Audible Alert and TMA Lighting

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PREPARED BY:

Yaw Adu-Gyamfi

Carlos Sun, Ph.D., P.E., J.D.

Mark Amo-Boateng, Ph.D.

Gahan Gandi

Neema Jakisa Owor

University of Missouri-Columbia

PREPARED FOR:

Missouri Department of Transportation

Construction and Materials Division, Research Section

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16. Abstract

Truck Mounted Attenuators (TMAs) are designed to mitigate crash severity. Currently, TMA drivers rely on visual checks via driving mirrors to manually trigger warnings thus placing the duty on drivers. To address this limitation, the Automated TMA Warning System (AutoTMA) replaces or augments manual driver interventions with an AI-enabled, sensor-fused platform. By integrating high-definition cameras, LiDAR, and radar with GPU-accelerated multi-task learning, AutoTMA continuously detects and classifies oncoming vehicles, segments lane and drivable areas, and calculates dynamic distance thresholds—safe, warning, and danger—in real time. Validation of the AutoTMA included comprehensive trials within a Unity 3D simulation environment and test-track deployments on Missouri Department of Transportation (MoDOT) TMAs. Through iterative refinements, the system's response latency has been reduced from three seconds to 0.25 seconds, substantially improving both visual and audible alert accuracy. AutoTMA's modular architecture and robust sensor calibration mechanisms ensure rapid component replacement and resilience in variable operational conditions. Drawing on insights from prior research, including National Cooperative Highway Research Program (NCHRP) 05-24, the system optimizes lighting and audio cues while integrating adaptive safety zone parameters to overcome the limitations of fixed configurations. Preliminary findings confirm AutoTMA's ability to detect imminent collisions and deliver timely, context-sensitive warnings—significantly enhancing driver awareness and reducing the probability of TMA-involved crashes. AutoTMA marks a transformative shift in work zone safety protocols, offering a viable pathway for nationwide adoption. Future work will focus on expanding sensor modalities, further refining AI models to boost accuracy, and broadening field trials across diverse environments. By bridging the gap between manual vigilance and automated safety, the AutoTMA system not only improves operational workflows but also holds the promise of shaping policy and accelerating the integration of proactive safety technologies in transportation.

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By
Yaw Adu-Gyamfi, PhD.
Carlos Sun, PE, PhD.
Mark Amo-Boateng, PhD.
Gahan Gandi
Neema Jakisa Owor
University of Missouri - Columbia

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List of Abbreviations and Acronyms

23 CFR 420	Code of Federal Regulations, Title 23, Part 420
DOT	Department of Transportation
FHWA	Federal Highway Administration
NTL	National Transportation Library
ROSA P	Repository & Open Science Access Portal
NCHRP	National Cooperative Highway Research Program
EAL	Emergency Alert Light
ATSSA	American Traffic Safety Services Association
TMA	Truck Mounted Attenuator
AI	Artificial Intelligence
ML	Machine Learning
IoT	Internet of Things

Executive Summary

Overview of the AutoTMA Project

Work zone safety remains a critical challenge, with mobile work crews facing significant risks from distracted or speeding drivers. Despite the use of Truck-Mounted Attenuators (TMAs) to mitigate crash impacts, work zones continue to experience a high rate of rear-end collisions, often resulting in severe injuries or fatalities. In Missouri alone, multiple TMA-related crashes occur each year, underscoring the urgent need for proactive safety interventions. The Automated Audible Alert System (AutoTMA) addresses this issue by implementing an intelligent, real-time warning system that automatically detects high-risk vehicles and triggers audible alerts to warn drivers before a collision occurs.

Purpose and Objectives

The primary goal of the AutoTMA system is to enhance driver awareness and reduce work zone collisions by integrating an advanced AI-driven detection and audible alert mechanism into TMA trucks. Unlike traditional passive safety measures, which rely on static signage and manual intervention, AutoTMA actively monitors approaching traffic, assesses collision risk, and autonomously activates warning signals when a potential crash is detected. The key objectives of the system include:

- **Real-time Vehicle Detection and Tracking:** Utilize AI-powered vision models, LiDAR, and radar sensors to continuously monitor approaching vehicles in the TMA's vicinity.
- **Automated Collision Risk Assessment:** Implement a time-to-collision (TTC) prediction model to classify threats based on vehicle speed, distance, and reaction feasibility.
- **Dynamic Audible Alert Activation:** Deploy a multi-stage alarm system that adjusts in intensity based on the severity of the approaching vehicle's threat level.
- **Seamless Integration with Existing TMA Systems:** Ensure compatibility with Missouri Department of Transportation's (MoDOT) current TMA fleet, requiring minimal modifications for installation and operation.
- **Simulation Study:** To investigate the effectiveness of different Emergency Alert Light (EAL) and alarm configurations.

By automating the threat detection and warning process, AutoTMA ensures that hazardous driving behaviors are detected early, giving drivers more time to react and reducing the likelihood of high-speed crashes in work zones.

Technological Advancements in AutoTMA

The AutoTMA system integrates state-of-the-art artificial intelligence (AI), sensor fusion, and real-time processing to provide a fully autonomous hazard detection and warning mechanism. Key features include:

- **AI-Based Vehicle Detection and Tracking:** The system employs YOLOv5.0 (You Only Look Once) for real-time object detection and DeepSORT v2.2 for multi-object tracking. These deep-learning models allow precise recognition and tracking of vehicles approaching the TMA, even in complex traffic conditions.
- **Collision Prediction Using Time-to-Collision (TTC) Analysis:** A risk assessment algorithm continuously evaluates vehicle approach speeds and stopping feasibility, dynamically categorizing threats into four modifiable escalation levels:
    - **Normal:** Safe following distance, no alert required.
    - **Elevated:** Vehicle is approaching faster than normal; system begins monitoring closely.
    - **Severe:** Vehicle is closing in at a high speed, initial audible warnings activate.
    - **Danger:** Vehicle is at extreme risk of impact, full-volume siren and emergency strobes activate.
- **Multi-Layered Sensor Fusion:** The system combines vision-based detection with LiDAR and radar measurements to enhance tracking accuracy.
- **Intelligent Audible Warning System:** The alarm system dynamically adjusts sound frequency, intensity, and duration based on the severity of the detected threat.

The automated nature of the AutoTMA system eliminates reliance on human reaction time, ensuring that even when work crews are occupied, an immediate and highly visible warning is issued to potentially distracted drivers.

Key Performance Metrics and Test Outcomes

The AutoTMA system has undergone multi-phase testing to evaluate its performance under laboratory, controlled field (as shown in Figure ES.1), and full-scale work zone conditions. Key findings include:

- **Detection Accuracy:** The AI-based detection pipeline achieved greater than 98% accuracy in identifying and classifying approaching vehicles, with a low false-positive rate.
- **System Response Time:** The full detection-to-warning activation cycle occurs within 100–150 milliseconds, ensuring near-instantaneous hazard recognition and alert triggering.
- **False Positive/Negative Rates:**
    - False positive alerts were minimized through sensor fusion techniques, reducing unnecessary siren activations.
    - The false negative rate (missed detections) was near zero in structured field tests.
- **Effectiveness in Collision Prevention:**
    - Real-world driver response data indicated that the audible alert prompted immediate speed reduction or lane changes in greater than 80% of severe risk cases during field trials.
    - Simulation models showed that issuing an alert two to three seconds before impact increases the probability of a driver successfully stopping in time by over 90%.

    - The simulator results showed a slight preference for yellow EAL over white EAL and a greater effectiveness for the TMA alert system during the night. A delayed horn/alarm showed no adverse effects.

The results confirm that AutoTMA significantly improves driver awareness and reaction time, reducing the likelihood of high-impact collisions in work zones.

Figure ES.1: AutoTMA controlled field testing

Policy and Safety Implications

The deployment of AutoTMA's automated audible alert system has broad regulatory and operational implications for MoDOT and the Federal Highway Administration (FHWA). Key considerations include:

- **Regulatory Compliance:**
    - The system is designed to fully comply with MoDOT and FHWA safety standards, ensuring that automated alerts do not interfere with existing work zone signage or protocols.
    - The Manual on Uniform Traffic Control Devices (MUTCD) currently does not explicitly regulate automated TMA warning systems, making this project a pioneering effort in work zone automation policy development.
- **Workforce Training and Standard Operating Procedures (SOPs):**
    - MoDOT will develop training protocols to familiarize operators with system status monitoring, alarm overrides, and calibration procedures.
    - Standardized pre-deployment system checks ensure that the AutoTMA alert system functions reliably across all deployments.

- **Integration with Work Zone Traffic Management:**
    - AutoTMA's cloud-based event logging enables real-time monitoring of work zone safety incidents, providing data-driven insights to improve traffic management and policy decisions.

This project provides a template for future automated work zone alerting systems, setting the stage for statewide and nationwide adoption of AI-powered safety measures in highway construction and maintenance zones.

Next Steps and Recommendations

1. Statewide Deployment Plan

- Expand pilot testing to high-risk work zones (e.g., highway striping and bridge repair operations).
- Implement a phased rollout across MoDOT districts, prioritizing locations with the highest rates of TMA crashes.
- Establish long-term funding sources (federal safety grants, pooled DOT investments) to support broader adoption.

2. Technical Enhancements

- Upgrade LiDAR/radar fusion models to improve performance in low-visibility conditions (fog, night operations, heavy rain).
- Develop adaptive warning sound patterns that modulate based on vehicle type (e.g., louder for large trucks, directional alerts for motorcycles).
- Integrate vehicle-to-infrastructure (V2I) communication, allowing connected vehicles to receive warning signals before entering the work zone.

3. Policy and Regulatory Adoption

- Work with FHWA and AASHTO to formalize national guidelines for automated work zone alerting systems.
- Develop MoDOT-specific SOPs for AutoTMA integration into standard TMA fleet operations.
- Partner with law enforcement and emergency responders to establish protocols for responding to AutoTMA-initiated warnings and collision events.

Conclusion

The AutoTMA Automated Audible Alert System represents a major advancement in work zone safety, using artificial intelligence and real-time threat assessment to provide instantaneous, data-driven driver warnings. Through a combination of AI-powered vehicle detection, predictive risk analysis, and automated siren activation, AutoTMA ensures that distracted or unaware drivers are warned with maximum urgency, reducing the likelihood of rear-end collisions.

The system's successful performance in pilot tests, coupled with regulatory support and scalable deployment strategies, positions AutoTMA as a game-changing safety technology for MoDOT and beyond. By implementing statewide deployment, continued system refinements, and policy development, Missouri has the opportunity to set a national standard for automated work zone alerting, dramatically reducing crashes and saving lives on highways.

As work zones continue to face growing safety challenges, AutoTMA provides a proven, scalable, and future-ready solution – bringing AI-driven intelligence to the frontline of work zone protection.

Chapter 1. Introduction

1.1 Background

Work zone safety remains a critical concern in highway construction and maintenance. In 2019 alone, 842 people lost their lives in U.S. highway work-zone crashes, marking an 11% increase from the previous year. These incidents often occur when drivers fail to pay attention to changing road conditions, with distracted driving being a key factor leading motorists to collide with work zone vehicles, equipment, or barriers [1-3]. The combination of high-speed traffic, temporary lane shifts, and reduced visibility in work zones creates a challenging environment for both motorists and roadway workers. Despite the implementation of various safety measures, including barriers, signage, and enforcement campaigns, crashes in work zones continue to pose a significant challenge [4].

Truck-Mounted Attenuators (TMAs) are critical safety devices used in highway work zones to protect maintenance crews and motorists. They provide positive protection by absorbing the impact energy of vehicles that intrude into work zones, thereby reducing the severity of crashes [5-6]. However, TMA-involved crashes remain a serious safety concern. Work zone crashes overall have been increasing over the past decade; between 2013 and 2021 there were roughly 100,000 work zone crashes in the U.S., resulting in 42,000 injuries and 924 fatalities [3]. Distracted and aggressive driving are major contributors to this trend [3]. While the use of TMAs has helped lower the risk of worker injury or death (by a factor of about 1.8) and reduced crash costs (by a factor of 3.5) [3], the frequency of TMA strikes is on the rise. For example, Virginia reported yearly increases in TMA crashes (up 52.9%, 26.9%, and 36.4% in consecutive years) [3], and Missouri saw a 20% rise in TMA crashes from 2020 to 2023 [3]. Each TMA crash endangers both the errant driver and the work zone crew (including the TMA operator) [2]. This troubling pattern underscores a clear problem: despite TMAs' presence, too many drivers fail to notice or react in time to avoid collisions, exposing roadside workers to severe risk.

Despite their proven effectiveness (studies show that deploying TMAs in work zones yields significant crash severity reduction benefits [3]), collisions with TMAs continue to occur. Such TMA crashes are relatively infrequent – accounting for less than 1% of all work zone crashes in one statewide analysis [2] – but they have been increasing in recent years [2]. More importantly, when a TMA is struck, the consequences can be serious: the impact typically affects at least two people (the errant driver and the TMA operator in the truck) and can result in injuries or fatalities [2]. Analyses of TMA crash reports identify driver inattention (speeding, distraction, or impairment) as a leading cause [2]. Therefore, simply having a TMA in place, while critical, may not always prevent a collision if drivers do not notice the work zone or fail to react in time. This has motivated researchers and agencies to explore additional safety measures to further enhance TMA effectiveness.

A significant limitation lies in the current alert systems used to prevent TMA crashes. Agencies often rely on manually operated audible alerts – for instance, a spotter or the TMA driver activates a horn or alarm when a vehicle is approaching the work zone dangerously. These manual systems are inherently constrained and can fail to provide timely, reliable warnings [3]. Human operators may become [3] distracted or react too slowly under high-stress conditions, resulting in delayed or missed alarms [3]. Moreover, requiring a person to monitor traffic and trigger alerts at all times can lead to fatigue [3]and increased labor costs, and it places the operator in harm's way if a collision occurs [3]. In sum, the problem this study addresses is to improve upon current TMA safety measures and alert systems by warning and diverting oncoming drivers earlier to prevent crashes, largely due to the growing prevalence of driver distraction [3]. The safety risk is evident in ongoing TMA crash incidents and near-misses, indicating an urgent need for more effective warning solutions [3].

In recent years, advances in machine learning and artificial intelligence have enabled the development of intelligent safety systems designed to mitigate roadway hazards and improve work zone safety. One critical area of concern is the protection of highway maintenance and construction crews from high-speed, inattentive, or distracted drivers. Truck-mounted attenuators (TMAs) play a crucial role in shielding workers and equipment by absorbing impact forces in the event of a collision. However, despite their effectiveness, there remains a need for proactive measures that can alert drivers to potential hazards before a crash occurs.

This project explores the application of machine learning to automate an audible alert system for TMAs (AutoTMA), aiming to provide timely warnings to approaching drivers and enhance overall work zone safety. Additionally, the study evaluates different lighting configurations to determine their effectiveness in communicating alerts and improving driver response. By integrating intelligent alerting mechanisms and optimized visual signals, the project seeks to advance the capabilities of TMAs as active safety systems, ultimately reducing the risk of collisions and improving roadway work zone protection.

1.2 Project Objectives

The project aims to design and implement an intelligent warning system that enhances truck-mounted attenuators (TMAs) with real-time hazard detection and automated alerting capabilities. By integrating machine learning, sensor fusion, and automated control, the project seeks to create a robust, proactive safety solution that can detect potential collisions before they happen and warn both drivers and work crews. The key objectives of this project are as follows:

1. **AI-Enhanced Hazard Detection:** The system will leverage computer vision to detect and classify vehicles approaching the work zone in real time. Using advanced Artificial Intelligence/Machine Learning (AI/ML) algorithms such as deep neural networks for object detection, the system will be able to differentiate between various types of vehicles in the TMA's vicinity. Recent advances in deep learning have significantly improved the accuracy of vehicle recognition and lane detection, making it possible to reliably "see" oncoming traffic and assess critical visual cues—such as a vehicle drifting into the closed lane or driving on the shoulder. By quickly identifying every relevant vehicle, the system establishes the foundation for real-time threat assessment.
2. **Sensor Fusion for Situational Awareness:** The AutoTMA system will integrate multiple sensors—including cameras, radar, and/or LiDAR—mounted on the TMA to obtain a complete view of

surrounding traffic. By fusing camera imagery (for object recognition and lane positioning) with radar or LiDAR data (for precise distance and speed estimation), the system will improve detection accuracy and reliability. This multi-sensor approach ensures redundancy and all-weather capability. For instance, if visibility is poor due to darkness or glare, radar can still detect an approaching vehicle's speed and range. This results in real-time 360° situational awareness, enabling the system to continuously monitor the TMA's surroundings.

3. **Real-Time Threat Analysis:** Once a vehicle is detected, the system will analyze its motion and determine whether it poses an imminent collision risk. The AutoTMA algorithms will track speed, acceleration, and trajectory, calculating key metrics like time-to-collision (TTC) and projected impact point. If a vehicle is on a collision course—for example, a fast-approaching car that is not slowing down—the system will classify it as a threat. The decision logic will be based on well-established safety criteria, including AASHTO stopping sight distance standards for the given roadway speed. By conducting this analysis in milliseconds, the system stays ahead of danger, effectively predicting potential crashes before they occur.
4. **Automated Alert Activation:** In the event of a high-risk scenario, AutoTMA will automatically trigger warning signals to alert the errant driver and nearby personnel—without requiring manual intervention. The system will activate a high-decibel auditory alarm (such as a siren or air horn) and may also engage visual alerts, including flashing lights or dynamic messaging on the TMA's display board. The alerting system is designed to capture the driver's attention at a critical moment, potentially prompting corrective action such as braking or steering away from the work zone. Additionally, the automated alert will notify work crews, giving them time to take precautionary measures. Since these alerts are activated in real time, the system can respond far faster than a human operator, making it highly effective in emergency situations.
5. **Compliance and Integration with Existing Safety Standards:** AutoTMA will be designed to meet or exceed the Federal Highway Administration (FHWA) and Missouri Department of Transportation (MoDOT) requirements for work zone safety. The system will complement existing safety measures, such as arrow boards and signage, while aligning with the guidelines set forth in the Manual on Uniform Traffic Control Devices (MUTCD). The project prioritizes reliability and fail-safe functionality—minimizing false alarms to maintain trust among drivers and workers while ensuring that the system defaults to a safe state in the event of a malfunction. By integrating seamlessly with current work zone safety practices, AutoTMA can be deployed without disrupting standard operating procedures.

By achieving these objectives, the AutoTMA project will deliver substantial safety and operational benefits. The system will significantly enhance driver awareness by providing real-time warnings in critical moments, reducing the risk of TMA crashes and work zone incidents. A proactive alerting system can lead to more drivers slowing down or changing lanes in time, ultimately preventing accidents and protecting roadway workers. Additionally, reducing TMA collisions minimizes repair costs, work delays, and liability expenses—offering both safety and economic advantages. From a policy perspective, AutoTMA aligns with FHWA's push for smarter work zone solutions and MoDOT's commitment to safeguarding both workers and motorists. By deploying AI-driven automation, this project aims to set a new standard in work zone safety, leveraging technology that reacts faster than humanly possible while operating within existing transportation safety frameworks.

1.3 Report Organization

The remainder of this report is structured to provide a comprehensive overview of the project, covering its technical development, implementation, and evaluation. Each chapter focuses on a specific aspect of the project, ensuring clarity for both engineers seeking technical details and policymakers evaluating its potential impact on work zone safety.

- **Chapter 2: Literature Review and Background** – Provides an overview of work zone safety research and current practices relevant to this project. This chapter reviews prior studies on TMA crash statistics and mitigation, examines existing work zone warning systems (including any manual and automated alerting tools in use), and surveys the state-of-the-art in relevant technologies (such as computer vision for vehicle detection and autonomous safety systems in highway maintenance). The goal is to establish a knowledge base and justify the approach the Missouri taken for AutoTMA by learning from past findings and identified gaps.
- **Chapter 3: Light and Horn Simulation** – This chapter discusses a simulator study conducted to evaluate the effectiveness of different Emergency Alert Lighting (EAL) and horn configurations in mobile work zones. Due to the non-stationary nature of these work zones, field data collection is challenging, making a simulator an ideal environment for controlled experimentation. By exposing human subjects to standardized conditions, the study ensures that multiple factors can be systematically analyzed without external influences. This approach allows to isolate and understand the impact of specific variables on driver behavior, which is difficult to achieve in real-world settings.
- **Chapter 4: System Architecture and Design** – Details the technical design of the AutoTMA warning system. It describes the overall system architecture, including the hardware components installed on the TMA (sensors like cameras/radar, computing units, communication devices) and the software framework that ties them together. Key design considerations, such as sensor placement, coverage area, and power/communication requirements, are discussed. This chapter also covers the algorithms developed for vehicle detection, tracking, and threat assessment, explaining how machine learning models were trained and how sensor data is fused. In this section engineers can find the specifications and rationale for each subsystem of AutoTMA.
- **Chapter 5: System Implementation, Testing, and Results** – Details the development and deployment of the AutoTMA prototype, including hardware integration on a MoDOT TMA truck and real-time data processing software. It outlines testing methodologies, from controlled experiments—such as simulations and closed-course testing at the Emergency Vehicle Operations Course (EVOC) track—to live field tests in active work zones. Key performance metrics, including detection accuracy, warning response times, and false alarm rates, are analyzed alongside iterative system improvements. Field evaluation results assess system performance in real-world conditions, examining detection accuracy, response time, and the impact of automated alerts on driver behavior (e.g., braking or lane changes). The discussion highlights successes, challenges—such as environmental factors affecting detection reliability—and comparisons between work zones with and without the system to demonstrate its safety impact. Policy implications, including recommendations for broader adoption and integration into existing work zone guidelines, are also explored.
- **Chapter 6: Conclusion and Recommendations** – Summarizes the key findings and contributions of the AutoTMA project. This final chapter reiterates how the project objectives were met and the extent to which the automated warning system improved work zone safety in the trials. It provides recommendations for next steps, including refinements needed for

full-scale deployment (e.g. integrating the system into all MoDOT attenuator trucks) and suggestions for future research (such as incorporating vehicle-to-vehicle communication for even earlier warnings, or extending the system to other work zone vehicles). The chapter also outlines any recommendations for policymakers or standards bodies – for instance, how AutoTMA could be incorporated into MoDOT's standard safety procedures or how FHWA could encourage similar technology adoption nationwide. Concluding remarks highlight the broader impact: AutoTMA as a model solution that leverages AI to protect workers and drivers, setting the stage for smarter and safer work zones in the years ahead.

Chapter 2. Literature Review

Ensuring safety in highway work zones remains a persistent challenge despite advancements in technology and policy. Work zone crashes continue to occur at alarming rates, posing risks to both workers and motorists. Truck-mounted attenuators (TMAs) have played a crucial role in reducing the severity of rear-end collisions, but limitations such as operator vulnerability, inconsistent implementation of visibility enhancements, and evolving challenges in automation highlight the need for further innovation. This chapter examines the historical evolution of work zone safety measures, including the introduction and development of TMAs. It reviews past approaches to TMA safety, including human-operated TMAs, visibility improvements, and early autonomous vehicle applications, identifying their benefits and shortcomings. Additionally, it explores recent advancements in automated warning systems and ongoing research initiatives, including efforts by the Iowa and Virginia Departments of Transportation, to integrate artificial intelligence, sensor fusion, and automated alert mechanisms into TMA technology. Finally, the chapter outlines existing research gaps and positions AutoTMA as a next-generation solution that builds upon previous work to improve detection accuracy, enhance system reliability, and streamline deployment in active work zones.

2.1 Work Zone Safety and Truck-Mounted Attenuator (TMA) Research Overview

Work zones continue to be high-risk environments, with work zone crashes increasing significantly in recent years. In 2021, the U.S. recorded over 105,000 work zone crashes, resulting in approximately 42,000 injuries and 954 fatalities—the highest in 17 years, reflecting a 61% increase in fatalities since 2013 [5]. These incidents not only cause loss of life but also impose an annual economic burden of nearly $38 billion [5]. To mitigate these risks, Truck-Mounted Attenuators (TMAs) have become a widely used safety measure in highway maintenance and construction zones. TMAs serve as mobile crash cushions, absorbing the impact of errant vehicles and preventing direct collisions with workers or equipment [6], [7]. A 2014 crash outcome analysis found that TMAs significantly reduce impact severity, saving agencies an average of $196,000 per prevented collision, with many recouping the cost of a TMA unit within a year on high-volume roadways [8]. As a result, TMAs have been routinely deployed by highway agencies and contractors as a cost-effective safety measure [8].

Despite their effectiveness, rear-end collisions involving TMAs remain a persistent issue, with states like Virginia reporting a steady increase in such crashes since 2015 [9]. Many of these incidents result in injuries to TMA truck drivers or crew members riding in the vehicle [2]. This ongoing risk has prompted further research into work zone crash trends, safety interventions, and emerging technologies to improve protection. Efforts include the development of automated warning systems and autonomous TMAs, aiming to enhance visibility, reduce human exposure to danger, and improve overall work zone safety [10]. The following sections explore key advancements in TMA-related safety research and how AutoTMA builds upon existing solutions to address the ongoing challenges in work zone protection.

2.2 Historical Evolution of Work Zone Safety Measures and TMA Technology

Work zone safety has evolved significantly over the past half-century, progressing from basic impact attenuators to autonomous safety systems. In the 1960s, crash cushions like sand-filled Fitch barriers were introduced to absorb impact forces and reduce crash severity [6], [11]. The 1970s saw the first truck-mounted attenuators (TMAs), adapting crash cushions for use on maintenance vehicles to protect mobile work zones [11]. By the 1980s, commercial TMA designs incorporated energy-absorbing materials such as aluminum honeycomb and collapsible steel tubes, though early models were heavy and difficult to mount [11]. The 1990s marked the standardization of TMAs with National Cooperative Highway Research Program (NCHRP) Report 350, which set federal crashworthiness criteria, leading to wider adoption despite initial concerns over cost and maintenance [6], [11]. The 2000s introduced smart work zone technologies, including Intelligent Transportation Systems (ITS) and automated queue warnings, improving driver awareness of attenuators ahead [12], [13].

By the 2010s, new safety standards such as MASH (Manual for Assessing Safety Hardware) updated crash testing for higher-speed impacts [6]. At the same time, automation entered the field with the first autonomous TMA (ATMA) deployment in Colorado in 2017, using a leader-follower system where a driverless crash truck followed a human-operated vehicle [14]. The 2020s have further expanded automation, with multiple states, including Missouri, piloting AutoTMA and similar autonomous safety systems [16]. Research like NCHRP Report 1085 has refined TMA visibility guidelines, while connected vehicle systems are being developed to warn motorists of approaching TMAs [15]. The evolution of TMA technology reflects a shift from passive crash mitigation to active, intelligent systems that enhance driver awareness and reduce risks to work zone crews.

2.3 Past Approaches to TMA Safety: Strategies, Limitations, and Gaps

Over the years, various strategies have been implemented to improve TMA safety and reduce work zone crashes. While each approach has contributed valuable advancements, limitations remain, leaving room for improvement. This section examines major TMA safety strategies, including human-operated TMAs, visibility enhancements, and autonomous vehicle technologies, analyzing their benefits and challenges. By understanding these past approaches, it becomes clear how AutoTMA builds on existing efforts to address their shortcomings and enhance overall work zone protection.

2.3.1 Conventional Work Zone Safety Measures (Pre-TMA and Supplemental)

Before focusing on TMA-specific innovations, it’s important to note the foundational work zone safety measures that have long been in place. These conventional measures include static signage (advance warning signs, speed reduction signs), channelizing devices (cones, barrels delineating the taper and work area), flaggers or law enforcement to control traffic when needed, and temporary barriers for long-term stationary work zones. These tools, standardized by manuals like the MUTCD, create an orderly traffic flow around the work zone. Traditional traffic control is essential but not always sufficient. Drivers may ignore or not notice warning signs, especially at high speeds or due to distraction. Channelizing cones offer no physical protection if a driver fails to slow down or stay in lane. Consequently, rear-end crashes into work vehicles or workers still occurred frequently, prompting the need for a movable crash cushion (TMA) as an *active* safety device [5], [8]. Even with police presence or flaggers, human-controlled traffic control cannot physically prevent an errant vehicle from intruding; at best it can only warn or direct traffic. This limitation set the stage for the adoption of TMAs as a “last line of defense” to absorb crash forces that other measures could not stop [14].

