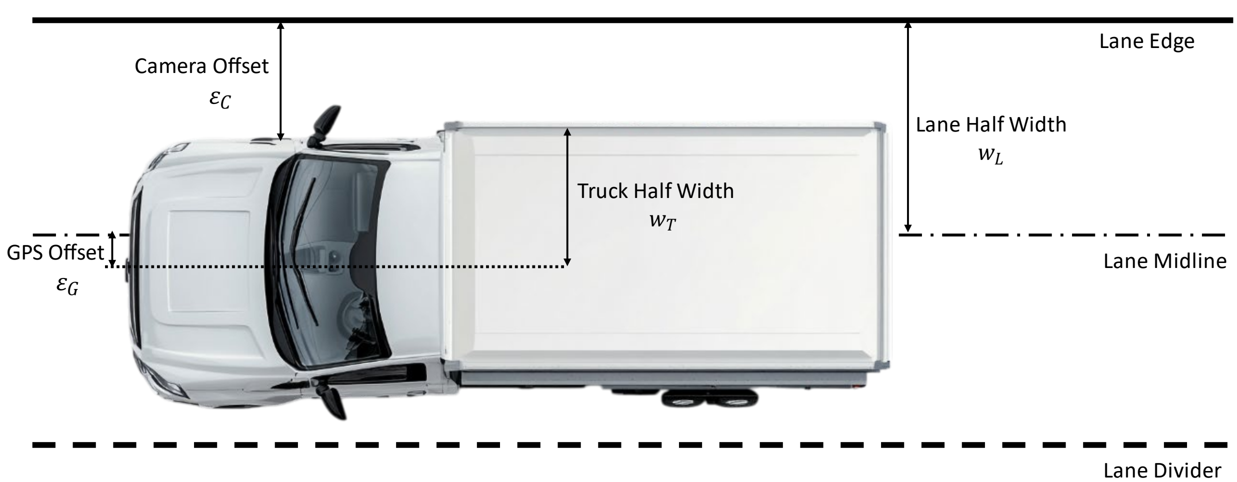

Figure 5.22: GPS and camera offsets when RCTMA is below lane midline

Inspection of Figure 5.21 and Figure 5.22 yields:

$$\varepsilon_C + w_T + \varepsilon_G = w_L \qquad above$$
$$\varepsilon_C + w_T = w_L + \varepsilon_G \qquad below$$

Where ε_C is the camera offset, ε_G is the GPS offset, w_T is the half-width of the truck, and w_L is the half-width of the lane. This means that the absolute value of the GPS and the camera offset differ by a value of $w_L - w_T$ that is almost 45 cm.

Therefore, because of the inherent difference in how either offset is defined, their values would not be necessarily similar. The fifth column of Table 5.8 shows how the difference between the two offset values compares against the $w_L - w_T$ value. It is realized that the ratio between the two lengths (difference between the GPS/Camera offset and the difference between the lane half-width and the truck half-width) is close to unity in most cases which corroborates with Figure 5.21 and Figure 5.22.

Conclusion

The lateral offsets obtained from measurements performed on the camera footage do not uniquely affirm those obtained from GPS data calculations. Since camera footage data is collected non-uniformly, it cannot be expected to give an accurate representation of the general lane-keeping performance of the RCTMA. It is gathered that the difference between the camera lateral offset and the GPS lateral offset could be partially due to how each error is defined which in turn depends on the geometry of the truck and the road. Bearing these facts in mind, it is noteworthy to mention that almost all lateral offsets are found to be in the acceptable range. For a trained remote driver who drives the RCTMA at normal speeds (10 or 15 MPH), the lateral offset is reasonable and below 2 feet.

Scenario 6: Following Gap-Distance Accuracy

Maintaining the gap distance between the attenuator truck and the lead vehicle is an important objective of the study of RCTMA performance. In all the test rounds, the gap between the RCTMA and the lead vehicle was measured by a rider sitting inside the RCTMA using a laser rangefinder as the truck went through the BC section of the track which is a straight path where the RCTMA is following the lead vehicle. Figure 5.23, previously given as Figure 5.1, is brought again for ease of reference and shows the aerial view of the test track and the BC section.

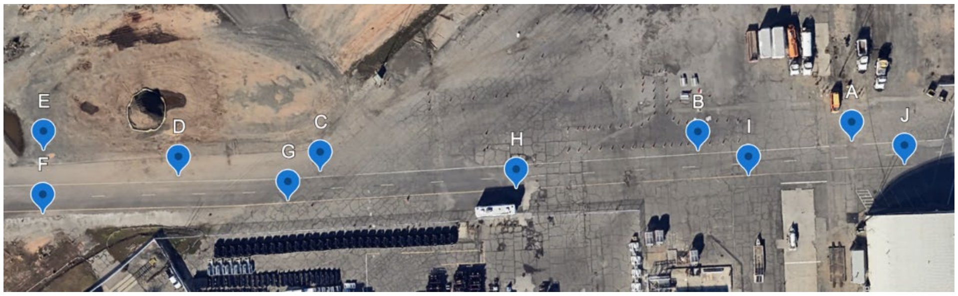

Figure 5.23: BC Section as the gap maintaining region of the test track (previously shown as Figure 5.1)

The gap distances in each test round were measured real-time as the RCTMA went through the test track. The working principle of the laser rangefinder is that it sends a laser pulse towards the object of interest (in this case the lead vehicle) and measures the time it takes for the pulse to come back to it. Since the laser rangefinder in use was an analog device with no memory to record the measured data, the gap distances could not be documented at the same time as they were being measured. Therefore, a camera was mounted in the middle of the truck's cab that would record the front view of the vehicle and as the rider inside the RCTMA read the measured gap distances aloud, it would retain the gap distance data. The camera footage from the middle camera was later inspected for each round and the gap distances were obtained. Table 5.9 gives the gap distances for the combined tests conducted and their average value.

Table 5.9: Measured gap distance data

	RCTMA-LV gap (ft)																		avg
5 MPH	130	133	133	164	160	117	140	180	80	80	75	85	88	95	100	75	85	90	**114**
10 MPH	140	130	150	135	120	125	130	125	130	120	180	175	161	155					**141**
15 MPH	135	125	132	150	165	200	205	170	187	185									**165**
20 MPH	170	150	240	290	305														**231**
Behind the Wheel	130	115	95	80	89														**102**
Inexperienced Driver	150	70	50	56	85	95													**84**
Gap-Maintaining	40	45	74	82	95	100	103	104	107	53	75	85	101	107	103	107	113	103	**89**

It is noticed in Table 5.9 that the different test rounds have had different numbers of gap measurements. The reason for that is that the laser rangefinder is extremely susceptible to vehicle vibrations due to acceleration/deceleration and vertical motions such as going over bumps or potholes. Hence, in order to collect sufficient gap distance measurements, the ride must be quite smooth. By taking the average value of the collected gap distance measurements, a comparison of their variations with speed is given in Figure 5.24.