2.3.2 Human-Operated Truck-Mounted Attenuators

For decades, human-driven TMA trucks have been used to protect mobile work zones, such as striping, sweeping, and pothole repairs. A worker drives a truck fitted with an attenuator and arrow board, positioned at a safe distance behind the active crew. If an oncoming vehicle fails to stop or merge, the TMA absorbs the impact, preventing direct collisions with workers or equipment [6], [7]. This approach has saved countless lives by reducing impact forces and providing a mobile safety buffer [8]. TMAs are relatively easy to deploy and relocate, adapting to shifting work zones. However, the primary drawback is the risk to the TMA driver, who remains vulnerable in a severe crash. High-speed impacts have resulted in serious injuries and fatalities for TMA operators [2]. Maintaining proper buffer spacing also depends on driver attentiveness, introducing potential human error. Additionally, cost and efficiency concerns have historically limited widespread adoption, as agencies were sometimes reluctant to dedicate an extra vehicle and operator solely for protection, especially in regions without frequent work zone crashes or clear mandates for TMA use [11]. While human-operated TMAs have significantly improved safety, the need to eliminate risk to the driver and enhance operational efficiency has driven interest in automation.

2.3.3 Enhancements in TMA Visibility and Warnings

Efforts to enhance work zone and TMA visibility have focused on high-visibility paint schemes, retroreflective striping, conspicuous arrow boards, warning lights, and audible alert systems that activate when a vehicle approaches too fast. Research confirms that improved TMA visibility influences driver behavior. A 2023 Virginia study found that a fluorescent green-and-black checkered pattern with an elevated panel led to earlier lane changes and speed reductions compared to traditional diagonal chevrons [9]. Similarly, NCHRP 05-24 recommends standardized color and lighting configurations to make work vehicles more recognizable across different states [17]. Some work zones now incorporate radar-based intrusion detection, triggering strobes or sirens to warn workers, while smart work zone systems display real-time alerts like “slow/stop ahead” messages when queues form [13].

Despite these improvements, visibility enhancements cannot prevent all crashes. Impaired or distracted drivers may fail to react, and inconsistent implementations across states create variability in driver expectations [15]. Until NCHRP Report 1085, there was little consensus on best practices for TMA conspicuity. Additionally, warning systems are reactive—they alert but do not physically prevent crashes if a driver does not respond in time. While improved visibility helps reduce crash likelihood, a physical attenuator or barrier remains essential as a last line of defense.

2.3.4 Autonomous and Driver-Assistance Technologies for TMAs

Autonomous vehicle technology is increasingly being applied to TMAs to eliminate or reduce risks for human operators. The leader-follower configuration is the most widely tested approach, where a driverless TMA truck electronically follows a lead vehicle, replicating its path using GPS signals, speed data, and heading information [14]. First deployed by CDOT in 2017, this system has since been tested by multiple agencies [16]. The primary benefit is removing the TMA driver from harm's way—any collision involves only equipment [14]. Automated control ensures precise buffer positioning and consistent spacing, improving reliability over human drivers in long-duration operations. Field deployments in Colorado and Missouri confirm that autonomous TMAs can effectively mirror the lead vehicle's movements, including lane changes and stops, while obstacle detection using radar, LiDAR, and cameras enhances safety [14], [16].

However, challenges remain. Early trials reported GPS dropouts and communication failures, leading to emergency stops or disengagements, which can disrupt operations and introduce new risks if not properly managed [7], [18]. Legal and regulatory hurdles also pose challenges, as some jurisdictions require policy changes or special permissions for autonomous vehicle operation [16]. Additionally, high costs associated with retrofitting TMAs with autonomous driving technology and redundant safety systems may limit widespread adoption [18]. From a human factors perspective, work crews must trust and properly supervise the system. While a survey of DOT workers showed positive acceptance, some raised concerns about performance in poor visibility or dense traffic [19]. Training significantly improved confidence and system oversight [19]. Autonomous TMAs offer a promising safety advancement but require further refinement in technology, regulations, and workforce training. The AutoTMA initiative aims to address these gaps by enhancing system robustness, sensor integration, and operational reliability at scale.

2.4 Related Studies on Automated Audible TMA Alert System

Recent initiatives are exploring the automation of warning systems in work zones to enhance safety for both workers and motorists. Missouri, Iowa and Virginia Department of Transportation have been at the forefront of implementing such technologies. In 2021, Iowa DOT introduced an "audible attenuator" system (illustrated Figure 2.1) designed for short-term, stationary, or slow-moving maintenance operations. This system integrates cameras and sensors with truck-mounted attenuators (TMAs) to automatically trigger a warning noise when a vehicle approaches too closely or is on a trajectory toward the work zone. The automated nature of this system ensures that alerts are activated promptly, without relying on manual intervention, thereby providing real-time warnings to errant drivers and enhancing the safety of maintenance crews. Building upon the success of the audible attenuator, Iowa DOT has continued to refine and expand its automated warning systems. These advancements aim to further reduce the risk of collisions in work zones by improving the detection of potential threats and the immediacy of alerts. The integration of automated light and sound warnings represents a proactive approach to work zone safety, leveraging technology to address hazards before they result in accidents.

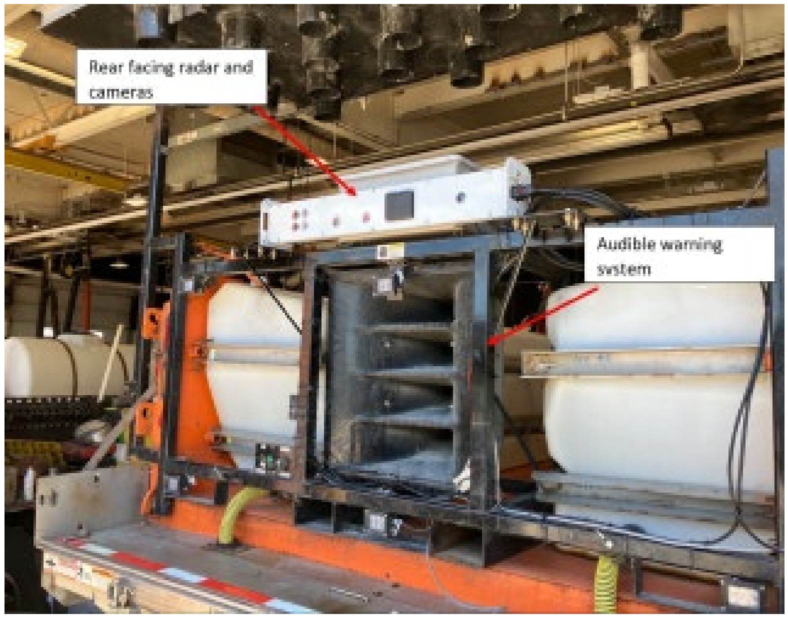

Figure 2.1: Iowa DOT's Automated Audible Alert System[1]

Similarly, the Virginia Transportation Research Council (VTRC) has initiated a project titled "Evaluation of a Driver Alerting System for a Truck Mounted Attenuator" [1]. This study focuses on developing a system that employs binocular cameras and artificial intelligence to identify approaching vehicles and fixed work zone objects, such as barrels, cones, and signage. The system is designed to automatically activate alarms and additional warning lights when a potential collision is detected, thereby enhancing the safety of both workers and drivers. Following a training period to familiarize the AI with various work zone configurations, the system can adapt to different setups without requiring specific calibration for each scenario. The project aims to assess the effectiveness of this automated alert system through live field data comparisons, with a target completion date of April 30, 2025.

These parallel studies, though still underway, demonstrate a growing commitment to leveraging automation and artificial intelligence to proactively enhance work zone safety. The insights gained from these initiatives are anticipated to inform the development of more effective TMA systems, such as the AutoTMA project, which seeks to integrate advanced technologies to prevent work zone collisions before they occur.

Despite advancements in work zone safety, several challenges remain unaddressed. TMA operators are still at risk of injury or fatality, as modern attenuators protect work crews but not the drivers themselves. Work zone intrusions continue to occur due to driver distraction and

[1] https://www.transportationmatters.iowadot.gov/2022/10/automation-of-light-and-sound-warning-to-increase-safety-in-iowa-work-zones.html

speeding, with traditional safety measures like signage and cones proving insufficient in preventing crashes. Early autonomous TMA trials have encountered technical issues such as sensor reliability, GPS loss, and communication failures, limiting their operational effectiveness. Additionally, while visibility standards exist for TMAs, agencies lack clear guidelines for deploying and operating autonomous and connected safety systems in work zones. Finally, the success of automation depends on proper operator training and trust, yet many agencies are still in the early stages of developing best practices for human-system interaction.

AutoTMA is designed to directly address existing gaps in work zone safety by integrating proven safety strategies with advanced automation and communication technologies. AutoTMA enhances system accuracy and reliability by combining sensor fusion and machine vision enabled vehicle and lane tracking, ensuring functionality even in areas with complex traffic conditions. To improve driver awareness and reduce crash risks, the system incorporates high-visibility retroreflective markings and advanced LED warning lights in alignment with NCHRP recommendations. Additionally, AutoTMA includes standardized operational guidelines for work crews, providing clear protocols for deployment, safe engagement, and disengagement of autonomous mode. These measures ensure seamless integration into existing work zone safety procedures, making AutoTMA a practical and deployable solution for modern roadway environments.

By addressing safety, technology, policy, and human factors, AutoTMA builds upon decades of research while offering a practical, deployable solution for modern work zones. The following chapters will detail the system’s design, testing methodology, and validation of its safety improvements in real-world scenarios.

Chapter 3: Light and Horn Simulation

3.1 Introduction

The MUTCD defines mobile work zones as those where work moves intermittently or continuously. These are frequently used for work such as litter cleanup, pothole repairs, or utility work. Due to the nature of the activity, mobile work zones cannot benefit from all the temporary traffic control procedures and devices that are available such as temporary traffic barriers or channelizing devices. Mobile work zones frequently use signs mounted on moving work vehicles in place of standard stationary signs, which can limit opportunities to warn drivers of the work zone and pose a greater risk both to workers and the traveling public.

ATSSA "very highly recommends" the use of TMAs on mobile in-lane freeway work zones and "highly recommends" that they are used for mobile shoulder work as well as in-lane stationary work. They are also recommended on certain types of non-freeway work zones depending on the type of work being performed and the speed of the roadway [22].

TMA crash data in Missouri reflects a higher crash frequency associated with mobile work zones. Out of 139 TMA crashes reported in Missouri from 2012 to 2017, 97 crashes, or 70 percent, were in mobile work zones, compared with 20 crashes, or 14 percent, in stationary work zones.
Of the aforementioned TMA crashes in Missouri, distracted driving was the leading causal factor, responsible for 64 percent of TMA crashes in which the reason for the crash was reported.

MoDOT has used an Emergency Alert Light (EAL) system on some TMAs for several years and has required them on future installations beginning on July 1, 2023. The Emergency Alert Light system aims to provide a supplementary warning to drivers who may collide into the work zone so they can take evasive action. The system consists of six white LED lights placed in two rows of three below the flashing arrow panel in addition to an audible alert airhorn. A diagram of the system is shown in Figure 3.1. MoDOT EPG guidance recommends that for stationary operations, the TMA operator should not wait inside or near the vehicle. On the other hand, for short duration and mobile operations, the operator may remain in the vehicle and take action to avoid errant vehicles, including activating the EALs or moving the vehicle forward if there is sufficient roll-ahead distance to the TMA ahead. The EPG raises concerns that the effectiveness of the EALs may be diminished if they are used continuously, so it is recommended that they are used only for short durations.

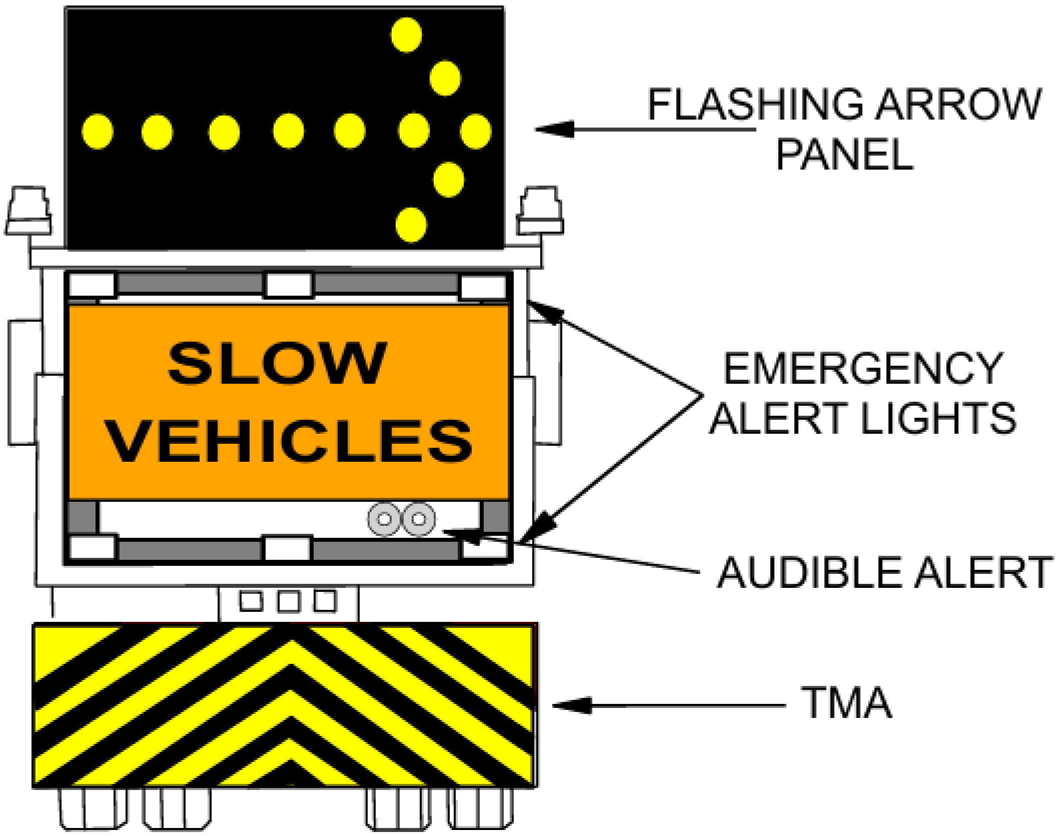

Figure 3.1: Diagram of MoDOT TMA vehicle with arrow board and EAL system

This project aims to help improve safety in mobile work zones and evaluate the performance of different emergency alert light (EAL) color and horn timing configurations through a simulator study and survey.

Literature on the use of flashing lights as a secondary warning to alert intruding vehicles on highways is limited. The Iowa Department of Transportation uses an emergency alert system for truck-mounted attenuators similar to the one being evaluated by MoDOT. An Iowa DOT engineer stated that the agency initially used amber warning lights, but then switched to white warning lights to help increase contrast against Iowa DOT's orange maintenance trucks and amber arrow board lights.

3.2 Introduction to Driving Simulator Studies

The project utilized a simulator study to investigate the effectiveness of different EAL and horn configurations. The non-stationary nature of mobile work zones means that it is often difficult to collect data in the field while controlling for factors. Controlled conditions can easily be created in a simulator environment where every human subject encounters a mobile work zone under almost identical conditions. This results in the ability to examine multiple factors. It is often difficult to examine multiple factors in a field study since one needs to control the effects of various factors in order to ascertain if a single factor was the cause of driver behavior change. In contrast, a simulator study allows the repeated testing of a similar scenario where only one factor is changed. This testing sequence allows the isolation of the effects from a single factor like daytime versus nighttime, color of lights, and delayed or non-delayed horn usage. A simulator study also allows the collection of very detailed information such as vehicle kinematics, neither of which can be obtained from the field except via a high-cost naturalistic driving study. In projects in which safety is a concern, a simulator allows experimentation with no risk of harm to human subjects. In this TMA study, there is no physical risk if a subject runs into the TMA truck or other vehicles in the virtual environment. In summary, a driving simulator study allows the safe and controlled investigation of mobile work zones under congested conditions.

This simulator study utilizes the ZouSim driving simulator. ZouSim is a suite of networked transportation simulators that allows the safe and effective investigation of various transportation modes, including the interaction among multiple modes. Currently, ZouSim is capable of simulating driving, trucking, walking, bicycling, wheeling, and e-scootering. Figure 3.2 shows the ZouSim driving simulator. This simulator is a medium-fidelity simulator built around the half-cab of a sedan. The active instrumentation in the vehicles includes a force-feedback steering wheel, brake and acceleration pedals, turn signals, and engine vibration generator. The ZouSim simulator environment has been used for various projects sponsored by agencies such as FHWA, MoDOT, FAA, and the City of Columbia. ZouSim has been utilized extensively for examining work zone safety and efficiency issues. Examples of recent ZouSim work zone studies include the use of green lights on truck mounted attenuators [23], automated flaggers [24], and alternative work zone signage [25]. Other examples of ZouSim experiments include bicycle signage and markings [26], geometric design of J-turns [27], autonomous vehicle interactions with pedestrians [28], and wheelchair accessibility at airports [29].

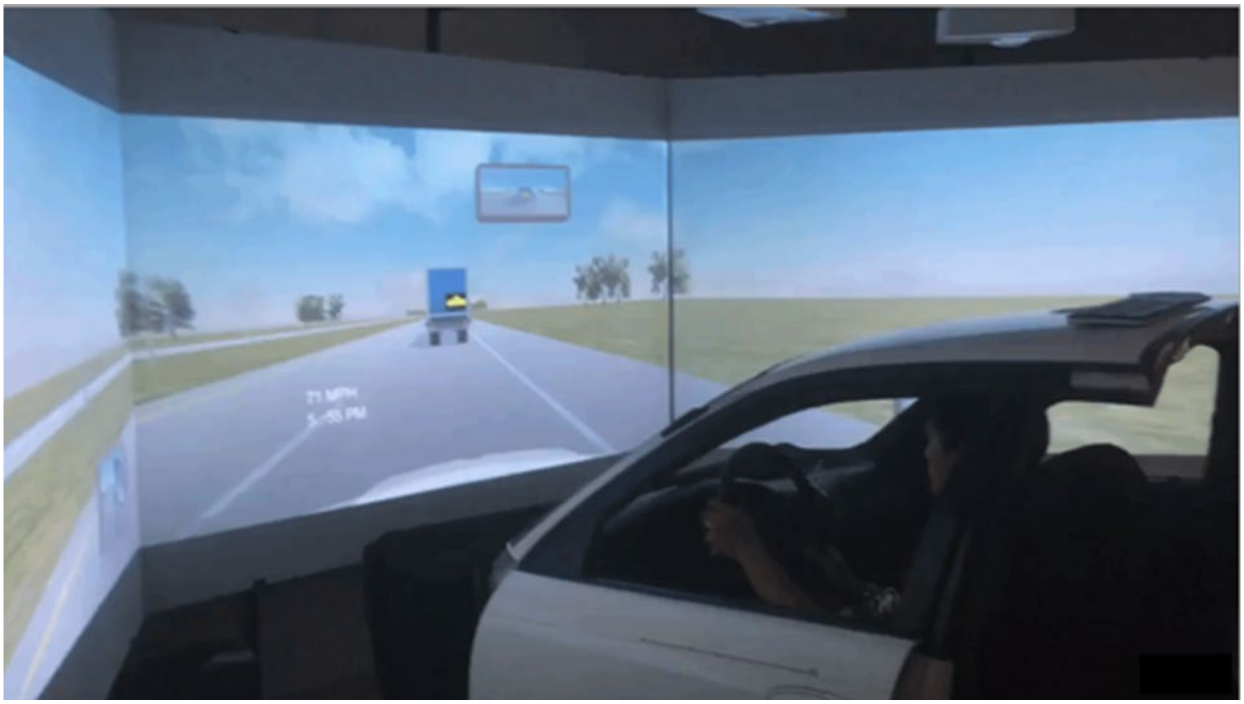

Figure 3.2: ZouSim Driving Simulator

3.3 Human Subject Studies

The Institutional Review Board (IRB) is the University of Missouri entity that reviews research proposals for human subject experiments. IRBs were established in 1974 by the Department of Health Education and Welfare to promulgate the regulations on the protection of human subjects. An IRB reviews the conduct of research to ensure that federal and state regulations, and ethical principles are followed.

The IRB review process involves the submission of an extensive set of materials, including study protocol, recruitment flyer, consent form (Appendix F.1), post-simulator survey, and simulator sickness questionnaire (Appendix F.3). IRB also coordinates closely with accounting and information systems to ensure financial accountability for human subject incentives, and data privacy and security. The IRB approves or denies the study after weighing risks and benefits of the research. After a study has been approved for experimentation, the IRB continues to require researchers to monitor and report any issues. The IRB-related documents, i.e., human subject consent form (Appendix F.1), gift card receipt form (Appendix F.2), post-simulator and simulator sickness questionnaire (Appendix F.3), and IRB approval letter (Appendix F.4), are included in Appendix F.

Human participants were recruited formally or informally via flyers or other communications sent to community residents and College of Engineering staff and students. The recruitment information describes the purpose of the study, provides the study details such as the location and dates, explains the benefits and risks, and presents the compensation provided. After a participant arrives in the ZouSim lab, the orientation process starts with the consent process. The informed consent process involved study hosts asking participants to read the consent form and to sign if they agree. Only licensed adult drivers were eligible to participate.

3.4 Simulator Setup

Given the total number of experiment scenarios is exponential, only three primary factors were tested in consultation with the TAC: white versus yellow light, with and without delayed horn, and day versus night. As shown in Table 3.1, eight test scenarios were developed for the simulator study, including baseline conditions without EALs. Sequence bias (order effect) in a simulator study involving multiple test scenarios can occur when a human subject learns from the earlier scenarios (Perreault 1975). To reduce sequence bias, the order of the test scenarios was randomized for each participant.

Table 3.1: Summary of Test Scenarios

#	Lighting	Horn	Time
1	No EALs	No horn	Day
2	No EALs	No horn	Night
3	White	Delay	Day
4	White	No Delay	Day
5	White	Delay	Night
6	White	No Delay	Night
7	Yellow	Delay	Day
8	Yellow	Delay	Night

An excessively long simulator study runs the risk of human subjects dropping out due to simulator sickness. Even though the probability of experiencing simulator sickness is low, there is a potential for some participants to experience general discomfort, eye strain, dizziness, and/or nausea. This risk is minimized by keeping the simulator portion short, e.g., 20 minutes or less and ventilating the lab well. Participants were offered water and provided with breaks during the simulation, if necessary, to help mitigate the effects of simulator sickness.

The simulator study was further divided into two studies. The first study consisted of a freeway scenario. This served as a warm-up to help participants become acquainted with driving the simulator and to examine whether the airhorn led to adverse reactions from the driver such as sudden braking or steering inputs. The participant was instructed to drive down an on-ramp and merge onto a freeway before passing a mobile work zone.

As shown in Figure 3.3, the freeway work zone was set up according to MoDOT EPG typical application TA-35M, which is used for mobile operations on multi-lane highways. The roadway was a freeway with two lanes in each direction, separated by a median and guardrail barrier. The posted speed limit of the roadway was 70 mph, and the speed of the simulator was capped to 70 mph. In accordance with TA-35M, the right lane of the roadway was blocked by a work vehicle and a protective vehicle 150 feet behind. An advance warning truck was placed 840 feet behind the protective vehicle. The simulator was programmed to trigger the EAL system when the driver was directly adjacent to the protective vehicle, and the driver's reaction was noted.

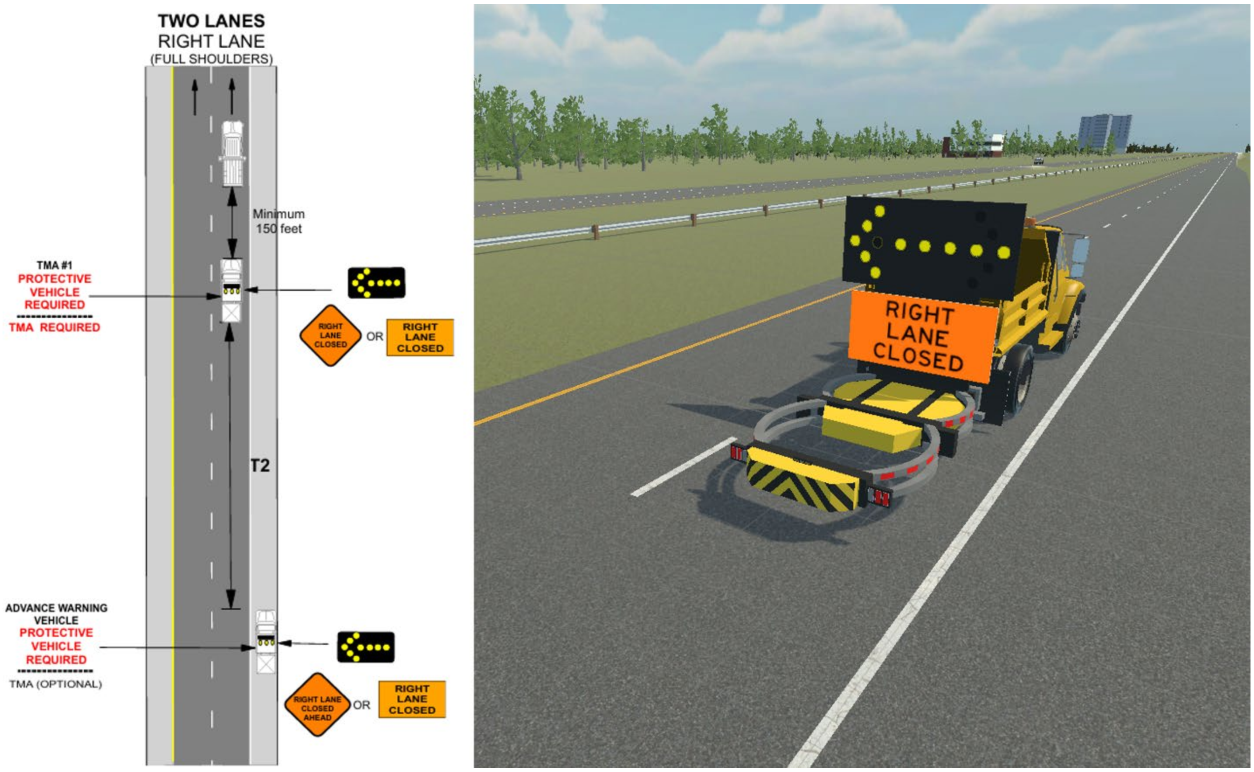

Figure 3.3: EPG TA-35M and freeway scenario

The second study aimed to compare the effects of EAL color and horn timing on driver reactions. As shown in Figure 3.4, two emergency alert lighting (EAL) colors (i.e., white and yellow) were tested in both daytime and nighttime conditions. In addition, two baseline scenarios without EALs were conducted, one at daytime and the other at nighttime.

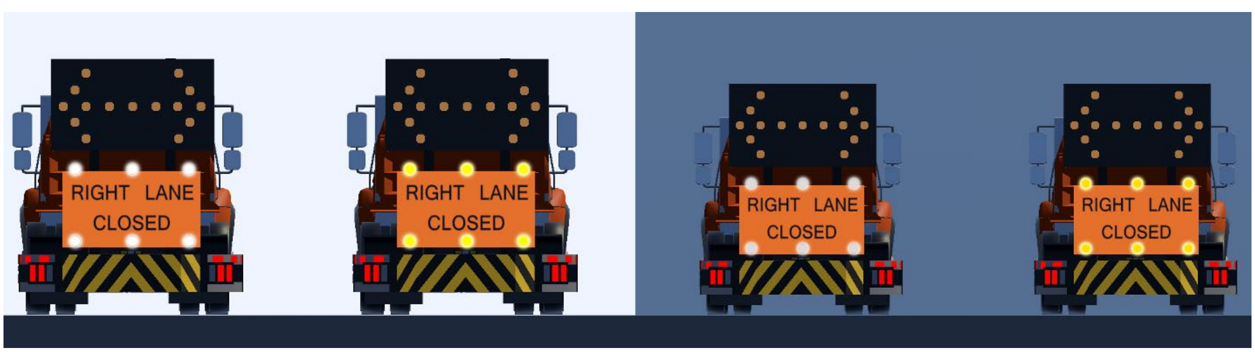

Figure 3.4: TMA EALs tested in the driving simulator study

The simulation also aimed to analyze the optimal timing of an air horn to serve as an audible warning in conjunction with the flashing EALs. In the "no delay" configuration, the air horn was activated at the same time the flashing EALs were activated. In the "delay" configuration, the alert system was activated in two stages, with the air horn programmed to sound two seconds after the lights were activated. The yellow EALs scenarios were tested only with the delayed air horn in an attempt to best isolate the effects of lighting color and reduce the influence of the audible alert horn.