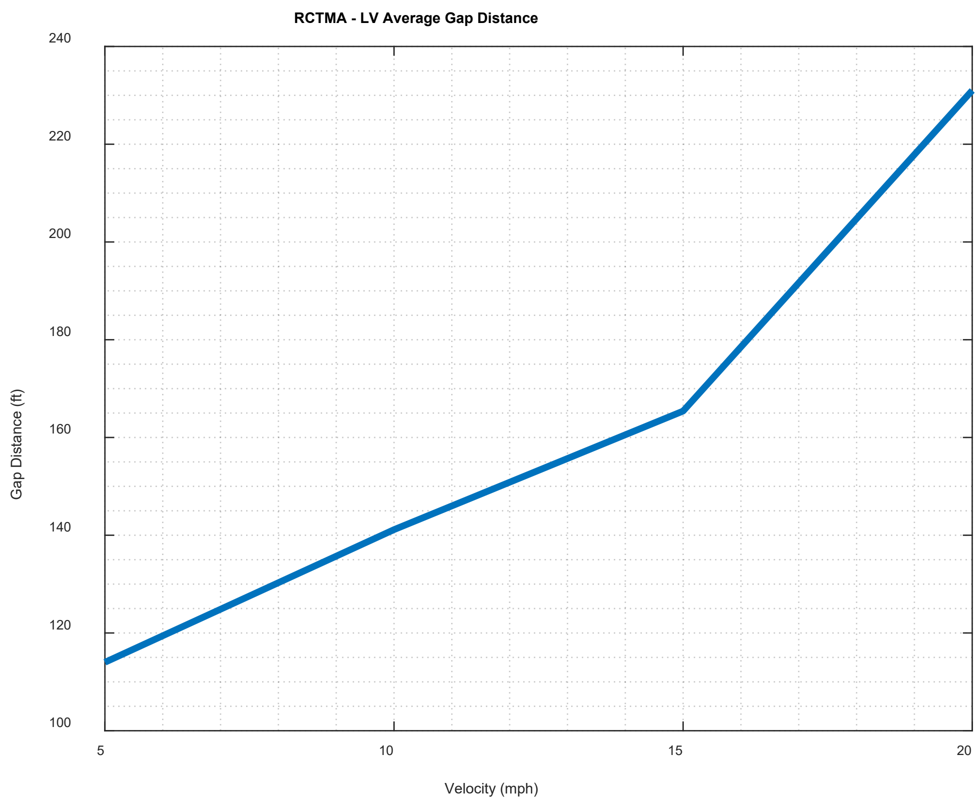

Figure 5.24: Variation of average gap distance with speed

It is observed from Figure 5.24 that the average gap distance has increased with increasing speed. It also shows an abrupt increase in the gap distance in the 20-MPH speed. However, it must be noted that few measurements were taken place at this relatively high speed.

In order to assess the RCTMA's performance in maintaining a constant gap between itself and the LV, two test rounds were conducted with this sole purpose, i.e., in these two tests no particular speed was targeted but rather the goal was to keep a constant gap of 100 feet between the RCTMA and the LV. Figure 5.25 shows the gap measurements between the RCTMA and the LV in these two rounds.

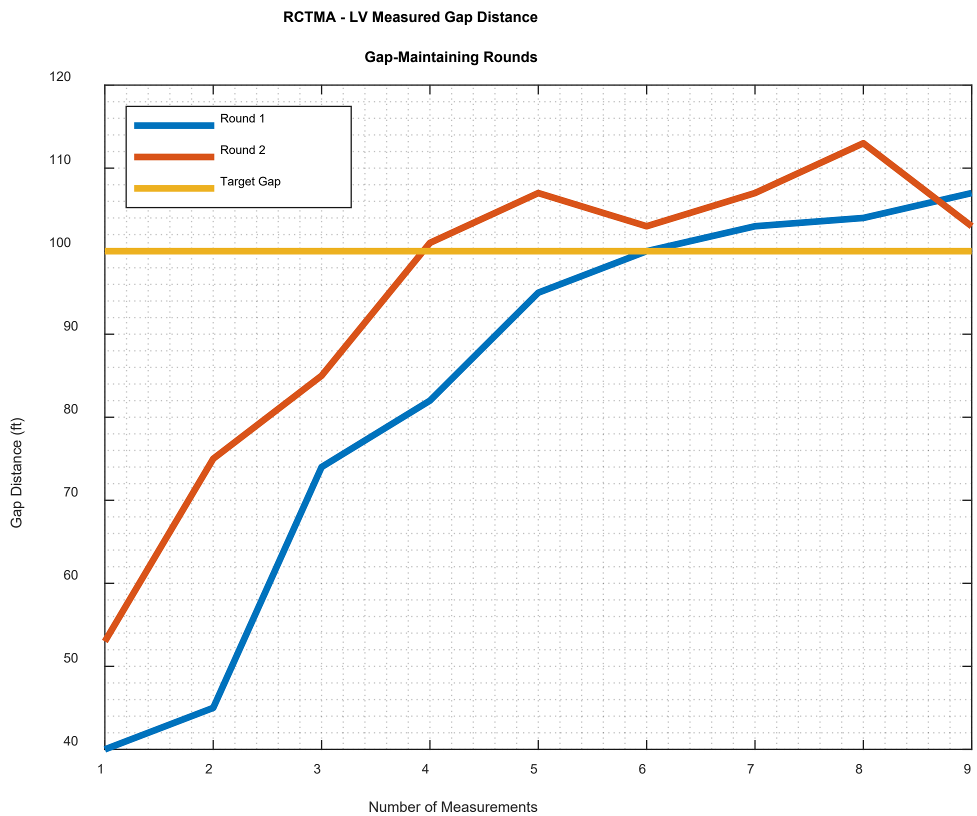

Figure 5.25: Measured Gap Distance values in Gap-Maintaining Rounds

Figure 5.25 shows that the measured gap distance follows a relatively similar trend in both gap-maintaining test rounds. During the first few measurements, the RCTMA has been building the gap and once the target gap was reached, it had been more or less maintained. In all test rounds, the RCTMA and the LV would have reached their target speed by the time they cross landmark point B, however, given that the two gap-maintaining rounds did not have a target speed, part of the initial acceleration phase and the difference in the two vehicle's speed has prevented the RCTMA to keep the target gap at all measurements, but once the target gap was reached, the RCTMA was able to maintain it.

Conclusion

Maintaining the same longitudinal gap between the RCTMA and the LV has proven to be possible via remote driving. Albeit some time needs to pass for the RCTMA to arrive at its target gap, but once the gap is reached, maintaining it in extended durations of following the lead vehicle has been verified. For the typical speeds of 10 to 15 MPH, it is possible to maintain a gap of about 100 feet via remote driving.

Scenario 7: Roll-out Maneuver

At the beginning of each test round, the RCTMA took the lane, i.e., left the shoulder and entered the lane at point A. The starting point was offset with respect to the lane to replicate the relative position of a shoulder on the road. Upon receiving the verbal que from the test conductor, the LV started its motion within the lane and the RCTMA first took the lane by entering it from the shoulder and then followed the LV through the test track. Taking the lane was achieved successfully in each of the test rounds via remote driving. The initial values of gap distance and lateral offset have been studied to assess the effect of taking-the-lane on gap-maintaining and lane-keeping performance. It is gathered that the initial gap distance after taking the lane is about 120 feet and the initial lateral offset after taking the lane is below 2 feet.

Conclusion

Taking the lane, as one of the most important functions of a TMA truck, was proven to be performed successfully in all rounds of the testing via remote driving. This maneuver was shown to not significantly impact gap-maintaining or lane-keeping.

Scenario 8: Acceleration/Deceleration

The RCTMA accelerated and decelerated multiple times as it went through the test track. In particular, the RCTMA once accelerates from point A to point B, decelerates from point D to point E and after making a turn comes to a full stop at point F, then accelerates from zero speed from point F towards point G, and finally decelerates from point I to come to a full stop at point J. All these acceleration /deceleration maneuvers took place smoothly and without glitches via remote driving and with little difference in the accelerated motion when the RCTMA was driven remotely and when it was driven behind the wheel.

Conclusion

It was verified that the RCTMA can accelerate and decelerate on command via remote driving and that the accelerated motion in remote driving is as smooth as when the RCTMA is driven behind the wheel.