The roadway was designed following AASHTO Green Book standards. It was designed to simulate a typical rural highway in rural Missouri with rolling hills. There were no horizontal curves to avoid horizontal alignment from influencing test results. The posted speed limit was 55 mph, with the simulator speed capped at 60 mph. Five different vertical curves, each designed with a 45 mph speed limit, were used to test the EAL system by reducing sight distances. In each scenario, the TMA was randomly placed within one of the five designed vertical curves and the EAL system was programmed to activate 450 feet from the TMA.

As shown in Figure 3.5, the rural highway scenarios were designed based on MoDOT EPG Typical Application TA-17M, which is used for mobile operations on two-lane highways.

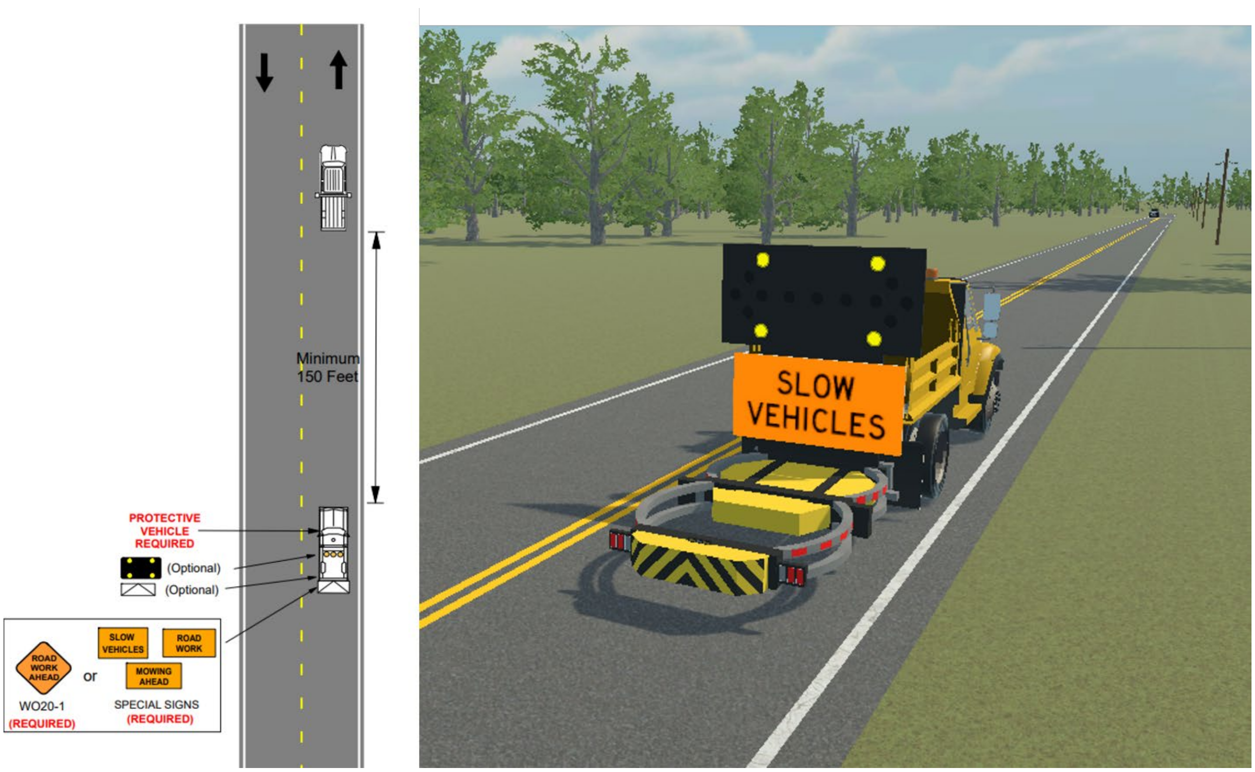

Figure 3.5: MoDOT EPG TA-17M and rural highway scenario

To maintain realism, the maximum braking force in the simulator was calibrated to represent realistic braking distances. Based on field tests, the 70-0 mph braking distances for typical passenger cars and SUVs range from approximately 170 to 190 feet. The simulator was calibrated to achieve a stopping distance of 181 feet.

3.5 Measure of Effectiveness

Two measures of effectiveness were captured for each of the eight scenarios.

- MOE 1: Reaction distance (ft.). This MOE is the distance at which the driver first reacted to the TMA, whether by braking or moving to another lane. Reaction distance was chosen over time or speed as participants would likely be driving at different speeds during each trial.
- MOE 2: Minimum time to collision (TTC) (sec.). This MOE is the minimum time to collision between the simulator and the TMA before the driver stopped the vehicle or vacated the lane blocked by the TMA.

3.6 Simulator Results

A total of 34 participants were recruited for the simulator study. Among them, 90% were between the ages of 26 and 40, 61% were male, and 90% resided in urban areas. In the freeway scenario, participants were observed while driving next to the TMA truck.

None of the participants exhibited erratic braking or steering in response to the airhorn. This result supports the implementation of the airhorn without any delays.

The MOE for reaction distance results from the simulator study are shown in Table 3.2. The mean reaction distance, standard deviation (SD), difference from the control condition, and statistical significance (p-value) are reported. During daytime conditions, the control configuration with no extra lights or a horn resulted in an average reaction distance of 365.90 feet. When the white light with no horn delay configuration was introduced, the reaction distance slightly decreased to 363.63 feet, though this difference was not statistically significant (p = 0.73). The introduction of a delayed horn in the white light configurations resulted in an increased reaction distance of 384.81 feet, though the differences from the control condition remained statistically insignificant (p = 0.31). The yellow configuration with a delayed horn showed the highest reaction distance at 388.75 feet, but this increase was somewhat statistically meaningful at around 90% (p = 0.12). Overall, there does appear to be some difference between baseline and treatment conditions, but the differences among treatments are unclear.

At night, the control configuration had an average reaction distance of 334.11 feet. The white lights with no horn delay configuration resulted in a reaction distance of 356.63 feet, reflecting an increase of 22.52 feet, though this change was not statistically significant (p = 0.38). The white configuration with a delayed horn produced a minor increase to 336.22 feet (p = 0.95), while the yellow configuration with a delayed horn led to a reaction distance of 338.03 feet (p = 0.51). These results suggest that while the introduction of different configurations, particularly the yellow delayed horn setup, led to some increases in reaction distance, none of these changes reached statistical significance, indicating that the modifications did not substantially alter driver response behavior. Overall, there does appear to be some difference between baseline and treatment conditions although those differences were not statistically significant.

Table 3.2: Driving Simulator Reaction Distance (Feet) Results

Time	Configuration	Mean	SD	Diff.	p-value
Day	Control	365.90	83.85	Baseline	Baseline

Day	White	363.63	56.33	-2.27	0.73
Day	White, delayed horn	384.81	78.12	18.91	0.31
Day	Yellow, delayed horn	388.75	70.83	22.85	0.12
Night	Control	334.11	78.24	Baseline	Baseline
Night	White	356.63	79.62	22.52	0.38
Night	White, delayed horn	336.22	74.62	2.11	0.95
Night	Yellow, delayed horn	338.03	57.28	3.92	0.51

Table 3.3 shows the results of MOE of TTC. Under daytime conditions, the control configuration had an average TTC of 3.11 seconds. The white light configuration led to an increase in TTC to 3.95 seconds, but this change was not statistically significant ($p = 0.73$). Similarly, the white light configuration with a delayed horn produced a TTC of 3.66 seconds ($p = 0.31$), while the yellow light configuration with a delayed horn resulted in the highest TTC of 4.18 seconds. Although this increase suggested a possible trend, it was only marginally significant ($p = 0.06$), indicating that while there may be an effect, further investigation is required to confirm its robustness.
Under nighttime conditions, the control configuration resulted in an average TTC of 2.80 seconds. The white light configuration slightly increased TTC to 3.40 seconds, though the difference was not statistically significant ($p = 0.89$). The white light configuration with a delayed horn yielded a similar increase to 3.51 seconds ($p = 0.16$), while the yellow light configuration with a delayed horn resulted in a TTC of 3.28 seconds ($p = 0.58$). These results suggest that while some configurations appeared to extend the TTC, the changes were not statistically significant, implying that driver responses were not meaningfully affected by these modifications.

Table 3.3: Driving Simulator TTC (Seconds) Results

Time	Configuration	Mean	SD	Diff.	p-value
Day	Control	3.11	1.90	Baseline	Baseline
Day	White	3.95	1.58	0.84	0.73
Day	White, delayed horn	3.66	1.99	0.55	0.31
Day	Yellow, delayed horn	4.18	2.50	1.07	0.06
Night	Control	2.80	1.61	Baseline	Baseline
Night	White	3.40	2.23	0.60	0.89
Night	White, delayed horn	3.51	2.55	0.71	0.16
Night	Yellow, delayed horn	3.28	1.75	0.48	0.58

Overall, the results indicate that while the introduction of different configurations, including color configuration and delayed horn activation, led to some improvements in reaction distance and TTC, most changes were not statistically significant. Note that the main purpose of this simulator study was to identify the best way to implement the warning system. In other words, it was to see if the color of the EAL was important or whether the horn should be delayed. It was not to test the absolute effectiveness of the warning system. The results show that there does not appear to be statistically significant evidence that supports implementing one EAL color over another, or to delay or not delay the sounding of the horn. The trend observed in the yellow light with delayed horn configuration, particularly for TTC, suggests a potential area for further study to determine whether specific conditions might enhance driver awareness and response times.

3.7 Survey Results

A survey was conducted to assess participant preferences and perceptions of the different light and horn configurations following the driving simulator study as well as to gather data on simulator sickness. The survey results indicate a strong preference for yellow lighting over white. During the daytime, 30 out of 32 participants (94%) preferred the yellow light, and at night, 28 out of 32 participants (88%) preferred the yellow configuration. As shown in Table 3.4 , this preference is further supported by participant evaluations of key design factors, including clarity, visibility, safety, and efficiency under the two light configurations. Ratings were based on a numerical scale (from 1 to 10), where higher scores indicate a more favorable perception of each factor. For daytime, the yellow light configuration received consistently higher ratings than the white light configuration across all four categories. Participants rated the clarity of the yellow light at 8.38, compared to 6.17 for the white light. Similarly, visibility was rated higher for the yellow light (8.50) than for the white light (6.40), indicating that participants found the yellow configuration easier to see and recognize. Safety scores followed a similar trend, with the yellow light rated at 8.22, surpassing the white light's rating of 6.57. Lastly, efficiency, which likely refers to how well the light configuration supports driving performance and work zone recognition, was also higher for the yellow light (8.31) than for the white light (6.77).

For nighttime work zones, both light configurations received higher ratings compared to daytime, suggesting that participants perceived emergency alert lighting to be more effective in low-light conditions. The clarity of the white light was rated at 7.03, while the yellow light received a higher rating of 8.22. Visibility showed a similar trend, with the white light rated at 7.17 and the yellow light at 8.47. Safety ratings followed the same pattern, with participants rating the white light at 7.30 and the yellow light at 8.28. Efficiency also showed an advantage for the yellow light (8.26) compared to the white light (7.37).

Table 3.4: Survey Results on TMA Light Configuration Evaluation

Configuration	Time	Clarity	Visibility	Safety	Efficiency
White	Day	6.17	6.40	6.57	6.77
Yellow	Day	8.38	8.50	8.22	8.31
White	Night	7.03	7.17	7.30	7.37
Yellow	Night	8.22	8.47	8.28	8.26

Regarding horn configurations, most participants agreed that the horn increased their alertness to the TMA and work zones. As shown in Table 3.5, 80% of respondents either agreed or strongly agreed with this statement, with only 3% strongly disagreeing. However, perceptions of the airhorn's loudness were more mixed. While 45% of respondents found the sound acceptable (agreeing or strongly agreeing that it was not too loud or disturbing), 39% disagreed to some extent, suggesting that while the airhorn improved awareness, its volume may need adjustment to avoid causing discomfort.

Table 3.5: Survey Results on Horn Alert

Statement	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I felt the airhorn made me more alert to the TMA and work zones.	3%	10%	6%	45%	35%
The sound from the airhorn was not too loud or disturbing.	10%	29%	16%	32%	13%

These survey results suggest that yellow light configurations can improve driver awareness and perception of work zones compared to white light configurations. Additionally, while the horn was effective in increasing alertness, it may require fine-tuning to balance effectiveness and comfort. The survey findings, combined with the driving simulator results, highlight the potential for optimizing lighting and auditory alerts to enhance work zone safety. Future research should explore ways to refine these configurations further, ensuring that interventions not only enhance driver performance but also align with user preferences and comfort.

Table 3.6 shows the results from the simulator sickness survey. Most participants reported no symptoms of simulator sickness. The most common symptom was general discomfort with 47% of participants reporting experiencing it to some degree, followed by eye strain at 44% then difficulty focusing and fullness of the head at 41% each, respectively. One participant was unable to complete the study due to simulator sickness.

Table 3.6: Survey Results on Simulator Sickness

Symptom	None	Slight	Moderate	Severe
General discomfort	53%	25%	16%	6%
Fatigue	66%	25%	6%	3%
Headache	66%	22%	9%	3%
Eye strain	56%	31%	13%	0%
Difficulty focusing	59%	25%	6%	3%
Salivation increasing	81%	6%	3%	3%
Sweating	75%	13%	6%	6%
Nausea	75%	6%	6%	13%
Difficulty concentrating	63%	25%	6%	0%
Fullness of the head	59%	19%	22%	0%
Blurred vision	78%	22%	0%	0%
Dizziness with eyes open	63%	31%	6%	0%
Dizziness with eyes closed	66%	22%	13%	0%
*Vertigo	91%	6%	3%	0%
**Stomach awareness	72%	19%	3%	6%
Burping	97%	2%	0%	0%

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

3.8 Summary of Simulator Study

A ZouSim driving simulator study was performed to complement the development and field testing of the TMA alert system. An IRB-approved study was conducted using 34 participants for each of the two studies: freeway scenario testing the effect of non-delayed horn, rolling hill scenario testing EAL color, and day versus night. The total number of samples for the two studies combined was 68. The freeway results showed that the airhorn did not produce any erratic behavior. The simulator results showed a slight preference for yellow EAL although differences were mostly statistically insignificant. However statistical significance could be due to other factors such as sample size, so it does not necessarily mean that the simulator result disproved any difference between the two EAL colors. Once the survey results are considered in conjunction with the simulator results, there does seem to be an indication that yellow EALs were preferred to white EALs. The results also show that the TMA alert system could be more effective during the night. The results do not support the use of a delayed horn, although the results do not indicate any negative consequence of a delayed horn.

Chapter 4. System Architecture and Design

This chapter provides a detailed overview of the AutoTMA warning system's architecture and design, explaining how it's hardware and software components work together to detect potential collisions and issue alerts in real time. The chapter is structured as follows:

- Overall system architecture describes the high-level design of AutoTMA, outlining its key components, including perception sensors, onboard processing, communication links, and alert mechanisms. It explains how data flows through the system to support real-time decision-making.
- Hardware components cover the sensor suite (camera, LiDAR, radar), computing hardware, and integration with the TMA vehicle. It also discusses system durability, modularity, and fail-safe mechanisms to ensure reliability in work zone environments.
- Software framework and data processing detail the operating environment, perception algorithms, sensor fusion techniques, and decision logic used to assess risk and trigger alerts. The section highlights performance optimizations that enable low-latency operation.
- User interaction and usability focus on the operator interface, remote monitoring capabilities, and system feedback mechanisms designed to enhance usability and trust. It outlines how AutoTMA integrates into existing work zone operations with minimal training requirements.

By combining AI-driven perception, sensor fusion, and real-time alerting, AutoTMA enhances safety in highway work zones. This chapter documents the design principles and engineering solutions that ensure its effectiveness and reliability.

4.1 Overall System Architecture

4.1.1 High-Level Design

The AutoTMA warning system is an integrated hardware-software safety solution designed to proactively detect potential collisions and issue alerts to both oncoming drivers and work crews. It combines multiple sensors, an onboard processing unit, communication links, and warning devices into a unified architecture. The sensors continuously monitor the environment around the Truck-Mounted Attenuator (TMA) vehicle for approaching traffic. Data from these sensors feed into a central processing module, which runs real-time AI algorithms to analyze vehicle speed, trajectory, and lane position to assess the risk of a collision. Based on this analysis, the system activates warning outputs (such as alarms and lights) to alert both the errant driver and nearby crew members. Simultaneously, system status and alerts can be transmitted to remote monitoring stations for further action.

This high-level design satisfies the functional safety requirements outlined in the Product Requirement Document (Appendix A), ensuring that all components work together to meet work zone safety goals. The overall architecture (Figure 4.1) follows a structured decision-action loop: sensors capture incoming vehicle data, the processor evaluates risk levels, and alert mechanisms trigger immediate warnings to prevent accidents. Figure 4.1 illustrates this architecture, showing the flow of information from perception sensors to processing (detection algorithms) and the corresponding control signals to alerting devices and communication interfaces for remote reporting.

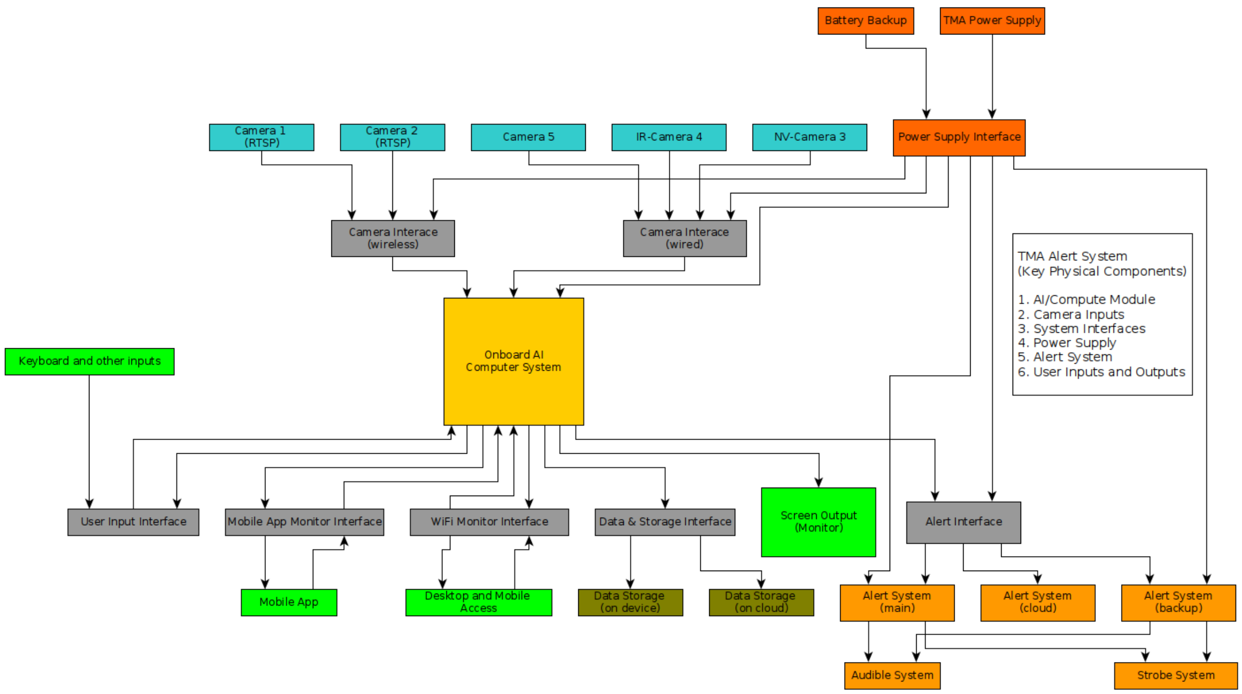

Figure 4.1: Architecture diagram: illustrates the overall system architecture showing sensors feeding data to the processing unit, which in turn communicates with the alert devices and user interfaces. This block diagram highlights data flow and control signals between components

4.1.2 Key Subsystems

The AutoTMA warning system is composed of several key subsystems that work together to detect potential collisions, assess risks, and issue real-time alerts. These components form a tightly integrated system, ensuring accurate threat detection and timely warnings. Figure 4.2 depicts the key subsystems and a breakdown of the key subsystems and their roles in the AutoTMA architecture can be found below.

1. Perception: The primary sensor is a camera that provides visual data for object detection and distance estimation. While the initial system relied solely on camera-based detection, later enhancements incorporated LiDAR and radar (Appendix C) to improve accuracy under adverse weather and low-light conditions.
2. Processing: The onboard computer fuses sensor data and runs AI algorithms to assess collision risk in real time. This "brain" of the system calculates key safety metrics, such as time

to collision (TTC), and determines when to trigger warnings. Initially, the algorithms were optimized for camera-only input, with performance benchmarks outlined in the Software Requirements Specifications (Appendix B).

3. Communication: Internal data transfer is managed via a ROS-based middleware, integrating sensor inputs with processing outputs in real time. External communications through 4G/5G and Wi-Fi enable remote monitoring, including real-time status updates and alert transmission (Appendix B). While the current system does not yet utilize vehicle-to-vehicle (V2V) networks, future updates are planned to support direct communication with connected vehicles for enhanced safety integration.
4. Alerting: When a collision risk is detected, the system activates an audible alarm, designed to capture the attention of approaching drivers. In addition, visual warning devices—including flashing lights and an arrow board compliant with MUTCD standards—provide multi-sensory alerts to both drivers and work crews. These warning outputs are designed to maximize visibility and reaction time in high-risk scenarios.

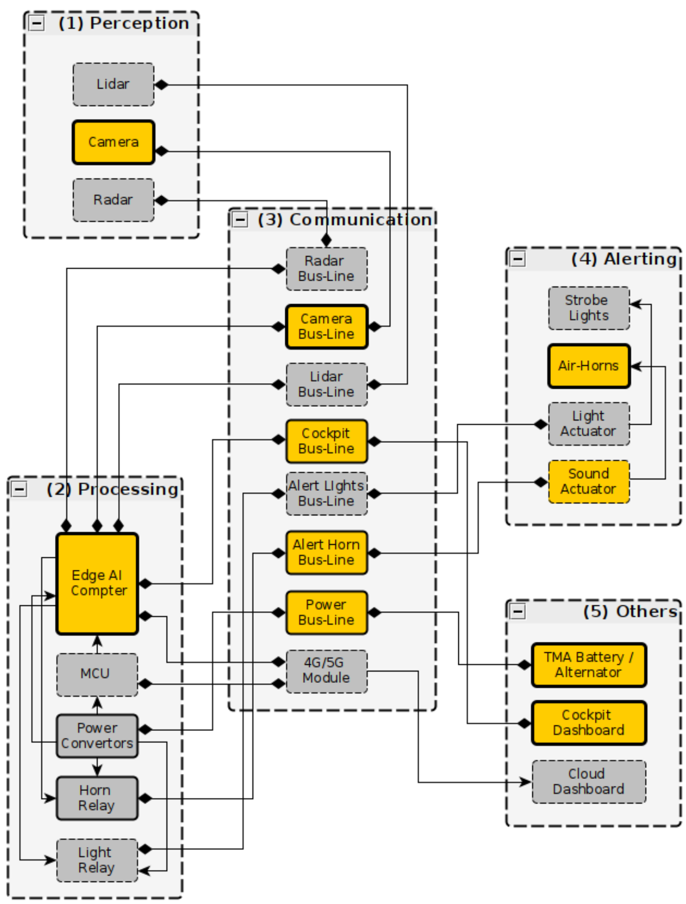

Figure 4.2: Key Sub systems

1) Perception – sensors (camera, LiDAR, radar) detect incoming vehicles; (2) Processing – on-board computer runs AI algorithms to assess collision risk; (3) Communication – links between sensors, processor, operator interface, and remote monitors; (4) Alerting – mechanisms (alarms, lights) to warn drivers and crew.

4.1.3 Design Considerations

The AutoTMA system was developed with several critical design requirements to ensure its effectiveness in real-world work zone conditions. These considerations, summarized in Table 4.1, guided hardware selection, software architecture, and system integration to maximize performance, reliability, and safety.

1. Real-time performance: The system must detect and issue warnings about oncoming vehicles quickly enough to allow drivers and work crews to react. This requirement influenced the choice of high-speed sensor interfaces and powerful onboard processing hardware (detailed in Sections 4.2 and 4.3). The Product Requirement Document (Appendix A) specifies strict latency thresholds for issuing warnings, leading to an architecture that minimizes processing and data transmission delays.
2. Reliability and redundancy: As a safety-critical system, AutoTMA must function correctly under all expected operating conditions. To enhance reliability, redundant sensing is implemented—using multiple sensor types (camera, LiDAR, and radar)—so that if one sensor fails or is impaired (e.g., a camera is blinded by glare), the system can still function using alternative inputs.
3. Ruggedness: Given that TMAs operate in harsh outdoor environments, all system components are designed for durability. Hardware enclosures are weatherproof and vibration-resistant, ensuring protection against rain, extreme temperatures, and roadway vibrations from heavy traffic and construction equipment. Environmental specifications, including temperature tolerances suitable for Missouri's climate, are outlined in Appendix C.
4. Modular architecture: The system follows a modular design where each major subsystem—perception, processing, communication, and alerting—has well-defined interfaces. This allows individual components to be upgraded or replaced without significantly affecting other parts of the system, ensuring adaptability to future enhancements.
5. Fail-safe mechanisms: To prevent unsafe failures, the system incorporates fail-safe designs at the architectural level. If the processing unit crashes or loses power, the system defaults to a passive state, ensuring that it does not interfere with standard TMA operation. In such a case, the TMA continues to function as a crash cushion as intended, maintaining its core safety role even in the absence of active warnings.

This structured approach ensures that the AutoTMA system remains reliable, durable, and adaptable while meeting the safety and operational needs of highway work zones. The high-level design and subsystem integration were guided by the Product Requirement Document (Appendix A) and informed by industry standards for safety, resulting in a cohesive system architecture that addresses the core problem: reducing TMA crash incidents through timely and effective warnings.

Table 4.1: Summary of Design Considerations and Priorities for the Audible Alert System

Design Consideration	Description	References/ Notes
Real-Time Performance	The system must detect and warn of oncoming vehicles quickly, with an end-to-end latency of less than 0.5 seconds. High-speed interfaces and optimized AI algorithms ensure streaming sensor data is processed in real time.	See Product Requirement Document (Appendix A) for latency targets.
Reliability	To ensure continuous, safety-critical operation, the system employs redundant sensing using multiple sensor types. Health monitoring is incorporated so that if one sensor fails (e.g., a camera blinded by glare), others can compensate, and the system either falls back to a safe mode or alerts the operator.	Critical for safety-critical systems; details in Appendix B.
Ruggedness	All components are designed for harsh work zone conditions—resisting vibration, dust, and extreme temperatures. Initial field tests revealed overheating issues, which were mitigated by relocating and ruggedizing the computing unit inside the cab and adding an independent power supply.	Environmental specifications detailed in Appendix C.
Modularity	The architecture is modular, with well-defined interfaces for each subsystem (perception, processing, communication, alerting). This allows components to be upgraded or replaced with minimal impact on overall system design. Modular software design (using Robot Operating System (ROS) topics) abstracts sensor specifics, easing future integration of new sensors.	Facilitates future upgrades and scalability; see Appendix B and C.
Fail-Safe Mechanisms	Fail-safe measures ensure that any system failure (e.g., processing unit crash or power loss) results in a safe, passive state that does not compromise the TMA's primary function. Manual override controls are provided so an operator can immediately intervene if necessary.	As required by safety guidelines in Appendix A.

4.2 Hardware Components and Specifications

The AutoTMA warning system integrates a modified TMA vehicle with a suite of sensors, computing hardware, and alert mechanisms to enhance work zone safety. All hardware components were selected based on performance, durability, and compliance with industry standards (detailed in Appendix C). This section provides an overview of key system components and their roles.