Effect of Latency

The communication latency was determined by the Verizon cellular network's coverage at the testing site and the encryption/decryption algorithm KRATOS used to transmit the video feed from the cameras showing the RCTMA's field of view to the control center which is KRATOS' intellectual property. Therefore, AHMCT had no control over manipulating the latency and intentionally assessed its effect on RCTMA performance. However, during all testing rounds it was noticed that latency was negligible and all RCTMA functions were operated smoothly and without glitch.

Statistical Significance

Every test condition and test scenario were conducted multiple times, and their individual corresponding data was collected to ensure the processed data would not yield random results but rather the average data would be a more appropriate representation of said condition/scenario. Therefore, statistical significance was established across the entire observations made from the testing data.

Driving Workload Assessment

One of the aspects which must be studied for the task of remote driving is its cognitive workload and how different it is from hands-on driving from a mental strain perspective. NASA has developed a tool in 1986 called the Task Load Index (TLX) which entails a subjective workload assessment where the subject that has performed a task fills a questionnaire in which they rate their performance across six different categories in terms of how substantial each one has been in their experience of performing the task [14]. These categories include mental demand, physical demand, temporal demand, performance, effort, and frustration.

After rating each category with a number between 0 and 10, the subject makes 15 binary choices where they choose one category over another as to which one has been more challenging in performing the task. This ranking enables a normalized weighting of the categories with respect to each other. Calculating the weighted sum of the ranked ratings yields a means to quantitatively measure mental workload from a subjective point of view.

A total of 3 questionnaires were collected after conducting the RCTMA tests, one with the main driver remotely driving, one with the main driver driving behind-the-wheel, and one with the inexperienced driver remotely driving.

Since there were two different subjects involved, it is rather difficult to make an objective assessment regarding the workload of the driving task to compare the two drivers' performance and assessment. However, their processed answers to the TLX questionnaire could still be regarded as a measure of workload despite its subjective nature.

Table 5.9 through Table 5.11 shows the recorded rankings and ratings for the individual subjects' response to the questionnaire and their weighted sum. The binary scores in the left side matrix determine which of the six categories has been more demanding with respect to the others which provide the weighting coefficients in the 8th column of the tables. The ratings for each category are then given in the 9th column as marked by the subject. The 10th column calculates a weighted sum which represents the total workload of the task.

Table 5.10: Task workload for driver-behind-the-wheel

Main Driver - Behind The Wheel									
	Mental (m)	Physical (phy)	Temporal (t)	Performance (per)	Effort (e)	Frustration (f)	Weight	Rating	Weighted Ratings
Mental (m)	x	m	t	per	e	m	0.5	1.5	0.75

Physical (phy)	m	x	t	phy	e	phy	0.5	4.5	2.25
Temporal (t)	t	t	x	per	e	t	0.66667	5.5	3.666666667
Performance (per)	per	phy	per	x	e	per	0.66667	1.5	1
Effort (e)	e	e	e	e	x	e	1	5.5	5.5
Frustration (f)	m	phy	t	per	e	x	0.16667	0.5	0.083333333
Total TLX									**13.25**

Table 5.11: Task workload for remote driving

Main Driver - Driving Remotely									
	Mental (m)	**Physical (phy)**	**Temporal (t)**	**Performance (per)**	**Effort (e)**	**Frustration (f)**	**Weight**	**Rating**	**Weighted Ratings**
Mental (m)	x	m	m	per	m	m	0.83333	7.5	**6.25**
Physical (phy)	m	x	t	per	e	phy	0.33333	6.5	**2.166666667**
Temporal (t)	m	t	x	per	t	t	0.66667	7.5	**5**
Performance (per)	per	per	per	x	e	per	0.83333	1.5	**1.25**
Effort (e)	m	e	t	e	x	e	0.66667	7.5	**5**
Frustration (f)	m	phy	t	per	e	x	0.16667	2.5	**0.416666667**
Total TLX									**20.08333333**