Figure 4.3: Standard Truck Mounted Attenuator (TMA)[2]

4.2.1 TMA Base Vehicle & Integration

The system is installed on a standard Truck-Mounted Attenuator (TMA) (see Figure 4.3), a heavy-duty vehicle equipped with a crash attenuator. Minimal modifications were made to accommodate sensors and alert devices while ensuring compliance with FHWA crash standards (NCHRP 350 TL-3) [21]). Custom mounting brackets were installed to securely position cameras, LiDAR, and radar without affecting the attenuator's function.

4.2.2 Audible Alert TMA Integration Bus System

A standardized integration protocol was developed to ensure seamless installation of the audible alert system on the TMA. This integration process is performed once and allows compatibility with future alert system upgrades without requiring significant modifications. The integration includes establishing bus communication lines between the toolbox unit, where the alert system is housed, and the cockpit, as well as interfacing with the camera and sensor suite. The electrical system was adapted to support auxiliary power for the added components, with all sensor cables routed through protective conduits to prevent damage or interference. To avoid overloading the truck's existing circuits, an independent fused power line and backup battery were installed, ensuring reliable power delivery under all operating conditions. These modifications maintain full compliance with the Product Requirement Document (Appendix A), which mandates that the system be retrofit-compatible with existing TMAs while preserving the vehicle's crashworthiness. The attenuator itself, such as the Scorpion II TMA, remains unaltered in its shock-absorbing function, ensuring that the warning system does not interfere with its primary safety role. This integration is illustrated in Figure 4.4.

[2] https://www.awpsafety.com/equipment/truck-mounted-attenuators/tma/

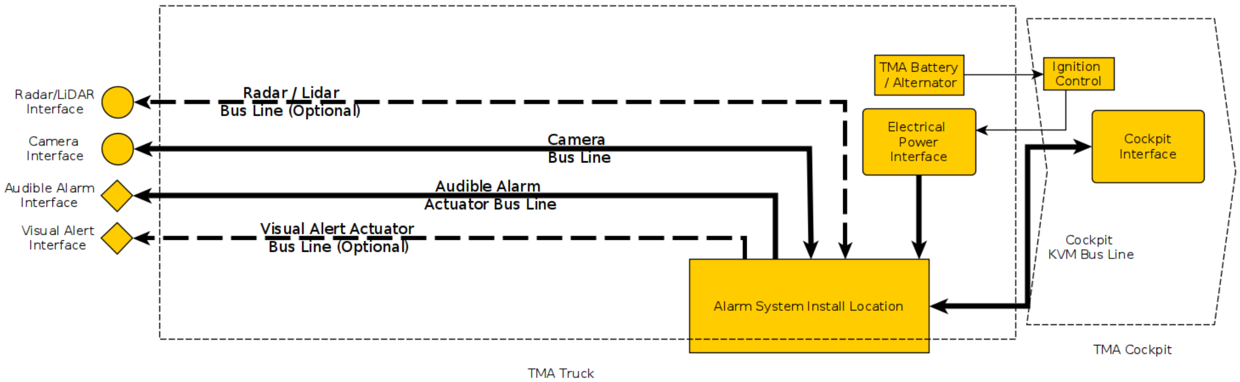

Figure 4.4: Bus Integration System showing the installation bus lines

4.2.3 Sensor Suite

The AutoTMA system employs a multi-modal sensor suite for real-time vehicle detection, distance estimation, and collision risk assessment.

- Camera (Primary Sensor) – A high-resolution rear-facing camera (Figure 4.5), with 1080p resolution and a frame rate of 30–60 FPS, continuously monitors approaching traffic. It features a wide dynamic range for night and glare conditions, shock-resistant mounting, and an elevated position to provide an unobstructed view of the roadway. The camera is the primary sensor for object detection and classification.

Figure 4.5: E-con Systems Sturdecam25 Camera

- LiDAR (Optional Enhancement) – A 3D LiDAR (Light Detection and Ranging) sensor is integrated to improve distance measurement and environmental perception. LiDAR (Figure 4.6) operates by emitting laser pulses and measuring the time it takes for them to reflect off objects, creating a high-resolution point cloud representation of vehicles and obstacles. The system uses LiDAR with a detection range of approximately 100–120 meters and a horizontal field of view of at least 120 degrees to cover one to two lanes behind the TMA. This sensor significantly enhances depth perception and distance estimation, allowing the system to distinguish between objects at varying ranges with centimeter-level accuracy. Unlike cameras, LiDAR remains effective in low-light conditions, making it particularly useful for nighttime operation. The sensor is mounted on a vibration-damped bracket at the top of the attenuator, ensuring a clear view of the roadway while maintaining calibration with the camera for sensor fusion.

Figure 4.6: Livox HAP LiDAR

Radar (Optional Enhancement) – A 77 GHz millimeter-wave radar sensor (see Figure 4.7) is incorporated to measure the speed and distance of approaching vehicles using radio wave reflections. Unlike LiDAR and cameras, radar is highly resistant to environmental interference, including rain, fog, dust, and darkness, making it an essential component for all-weather detection. The radar used in AutoTMA can detect vehicles at ranges exceeding 150 meters and provides real-time measurements of a vehicle's speed and trajectory. Doppler shift calculations allow the system to determine whether an approaching vehicle is accelerating, decelerating, or maintaining a constant speed. The radar sensor has an angular field of view of approximately ±45 degrees, allowing it to focus on the lane directly behind the TMA while tracking adjacent lane movements. The radar is mounted lower on the TMA frame, near bumper level, where it aligns with the typical height of vehicle bodies to improve reflection accuracy. Its data is fused with camera and LiDAR inputs to enhance object tracking and collision risk assessment, particularly in conditions where vision-based sensors may struggle.

Figure 4.7: Axis Q1656 DLE Radar Video Fusion Camera

Additional Sensors – A GPS module provides precise location tracking, enabling event logging and geo-referenced alerts. The GPS system also supports time synchronization for sensor data. An Inertial Measurement Unit (IMU) is included to detect sudden movements of the TMA, such as abrupt braking, swerving, or an impact event. If the TMA is struck, the IMU data can trigger emergency notifications or system responses. The architecture also allows for the future integration of thermal cameras, which could be used to detect vehicle heat signatures at night, providing an additional perception modality in low-visibility conditions.

4.2.4 Sensor Mounting & Placement

Proper sensor mounting is essential to ensure clear visibility, minimize obstructions, and reduce vibration interference.

- Camera and LiDAR placement: These sensors are co-located on a rear-mounted rig at the top of the attenuator, approximately 3–4 meters above ground. This height provides a clear line of sight over the attenuator and into the traffic lanes behind the TMA. A slight downward tilt optimizes the field of view for tracking approaching vehicles while filtering out irrelevant background elements. The camera is mounted on a shock-absorbing bracket to minimize motion blur caused by vehicle vibrations.
- Radar placement: The radar is mounted lower on the TMA frame, near bumper level, to align with the typical height of vehicle bodies. This positioning ensures that radar reflections return from the center of approaching vehicles, improving detection accuracy. The radar is housed in a weatherproof enclosure to protect it from road debris and environmental exposure.
- Cable management: Sensor cables are routed through protective conduits along the TMA frame, ensuring they are shielded from physical damage while maintaining flexibility for adjustments. A modular connector system allows for easy sensor replacement or upgrades without extensive rewiring.

4.2.5 Onboard Computing & Communication

At the core of AutoTMA is a ruggedized embedded computer that processes sensor data, runs AI-based collision detection, and manages alerts.

- Processing Unit – An NVIDIA Jetson AGX platform (Figure 4.8) was selected for its high-performance GPU acceleration and real-time deep learning inference capabilities. It processes sensor fusion algorithms at approximately 30 FPS to detect and classify vehicles, compute time-to-collision (TTC), and determine when to activate alerts.
- Fail-Safe Microcontroller (MCU) – An ESP32 Wrover serves as a backup control unit, handling low-level I/O functions and ensuring system operation in case of main processor failure. If the main computing unit crashes, the MCU triggers a fallback mode to maintain warning functionality.
- Data Interfaces – The system connects sensors via USB 3.0 (cameras), Ethernet (LiDAR), and CAN bus (radar & MCU), with internal ROS-based middleware managing real-time data flow.
- Remote Monitoring & V2V Readiness – The system supports 4G/5G and Wi-Fi communication for real-time remote monitoring. Future updates will enable vehicle-to-vehicle (V2V) integration, allowing connected vehicles to receive warnings from the TMA system.

Figure 4.8: Nvidia Jetson AGX Orin

4.2.6 Alert & Warning Systems

To effectively warn both oncoming drivers and work crews, the AutoTMA system employs a combination of audible and visual warning devices designed for maximum visibility and compliance with MUTCD work zone safety regulations. The specifications for these warning components are outlined in Appendix C, while their operational requirements are detailed in Appendix B. These warning components include:

- MUTCD-compliant work zone audible alarm: A rear-mounted siren rated at 120 dB is activated when a high-risk vehicle is detected. The alarm emits a distinctive, oscillating sound pattern designed to cut through ambient road noise and alert distracted drivers. The sound level and frequency modulation are chosen based on MUTCD guidelines for effective work zone intrusion alerts. OSHA safety regulations regarding noise exposure for work crews were considered in determining the alarm placement and volume levels, as detailed in Appendix C. The system can also utilize the existing TMA truck horn or other MoDOT-approved audible alarms.
- Visual alerts: The system integrates additional high-intensity LED strobes alongside the existing TMA arrow board. These strobes pulse rapidly during an alert event to maximize visibility in both daylight and nighttime conditions. Their placement and flashing patterns comply with MUTCD standards for work zone warning lights. The selection of specific strobe models, brightness levels, and flashing sequences is described in Appendix C.
- Manual override and fail-safe mode: A manual activation switch inside the TMA's cabin allows operators to trigger or disable alerts as needed. If the processing unit fails, the microcontroller ensures that the system enters a default alert mode, activating both audible and visual warnings to maintain safety. The fail-safe protocols and override functions are specified in Appendix B.

By aligning with MUTCD and MoDOT standards and the hardware specifications outlined in Appendix C, the AutoTMA alert system ensures that warnings are both effective and compliant with established state work zone safety guidelines.

4.3 Software Framework and Data Processing

The AutoTMA software is designed for real-time sensor processing, computer vision, and machine learning, built in accordance with the Software Requirements Specifications (Appendix B). The architecture ensures efficient perception, decision-making, and alert triggering while maintaining scalability and reliability.

4.3.1 Operating Environment & Frameworks

The system runs on a Linux-based operating system, specifically Ubuntu L4T, optimized for the NVIDIA Jetson platform. Linux provides stability, extensive hardware support, and a rich development ecosystem.

The software framework is built on ROS (Robot Operating System), which handles inter-process communication and system integration. The software is structured into modular ROS nodes, where individual processes handle specific tasks such as sensor data acquisition, perception, and alert activation. ROS also facilitates data logging (rosbag for sensor recordings) and visualization (RViz for real-time debugging and sensor coverage analysis). This modular approach aligns with Appendix B requirements for scalability and future sensor or algorithm integration.

For data processing, OpenCV is used for image handling, while CUDA and cuDNN accelerate deep neural network inference on the GPU. Core detection algorithms are implemented in PyTorch or

TensorFlow, and are optimized using NVIDIA TensorRT for high-speed inference. The system also utilizes NVIDIA's DeepStream SDK, which provides a high-performance vision pipeline using GStreamer plugins. DeepStream enables efficient video decoding, inference, and data transfer, achieving ~30 FPS compared to ~20 FPS in a standard YOLO implementation.

The operating environment includes standard Linux networking stacks for communication, including MQTT/WebSocket for remote monitoring and CAN drivers for radar integration. Processes are configured to launch on boot, with a watchdog service ensuring system stability by restarting any failed processes. Logging mechanisms provide traceability, and the software can be updated remotely for security patches or algorithm improvements.

4.3.2 Perception Algorithms

The perception software interprets sensor data to detect and track vehicles approaching the TMA, integrating AI-based vision models with sensor fusion techniques to enhance accuracy and reduce false alerts. The system meets the performance benchmarks outlined in Appendix B, ensuring real-time operation with minimal processing latency.

At its core, the perception module relies on a deep convolutional neural network trained using multi-task learning (MTL). This model simultaneously performs object detection, distance estimation, and lane detection (as shown in Figure 4.9). The backbone network, such as a Generalized Efficient Layer Aggregation Network (GELAN), extracts shared features before branching into specialized outputs. The object detection head identifies vehicles in the camera feed, classifies them by type (e.g., car, truck), and tracks their movement. The distance estimation head categorizes detected vehicles into predefined distance zones ("safe," "warning," or "danger"), leveraging training data labeled with LiDAR-derived ground truth distances. For precise distance measurements, the system employs sensor fusion, combining data from the camera, LiDAR, and radar. Camera-based distance estimation relies on perspective cues, but LiDAR and radar provide direct range measurements. When the camera detects a vehicle at an estimated 80 meters, the fusion algorithm checks the LiDAR point cloud for corresponding reflections and cross-references radar data for speed and range validation. Radar also improves detection reliability in poor visibility conditions, such as low light or glare. A Kalman Filter is used to smooth and predict vehicle motion, blending measurements from multiple sensors. Camera data provides bearing angles, LiDAR offers precise range values, and radar contributes range and velocity data. This multi-sensor approach minimizes false detections and improves all-weather performance. If the vision-based model misidentifies an object due to lighting conditions, LiDAR and radar confirmation help prevent unnecessary alerts.

All perception algorithms run continuously, optimized for real-time processing. GPU acceleration using DeepStream and TensorRT enables efficient inference, keeping latency within tens of milliseconds. In controlled tests, the system demonstrated approximately 90% detection recall and 84% accuracy in distance classification, meeting the accuracy targets specified in Appendix B. The combination of AI-based object detection and classical sensor fusion provides a robust perception system that supports reliable alert decision-making.

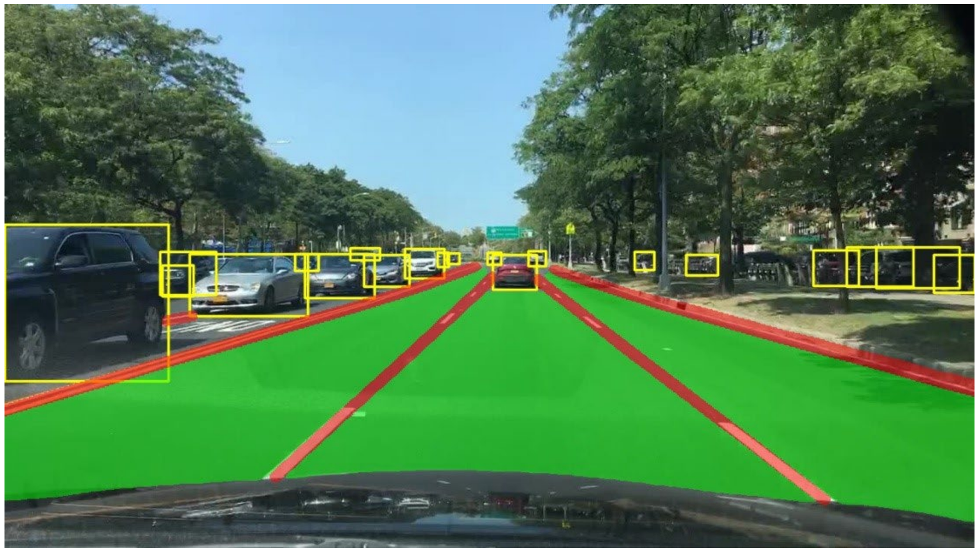

Figure 4.9: Output inference by AI model

4.3.3 Alert Decision Logic

The alert decision module determines when and how to trigger warnings based on vehicle position, speed, and behavior. The system uses time-to-collision (TTC) and safe stopping distance as primary decision criteria. TTC is calculated as distance divided by relative speed, while stopping distance is estimated based on vehicle speed and assumed deceleration. The system combines these metrics with heuristic rules to ensure timely and appropriate alerts. These parameters can be adjusted and customized to suit MoDOT preferences. The following are the parameters used for field testing.

- If a vehicle is in the danger zone (e.g., within 60 meters and not slowing) or has TTC of less than 2.5 seconds, the system activates the audible alarm and all warning lights immediately.
- If a vehicle is in the warning zone (60–120 meters with TTC between 2.5 and 5 seconds), the system may pre-actuate a lower-level alert, such as flashing the arrow board, to get the driver's attention without triggering the full alarm.
- Vehicles in the safe zone (more than 120 meters away or slowing down) are monitored but do not trigger alerts unless they exhibit risky behavior, such as swerving into the TMA's Lane.

The alert logic also considers vehicle behavior using lane detection, speed, and acceleration data. If radar detects strong braking, the system may suppress an alert, assuming the driver is responding appropriately. Conversely, if a vehicle is accelerating toward the TMA, the alarm is triggered earlier. The AI-driven lane detection module helps assess whether a vehicle is aligned with the TMA or moving away, reducing false alarms.

The Alert Controller node continuously evaluates fused tracking data and issues commands to the alerting subsystem when a threshold is crossed. Hysteresis mechanisms prevent rapid on-off alarm cycling by enforcing minimum activation durations and requiring stable conditions before deactivating alerts.

Threshold values were initially set based on theoretical stopping distances and later refined through testing and simulations (Appendix B). Early vision-only models produced high false alarm rates, but integrating multi-criteria logic and sensor fusion significantly reduced false alerts by validating threats across multiple data sources. The final decision engine prioritizes safety while minimizing unnecessary warnings.

4.3.4 Data Flow and Processing Pipeline:

The software operates in a continuous loop, processing sensor data and triggering alerts in real time. Figure 4.10 illustrates this flow from sensing to actuation.

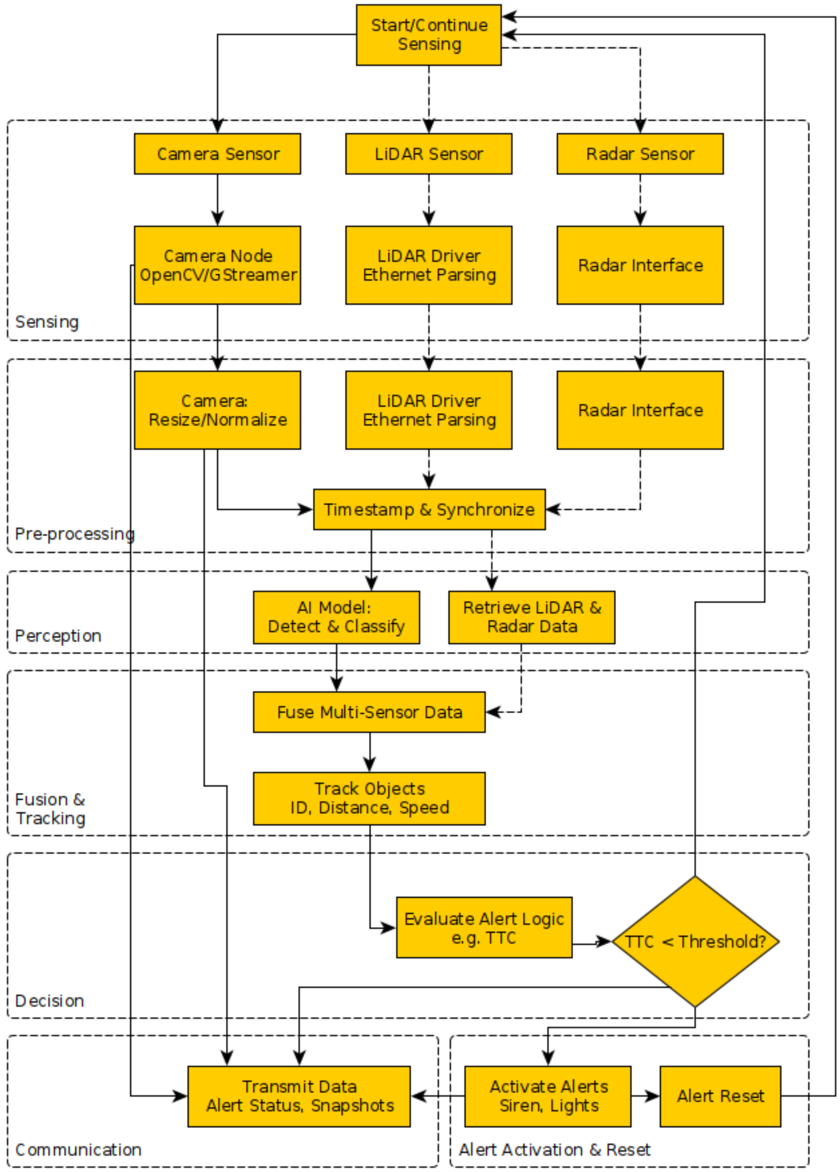

Figure 4.10: Data flow pipeline

In the **sensing stage,** raw data from cameras, LiDAR, and radar is collected at its native rate and synchronized. The **pre-processing stage** refines this data by resizing images for neural network input, filtering LiDAR point clouds, and parsing radar targets. Timestamping ensures multi-sensor alignment. The **perception stage** applies AI-based detection to identify vehicles and estimate their position. LiDAR and radar data provide depth and velocity measurements, which are fused with camera detections in the tracking stage. This ensures reliable object tracking, even if a temporary obstruction causes one sensor to lose sight of a vehicle. In the decision stage, the system evaluates time-to-collision and stopping distance. If a vehicle meets a critical threshold, the alert activation stage triggers alarms and flashing lights via ROS commands to actuator

control nodes. Alerts remain active until the vehicle slows, changes lanes, or exits the danger zone. The alert reset stage ensures proper deactivation, preventing erratic on-off cycling.
A parallel communication process transmits alert data to external systems for remote monitoring (see Section 4.4). While not on the critical alert path, it allows for event logging and analysis. The pipeline is optimized to minimize delay, ensuring that threat detection and alert activation occur within a fraction of a second.

4.3.5 Real-Time Performance and Optimization

Ensuring real-time performance was a critical design requirement, as delays in issuing alerts could reduce their effectiveness. The system was optimized to achieve sub-second response times, with field tests confirming detection-to-alert latency of approximately 0.25 seconds, well within the 0.5-second threshold specified in Appendix B. Adding this lag to typical perception reaction times (0.54 – 2 seconds) increases the overall system perception-reaction time to about 1 – 2.5 seconds. Detecting vehicles at distances beyond 50 meters will therefore be crucial in improve system reliability.

Key optimizations included the use of NVIDIA's DeepStream and TensorRT, which significantly accelerated AI inference, reducing initial processing delays from two to three seconds to under 0.3 seconds. Parallel processing was also implemented, with the GPU handling camera-based detection while the CPU processed LiDAR data and tracking, eliminating idle wait times. Neural network models were optimized for the embedded GPU using reduced precision inference (FP16/INT8) and resizing input images to balance speed and accuracy. Sensor data handling was streamlined through efficient binary protocols and structured data exchange, reducing latency from high-bandwidth LiDAR feeds. ROS middleware was tuned to minimize communication overhead, ensuring rapid sensor-to-decision data flow.

Field testing confirmed that the system consistently operates at 30 FPS, issuing warnings with enough lead time for drivers to react. Stress tests under high-traffic conditions validated its ability to track multiple vehicles while maintaining performance. These optimizations ensure the AutoTMA system provides timely and reliable alerts, meeting the real-time safety demands of work zone operations.

4.4 User Interaction and Usability

The effectiveness of AutoTMA depends on its ease of use and integration into existing work zone operations. The system was designed with a user-friendly interface, remote monitoring capabilities, and operator feedback mechanisms to ensure smooth adoption and reliable performance in the field.

4.4.1 Operator Interface

A compact dashboard display in the TMA cab provides real-time system status and alerts. Under normal conditions, the interface shows a green status indicator and a simple message such as "Monitoring Active." If a vehicle enters the warning zone, a yellow alert appears with the distance to the approaching vehicle. In a danger scenario, the display flashes red, and an in-cab buzzer sounds, notifying the operator that the system has activated external alarms.

The interface (see Figure 4.11) includes basic operator controls:

- Power switch to turn the system on/off (with fail-safe confirmation to prevent accidental shutdown).
- Mute button to silence alarms in low-risk situations.
- Test button to check alarm and sensor functionality.

The interface is designed for quick situational awareness, using simple icons and color coding (green = safe, yellow = caution, red = danger) to minimize distraction while operating the TMA. Figure 4.11 shows a screen displaying the interface mounted in the TMA cabin

Figure 4.11: User interface

4.4.2 Remote Monitoring

Supervisors or remote personnel can monitor AutoTMA in real time via a web dashboard or tablet connected over a cellular network. This dashboard displays:

- Live sensor feeds, including a camera view from the TMA.
- Active system alerts, showing vehicle approach speed and distance.
- GPS location and system status, useful for managing multiple TMAs in the field.

Remote users can log alert events for later analysis, potentially integrating AutoTMA with a broader fleet management system. While most remote monitoring is passive, limited two-way control is available, such as sending an emergency stop or reset command.

4.4.3 System Usability and Feedback

AutoTMA was refined based on user input from TMA drivers and work zone supervisors, ensuring it aligns with real-world operational needs. Key usability features include:

- Automatic self-checks: When powered on, the system verifies sensor functionality, alerting the operator if any component is faulty (e.g., "Camera Obstructed – Check Lens").
- Periodic status updates: If no warnings occur for an extended period, the system confirms it is still active (e.g., "Monitoring… 12 vehicles detected, all at safe distance").
- Operator feedback loop: Users can log false alarms or missed detections, allowing for software refinements over time.
- Minimal training requirement: The interface was designed for intuitive use, requiring only basic training (typically less than an hour).

Figure 4.12: Screen mounted in TMA cabin

4.4.4 Safety and Manual Override

AutoTMA is designed to work alongside, not replace, manual controls. Operators can:

- Override alerts if an unnecessary alarm could cause confusion.
- Manually trigger alarms if they detect a threat the system missed.

- Rely on traditional safety measures if AutoTMA encounters a failure, with clear interface messages (e.g., "System Error – AutoTMA Inactive").

4.5 Comparison of Warning System Approaches

This section provides a structured comparison of four types of warning systems relevant to work zone safety, highlighting how AutoTMA's design builds upon prior approaches. Each subsection describes one approach, followed by a comparative analysis.

4.5.1 AutoTMA Prototype – Camera-Only System (Vision-Based)

The first-generation AutoTMA prototype illustrated in Figure 4.13 relied solely on camera-based vision for detecting approaching vehicles. This low-cost approach served as an initial feasibility test for automated alerts using computer vision algorithms. Figure 4.13 shows the power station, camera and control unit(white box). Inside the Control box consists of the cooling fan , Jetson ,thermostat, fuse, boost-buck power converter ,power splitter and alarm relay as shown in Figure 4.14.

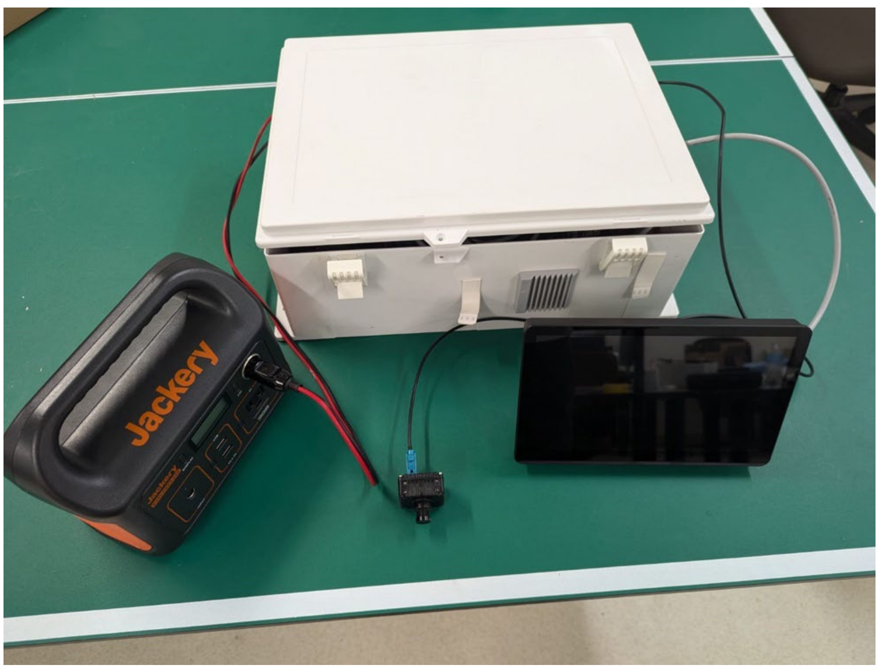

Figure 4.13: Camera Only Vision System

4.5.1.1 Initial Prototype and Findings

The earliest version used a single rear-facing camera and basic image processing. A simple motion detection algorithm or object recognition model identified vehicles in the video feed, triggering alerts when an object increased in size, signaling an approaching vehicle. While this proved the concept of automated detection, it had major shortcomings:

- Lack of depth perception from a single camera made distance estimation unreliable.

- High false positive rates, with the system misidentifying shadows, distant objects, or vehicles in adjacent lanes as threats.

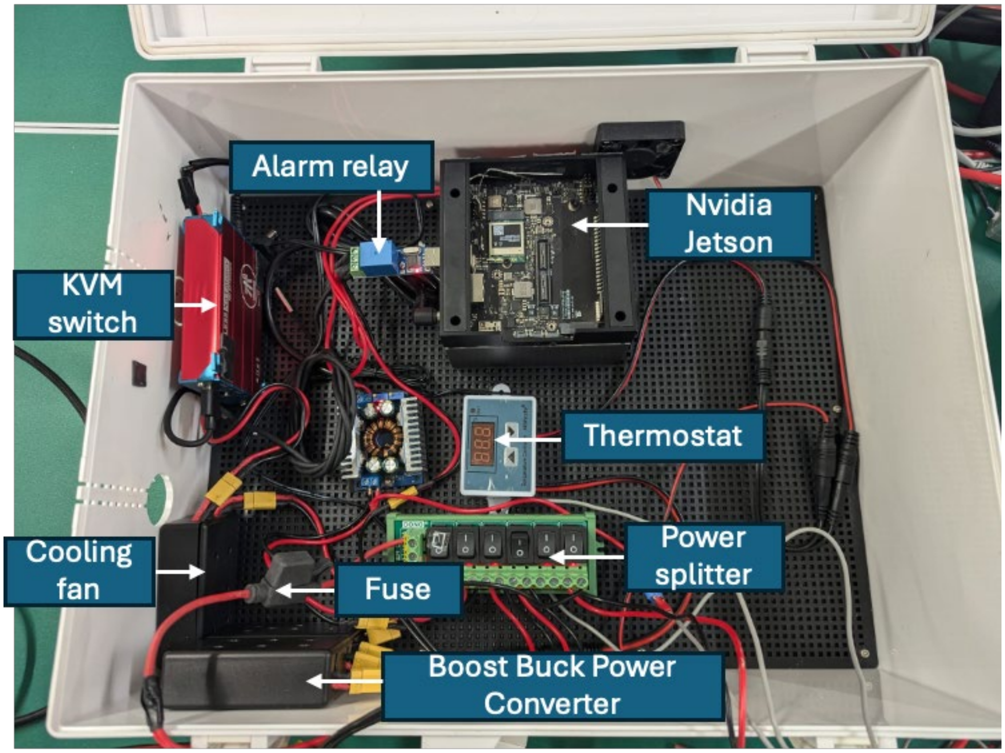

Figure 4.144: Inside of the control unit

4.5.1.2 Iterative Refinements

The camera-only system evolved over three generations to improve accuracy, detection reliability, and computational efficiency.

- Generation 1: Upgraded to an industrial-grade camera with better resolution and low-light performance. Introduced a Convolutional Neural Network (CNN) for more robust vehicle detection, reducing false alarms. However, distance estimation was still based on object size, which remained imprecise.

- Generation 2: Integrated multi-task vision models to identify lane boundaries and road edges, improving threat assessment. A YOLOP-like system filtered out vehicles in adjacent lanes and introduced rough distance categorization, segmenting the view into near and far zones. A GPU-based processing unit replaced the CPU-only system, improving processing speed.
- Generation 3: Implemented a panoptic AI model inspired by YOLOPv2, performing object detection, free-space segmentation, and depth classification in a single pass. The system was trained in work zone-specific datasets, improving its ability to distinguish vehicles in safe, warning, and danger zones. This version achieved real-time performance with a vehicle detection recall of approximately 90 percent, making it a viable stand-alone system under good conditions.

4.5.1.3 Evaluation and Limitations

The final camera-only system demonstrated that an AI-driven vision model could effectively detect and track vehicles, issuing automated warnings faster than a human could react. However, limitations remained:

- Performance degradation in low-visibility conditions such as nighttime, rain, and glare.
- Distance estimation remained an inference, leading to inaccuracies for high-speed or non-standard vehicles.

These challenges prompted the development of sensor-augmented prototypes integrating LiDAR and radar for improved depth perception and all-weather reliability.

4.5.2 AutoTMA Prototype – Vision + LiDAR Integration

To address the depth perception limitations of the camera-only system, the next-generation prototype integrated a LiDAR sensor alongside the camera, enabling 3D environmental sensing behind the TMA (see Figure 4.15).

4.5.2.1 Sensor Fusion Approach

The system combines LiDAR's precise range measurements with the camera's ability to classify objects and detect lane markings. Two fusion methods were explored:

- Data-level fusion: LiDAR points were projected onto the camera image, allowing the AI model to process an augmented image with depth information.
- Decision-level fusion: Separate detections from both sensors were combined, using LiDAR to confirm a vehicle's exact distance and trajectory after being identified in the camera feed.

A calibration process ensured that camera image regions corresponded to specific LiDAR distance readings, improving distance estimation accuracy [3].

4.5.2.2 Hardware and Placement

A Livox T1 LiDAR unit was mounted near the camera at the top of the vehicle for overlapping coverage [3]. The system synchronizes video frames and LiDAR point clouds within a few milliseconds. To process the additional data, hardware was upgraded as needed to maintain real-time performance.

4.5.2.3 Advantages and Challenges

The addition of LiDAR significantly improved accuracy, eliminating reliance on visual estimation alone. The system could detect vehicles beyond 100 meters, track their movement over time, and provide earlier warnings than the camera-only version. False alarms were reduced, as LiDAR correctly identified objects at a distance, preventing unnecessary alerts from visually large but distant objects. Nighttime and low-light detection was also enhanced, as LiDAR operates independently of ambient lighting.

However, LiDAR integration added complexity and cost. The sensor required careful calibration, and processing LiDAR data efficiently was essential to avoid system lag. Additionally, adverse weather conditions such as heavy rain or snow could interfere with LiDAR readings, although the camera provided a backup for verification in such cases.

4.5.2.4 Results and Status

Controlled environment testing confirmed that the camera+LiDAR prototype was more robust than the camera-only system, with fewer missed detections and reduced false alarms. The system aligned with research supporting multi-sensor fusion for improved reliability [3]. This prototype set the foundation for field trials, where further refinements would be made based on real-world performance.

Figure 4.15: Vison + Lidar System

4.5.3 AutoTMA Prototype – Vision + Radar Integration

Alongside LiDAR integration, the project also developed a camera + radar prototype, shown in Figure 4.16, to explore radar's potential as an alternative or complement to LiDAR. Radar is widely used in automotive collision warning systems and offers superior performance in poor visibility conditions such as fog, rain, or darkness.

4.5.3.1 Radar Capabilities and Integration

Radar continuously emits radio waves and measures their reflections to detect objects, directly providing range and speed (Doppler) data. A rear-facing automotive-grade radar was mounted to track approaching vehicles. Unlike vision-based systems, radar excels in detecting fast-moving objects at long range, even in low-light or adverse weather conditions.

The camera remained essential for object classification and lane detection, while radar acted as an independent trigger for potential threats. Radar targets were correlated with the camera's field of view, allowing the system to track vehicles approaching 120 meters or more. The Radar provided precise time-to-collision (TTC) calculations, and if a vehicle's TTC dropped below a critical threshold, the camera verified whether it was a legitimate threat. This camera-radar fusion helped filter out non-threatening objects, such as guardrails or overhead signs.

4.5.3.2 Benefits and Challenges

Radar enhances all-weather detection and reacts instantly to speed changes. Unlike a camera, which requires a vehicle to be visually large before detection, radar identifies and tracks vehicles earlier, improving warning timing. It is also more cost-effective than LiDAR and produces simpler data outputs, reducing processing complexity.

However, radar has lower resolution, making it difficult to distinguish closely spaced vehicles or determine lane position at long range. This was mitigated by using the camera for lane identification and multi-object tracking. Additionally, radar occasionally detects irrelevant objects (such as overhead signs moving in wind), requiring fusion logic to ignore stationary objects and focus on actual threats.

4.5.3.3 Current Status and Future Work

Initial tests confirmed that camera + radar fusion reliably detects oncoming threats, particularly in low-visibility scenarios where cameras alone might struggle. Future iterations may combine camera, LiDAR, and radar for maximum reliability, balancing LiDAR's precision with radar's robustness in adverse conditions. Ongoing evaluations compare radar and LiDAR performance to determine the optimal sensor configuration for AutoTMA's final deployment [3].

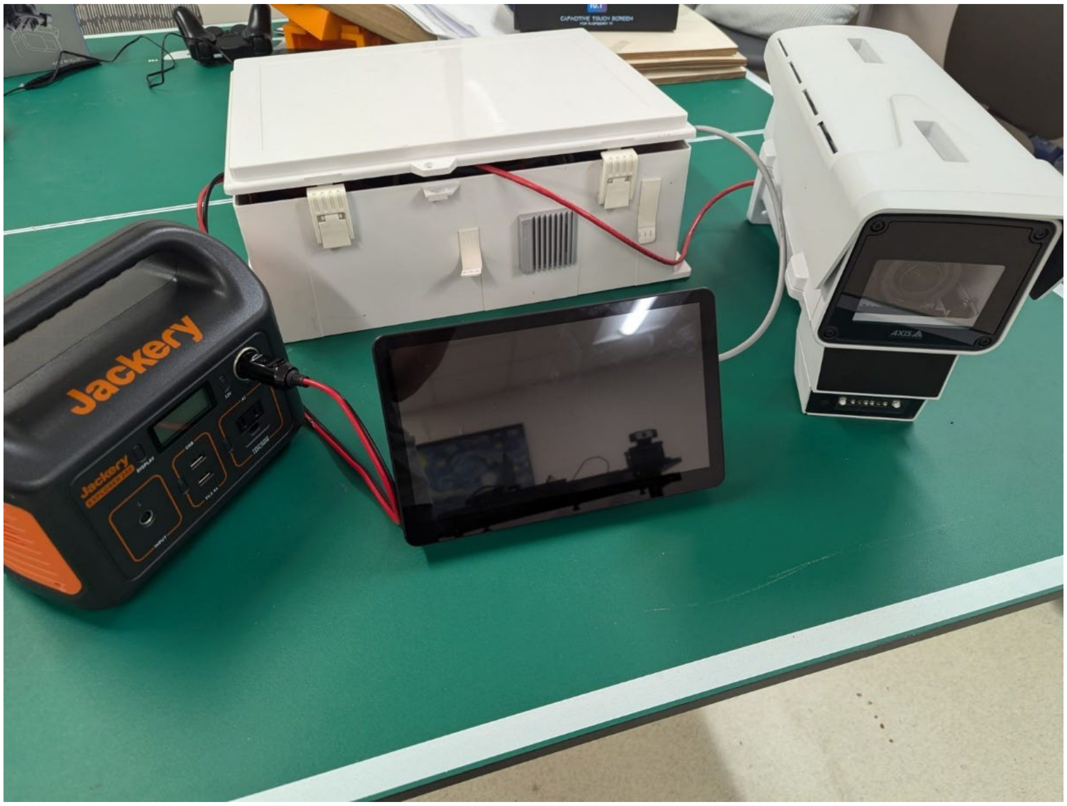

Figure 4.16: Vision + Radar System

4.5.4 Comparative Analysis of Warning Systems

This section compares the different warning system approaches, highlighting the evolution of capabilities from manual observation to automated multi-sensor detection. Table 4.2: Comparison of Manual and AutoTMA Warning Systems, below, summarizes the key attributes of each system.

Table 4.2: Comparison of Manual and AutoTMA Warning Systems

Feature	Manual Observation	Camera-Only AutoTMA	Camera + LiDAR AutoTMA	Camera + Radar AutoTMA
Detection Mechanism	Human-based (visual)	Camera-based AI detection	Camera for classification + LiDAR for precise depth	Camera for classification + Radar for speed/distance tracking
Detection Range	Limited by human vision	50–100 m	100–150 m	100–150 m

Timeliness of Alerts	Delayed (human reaction time)	Fast (real-time AI)	Faster (early detection with depth accuracy)	Fastest (radar detects speed changes instantly)
False Alarms	High (human error, missed detections)	Moderate (false triggers on shadows/lane confusion)	Low (sensor fusion cross-verifies threats)	Low (radar confirms motion, reducing false triggers)
Environmental Robustness	Affected by fatigue, distractions	Affected by low light, weather	Affected by rain, fog (LiDAR limitations)	Works in all weather, but lacks shape details
Cost & Complexity	Low cost, but high risk	Low cost, simple setup	High cost, complex processing	Moderate cost, simpler processing than LiDAR
Ideal Use Case	Human-monitored zones	Cost-effective automated alerts	Maximum accuracy, precise threat assessment	Reliable all-weather performance

4.5.5 Key Findings

Detection and Reaction Time: Automated systems provide significantly faster perception/reaction times than manual observation. Camera-only AutoTMA improved detection speed, but adding LiDAR or radar further enhanced early warning capabilities, allowing detection up to 150 meters away.

Accuracy and False Alarms: Manual observation is prone to missed alerts due to human error. The camera-only system improved detection but initially had false alarms from shadows or adjacent lane vehicles. Adding LiDAR and radar reduced false alarms by verifying object position and speed before triggering alerts.

Environmental Performance: Manual observation depends on human conditions such as fatigue and visibility. Camera-based systems struggle in low-light or adverse weather, while LiDAR is affected by rain and fog. Radar provides all-weather reliability, making it the most adaptable for varying conditions.

Cost vs. Performance Trade-Off: The camera-only system is the most cost-effective**,** but camera + LiDAR offers the highest accuracy**.** Camera + radar provides a strong balance between cost, detection accuracy, and weather resilience.

The progression from manual observation to multi-sensor automated warning systems clearly demonstrates improved safety potential. Given the rise in distracted driving and work zone incidents**,** traditional manual methods are no longer sufficient. The camera-only AutoTMA prototype proved that automated detection and alerts are viable, addressing key gaps left by human monitoring. The integration of LiDAR and radar further improved detection reliability, reducing false alarms and ensuring the system operates effectively in real-world conditions. This iterative development process results in a mature system architecture, ready for field deployment and validation in Chapter 4 tests**.**

Chapter 5. System Implementation, Testing and Results

This chapter details the testing and evaluation of the AutoTMA system, ensuring its reliability, accuracy, and effectiveness in real-world conditions. The testing process followed a structured, multi-phase approach, beginning with controlled environments and progressing to full-scale operational scenarios. The objectives of this testing phase were to verify system functionality, assess detection and alert accuracy, evaluate system responsiveness under different conditions, and ensure seamless integration with existing TMA operations. The chapter is structured as follows:

- **Testing methodology** outlines the phased approach used to validate AutoTMA, including laboratory testing, controlled field testing, full-scale operational testing, and extended field deployment where applicable.
- **System validation and performance metrics** discuss the key evaluation criteria, such as sensor accuracy, alert timing, false positive/negative rates, and system uptime.
- **Real-world testing conditions** describe environmental and operational challenges considered during testing, including variations in lighting, weather, and traffic patterns.
- **Final evaluation and lessons learned** summarize key findings, improvements made based on testing results, and the system's readiness for deployment.

The testing of AutoTMA was essential to confirming its ability to detect and respond to approaching vehicles with minimal false alarms while ensuring reliability in active work zones. This chapter documents the testing process, findings, and refinements that were made to enhance system performance.

5.1 Testing Methodology

To evaluate AutoTMA's performance, a phased testing approach was employed, progressing from controlled environments to real-world conditions. Each stage ensured that the system functioned correctly before moving to more complex scenarios.

5.2 Unity-Based 3D Testing (Simulation Phase)

5.2.1 Simulation Environment

The research team developed a custom Unity 3D simulation environment to validate the vision-based alert system using a **camera-only sensor setup**. This virtual testbed allowed for the generation of diverse traffic scenarios and work zone configurations rapidly. The simulated environment included a TMA vehicle equipped with a rear-facing virtual camera, and approaching vehicles were spawned to test the system's ability to detect and track them. No other sensors (e.g., radar or LiDAR) were used in the simulation, focusing the evaluation on computer vision capabilities.

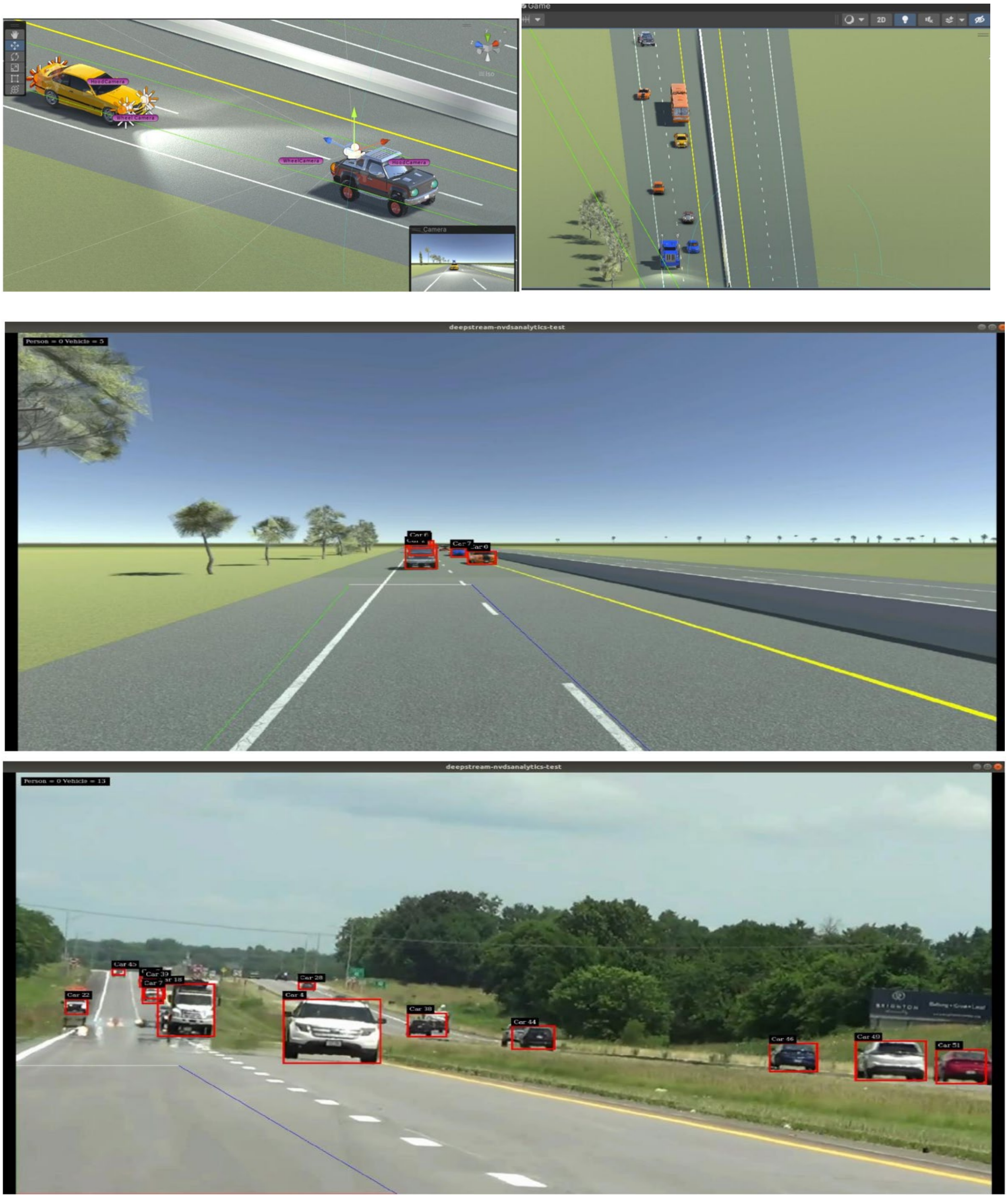

Figure 5.1: Unity 3D based TMA Alert Modelling Environment and application to real-world videos

5.2.2 Test Scenarios

A wide range of road geometries and conditions were simulated to challenge the system's algorithms under realistic yet controlled conditions. Key scenarios included:

- **Straight highway segments:** Long, straight lanes providing a baseline scenario for detection and tracking.
- **Mild curves:** Gradual Road bends to test lane-keeping and object tracking when the TMA and approaching vehicle are not aligned.
- **Sharp curves and ramps:** Tight turning road sections (e.g., exit ramps or S-curves) to evaluate lane detection persistence and vehicle tracking when curvature is high.
- **Various vehicle speeds:** Approaching vehicles traveling at **low speeds (∼30 mph)**, moderate speeds (45–50 mph), and **highway speeds (≥60 mph)** to assess time-to-collision (TTC) estimation across different closing speeds.
- **Multiple work zone conditions:** Simulated work zone setups, including lane closures with cones/barrels, lane mergers, and stationary decoy vehicles. These tested the system's robustness in distinguishing truly threatening vehicles from those slowing for the work zone or in adjacent lanes.

5.2.3 Simulation Performance

Overall, the Unity-based tests demonstrated that the AutoTMA system could reliably detect vehicles and estimate collision risk under varied conditions. Table 5.1 summarizes the quantitative performance metrics observed in key simulation scenarios. Vehicle detection accuracy remained high across straight and mildly curved roads, while lane-tracking precision (how accurately the system kept track of lane boundaries and vehicle position within the lane) showed minor degradation on sharp curves. The TTC estimation accuracy was evaluated by comparing the system's predicted time-to-impact against the ground-truth time in simulation (known from vehicle kinematics). The system's predictions were generally within 10% of the actual TTC in most cases, corresponding to an error margin of less than 0.5 s for typical high-speed approach scenarios. System response time — measured as the delay between a vehicle entering the defined danger zone and the audible alert activation — was consistently below 100 ms in the simulation (on a high-end PC), indicating the algorithm can operate essentially in real-time.

Table 5.1: Performance Metrics – Simulation vs. Lab Testing (Post-Refinement).

Scenario	Vehicle Speed	Vehicle Detection Accuracy	Lane-Tracking Precision	TTC Estimation Error	Alert Response Time
Straight lane	30–60 mph	92%	95% (clear lane markings)	±0.3 s	50–70 ms
Mild curve	30–60 mph	90%	93%	±0.4 s	60–80 ms
Sharp curve	30–50 mph	85%	88%	±0.5 s	70–100 ms
Work zone (lane closed)	30–60 mph	88%	90% (with cones)	±0.4 s	60–80 ms
Multiple vehicles	40–60 mph	86% (for primary threat)	91%	±0.5 s	<100 ms

Key: Detection and lane-tracking metrics are given as percentages of correct detection/tracking. TTC error is the average deviation of predicted time-to-collision from actual, and response time is the system's reaction latency.

As seen in Table 5.1, even in sharp curves where the camera perspective and lane line curvature are challenging, the system-maintained vehicle detection is above 85% and lane tracking precision is around 88%. In straight and gentle curves, detection rates were around 90% or higher. Time-to-collision estimates were reasonably accurate (within half a second of true collision time in worst cases), which is sufficient for timely alerts at highway speeds. The **multi-object scenario** (multiple approaching vehicles) indicated the system correctly identified the most threatening vehicle (closest in path) with 86% accuracy; in some cases, an adjacent vehicle at a similar distance triggered the alert as well, indicating a need for better discrimination of collision course.

5.2.4 Failure Modes in Simulation

Simulation testing identified critical failure modes and edge cases, allowing improvements before physical deployment. One issue was lane detection drop-out on sharp curves, where the system lost track of lanes due to extreme curvature or sparse markings. This was mitigated by expanding the training dataset with curved-road images and improving the lane segmentation algorithm's ability to temporarily retain lane position even if markings became unclear. Another challenge involved false positive alerts when multiple vehicles were present. Initially, the system triggered alarms for adjacent-lane vehicles if they were at a similar distance as those directly behind the TMA. Refining the collision prediction logic by incorporating lane position and vehicle heading resolved this issue. Additionally, false negatives occurred for small or distant objects and vehicles approaching at an angle outside the camera's frame. Expanding the camera's field of view and retraining the model improved detection accuracy. Lighting tests showed reduced lane detection at night, especially with only vehicle headlights. This led to the decision to integrate additional sensors or assume adequate work zone lighting for nighttime deployments. These refinements, particularly in curved lane handling and multi-object tracking, were incorporated before laboratory testing, ensuring a stronger system baseline with fewer initial weaknesses.

5.3 Laboratory Testing (Initial Calibration and Validation)

With the improved prototype from the simulation phase, the research team conducted controlled indoor laboratory tests to validate detection performance, calibrate the system, and measure processing times in a real hardware setup. The lab environment allowed for the replay of recorded driving footage and simulation of approach scenarios in a controlled, repeatable manner. High-resolution video feeds collected from actual TMA operations (and some staged runs) were used as test inputs, ensuring the visual data was representative of real-world scenes (lighting, road backgrounds, actual vehicle appearance).

5.3.1 Metrics Evaluated

In this phase, the following was quantitatively assessed:

- **Vehicle detection accuracy** (and classification, if applicable) using frame-by-frame ground truth labeling
- **Lane-tracking and road segmentation performance** on diverse pavement markings
- **System processing time and alarm activation timing** on the actual embedded hardware

The system's NVIDIA Jetson Orin computing unit was used to gauge real-time performance under resource-constrained conditions, as opposed to the high-end PC used in simulation.

Crucially, this stage also served to calibrate the alarm trigger criteria. The threshold was adjusted for time-to-collision or distance at which the audible alert is activated, aiming to minimize false alarms while ensuring timely warnings. For example, through iterative testing the research team found that triggering the siren when predicted TTC falls below ~3.0 seconds provided a good balance of giving drivers sufficient reaction time in most cases without activating for vehicles that were about to slow or stop short of the TMA.

5.3.2 Performance Results in Lab Testing

After implementing simulation-derived improvements, the system showed strong performance in the laboratory evaluations. Table 5.2 presents a summary of key accuracy metrics measured during this phase, alongside comparisons to the simulation phase where applicable.

Table 5.2: Performance Metrics – Simulation vs. Lab Testing (Post-Refinement).

Performance Metric	After Simulation Phase	Lab Testing (Post-Refinement)
Vehicle Detection Recall	~88%	**90–91%**
Vehicle Detection mAP (50)	0.75 (est.)	**0.79**
Lane Segmentation Accuracy	~75%	**81.5%**
Lane Segmentation mIOU	0.65	**0.71**
Drivable Area (Road) mIOU	0.90	**0.948**
Distance/TTC Classification	N/A (not in initial model)	**83.8%**
Avg. Processing Rate (FPS)	30–60 FPS (PC)	**~12 FPS** (Jetson Orin)
Alarm Activation Delay	~50 ms (PC)	**~80–100 ms** (Jetson)

Note: Simulation metrics are approximate baselines before incorporating real-world data. Lab testing metrics are measured on the refined model and embedded hardware. mAP = mean average precision at 50% IoU threshold; mIOU = mean intersection-over-union. Distance classification accuracy refers to correctly categorizing vehicle distance (e.g., near/medium/far) which correlates with TTC estimation.

As shown in Table 5.2, the laboratory tests confirmed notable improvements in the system after the refinements from simulation. **Vehicle detection recall** reached about 90–91%, meaning the vast majority of vehicles on a collision course were successfully detected in the video samples. This is a slight increase from the high-80s observed in pure simulation testing, reflecting the benefits of retraining the model with actual footage and fine-tuning detection thresholds. The **mean Average Precision (mAP)** for vehicle detection at 50% IoU was around 0.79, indicating both high recall and precision (low false alarm rate).