Table 5.12: Task workload for inexperienced remote driver

Inexperienced Driver Driving Remotely									
	Mental (m)	**Physical (phy)**	**Temporal (t)**	**Performance (per)**	**Effort (e)**	**Frustration (f)**	**Weight**	**Rating**	**Weighted Ratings**
Mental (m)	x	m	m	per	e	m	0.66667	8.5	**5.666666667**
Physical (phy)	m	x	phy	per	e	phy	0.5	4	**2**
Temporal (t)	m	phy	x	per	e	f	0.16667	4	**0.666666667**
Performance (per)	per	per	per	x	per	per	1	7	**7**
Effort (e)	e	e	e	per	x	e	0.83333	8	**6.666666667**
Frustration (f)	m	phy	f	per	e	x	0.33333	9.5	**3.166666667**
Total TLX									**25.16666667**

It must be noted that the task load index is highly subjective as ratings and rankings depend on the subject's opinion, however, for the two cases where the main driver was once behind the wheel and once driving remotely, the subject is the same and therefore further comparisons can be made between the two cases. Figure 5.26 depicts how the two cases compare concerning the main demands for the driving task.

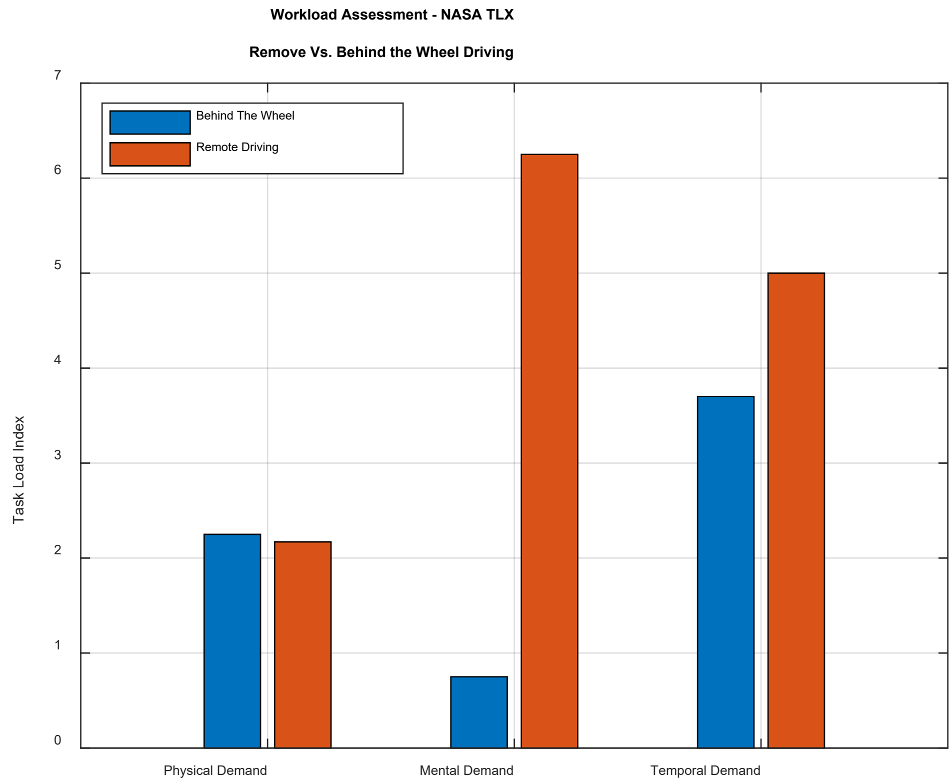

Figure 5.26: Remote vs. Behind the Wheel driving - Demand variation

It is noticed from Figure 5.26 that the physical demand for the two driving cases is relatively similar and that behind the wheel driving is slightly more physically demanding. On the other hand, temporal demand is considerably larger for remote driving, and it is evident that when driving remotely, the driver felt as though they were in a hurry more than they did when driving behind the wheel. Finally, the most pronounced difference between the two cases is the mental demand for which remote driving has shown to be six times more mentally demanding than when driving behind the wheel. This noticeable difference plays a significant contribution to the total workload index and verifies that remote driving is a much more mentally draining task.