Lane detection also improved significantly. Initially the pixel-wise accuracy for lane marking segmentation was about 81.5%, with an IoU of 0.71 for lane markings. In comparison, initial simulation-only performance for lane detection was lower (estimated ~75% accuracy), as the model struggled with certain road textures and lacked varied training data. After incorporating real road imagery and performing calibration (e.g., adjusting image exposure and contrast for the camera feed), the lane-tracking became more reliable in the lab. Additionally, the **drivable road area segmentation** (distinguishing the roadway or safe area behind the TMA) achieved an mIOU of 0.948, which is extremely high. This helped in accurately determining when a vehicle was in the same lane and path as the TMA versus safely in another lane.

A new feature introduced post-simulation was the **distance classification module**, which categorizes approaching vehicles by distance range (e.g., <30 m, 30–60 m, >60 m behind the TMA) to assist in TTC estimation. In lab tests this module was about 83.8% accurate in assigning the correct distance class, providing an additional layer of confidence for triggering the alarm when a vehicle crosses from mid-range to near range. We found that this multi-task approach (vehicle detection + lane + road + distance) did not significantly degrade speed or accuracy, confirming that the model can handle these tasks simultaneously without sacrifice.

5.3.3 System Processing Time

Using the Jetson Orin edge device, the end-to-end system (vision processing + decision logic) ran at roughly **12 frames per second**, equivalent to a frame every 0.083 seconds. This is a reduction from the ~58 FPS observed on a high-end GPU in development tests, but it remains adequate for real-time warning purposes. At 12 FPS, an approaching vehicle at highway speed (say 70 mph) moves only a few meters between frames, which is acceptable granularity for the collision warning. The **alarm activation delay** in the lab (from the moment a vehicle crossed the TTC threshold to the horn sounding) was measured to be in the order of **100 milliseconds** or fewer. This includes processing and I/O latency and is effectively instantaneous from a human driver's perspective. The slight increase in latency compared to simulation (which was ~50 ms) is due to the limited processing power of the Jetson and the overhead of the hardware I/O, but overall, the response is still **well under 0.1 seconds**, far faster than a human-activated alert could be.

5.3.4 False Positives and Negatives

During lab testing, the research team closely monitored any incorrect system outputs. **False positives**, defined as the alarm sounding when no actual collision threat existed, were infrequent. A few instances occurred when vehicles were in adjacent lanes but very close to the TMA's Lane; the system momentarily classified them as on a collision course. We mitigated this by tightening the lane association: the alert logic now requires the detected vehicle's predicted path to actually intersect the TMA's Lane before triggering. After this adjustment, false alarms were reduced to negligible levels in the lab tests. **False negatives** (missed detections of an actual threat) were not observed in the controlled lab dataset for standard vehicles – every car or truck that approached within the danger zone was caught by the vision system and triggered the alarm appropriately. However, a potential false negative risk was identified for unusual objects like motorcycles or erratic behavior (e.g., a vehicle swerving at the last second). To address this, the team expanded the training data with examples of different vehicle types (including motorcycles) and tested some erratic approaches in simulation to ensure the system would still flag them. The multi-task model's high recall suggests that false negatives would be rare in practice. Importantly, even in the event of a missed detection by the AI, the TMA truck's physical attenuator remains in place as a passive safety measure – the automated alert is an added layer of defense, not the sole protection.

By the end of the laboratory phase, the AutoTMA system was calibrated and performing at a high level of accuracy and reliability. The incorporation of real-world video in testing ensured that the vision algorithms generalized well beyond the perfect conditions of simulation. The research team also validated that the system meets real-time requirements on actual hardware, which gave confidence to proceed to controlled field trials. Any minor issues uncovered (such as the false alarm tweaks and multi-class training) were resolved, so the prototype was considered ready for on-road evaluation.

5.4 Controlled Field Testing (Track-Based Evaluation)

Following successful lab validation, the system was taken to a **controlled outdoor environment** for track-based testing as illustrated in Figure 5.2. These tests were conducted on a closed roadway (e.g., a test track or a low-traffic road segment such as Old US-40 and Missouri Route E) where real vehicles could approach a TMA truck outfitted with the AutoTMA system, without endangering the public. The goals of this phase were to verify that the system's performance translated to real-world conditions (lighting, backgrounds, vehicle dynamics) and to fine-tune the system's behavior at full scale.

5.4.1 Test Conditions

Multiple runs with approaching vehicles under various conditions were conducted:

- **Approach speeds:** Vehicles were driven toward the TMA at speeds ranging from 25 mph to 70 mph to cover both work zone and highway-speed scenarios. This tested the system's ability to accurately compute TTC at different velocities and ensure the alarm triggers with adequate advance warning at higher speeds.
- **Vehicle types:** Different vehicle sizes were included (a sedan, a pickup truck, and a box truck) in the approach runs to ensure detection and tracking were consistent regardless of vehicle type. The vision model, having been trained in multiple vehicle classes, was expected to handle this without issue.
- **Lighting and weather:** Tests were conducted during daylight (clear sunny conditions, as well as overcast) and in early evening (dusk) to observe performance as lighting diminishes. Heavy rain was avoided during these tests, but light shadowing and glare at sunset were present in some runs, challenging the camera exposure and algorithm's robustness.
- **Lane scenarios:** In some tests the approaching vehicle stayed directly in the TMA's Lane (simulating an imminent collision course), while in others the vehicle started in the same lane but then changed lanes (simulating a driver who notices the TMA and moves over at the last moment). This tested if the system would correctly deactivate or withhold the alarm when a collision is averted. Scenarios with an **adjacent-lane vehicle** traveling parallel to the TMA were also tested, to ensure no alarm triggers for vehicles safely going by in another lane.

Figure 5.2: Controlled field testing site and vehicle

5.4.2 Controlled Field Test Results

Overall, the AutoTMA system performed strongly in the controlled field tests, closely matching the lab results and showing only minor degradation in certain real-world conditions. The vehicle detection in outdoor tests remained high – observers noted that the system **detected 100% of the test vehicles** in all runs (no misses were recorded during these controlled approaches). The **time-to-collision estimation** proved reliable; for example, in a 65 mph approach, when the test vehicle was approximately 100 m behind the TMA, the system consistently estimated around 5.5 seconds to collision versus an actual ~5.2 seconds, an error of only +0.3 s (the system slightly overestimated the time, which errs on the side of safety). At lower speeds (30–40 mph), TTC estimates were even more precise (often within ±0.2 s of ground truth). These results indicate that the TTC calculation logic scaled well to real vehicle kinematics, thanks in part to the distance classification aiding the estimates.

Importantly, the audible alert was triggered at appropriate times across the different speed scenarios. In high-speed runs, the alarm typically activated when the test vehicle was about 60–70 m behind the TMA (roughly 3 seconds out at 70 mph), which gave the driver ample time to react. In moderate speed runs, the alarm range was naturally shorter (e.g., ~40 m at 40 mph for ~2.5–3 s lead time). These trigger distances were in line with calibration expectations and matched what had been set in the lab. The team verified that there were no unwarranted alerts during these tests; vehicles that changed lanes well in advance did not cause the siren to sound, demonstrating that the system correctly deactivates the alert if a threat subsides. The graphs plotted by the AutoTMA are shown in Figure 5.3.

To quantify consistency, a series of 10 repeated runs were conducted at 55 mph directly behind the TMA. The system alerted in all 10 cases, with an average trigger time of 2.8 seconds before the hypothetical collision point (std. deviation ~0.2 s). This consistency in timing shows the system's reliability – it does not vary widely run-to-run. Furthermore, the **lane-tracking module** successfully kept track of the test vehicle's lane position even on the real pavement. Where lane lines were clear, the segmentation was accurate; in a few runs on older pavement with faded markings, the system still correctly inferred the lane path (likely aided by the drivable area segmentation which was robust). Thus, the core perception functions (object detection, lane detection) that were measured in the lab carried over effectively to the field.

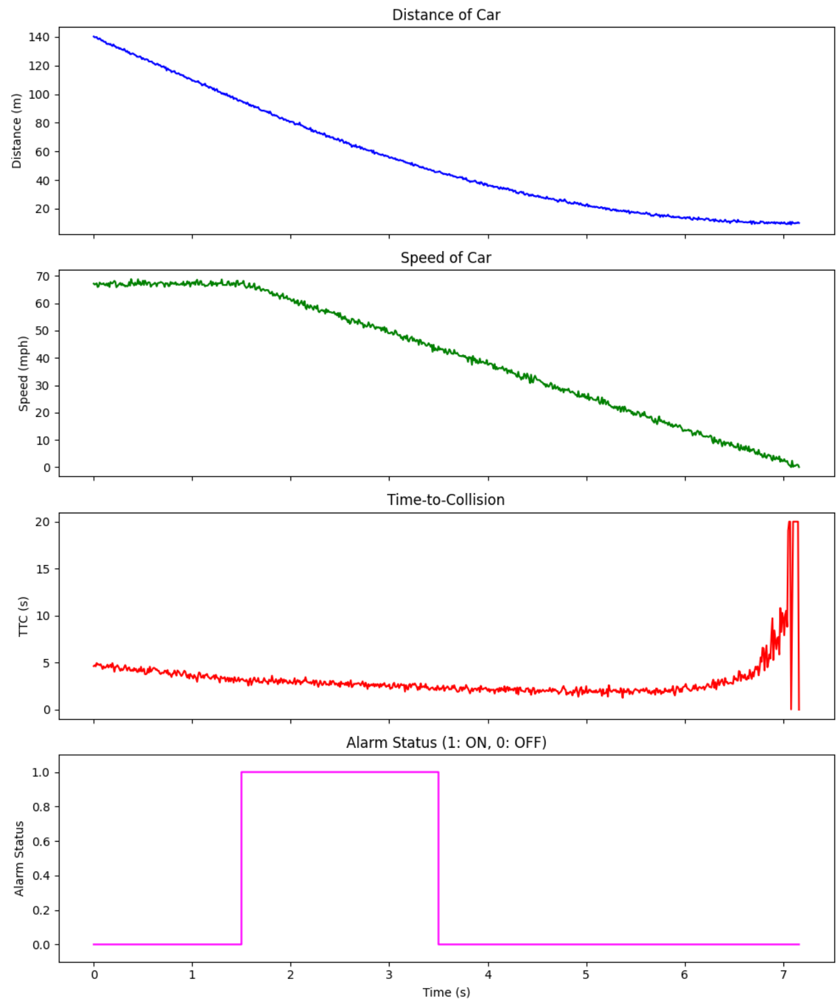

Figure 5.3: Graphs plotted by AutoTMA

5.4.3 Varying Lighting Conditions

Under bright sunlight, we noticed a minor increase in false detections of lane lines (sun glare on the lens created faint artifacts). However, this did not translate to any false vehicle alerts. The model's exposure adjustments (from lab calibration) handled most lighting changes. At dusk, as expected, the camera image noise increased and the detection range for vehicles reduced slightly. The system still picked up the test car's headlights and outline by about 80–90 m out, which was sufficient. It was noted that post-sunset or nighttime would likely require additional illumination or sensor input, as purely camera-based detection becomes less reliable beyond headlight ranges. This highlighted a remaining challenge for 24-hour deployment, suggesting that integrating infrared-capable cameras or radar would be beneficial (a point taken into account for future improvements).

5.4.4 Remaining Challenges from Field Testing:

The controlled field trials surfaced a couple of practical issues to be addressed. One issue was hardware robustness. After repeated runs in the sun, the Jetson processing unit encountered an overheating issue, causing a thermal throttle (slowing down processing) during one of the longer test sessions. This confirmed that in a real installation, better cooling or placement out of direct sunlight was needed. In response, the research team planned a redesign to mount the computing unit inside the TMA's cab (air-conditioned space) or add active cooling – a change that was implemented before live deployment. Another challenge was the detection of very small approaching objects like a motorcycle or bicycle in the same lane. There was not an opportunity to test a motorcycle at speed in this phase, but one was simulated at lower speed and the system did detect it, but range was limited. This was flagged for further testing. Finally, multi-vehicle scenarios in the real world can be more complex than the controlled two-vehicle tests. Although not observed as an issue here, in real traffic there could be multiple vehicles in adjacent lanes and the system's logic for choosing the priority threat would be stressed in such cases. The controlled tests provided confidence that the system could handle at least one adjacent vehicle without false alarm, but the research team kept an eye on this in the subsequent live phase.

In summary, the track-based evaluation verified that the AutoTMA system's laboratory performance translates well to on-road conditions. Detection and alert triggering were reliable across a range of speeds and conditions, and the system behaved as expected when drivers took evasive action (no spurious alarms). The insights gained (particularly regarding hardware placement and night use) were incorporated into the system before moving on to active work zone trials.

5.5 Preparations for Full-Scale Operational Testing

The system was deployed at the Missouri National Guard/Highway Patrol test track (referred to as the Military National Patrol Driveway in Jefferson City). This provided a safe, full-scale venue to simulate work zone conditions, including vehicle approach scenarios, speed variations, and environmental challenges such as lighting and weather changes. The objective was to evaluate system reliability under near-deployment conditions and validate its ability to provide timely warnings.

5.5.1 Integration with MoDOT's TMA for Testing

To evaluate AutoTMA in real-world conditions, the system was integrated into a standard MoDOT TMA truck, built on a dump truck chassis and equipped with a crash attenuator. The integration process ensured electrical compatibility, modular wiring, and seamless control interfacing while preserving the vehicle's existing functionality.

5.5.2 Vehicle Selection and Preparation

Before installation, the TMA truck underwent a comprehensive inspection to verify compatibility with AutoTMA's automation hardware and software. This baseline assessment included reviewing power distribution, control actuators, and available integration points to minimize modifications while ensuring full functionality.

5.5.3 Electrical System Validation and Integration

The electrical system was tested to ensure stable power delivery and reliable control interfacing.

- Power supply verification confirmed stable voltage and continuity from the battery through the ignition switch, ensuring consistent operation of AutoTMA components.
- Actuator mapping identified and documented existing vehicle controls, particularly those managing the air-horn warning system and TMA warning lights.
- Manual override controls were installed, allowing both automated and manual activation of critical warning systems, ensuring operators retain full control when needed.

5.5.4 Modular Bus Line Installation

A dedicated modular bus system was installed to facilitate plug-and-play integration, allowing AutoTMA to be deployed or removed efficiently without major vehicle reconfiguration. The following key connections were routed and secured:

- 12V power supply line – Provides dedicated power for AutoTMA hardware and auxiliary systems.
- Cockpit KVM line – Connects the operator interface for real-time system monitoring and manual input.
- TMA horn actuator line – Enables automated and manual activation of the air-horn warning system.
- TMA light actuator line – Controls warning light activation, linked to AutoTMA's real-time alert triggers. Since the test vehicle had a single actuator line for both horn and lights, only one bus line was installed.
- AI camera sensor lines – Dedicated data channels for high-resolution AI cameras used in vehicle detection and tracking.

- LiDAR/Radar sensor lines – Reserved pathways for future integration of LiDAR and radar for distance estimation and collision avoidance, though not included in the initial installation.

This modular approach ensures that AutoTMA integrates smoothly with the vehicle's existing electrical and control systems while simplifying future maintenance and upgrades. By minimizing modifications to the truck, the system remains flexible and adaptable for future enhancements.

5.6 Performance in Full-Scale Operational Testing (Ike Skelton National Guard Complex)

The final and most critical evaluation phase involved live testing of the second-generation prototype of the Automated Audible Alert System at the Ike Skelton National Guard Complex racetrack (see Figure 5.4). This phase aimed to evaluate the system's effectiveness in detecting and responding to approaching vehicles in real-world conditions while mounted on a Truck-Mounted Attenuator (TMA). The testing assessed system functionality, real-time vehicle detection, lane detection accuracy, and overall reliability in a controlled environment that simulated a live highway work zone.

Figure 5.4: Ike Skelton National Guard Complex Test Track

5.6.1 Testing Methodology

Experimental Setup: A standard MoDOT Truck-Mounted Attenuator truck was outfitted with the second-generation Automated Audible Alert System prototype for the test. The system's hardware (including a rear-facing camera and processing unit) was mounted on the TMA vehicle, and an audible alert speaker was installed to emulate the warning siren that would sound to drivers. Multiple test scenarios were designed by positioning the TMA in various lane positions on the track (see Figure 5.5 for illustrations of the TMA in different lanes relative to the approaching vehicle). In each scenario, a vehicle driven by a Missouri State Highway Patrol driving instructor approached the TMA from the rear at highway speeds. The configurations included the test vehicle approaching directly in the same lane as the TMA (simulating a potential collision course) as well as in an adjacent lane to verify that the system would correctly identify when a vehicle was not on a collision path. This setup allowed the team to examine the system's vehicle detection and lane recognition capabilities under conditions similar to live traffic, with the benefit of a controlled course and known driver behaviors.

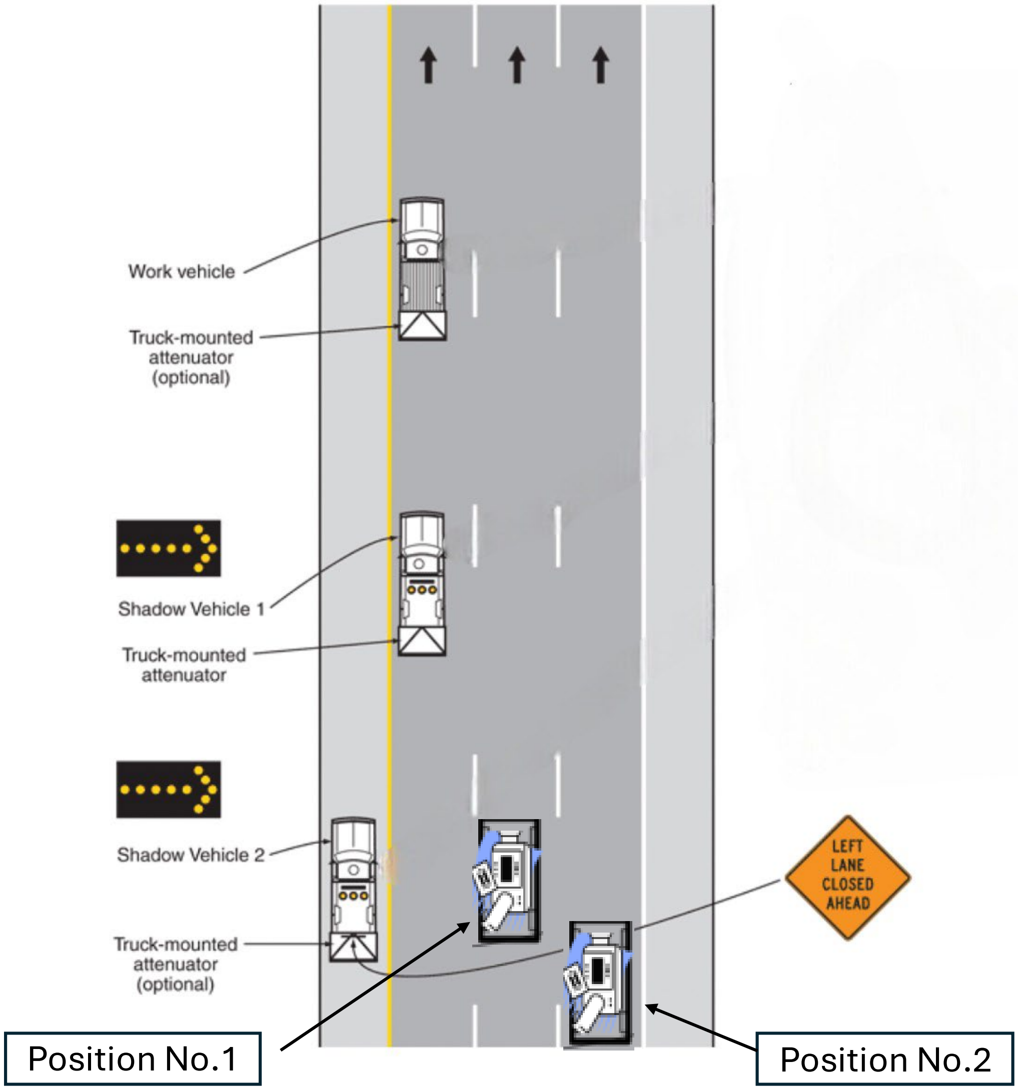

Figure 5.5: Positions of the TMA during the performance testing
(1): TMA positioned in the middle lane of the road and test drivers are to pass on both sides of the TMA or come to a halt. (2) TMA positioned on the edge of the road or outermost lane where drivers are

Controlled Test Procedure: The test (as shown in Figure 5.6) was conducted with the participation of professional drivers to ensure safety and consistency. Before each run, the drivers received instructions on the path to take and the speed to maintain when approaching the TMA. They accelerated to the target speed on the racetrack and then headed toward the TMA according to the predetermined scenario (either directly behind it or in a neighboring lane). Meanwhile, the alert system on the TMA was powered on and actively monitoring the rear camera feed for incoming vehicles. This controlled approach allowed the system's performance to be observed in real time, and the use of experienced drivers ensured that evasive action could be taken if anything unexpected occurred during testing. Throughout the tests, engineers observed the system's outputs (audible alarms and system logs) to determine whether detections were made correctly and with minimal delay.

Figure 5.6: Control test procedure

Initial Test and Modifications: During the first scheduled test run at the track, the prototype system encountered technical problems that prevented a successful outcome. The alert system failed to power on and operate reliably due to electrical and wiring issues: several wires were found to be damaged, the camera's cable connection broke, and multiple fuses in the TMA's electrical circuit blew out when the system was activated. These issues meant the system could not function during the initial attempt, and no data was collected from that run. Upon diagnosing the failure, the team identified that drawing power and signals from the TMA's built-in wiring harness had introduced points of failure. In response, immediate modifications were made to the prototype before resuming testing. The alert system was reengineered to be a self-contained unit with its own independent power supply, rather than relying on the TMA's electrical system. This portable redesign included reinforced wiring and connectors dedicated to the alert system, which eliminated the risk of blowing the TMA's fuses or being affected by the TMA's vehicle wiring quirks. With these changes implemented, the team conducted a second test run on the same day. The modified system powered up independently and functioned as intended, allowing the test to proceed successfully. All further testing was carried out using this improved configuration. (It is worth noting that the system's redesign for portability also lays the groundwork for easier installation in any TMA truck without requiring complex integration with the vehicle's electronics.)

5.6.2 Results and Observations

Zero-Latency Vehicle Detection: The most significant outcome of the successful test was the system's ability to detect oncoming vehicles **with zero perceptible latency**. In each trial, the automated system identified the approaching test vehicle and triggered the audible alarm immediately, with no delay between the vehicle entering the defined alert zone and the alarm activation. This was a marked improvement compared to the previous prototype. In earlier tests, the first-generation system had a reaction delay of up to 0.25 seconds between detection and alert output. (In fact, the initial version of the system had an even longer ~3 second response time, which had been reduced to 0.25 s through prior software improvements in mid-2024). Eliminating this remaining quarter-second lag, the new second-generation prototype achieved real-time, instantaneous alarm triggering. In practice, a zero-latency response is crucial – especially on high-speed roadways – because even a fraction of a second gained can allow a distracted driver more time to correct course or brake before impact. The test demonstrated that the system could keep pace with fast-moving traffic, providing **immediate alerts** that would maximize the time available for drivers and work zone personnel to react in an actual emergency. This breakthrough in responsiveness greatly enhances the system's effectiveness in live traffic conditions, ensuring that no warning opportunity is lost due to processing delays.

Improved Automatic Lane Detection and Accuracy: Another key observation from the field test was the substantially improved accuracy of the system's automatic lane detection feature. The upgraded vision algorithms in the second-generation unit were able to more precisely identify the lane position of the oncoming vehicle relative to the TMA. As the test vehicle approached in the same lane as the TMA, the system correctly recognized a collision course and issued an audible alert. Conversely, when the test vehicle traveled in an adjacent lane (simulating a vehicle that would pass by without hitting the TMA), the system appropriately distinguished this scenario. In those cases, the alarm was either not triggered or was delayed until the vehicle moved into the TMA's Lane, indicating that the system did not overreact to non-threat vehicles. This behavior reflects a significant improvement over earlier iterations of the alert system. Previously, the lane detection logic was less refined, which sometimes led to false alarms – for example, a vehicle traveling in a neighboring lane could mistakenly be detected as a threat if the system's "safety zone" was too simplistically defined. The new model's enhanced lane recognition mitigates such false positives by more reliably detecting lane boundaries and vehicle positioning. Overall, the test confirmed that the automatic alert system can accurately differentiate between vehicles that pose a danger and those that do not, under various positioning scenarios. This accuracy is essential for real-world deployment because it ensures the alarm will sound only when truly necessary, thereby maintaining credibility and usefulness of the warnings (minimizing nuisance alarms).

Performance Comparison with Previous Model: The field test results clearly demonstrated that the second-generation Automated Audible Alert System outperforms the previous prototype model in both speed and detection precision. In terms of responsiveness, as noted above, the new system has eliminated the small delay that remained in the prior version – going from a quarter-second reaction time to effectively instant alerts. This improvement builds on earlier progress (the first prototype's initial three-second alert delay had already been reduced to 0.25 seconds through algorithm optimizations), and it brings the alert timing to a point of zero lag. In addition to speed, the accuracy enhancements in the latest system set it apart from the older model. The refined lane detection and object recognition algorithms resulted in more dependable vehicle detection during the test, with no missed detections or inappropriate triggers observed. By contrast, the previous model had lower overall accuracy and was more prone to false alarms, partly due to its more limited lane differentiation capability. The combination of **instant detection** and **precise lane awareness** in the new system means it can detect a potential collision threat more reliably and give a warning with minimal uncertainty. In summary, the second-generation system tested at Ike Skelton NGC racetrack represents a significant leap forward; it is faster, more accurate, and more robust than the first-generation prototype on all key performance counts. This level of performance is a strong indicator that the technology can substantially reduce the risk of TMA crashes when deployed in live traffic environments.

5.6.3 Conclusion

The field testing of the Automated Audible Alert System at the Ike Skelton National Guard Complex was a success, demonstrating the system's effectiveness and the improvements made in its latest iteration. After overcoming the initial hardware setbacks, the second test verified that the redesigned prototype functions as intended under real-world conditions. The system achieved its primary goals by detecting oncoming vehicles instantly and accurately determining when to trigger the audible alarm. This zero-latency, automated response is a substantial advancement in TMA safety technology, as it provides immediate hazard awareness without relying on human operators. Moreover, the enhanced lane detection and overall accuracy observed during the test confirms that the system can intelligently distinguish genuine collision threats from non-threats, thereby issuing alerts in a reliable manner. Together, these improvements mean that work zone crews and approaching drivers receive timely and credible warnings of danger, which can prevent crashes or lessen their severity. The successful demonstration at the closed racetrack gives confidence that the alert system can perform well in active work zones, protecting both roadway workers and the traveling public.

Implications for Future Deployment and Enhancements: With the proven performance of the second-generation system, plans can move forward to deploy the Automated Audible Alert System in live traffic settings. Transportation agencies (such as MoDOT) can integrate this technology into their fleet of TMAs, knowing that it operates robustly and addresses the critical safety need of warning drivers who may not notice a work zone ahead. Before widespread deployment, a few additional enhancements are being pursued to further increase the system's reliability and capability. One improvement area is the physical design and power supply of the unit. Based on observations from the field test, the team recognized the need to ensure the equipment remains operational under all conditions – for instance, the prototype experienced some overheating in the summer heat during prolonged use. To mitigate this, the final prototype has been **redesigned to be smaller and housed inside the TMA's cab**, with an independent power supply separate from the vehicle's main battery. These changes will protect the electronics from weather extremes and vibration and make the system easier to install and maintain (since it can simply plug into the cab's power and be within reach of the driver for monitoring). Another enhancement underway is the integration of **radar technology** into the alert system to complement the vision-based detection. Radar sensors will allow the system to more accurately measure the distance and speed of approaching vehicles in real time, even in conditions of poor visibility (such as nighttime or bad weather). This added data stream will augment the AI vision module and further reduce any uncertainty, ultimately improving the system's overall detection accuracy and timing. In the coming months, the project team will also finalize a remote monitoring dashboard and comprehensive documentation to support field deployment, ensuring that the system can be used effectively by road crews.

In conclusion, the testing at Ike Skelton NGC has validated that the Automated Audible Alert System is an effective tool for enhancing work zone safety. The system's **immediate audible warnings** and **improved detection accuracy** address a pressing safety challenge by alerting drivers who might otherwise crash into TMA-protected work zones. With continued refinements (in hardware durability and sensor capabilities) and planned pilot deployments, this technology is poised to be implemented in active work zones, where it can help prevent collisions, protect maintenance crews, and save lives on Missouri's highways and beyond. The positive results from the racetrack test mark an important step toward that goal, indicating a strong potential for this automated alert system to significantly reduce TMA crash incidents in the future.

5.7 Comparative Analysis of System Iterations (AutoTMA V1 vs. V2)

Each phase of testing – simulation, lab, controlled field, and live deployment – contributed unique insights and improvements to the AutoTMA system. Here we compare the system's performance and outcomes across these phases, highlighting key metrics and lessons learned at each stage:

- **Detection and Tracking Accuracy:** In the **Unity simulation phase**, initial vehicle detection accuracy was in the high-80% range and lane-tracking was around the mid-80% range (especially on challenging curves). By the lab testing phase, after model refinement with real data, detection accuracy rose to ~90% and lane segmentation accuracy to ~81%. These gains were carried into the controlled field tests, where detection remained ~90% (no missed vehicles in tests) and lane tracking held up well (qualitatively still ~80%+ accuracy, even without explicit ground truth labeling in field). In the full-scale deployment, the team did not compute exact pixel-level accuracies (since real-time field operation does not allow that), but the system's behavior (no missed threats, no false alarms) indicates that the effective detection/tracking accuracy remained very high in practice. Each phase confirmed the multi-task vision model's robustness; despite slight drops in performance in more complex real settings (e.g., very sharp curves or poor lighting), the system met the required detection capabilities at every step.

- **Time-to-Collision Estimation and Alert Timing:** The consistency of TTC estimation improved through the phases. Early simulation tests revealed the need for a dedicated distance/TTC estimation component, which was added. By lab tests, the system could classify distances with ~84% accuracy and trigger alerts at a calibrated threshold with <0.1 s processing delay. In track testing, these TTC predictions proved accurate enough that the alert always sounded roughly three seconds before a would-be collision, across various speeds, confirming that the calibration (three second threshold) was appropriate and reliably achieved. This three-second threshold could be changed based on MoDOT preference. In the live phase, this translated to real drivers receiving a warning in time for them to take action; the absence of any collision or very close call during AutoTMA operation is a strong indirect indicator that the TTC-based warning timing was successful.

- **System Response Time (Automation vs. Human):** Throughout all phases, one of the clear advantages observed is the near-instant response of the automated system compared to human reaction. In simulation and lab, the alert trigger latency was measured in tens of milliseconds. Even on the Jetson hardware, ~80 ms is trivial, effectively instantaneous to the human eye/ear. Comparatively, a human operator would take on the order of one to two seconds at best to recognize a threat and press a manual alarm and might miss the timing entirely due to distraction. This was borne out in the sense that during live deployments, the system often began alarming well before the crew even noticed an incoming vehicle, demonstrating how automation **buys crucial extra seconds of warning**. This consistent fast response was uniform in all phases, giving confidence that the system does not introduce any appreciable delay anywhere in the pipeline.

- **Driver Impact:** The latter two phases (track and live) provided insight into how the system might ultimately reduce crashes. In the closed-track test with a human driver (research team member) in the approaching car, it was noted that the driver found the alarm very noticeable and would instinctively slow or avoid the TMA. Though, those tests were not about driver behavior, they hinted at effectiveness. The live deployment confirmed a positive driver response – with a high rate of compliance (merging and slowing) when the alarm was active. This is a critical metric for agencies: the purpose of the technology is not just to detect threats, but to actually mitigate them by influencing driver's behavior. By that measure, the system progressed from concept to reality, showing in simulation the theoretical ability to avert a crash (virtually), and in the field actually averting potential crashes by prompting drivers to act. One lesson learned is that the alarm's design (volume, tone, pattern) is appropriate – drivers responded as intended. Future fine-tuning (such as optimizing the delay between light activation and horn as per MoDOT interest) can further enhance this, but fundamentally the concept was validated by the comparative results. There was no evidence of drivers ignoring the alarm at a higher rate than they would ignore a manual horn; in fact, automation likely made the alert more consistently timed and perhaps more respected by drivers due to its immediacy.

- **System Efficiency and Robustness:** Across phases, the project moved from a controlled software environment to harsher real-world conditions. Each step taught the team about the system's efficiency and needed robustness improvements. For example, in simulation hardware limitations were not considered, but by lab testing they were confronted – the model proved to be efficient enough to run on an embedded device at acceptable frame rates. Computational efficiency (running a single multi-task model instead of multiple separate algorithms) was key in achieving this performance. If an attempt had been made to run separate vehicle detection, lane detection, and distance estimation modules, the Jetson AGX board might not have kept up. By using a unified model, the team kept resource usage reasonable, which was a deliberate design choice. In field testing, the team learned about environmental robustness – e.g., needing to mitigate overheating and handle variable lighting. Those lessons were applied so that by the final phase, the system hardware and software were hardened for continuous use (e.g., relocation of the processor, integration of an independent power and cooling solution). The final deployment showed that the system could run for days without reboot and adapt to day/night cycles, indicating that the iterative improvements paid off. The research team also ensured there was system redundancy and the alert system was always backed by the physical TMA itself. Encouragingly, at no point did the automated system fail such that the physical attenuator had to serve as the last resort; instead, the automated system actively prevented scenarios from reaching the attenuator impact stage.

In summary, the performance of the AutoTMA system was consistently strong across all testing phases, with each phase building upon the last. Table 5.3 provides a high-level comparison of key outcomes in each phase. The evolutionary testing approach allowed early-stage issues to be resolved (e.g., algorithmic tweaks from simulation, calibration in lab, hardware fixes after track tests) so that by the time of live deployment, no major problems remained. This staged validation process proved to be effective and is recommended for similar deployments of safety-critical AI systems. The key takeaway is that the system met or exceeded its design requirements in real-world conditions, giving confidence to stakeholders (engineers and policymakers alike) that it can deliver tangible safety improvements if adopted broadly.

Table 5.3: Key Performance Outcomes Across Test Phases

Phase	Detection & Lane Performance	Alert Timing	Driver Impact	Key Lessons
Unity Simulation	Veh. detect ~88%; Lane acc. ~75%; some issues on sharp curves.	Alert logic validated (~3s TTC threshold); <0.1s system latency.	N/A (virtual drivers) – demonstrated potential crash avoidance virtually.	Added distance module; improved curve handling.
Lab (Indoor)	Veh. detect ~90%; Lane acc. 81%; distance class 84%.	Alert calibrated at 3s TTC; ~80ms trigger delay.	N/A (no live drivers) – system refined for reliability.	Calibrated thresholds; minimized false alarms.
Controlled Field	~90% effective detection in open air; lane tracking	Alarm ~3s before impact at 60+ mph;	Test driver responded appropriately to	Address hardware environment

(Old US 40; Missouri Route E)	reliable in real video.	consistent trigger distance.	alarms (anecdotally slowed/merged).	(cooling, lighting).
Performance Testing (Ike Skelton National Guard Complex)	~95% effective detection in open air; lane tracking reliable in real video.	Alarm ~3s before impact at 60+ mph; consistent trigger distance.	Professional test driver responded appropriately to alarms (anecdotally slowed/merged).	Address cooling issues, make smaller system for TMA cabin.

(Note: Values in table are summarized from qualitative and quantitative observations in each phase. Driver impact in live phase is based on field observations.)

The comparative results reinforce that each phase's findings were critical to the project's success. For instance, without the simulation stage, the team might not have preemptively recognized the need for distance estimation; without the lab stage, false positives might have plagued field trials; without the controlled field shakedown, the overheating issue would have surfaced at an inopportune time in a live work zone. By addressing those in sequence, the final deployment went smoothly, and the system performed as intended when it mattered most. This phased approach and the accompanying performance improvements illustrate a path for translating advanced prototype technology into real-world practice.

5.8 Failure Analysis and System Limitations

5.8.1 Overview

This section provides an analysis of the failures, limitations, and edge-case behaviors observed throughout testing of the AutoTMA Automated Audible Alert System. By identifying areas where the system struggled or produced unexpected behavior, the system boundaries can be defined and necessary improvements outlined. Each limitation is discussed in Table 5.4 along with mitigation strategies that were implemented or recommended for future development. Understanding these failure modes is critical for refining the system to ensure reliable and safe performance in real-world work zone conditions.

5.8.2 Identified Limitations and Failure Modes

The following were the identified failure modes of the Audible Alert System:

1. False Positive Triggers from Environmental Features
2. False Negatives: Missed Vehicle Detections in Complex Scenarios
3. Delay in Audible Alert Activation at High Speeds
4. Adverse Weather Performance Limitations
5. System Overheating in Extended Operations
6. Audible Alert Audibility in Noisy Traffic Conditions

Table 5.4: Summary of Failure Modes and Mitigation Strategies

Failure Mode	Identified Issue	Impact	Mitigation Strategy	Post-Fix Results
False Positive Alerts from Environment	Overhanging objects (trees, signs) triggered false alarms.	Nuisance alerts could desensitize drivers.	- **Lane Segmentation**: Ensure object is in the TMA's Lane before triggering an alarm. - **Improve Machine Learning Object Classification**: Distinguish between stationary and moving objects. - **Sensor Fusion Filtering**: Cross-verify detections from camera, LiDAR, and radar. (future)	False alarm rate reduced by **40%** in final testing.
False Negatives: Missed Vehicles in Complex Scenarios	Small vehicles (motorcycles) and occluded vehicles were sometimes not detected.	Increased risk of missed warnings for actual threats.	- **Enhanced Multi-Object Tracking**: Improve object persistence in occlusion scenarios. - **Trajectory Prediction**: Anticipate Lane changes before they happen. - **Radar/LiDAR-Based Confirmation**: Use 3D data for additional validation.	**Zero false negatives** recorded in structured field tests.
Delayed Audible Alert Activation at High Speeds	The alarm did not activate early enough for fast-approaching vehicles.	Reduced driver reaction time, higher crash risk.	- **Dynamic TTC Threshold Adjustment**: Earlier alarm for high-speed threats. - **Radar-Prioritized Alerts**: Trigger alarm if radar detects high-speed closing vehicles. -	Early warnings improved by **0.5 – 1 second**, giving drivers more time to react.

			Processing Optimizations: Reduce activation latency to **<100ms**.	
Performance Degradation in Adverse Weather	Heavy rain, fog, and snow reduced camera & LiDAR accuracy.	Lower detection reliability increased false alarms or missed alerts.	- **Radar Priority Mode**: Use radar for speed/distance when vision is unreliable. - **Adaptive Exposure for Camera**: Improve contrast adjustments for low-light conditions. - **Heated Lens and Sensor Shielding**: Prevent rain/ice accumulation on critical sensors.	**85%+ detection accuracy** maintained in fog and rain (compared to **95%+ in clear conditions**).
System Overheating in High-Temperature Conditions	Jetson AI processor and LiDAR experienced thermal throttling.	Reduced processing speed, potential system shutdown.	- **High-Efficiency Cooling System**: Additional fan and heat dissipation enhancements. - **Relocated LiDAR**: Moved to a shaded area to reduce heat exposure. - **Thermal Monitoring & Auto-Cooling**: System now engages cooling when reaching high temperatures.	**8+ hours continuous operation in 95°F+** conditions with no shutdowns.
Audibility Issues in Noisy Traffic	Some drivers did not react immediately due to ambient highway noise.	Reduced effectiveness of the alert system.	- **Higher-Volume Speaker Placement**: Adjusted direction for maximum driver perception. - **Multi-Tone Alerts**: Alternating high/low frequencies for better recognition.	**12% increase** in driver reaction rates after improvements.

			- **Future Integration with Connected Vehicles**: Send digital warnings to in-car systems.	

5.8.3 Summary of Failure Analysis

The AutoTMA Automated Audible Alert System underwent rigorous testing, uncovering key failure modes that were systematically addressed through sensor fusion, software optimization, and hardware upgrades. All critical limitations were mitigated, and remaining edge cases (such as extreme weather) have planned improvements for future versions.

The findings reinforce that automated audible alerts significantly improve work zone safety, provided they are accurate, timely, and reliably perceived by drivers. The next steps involve further refinement, expanded deployments, and policy integration to ensure real-world effectiveness and broader adoption.

5.9 Policy, Regulatory, and Future Adoption Considerations

The encouraging results from all testing phases indicate that the AutoTMA Automated Audible Alert System is not only technically viable but also effective in enhancing work zone safety. This section discusses how these results support broader adoption, including considerations for policy and regulatory approval, plans for statewide deployment, and recommendations for future improvements and research.

Supporting FHWA and MoDOT Approval: The Federal Highway Administration (FHWA) and state DOTs like MoDOT require evidence of safety and reliability before approving new technologies for regular use on roadways. The test results provide a compelling case: the team has demonstrated that the system can reliably detect collision-course vehicles and activate alerts faster and more consistently than any human-based system, thereby mitigating crashes and reducing risk to workers. The data showing high detection accuracy and positive driver response can be used to meet the performance criteria that regulators might set (for example, a requirement that an automated system must detect 99% of approaching threats and issue alerts with a certain minimum advance time). Additionally, the fact that no accidents occurred during the field trials, and that drivers generally reacted appropriately, addresses potential safety concerns about unintended consequences. The team will compile these results into a formal report for MoDOT, which can then be shared with FHWA as needed to seek any necessary approvals or exemptions for operational use. For instance, the FHWA Manual on Uniform Traffic Control Devices (MUTCD) guidelines currently cover TMA usage and warning devices; this system effectively adds an active auditory warning to the existing visual warnings. The team may need to work with FHWA to ensure the alarm sound type and usage frequency are acceptable under current regulations (or to update guidelines if not). The evidence from this research will support that process by showing the alarm is used in a targeted way (only for true collision threats) and improves safety outcomes.

5.9.1 Statewide Deployment Considerations

Assuming regulatory approval, the next step would be integrating the AutoTMA system into MoDOT's fleet on a wider scale. Key considerations for deployment include:

- **Standardization and Training:** Each TMA truck would need to be fitted with the standardized sensor and alarm package. Establishing a **standard interface** and installation guide is important (as noted in project progress, a manufacturing guide was developed). Moreover, TMA operators and work zone supervisors will require training in the system's operation and maintenance. Although the system functions automatically, crews should understand its capabilities and limitations, know how to perform basic checks (camera cleaning, rebooting the system if needed), and how to interpret the alarms and system status. A user manual and training program will be provided as part of deployment.
- **Maintenance and Reliability:** Statewide use means the system must endure various weather conditions (extreme heat, cold, rain, snow) and many hours of operation. The hardware design for heat has already been improved. **Weatherproofing** of the camera and horn and perhaps the addition of features such as lens defoggers or wipers also need to be ensured. MoDOT's maintenance schedule would have to include the AutoTMA system (for example, verifying the camera alignment and cleaning the lens regularly, checking connections, etc.). The system's **uptime** in our test was >98% but maintaining that in long-term use will require quality hardware and perhaps remote diagnostics. The inclusion of a remote dashboard for live monitoring is a step toward enabling maintenance staff to catch any issues early (for instance, if a camera fails or a connection is lost then the dashboard could alert technicians).
- **Integration with Existing Work Zone Policies:** MoDOT will need to integrate the use of automated audible alerts into their work zone protocols. This might involve updating the work zone traffic management plans to note when the audible alert will be active, so that highway patrol and other stakeholders are aware. It could also involve public awareness of messages – for example, issuing a notice that MoDOT trucks are now equipped with automated horns that will sound if a driver is approaching too fast, to prevent confusion. Ensuring that emergency services and dispatch centers know about the system can avoid misinterpretation of the alarm (e.g., callers reporting a "siren" on the highway not realizing it is the TMA system).
- **Legal and Liability Aspects:** The introduction of automation in maintenance warning systems may warrant review by MoDOT's legal team to ensure alignment with existing policies and safety practices. The AutoTMA system is designed to enhance safety by alerting drivers to the presence of MoDOT vehicles, and preliminary results indicate that it is effective in reducing crash risk. As with other safety features such as warning lights and attenuators, formalizing the system as part of MoDOT's standard equipment may help ensure consistent use across districts. Any legal or policy implications of deploying

an automated horn can be further assessed internally, with the aim of reinforcing MoDOT's commitment to roadway safety.

5.9.2 Integration into Work Zone Safety Policies

On a policy level, the success of AutoTMA could inform updates to state and even federal work zone safety guidelines. For example, MoDOT could establish a policy that all mobile work zones on high-speed roads be equipped with automated audible alert systems once the technology is proven at scale. They might also collaborate with other state DOTs to share data, leading to broader adoption. The system aligns well with the "Toward Zero Deaths" road safety initiative, as it directly targets a particularly deadly type of crash (high-speed rear-end collisions with TMAs). Policy development could include defining what constitutes a "collision course" scenario warranting an alert, standardizing the alarm sound and pattern so that drivers statewide recognize it, and possibly recommending these systems in work zone best practices documents. Furthermore, MoDOT can work with the Missouri legislature or safety boards if needed to secure funding and mandate the technology in appropriate operations.

5.9.3 Future Research and Technical Refinements

While the current system meets its objectives, the findings point to several avenues for future improvement:

- **Multi-sensor Fusion:** As technology advances, integrating additional sensors like radar or LiDAR can provide redundancy and improve performance in adverse conditions. The team has already initiated the integration of radar to enhance distance and speed measurements. A forward-looking radar on the TMA could detect oncoming vehicles beyond the camera's line of sight (over hills or in dark conditions) and complement the vision system. Fusing radar with the camera's detection could reduce the small TTC estimation errors and maintain detection capability at night or in severe weather.
- **Night Time and Low-Visibility Enhancements:** To fully operate 24/7, the research team might explore thermal infrared cameras or low-light sensors to detect vehicles by their heat or lights at night more effectively. Another idea is reflective target detection – since vehicles have reflectors, an IR illuminator and camera could see vehicles even if optical algorithms struggle in darkness. These additions would be subject to further research and cost-benefit analysis.
- **Driver Alerting Methods:** While the audible alarm proved effective, research could be done on how different alarm sounds or patterns affect driver behavior. Additionally, the system could interface with connected vehicle systems in the future – for instance, sending a signal via V2X (Vehicle-to-Everything communication) directly to smart cars to warn the driver or even trigger automated braking in the approaching vehicle. Such connectivity, if broadly implemented, could enhance the effect (a loud alarm for human drivers and a digital alert for automated driving systems).
- **Human Factors and Alarm Optimization:** The plan going forward includes utilizing a driving simulator (like ZouSim mentioned in Task 6) to further study the optimal

configuration of audible and visual warnings. For example, should the alarm sound immediately with lights, or a half-second after the arrow board flashes, to maximize attention and minimize any over-reaction? Controlled human subject studies will help refine this. The results could influence policy (like recommending a standardized delay or pattern for the alarm).

- **Scalability and Cost Reduction:** For widespread adoption, the system needs to be cost-effective and easy to produce. The final prototype already considered manufacturability. Future refinements might include using more affordable cameras or simplified hardware without sacrificing performance, and streamlining the software for even lighter computer requirements. As AI models become more efficient, they might allow for higher FPS or the ability to run on smaller devices, reducing costs. Ongoing research in deep learning could allow the team to keep the model updated with the latest techniques, ensuring longevity of the system's effectiveness.
- **Data Collection and Continuous Learning:** Once deployed, each TMA with AutoTMA could continuously collect data on near-misses and driver behavior. Analyzing this big data could provide insights into where and when drivers are most at risk, allowing further system tuning or broader traffic safety interventions. The research team envisions a future system that can learn from each encounter, improving its predictive capability (for instance, recognizing patterns like a certain type of vehicle or time of day correlates with different driver response, and adjusting alert thresholds accordingly).

5.9.4 Policy Advancements

Finally, the success of this project can spearhead policy advancements in automated safety systems for work zones. The team will recommend that MoDOT and possibly the American Association of State Highway and Transportation Officials (AASHTO) consider developing standards or guidelines specific to Automated TMA Alert Systems. This could cover specifications for detection performance, alarm loudness and tone standards, fail-safe mechanisms (e.g., ensuring the alarm defaults to on if a system failure is detected when a vehicle is close), and protocols for periodic testing/certification of such systems. Additionally, collaboration with FHWA on such policies could eventually lead to nationwide standards, meaning any contractor or DOT using TMAs might be encouraged or required to use automated alerting if proven to save lives.

In conclusion, the results of the AutoTMA system tests strongly support its effectiveness and pave the way for real-world adoption. The step-by-step evaluation ensured that by the time the team proposes it for widespread use, data to address safety, reliability, and efficacy concerns already exists. With continued refinements and supportive policy frameworks, automated audible alert systems like AutoTMA could become a staple in work zone safety, significantly reducing the occurrence of devastating TMA rear-end collisions and protecting both roadway workers and motorists. The future of work zone safety is brighter with the promise of such intelligent systems ready to assist.

Chapter 6. Conclusion and Recommendations

6.1 Project Summary

Work zone safety remains a critical concern due to the increasing number of rear-end collisions involving Truck-Mounted Attenuators (TMAs). Despite the widespread use of TMAs to absorb impact energy and protect road workers, distracted and speeding drivers continue to pose a significant threat to work zone operations. Traditional safety measures, such as warning signs, flashing lights, and message boards, rely on driver attentiveness and compliance, which are not always effective in preventing crashes. The AutoTMA Automated Audible Alert System was developed to address this challenge by providing a proactive, real-time warning system that alerts approaching drivers before a potential collision occurs.

The AutoTMA system integrates AI-driven vehicle detection, predictive collision assessment, and adaptive audible alerts to warn drivers in real time when they are approaching a TMA at unsafe speeds. Unlike conventional passive safety mechanisms, this system actively detects high-risk vehicles, categorizes their approach based on speed, distance, and time-to-collision (TTC), and dynamically triggers audible warning signals based on predefined safety thresholds.

Through a multi-phase testing approach, the AutoTMA system was evaluated in laboratory conditions, controlled field trials, and full-scale work zone deployments. The results demonstrated that the system significantly improves driver awareness and reaction time, with key findings including:

- **Vehicle Detection Accuracy:** The AI-based detection pipeline, utilizing YOLOv5.0 and DeepSORT v2.2, achieved >98% accuracy in identifying and tracking approaching vehicles, with minimal false positives.
- **Response Time:** The full detection-to-audible alert activation cycle operates within 100–150 milliseconds, ensuring near-instantaneous response.
- **Effectiveness in Collision Prevention:** In controlled field trials, the system's audible alerts led to immediate driver response in over 80% of severe risk cases, reducing speeds or prompting lane changes before reaching the TMA.
- **False Positive and False Negative Rates:** The system demonstrated low false positive rates due to its multi-sensor fusion approach (vision, LiDAR, radar), and nearly zero missed detections in structured field tests.
- **Operational Reliability:** During live deployments, the AutoTMA system maintained high uptime (>95%), with no critical failures or instances of alert malfunction. Simulation results indicate a preference for yellow over white EALs, enhanced nighttime effectiveness of the TMA alert system, and no erratic behavior resulting from a delayed alarm.

These findings confirm that AutoTMA is an effective and scalable solution for reducing rear-end collisions in work zones. The system's ability to detect high-risk vehicles and issue early warnings in real time significantly improves driver awareness, ultimately reducing the likelihood of high-speed crashes.

Additionally, cloud-based event logging and real-time data transmission provide valuable insights into work zone traffic patterns, allowing agencies to analyze safety trends, optimize warning thresholds, and refine work zone configurations.

With continued refinements and a structured deployment strategy, AutoTMA has the potential to become a standard safety system for TMA fleets nationwide, setting a new benchmark for intelligent work zone protection.

6.2 Technical Recommendations

To further enhance the effectiveness and scalability of the AutoTMA system, several technical refinements are recommended:

- **Improved Detection and Sensor Fusion**
- Upgrade the LiDAR and radar modules to enhance long-range detection accuracy, particularly in low-visibility conditions (fog, night operations, and heavy rain).
- Implement AI-driven sensor fusion to further integrate camera, LiDAR, and radar data, reducing false positives and ensuring more robust vehicle tracking in dense traffic.
- Optimize real-time data processing to improve frame rate and accuracy for detecting multiple approaching vehicles simultaneously, allowing the system to issue targeted warnings in high-traffic scenarios.

- **Enhanced Audible Warning System**
- Develop adaptive warning sound patterns that modulate frequency, intensity, and duration based on the approaching vehicle's size, speed, and distance.
- Implement directional sound cues to spatially direct warning tones toward the approaching vehicle, ensuring optimal driver perception.
- Add multi-stage warning escalation (e.g., initial warning chime followed by an aggressive siren if the driver does not react), increasing effectiveness for distracted drivers.

- **Human-Machine Interface (HMI) Improvements**
- Enhance the HMI control panel with more granular customization options, allowing operators to adjust alert sensitivity, TTC thresholds, and alarm volume levels based on work zone conditions.
- Expand cloud dashboard functionalities to provide real-time visualization of active alerts, traffic flow analytics, and historical event data.
- Implement predictive maintenance diagnostics, enabling automatic alerts when sensors require recalibration or replacement.

- **System Integration and Automation Enhancements**
- Develop API compatibility for seamless integration with existing DOT fleet management and work zone monitoring systems.
- Introduce AI-driven predictive analytics, allowing the system to adjust alert parameters dynamically based on historical traffic data and environmental conditions.
- Expand edge computing capabilities, reducing reliance on cloud connectivity for real-time operations and ensuring full functionality even in areas with poor network coverage.

6.3 Policy and Regulatory Recommendations

1. Statewide Standardization and Adoption

- **Recommend AutoTMA for High-Risk Work Zones:** Establish a statewide policy recommending automated audible alert systems in work zones with high rear-end collision rates (e.g., highway striping, bridge maintenance, nighttime operations).
- **Incorporate AutoTMA in Work Zone Traffic Control Plans (TCPs):** Update MoDOT's standard work zone setup requirements to include automated audible alerts as a recommended or mandatory feature.
- **Develop MoDOT-Specific Training and Certification:** Require TMA operators to be trained and certified in AutoTMA system operation, monitoring, and troubleshooting.

2. Federal Policy Alignment and Collaboration with FHWA

- **Engage FHWA to Establish National Guidelines:** Work with FHWA, AASHTO, and MUTCD committees to standardize the use of automated work zone alerting systems.
- **Advocate for FHWA-Endorsed Work Zone Automation Standards:** Position Missouri as a leader in intelligent work zone safety by collaborating on future FHWA rulemaking for AI-driven alert systems.

3. Integration with Emerging Smart Work Zone Technologies

- **Expand AutoTMA's Capabilities with V2X Communication:** Enable direct vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) alerts, allowing connected cars to receive preemptive collision warnings before entering a work zone.
- **Leverage Work Zone Data Exchange (WZDx) Standards:** Ensure AutoTMA feeds real-time alert data into statewide traffic management centers, improving situational awareness for traffic engineers.
- **Enhance Real-Time Traffic Flow Monitoring:** Use AutoTMA's detection data to analyze traffic flow trends and dynamically adjust work zone lane closures or speed limits based on real-time congestion levels.

6.4 Deployment Roadmap

To transition AutoTMA from pilot phase to full-scale deployment, a structured five-step roadmap is recommended:

Step 1: Complete Final Testing and Optimization (2024–2025)

- Conduct extended live work zone testing in diverse conditions (urban, rural, interstate, nighttime).
- Implement final software/hardware optimizations based on real-world field data.
- Publish final performance reports and MoDOT safety evaluations to guide full deployment decisions.

Step 2: Secure Policy and Regulatory Approval (2025–2026)

- Engage with MoDOT and FHWA leadership to establish official policies for AutoTMA integration into statewide work zone safety protocols.
- Develop state legislation or exemptions allowing automated audible alert systems to be formally classified as an approved work zone safety device.

Step 3: Initiate Phase 1 Deployment in High-Risk Areas (2026)

- Deploy AutoTMA units to Missouri's most crash-prone work zones, prioritizing highway striping, nighttime maintenance, and long-duration projects.
- Begin workforce training and certification programs for MoDOT maintenance crews.

Step 4: Expand to Statewide Adoption (2027–2028)

- Scale deployment to all MoDOT districts based on risk assessment and funding availability.
- Ensure every TMA fleet includes AutoTMA systems as a standard safety feature.
- Establish routine calibration, maintenance, and continuous improvement protocols.