The calculated net workload scores for all 3 tasks are given in Figure 5.27.

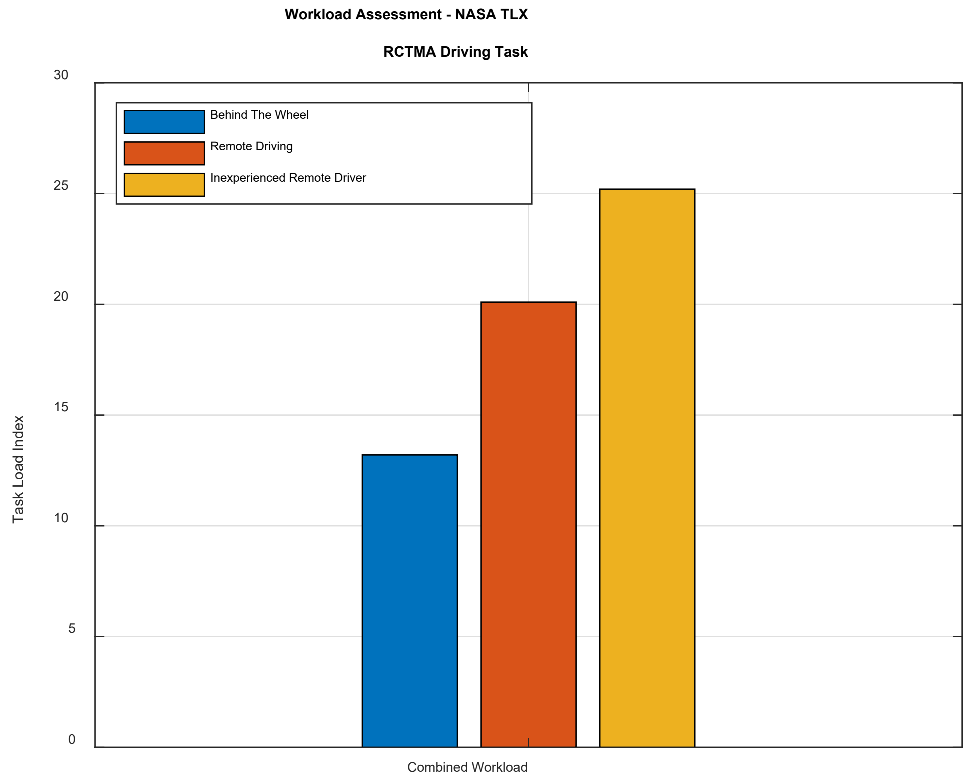

Figure 5.27: Comparison of the Task Load Index for the 3 driving tasks

It is observed from Figure 5.27 that the behind-the-wheel driving task has had the smallest workload with a TLX value of 13.2 which could be described as a baseline. Next is the task of remote driving with the main driver with a TLX value of 20.1 and finally the task of the inexperienced driver driving remotely has had the largest workload index with a TLX value of 25.2.

It is gathered from Figure 5.27 that there was a 50% increase in the task load index going from behind-the-wheel to remote driving which shows that despite having training, the task of remote driving has still proven to be demanding. Furthermore, the task load index for the inexperienced driver driving remotely had a 90% increase with respect to the behind-the-wheel baseline and a 25% increase with respect to the trained driver driving remotely. This clearly indicates the importance of training for remote driving.

Conclusion

The NASA TLX (task load index) method has been developed to quantitatively assess a task's workload. It considers various aspects of a task including mental, physical, and temporal demands as well as effort, performance, and frustration concerns. It was gathered that amidst the conducted tests, the highest task load index pertained to the case of the inexperienced driver driving remotely. The smallest task load index pertained to the case of behind-the-wheel driving. The task load index is another measure that highlights the importance of driver training for remote driving.

Results Conclusion

Through a rigorous testing of 22 rounds with different speeds and driving scenarios, it was shown that the main functions of a TMA truck including lane-keeping in both straight and curved paths, maintaining the gap distance with the LV, taking the lane, avoiding obstacles, maintaining communication, pausing and stopping motion, and acceleration and deceleration can be achieved via remote driving with satisfactory performance. There are differences in remote driving and behind the wheel driving that highlight the importance of training for remote drivers. It was also gathered that remote driving demands a higher workload. It is our understanding that with sufficient training, a robust cellular network, and a driver with peace of mind, all the duties of a TMA truck can be adequately achieved via remote driving as well as protecting the RCTMA driver from errant vehicles.

Chapter 6: Conclusions and Future Research

The results of this research have provided data indicating that remote driving is a viable option for Caltrans' TMA trucks in areas where the cellular network has a sound coverage, and the roadway lane width and geometry do not provide very tight and complex driving conditions.

The test results showed that RCTMA was able to perform all the test scenarios with sufficient efficacy. Below is a brief description of the major test results across various test scenarios.

Communication

On AT&T network in Northern California, the communication latency was minimal, and remote driving was efficient and lag-free. Radio communication was maintained between the remote driver and on-site personnel for ensuring safety and proper execution of TMA duties.

Pause and Stop

The remote driver was able to pause the RCTMA motion and have it come to a full stop on demand.

Obstacle Avoiding

The remote driver was able to avoid the obstacle by negotiating around it at all speeds (5, 10 and 15 MPH). However, obstacle-avoidance at higher speeds came with a more pronounced lateral offset.

Lane-Keeping

RCTMA was able to keep its lane at typical 10 MPH and 15 MPH speeds with an average lateral offset below 2 feet while being driven remotely. Driver training proved essential to satisfactory lane-keeping. It was found that higher speeds and curved paths are more challenging for lane-keeping than low speeds and straight paths. The same challenges were observed when the driver was behind the wheel on such paths or at such speeds.

Gap maintaining

When instructed to maintain the gap with the lead vehicle, the remote driver was able to maintain a gap of 100 feet over a distance of 400 feet. Maintaining the gap while maintaining a speed proved challenging and requires extra training. Similar results are expected when the driver is behind the wheel.

Taking the Lane

The remote driver was able to take the lane by starting the RCTMA motion in the road's shoulder and joining the lane in minimal distance.

Acceleration/Deceleration

The remote driver was able to smoothly and rapidly accelerate or decelerate whenever necessary.

Driver Workload

Using NASA's Task Load Index method showed that remote driving had a 50% higher mental workload index as compared to behind the wheel driving. An inexperienced remote driver showed a further 40% increase in the mental workload. It was understood that remote driving is more demanding than behind the wheel driving. Therefore, in addition to training, the work schedule and the workload of the remote driver should be adjusted accordingly. Another thing that should be noted is that driver training is immensely important for the remote driving task and that good remote driving is not the same as good behind-the-wheel driving.

Driver Training

Finally, it was found that driver training is of utmost importance for remote driving and significantly affects the performance of the RCTMA across many test scenarios, such that inexperienced drivers did not perform as well as trained drivers for important features such as lane-keeping and gap-maintaining. Furthermore, trained drivers seemed to experience lower mental workloads for the remote driving task than inexperienced drivers.

Future Work

Future work can include investigation of mechanisms to reduce the latency of the connection and data transmission, including increasing cellular connection redundancy and optimizing encryption/decryption algorithms used for transmission of the video signals.

Training methods and schedules need to be developed for remote drivers.

Geographic areas need to be assessed for their cellular network coverage and geometry to obtain select areas for safe operations of RCTMAs.

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