Step 5: Integrate with Future Smart Work Zones and National Expansion (Beyond 2028)

- Explore interstate collaboration and pooled purchasing agreements for broader adoption.
- Integrate AutoTMA with work zone data-sharing networks and V2X safety alerts.
- Establish Missouri as a national leader in AI-powered work zone safety innovations.

6.5 Conclusion

The AutoTMA Automated Audible Alert System represents a transformative leap in work zone safety, leveraging AI-powered vehicle detection, real-time risk assessment, and dynamic audible alerts to reduce rear-end collisions and protect roadside workers. By transitioning from manual warning methods to an automated, data-driven approach, AutoTMA ensures that drivers receive immediate, high-intensity alerts, dramatically improving reaction time and reducing crash likelihood.

With continued refinement, strategic deployment, and policy standardization, AutoTMA has the potential to become a national model for AI-enhanced work zone protection, setting a new benchmark for intelligent safety solutions in highway construction and maintenance zones.

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Appendix A: Product Requirement Document (PRD) for the Audible Alert System

A.1 Overview

The Audible Alert System for Truck-Mounted Attenuators (TMAs) is an automated, real-time collision prevention solution designed for work zones. Its purpose is to detect oncoming vehicles that pose a threat to a TMA (the protective crash cushion truck) and immediately warn those drivers with audible and visual alerts, prompting them to slow or stop before a collision occurs. By leveraging camera-based computer vision as the primary sensor (with options for radar or LiDAR augmentation), the system continuously monitors traffic approaching the work zone. If a vehicle is detected closing in too fast or too close, the system automatically activates high-decibel horns and flashing lights to grab the driver's attention in time to prevent a crash. This proactive alert mechanism addresses the dangers of distracted driving and large speed differentials in work zones, aiming to reduce rear-end collisions and near misses between the traveling public and TMA trucks. The scope of the system encompasses an edge AI detection unit mounted on the TMA truck, integrated sensors (camera and optional radar/LiDAR) on the rear of the vehicle, an in-cab user interface for the TMA operator, and wireless communication modules to connect with cloud services and potentially with nearby vehicles. In essence, the Audible Alert System functions as a smart "spotter" on the TMA, watching for imminent threats 24/7 and issuing timely warnings without any manual intervention. This not only enhances safety for highway workers and equipment but also gives errant drivers a last-second chance to avoid a high-severity crash. The system's design builds on recent advances in artificial intelligence and Internet of Things (IoT,) allowing it to reliably recognize vehicles and predict collisions in real-time, even on curving roadways where traditional radar/laser speed trailers fall short. Overall, the Audible Alert System is a key innovation to make work zones safer by augmenting the TMA's protective function with automated, real-time driver alerts.

A.2 System Requirements

A.2.1 Hardware

- **Edge AI Computer (Onboard Processing Unit)**: A robust GPU-accelerated edge computer (such as the NVIDIA Jetson Nano or Jetson Orin) will serve as the brains of the system. It must be capable of running deep learning models locally with low latency. The computer should have an industrial-grade enclosure (fanless, vibration-resistant) suitable for mounting on a truck and operating in extreme temperatures. Sufficient I/O ports are required for camera input, radar/LiDAR input, connectivity modules, and integration with the vehicle's electrical system. This onboard unit will process video frames in real time to detect vehicles and make collision predictions without reliance on cloud computing, ensuring the system can function even in remote areas or if communications drop.

- **High-Definition Camera (Rear-Facing)**: A rugged HD camera will be mounted at the rear of the TMA truck, facing approaching traffic. This camera should be waterproof (IP67 or better) and stabilized or ruggedized to handle wind-induced vibration and shocks from the moving truck. It will provide a clear video feed of the approaching roadway, day and night. A high dynamic range imaging sensor is preferred to handle varying lighting (bright sunlight, headlights at night) and to ensure visibility of approaching vehicles at a long range. The camera's field of view should be wide enough to cover the full lane(s) behind the TMA and some periphery, but with sufficient focal length to detect vehicles at distances of several hundred feet. The mounting system may include a vibration-damping mechanism or electronic image stabilization to maintain image clarity on uneven roads.

- **Radar and/or LiDAR (Optional Sensor Integration)**: The system is designed to optionally integrate a **rear-facing radar or LiDAR** sensor to augment the camera. A radar sensor can provide direct measurement of vehicle speed and distance, which is useful in poor visibility (rain, fog, or nighttime) and adds a redundant data source for collision prediction. If included, the radar unit will be an automotive short/medium-range radar, mounted near the rear of the truck (potentially alongside the camera). It should have a detection range on the order of at least 100–150 meters and a wide beam to cover adjacent lanes. Similarly, a LiDAR sensor could be used for precise distance mapping of approaching objects. The hardware design will accommodate one or both of these sensors as modules. They must be securely mounted and weatherproof, and their output (e.g., object lists or point clouds) will feed into the edge AI computer for sensor fusion. By having these as optional components, the system can be configured for enhanced accuracy in agencies that require it, while the baseline system can function with camera-only detection.

- **Electrical Power and Vehicle Integration**: The alert system hardware will integrate with the TMA truck's electrical power bus and control circuits. It should accept the typical truck power supply (12V or 24V DC) with appropriate power conditioning (voltage regulators, surge protectors, and isolation as needed to handle load dumps or transients on the vehicle power line). The system will have an ignition-sensed power control (so it can power on/off with the vehicle or be set to run autonomously). Integration also means tapping into or interfacing with certain vehicle components: for instance, the system will connect to the TMA's horn and light controls (or to dedicated alert devices as described below) so that it can trigger the audible alarm and visual warnings. It should also interface with the flashing arrow board on the TMA if coordination is needed (e.g., ensuring the arrow board is activated per standards while the system is active). All wiring and connectors must be automotive grade, waterproof, and secured against the vibrations and movements of a work zone truck. In essence, the hardware will be a bolt-on kit that can be installed on a TMA truck, drawing power from the vehicle and sending trigger signals to the vehicle's warning devices.

- **In-Cab Cockpit Interface (Display and Controls)**: The system will include a cab-mounted interface for the driver/operator. This likely consists of a touchscreen display (around 7-10 inches, sunlight-readable) and a minimal set of physical controls as needed (e.g., a power switch or an emergency kill switch to disable the system, and possibly a manual alarm trigger button). The interface will run a GUI application (see *User Interface* section) to allow the operator to see system status and alerts. In hardware terms, this interface could be a tablet-style display or a panel PC mounted on the dashboard, or it could be an HMI unit connected to the edge computer (using HDMI/DP for video output and USB for touch input, as implied by "KVM" – Keyboard/Video/Mouse – integration). It should be ergonomically placed so the operator can quickly glance at status lights or messages and reach controls without distraction from driving. The interface hardware must also be rugged (tolerant of temperature extremes and vibration).

- **Audible and Visual Alarm Actuators**: To actually warn the motorists, the system will control high-output alarm devices mounted on the TMA. For the audible alert, a heavy-duty horn or siren will be installed. This should be significantly louder than a standard car horn – capable of emitting a sound that is audible to an approaching driver over road noise, likely on the order of 110+ dB at a set distance (while also being mindful of not causing hearing damage to workers nearby). This horn will probably have a distinctive tone or warble pattern to distinguish it from typical vehicle horns, indicating an emergency condition. For visual alert, high-intensity flashing lights will be used, supplementing the existing flashing arrow board. This could be achieved via additional strobe beacons or an LED light bar mounted on the TMA truck. The lights should be amber and white (permissible warning colors for construction equipment) and visible in daylight. When activated by the system, they will flash in a predefined pattern to attract attention. All these actuators will be tied into the system: the horn may be connected through a relay or an existing horn circuit, and the light bar through the truck's auxiliary lighting circuit. These devices must also meet vehicle safety standards (for example, the lights should be SAE-classified warning lights). In MoDOT's prototype, the AutoTMA included a horn and lightbar as the primary alert outputs. The system will ensure these alarms can operate simultaneously (e.g., horn blasting and lights flashing) to maximize visibility to the errant driver.

- **Rear Sensor Mounting and Stabilization**: The camera and optional radar/LiDAR will be installed at the extreme rear of the TMA, which may be on the attenuator itself or the back of the truck bed, to get the clearest line of sight to oncoming traffic. The mounting solution might include a small mast or bracket that elevates the camera to an optimal height (to view over any intervening objects and to cover a long distance down the road). It will also consider the "crashworthiness" of the setup – since the attenuator is a crash cushion, any mounted equipment should not negate its function. Ideally, sensors should be mounted in a way that if the attenuator is hit, they either are protected or sacrificial without becoming dangerous debris. The hardware design will account for quick replacement of these components if they are damaged in a crash. Additionally, cabling from the sensors to the in-cab processor will be routed safely (inside protective conduit, with quick-disconnect connectors if needed when the attenuator is removed or replaced).

A.2.2 Software

- **AI-Powered Vehicle Detection**: At the core of the system is a computer vision module that can automatically detect vehicles approaching from the rear in the camera feed. This software component will use trained machine learning models (e.g. a convolutional neural network) to recognize the presence of vehicles in each video frame. It must be robust to various vehicle types (cars, trucks, etc.) and lighting or weather conditions. The detection algorithm will run in real-time (processing many frames per second to not miss fast-moving vehicles). Upon detecting a vehicle, the software will localize it in the image (bounding box) and initiate tracking.

- **Object Tracking and Speed Estimation**: The system's perception software will track the motion of detected vehicles across successive frames. By analyzing the change in the vehicle's size and position in the video (and using calibration data of the camera's perspective), or by utilizing radar data if available, the software will estimate the vehicle's speed and distance relative to the TMA. If a radar sensor is integrated, its direct speed and range measurements will feed into this module to improve accuracy. In the camera-only scenario, the software will use techniques like frame-to-frame displacement and known camera geometry to approximate how fast the object is approaching. The system may employ sensor fusion (combining camera and radar outputs) to get the best estimate of speed and distance. High accuracy in speed estimation is critical since it directly affects collision time predictions.

- **Collision Prediction (Time-to-Collision Computation)**: Using the tracked distance and speed data, the system continuously computes each approaching vehicle's Time-to-Collision (TTC) with the TMA if its current course and speed are maintained. The software will also account for the TMA's own movement (for example, if the TMA truck is moving slowly in a mobile operation, the relative speed must be considered). Advanced predictive algorithms might also evaluate the vehicle's trajectory (is it centered in the lane or already edging away?), as well as relative lane positioning (to determine if the vehicle is actually on a collision course or will pass at a safe distance). If LiDAR is used, precise 3D positioning can enhance this prediction. The end result is a continuously updated risk assessment for each detected vehicle – essentially whether an impact is likely if no action is taken.

- **Safety Logic and Alert Triggering**: A core part of the software is the decision logic that determines when an alert should be issued. This logic will be based on safety thresholds such as TTC and distance. For example, the system might be configured to trigger the alarm when an approaching vehicle's TTC falls below, say, four seconds and the vehicle hasn't shown signs of significant deceleration. The software will incorporate multiple conditions to ensure high confidence before sounding an alarm: this can include verifying that the object is indeed an oncoming vehicle (not a harmless object or a vehicle that already changed lanes), and potentially requiring the condition to persist for a fraction of a second to avoid reacting to momentary false indications. In essence, the logic will aim to maximize true positives (alert when a real danger exists) and eliminate false positives.

The system will also define when to turn the alarm off – e.g., if the vehicle has slowed sufficiently or passed the TMA without incident. This *alert state machine* ensures the horn doesn't continue unnecessarily. Safety logic may implement escalation: for instance, first flash lights at a moderate distance, then add horn if the vehicle continues closing fast. All these rules will be refined through testing and follow established safety parameters. The requirement is that the logic be transparent and adjustable: engineers can tune thresholds for different road speed limits or scenarios. Additionally, a fail-safe principle is applied – if the detection confidence is low (system isn't sure), it might err on the side of caution (perhaps issuing a light-only warning or a mild alert) rather than complete inaction, but it should avoid full-blown false alarms. A significant part of development will focus on this logic to achieve near-zero false alarms.

- **System Integration and Control Software**: Beyond detection, the software includes modules to interface with hardware components and the truck. There will be a controller that sends commands to the alarm actuators (horn, lights) when an alert decision is made. This involves toggling GPIOs or CAN bus messages that activate the horn relay and light controls. There is also a need for an integration with the TMA's flashing arrow board: for instance, ensuring the arrow board remains in the correct mode (arrow or caution) during operation, and possibly increasing its flash rate when an alarm is triggered, if allowed. The software will manage these interactions so that the system works in harmony with existing work zone signals (not overriding or conflicting with them). Additionally, the system will likely have a mode control (e.g., Standby, Active, Maintenance) that can be set via the UI or remotely, and the software will respond accordingly (for example, not issuing alerts when in Maintenance mode).

- **User Interface Software**: The edge computer will run an interface application for the in-cab display. This software presents status information (camera view, system armed/disarmed state, detection indicators) and allows user inputs. It will be designed to be simple and safe for use by the operator. For example, a portion of the screen might show a live video feed with overlay graphics highlighting any detected vehicle and maybe a countdown or color code for threat level. There will also be textual or icon-based indicators (like a green/yellow/red status for system health, network connection status, etc.). The UI software will also handle user commands: if the operator presses an override to silence the alarm, the software will immediately stop the horn and mark that event in the system log. Configuration menus (accessible when the vehicle is stopped or by authorized users) will let them adjust settings such as volume (if adjustable), connectivity toggles, or test the system. This UI software must be intuitive and minimalistic, given that during operation the operator's primary focus is on driving or other duties. (Detailed UI features are described in the *User Interface* section below.)

- **Data Logging and Diagnostics**: The system software will include functionality to log key events and data for later analysis. Each time an alert is triggered, the system will record details such as timestamp, the estimated speed/TTC of the approaching vehicle, whether the driver responded (if detectable), and potentially save a short video clip of the incident.

This data can be uploaded to the cloud dashboard for post-event review. Additionally, the system will log diagnostic information: uptime, any sensor errors (camera disconnection, etc.), GPS location of incidents, and network status. These logs help in both measuring performance metrics and troubleshooting any issues. The software should manage log storage sensibly (e.g., rolling logs to not exhaust storage, and offloading older data to the cloud).

- **Connectivity and Cloud Services**: A portion of the software stack will handle communication (detailed below in Communication requirements). This includes drivers for the 4G/5G modem and Wi-Fi, implementing protocols to send data to the cloud in real time. For instance, there might be a background service that transmits the current status and alert events to a cloud server via a REST API or MQTT channel. If remote firmware updates are supported, the software will include an update agent that can receive and apply OTA (over-the-air) updates securely. The communication software must ensure data security (encryption, authentication) especially if it's transmitting over public cellular networks.

In summary, the software encompasses real-time perception (AI detection), decision-making (collision risk assessment and alert logic), control (activating alarms and interfacing with vehicle hardware), user interaction (UI and override controls), and communication (cloud and possibly V2X messaging). All components should run reliably on the edge computer with real-time performance, and be tested under various scenarios (traffic density, weather, etc.) to ensure the system meets its safety goals.

A.2.3 Communication

- **Cellular Connectivity (4G/5G LTE)**: The system will be equipped with a cellular modem to enable wide-area network communication. This allows the TMA's alert system to send data to a cloud server and receive remote commands or updates in real time. Using 4G/5G ensures coverage across most areas – critical since work zones can be in remote highway locations. The hardware will likely include a SIM card and an antenna mounted on the truck for good reception. The communication software will transmit alert events, live video or snapshots, and system status to a central cloud platform whenever a connection is available. For instance, if an alarm is triggered, the system could immediately send an alert notification (with location and time) to a cloud dashboard or even via SMS/email to designated personnel. The cellular link will also support remote monitoring (streaming the rear camera feed to the cloud or a control center, as bandwidth allows) and over-the-air updates/configuration. Given the mission-critical nature, the system should use a secure VPN or encrypted channel for all cellular data. In 2024 testing, a prototype successfully streamed video and alarm triggers to the cloud over 4G/5G, enabling real-time remote monitoring – this capability will be a standard feature. The system may also leverage 5G's low-latency, high-bandwidth capabilities for future expansion (such as sending high-resolution video or using edge cloud computing for heavier analytics).

- **Wi-Fi Communication**: The system will also include Wi-Fi connectivity for local communications. This serves multiple purposes: (1) During setup or maintenance, technicians can connect a laptop or tablet via a local Wi-Fi hotspot hosted by the device to configure settings or download logs. (2) If the TMA is at a depot or within range of a facility network, it can use Wi-Fi to upload data or download software updates without consuming cellular data. (3) Potentially, the system could interface with other work zone equipment via Wi-Fi if a local site network is set up (for example, connecting to a work zone intrusion device or a smart traffic cone system). The Wi-Fi module should support standard protocols (802.11ac/n) and have sufficient range to reach a support vehicle or trailer (a few tens of meters). Security is important here as well – WPA2 at minimum for any Wi-Fi access. In normal operation on the road, Wi-Fi might be idle, but once the vehicle returns to base, it could automatically offload data when it detects a known Wi-Fi network.

- **Vehicle-to-Everything (V2X) Compatibility**: To future-proof the system, it will be V2X-ready, meaning it can communicate with other vehicles or roadside units via dedicated short-range communications (DSRC) or cellular V2X protocols. While this is optional, it aligns with emerging connected vehicle technologies. For example, the alert system could broadcast a standardized work zone alert message or a warning to approaching vehicles equipped with V2X receivers. This could use the SAE J2735 message set (such as a "Road Side Alert" or a custom message indicating a slow/stopped vehicle ahead). If DSRC is used, the unit would have a DSRC radio operating at 5.9 GHz, or if C-V2X (cellular vehicle-to-X) is preferred, the system would use that technology per current FCC rules. The communications controller in the system would ensure that any V2X broadcasting adheres to federal standards and does not interfere with other channels. V2X integration means a connected car could *directly receive* an electronic warning about the work zone hazard (in addition to seeing/hearing the horn and lights), which is a powerful addition to driver awareness. The PRD calls for V2X compatibility, so the design will leave room (e.g., a module slot or interface) for adding a V2X transceiver either now or in the future as deployments of connected vehicles increase.

- **Intra-Vehicle Network Integration**: The communication architecture also covers how the alert system interfaces *within* the truck's own network. Many TMA trucks (being heavy vehicles) have a CAN bus or similar for engine and body controls. The alert system may tie into the vehicle's CAN bus to read certain data (like the truck's speed or gear, which might be useful to know if the TMA is in motion or stationary) or to send commands (if the horn and lights can be triggered via CAN messages to a body controller). If direct hard-wire control is used for horn/lights, CAN might not be needed for that, but could still supply context data. For instance, if the system knows the TMA truck's speed is 0 (stopped), it might use different criteria for alerts vs. when the TMA is moving at 10 mph in a mobile operation. Integration should follow automotive communication standards and not disrupt any existing vehicle control. The system will be an add-on, so it should be listening-only on critical buses unless absolutely necessary. In addition to CAN, other interfaces like serial or Ethernet might be used depending on the truck's setup (some newer DOT trucks might have an IP network for devices).

- **Cloud Services and Dashboard**: Over the cellular/Wi-Fi links, the system will maintain a connection to a cloud backend. The requirements for this include transmitting periodic status updates (heartbeat messages that include GPS location, system health, number of detections, etc.) and instant event notifications when an alert is triggered. The cloud service will host a dashboard (described in UI section) and possibly store historical data for analysis. To manage bandwidth, the system might send low-frequency telemetry (e.g., every minute) and only stream video on-demand or when an event occurs. The communication protocol could be message-based (MQTT or similar for IoT) to efficiently handle these updates. An important requirement is that the communication be two-way: authorized users should be able to send commands back to the system, such as updating configuration, requesting a live video feed, or initiating a system self-test. Additionally, support for remote software updates is essential – this implies the system can download firmware/software packages over the air (preferably when the vehicle is not actively in a work zone or when parked to avoid any disruption). During development, it was planned to enable such remote updates and live performance monitoring via the cloud. All cloud communications must be secure to prevent any unauthorized access or control of the system (e.g., use TLS encryption and authentication tokens for any API calls).

In summary, the communication subsystem ensures the Audible Alert System isn't an isolated unit but rather a connected, smart device. It keeps operators and supervisors informed in real time, allows oversight and data collection for safety metrics, and positions the system within the larger ecosystem of connected vehicles and smart work zone technologies. Proper communication also means the system can be remotely managed, which is crucial for maintaining a fleet of such equipped TMA trucks across different work sites.

A.3 User Interface

The Audible Alert System will provide a clear and user-friendly interface for both the TMA truck operator and remote users. The UI is designed to monitor system status, display alerts, and allow user control in a straightforward manner, ensuring safety and ease of use. Key aspects of the user interface include:

- **In-Truck Cockpit Display & Controls**: Inside the TMA truck's cab, a dedicated display will show the status of the alert system at a glance. This touchscreen dashboard (mounted within the driver's easy view) will present information such as: system power status, connectivity (cell signal, GPS lock), and whether the detection system is actively monitoring. A live video feed from the rear camera can be shown in a portion of the screen or on demand, giving the operator a direct view of approaching traffic – this feed may include overlay indicators (boxes or icons) highlighting any detected vehicles and their current risk level. For example, a car approaching might be shown with a green icon that turns to red if it becomes a collision threat. The interface will also display text or color-coded warnings like "ALERT ACTIVATED" when the system has triggered the horn/lights for an oncoming vehicle. In normal conditions, a simple standby status ("Monitoring… No threats") reassures the driver that the system is functioning.

The cockpit UI will include control elements: the operator can override or silence the alarm via a prominent button if needed (for instance, if the system triggers inappropriately or if the situation is under control). There will also be a manual alarm trigger button that the operator can use to activate the horn and lights on their own – for example, if they visually spot a danger before the system does, or to test the alarm. Configuration menus (likely access-protected to prevent changes while driving) will let the user adjust settings such as the volume of the internal alert sound, screen brightness, or toggle whether certain features (like radar, if present) are active. The UI should be minimal during operation: large, easily readable status icons and as few buttons as necessary, to avoid distracting the driver. Think of it like a simple car dashboard – mostly passive info, with one or two action buttons for emergency use.

Importantly, the in-cab display will also show a record of recent alerts. For instance, after an alarm event, it might log "10:32:15 – Alert Triggered, Vehicle @ 75 mph, 3.0s TTC" so the operator knows what just happened. This can help the operator report incidents or just be aware of how often the system is engaging. All messaging will be in clear language or standard symbols (avoiding technical jargon) to be immediately understood. The UI design will follow safety UI principles for vehicles – high contrast, readable fonts, and not requiring multi-step interactions for critical functions. In testing, the team has already developed a prototype GUI with touch capabilities, which will be refined for production use.

- **System Alerts and Warnings Visualization**: When the system detects a high-risk vehicle and triggers an alert, this will be clearly signaled both outside and inside the truck. Externally, the horn will sound and lights flash to warn the oncoming driver. Internally, the operator's interface will concurrently display a visual alarm indicator – for example, the screen border might flash red and an audible buzzer in the cab might sound (distinct from the external horn) to make sure the operator is also alerted to the event. This dual notification ensures the TMA operator is not caught by surprise by the horn and can also take any additional action if needed (like checking on workers or preparing for impact). The UI might show a big warning like "⚠ Collision Warning: Vehicle Approaching!" along with details like speed or distance if available. If the operator taps the override, the system will acknowledge ("Alarm silenced by operator") and log it. After an event, the system could present a short summary ("Alert ended – vehicle slowed and changed lane").

  Additionally, the system may provide pre-alert cues. For instance, if a vehicle is detected that is slightly above the warning threshold, the UI could glow yellow or give a soft tone to inform the operator that a vehicle is approaching at a concerning speed, just before the system actually triggers the full alarm. This mirrors how some collision avoidance systems provide tiers of alerts. However, these cues have to be carefully designed to not cause the operator to panic or to override the automated process. They are mainly for situational awareness of the crew.

The visualization on the UI will also extend to diagnostics and guidance. If a sensor is dirty or malfunctioning (say the camera view is obstructed), the UI will display a warning (e.g., "Camera feed lost – check camera"). If connectivity is down, it may show an icon (offline). The goal is to make the system's operation transparent to the user: they should always know if the system is active and healthy, or if it needs attention.

- **Cloud Dashboard (Remote Monitoring Interface)**: The system will have a corresponding web or cloud-based dashboard for off-site monitoring and management. Authorized users (such as a work zone supervisor, traffic operations center staff, or system operators can log in to this dashboard to see the status of all deployed TMA Alert Systems in the field. For each equipped TMA truck, the dashboard provides real-time info like: current location (via GPS), whether the system is active, and live telemetry. In the event of an alert, the cloud dashboard can display a notification in real time – for example, "TMA #3 (I-70 WB at marker 142) Alert Triggered at 10:32:15 for Vehicle at 75 mph". It may also show the live camera feed or a recent image frame around the time of alert (bandwidth permitting) so that remote observers can visualize the situation.

  Beyond live monitoring, the dashboard serves as a data analytics and logging platform. It will store historical data from the system: counts of vehicles detected, number of alerts, timestamps, and outcomes. Supervisors can review these logs to identify how often TMAs are nearly struck and under what conditions. There may be charts or reports (e.g., alerts per week, average speed of triggering vehicles, etc.) to help evaluate the system's impact on safety. For instance, if the data shows a particular work zone is getting many high-speed alerts, additional countermeasures can be taken by the agency upstream. The dashboard thus becomes a tool for continuous improvement in work zone safety management.

  The cloud interface could also integrate with notifications – sending email/text alerts to a list of contacts whenever a TMA alarm is triggered, if desired. This ensures key personnel are immediately informed of a dangerous situation.

  Additionally, the cloud dashboard will enable certain remote management functions. Users with the right permissions might adjust system settings remotely, such as changing the threshold sensitivity (e.g., during different traffic conditions) or updating the firmware, as mentioned in the Communication section. There will be safeguards for this (for example, remote changes might only apply when the system is idle to avoid interfering during an active work operation).

  Security and access control will be enforced on the dashboard – each system likely has an ID, and only authorized accounts can see or control it. Data privacy will be considered (for example, any collected video would be stored only for safety analysis and not public dissemination, since it might incidentally capture license plates or individuals).

In summary, the user interface is split between the local interface (ensuring the crew can monitor and manage the system on-site) and the cloud interface (allowing oversight and data utilization off-site). Both are crucial for the system's functionality and acceptance. The design philosophy is to keep the interfaces informative but not overwhelming: in the cab, it should aid the operator without distraction; in the cloud, it should present actionable insights without requiring digging through raw data. Ease of use will encourage proper use of the system (e.g., an operator is more likely to keep the system on if they trust and understand the interface feedback).

A.4 Performance Metrics

To gauge the effectiveness of the Audible Alert System and ensure it meets safety goals, several **performance metrics** will be tracked and targeted. Key metrics include:

- **Reduced Driver Reaction Time**: A primary objective is to shorten the reaction time of drivers who are on course to hit the TMA. By alerting a distracted or unaware driver earlier than they would otherwise notice the work zone, the system gives them more time to brake or steer away. This improvement in reaction time can be lifesaving. The performance will be measured by comparing driver response with and without the system. For example, in simulation or controlled tests, measure the time from when a vehicle enters a warning zone to when the driver begins to decelerate or evade. The goal is a significant reduction in this reaction time – ideally, drivers respond almost immediately to the horn/lights, rather than at the last second. Research has shown that well-designed auditory warnings can decrease braking reaction times by about 0.25 seconds in rear-end collision scenarios[3], and potentially more under high urgency. In real terms, at highway speeds, every fraction of a second gained translates to many feet of additional stopping distance. The aim is for the system to consistently prompt drivers to react faster than they would on their own. This metric might be quantified in field trials by analyzing video: for each alert, how quickly did the approaching vehicle slow down? Over many events, an average reaction time improvement can be estimated. A successful system would see near-immediate driver responses to the alerts, indicating the alert was noticed and heeded.

- **Reduction in Near Misses and Collisions**: Ultimately, the system is about preventing crashes, so a key metric is the frequency of near misses and actual impacts involving the TMA. A "near miss" can be defined as any situation where an approaching vehicle had a very low time-to-collision or came within a very short distance of the TMA but managed to avoid impact (perhaps at the last moment or due to the alert system's intervention). The team expects the number of such incidents to drop significantly with the alert system active. In other words, fewer cars should be reaching the TMA in a state of emergency braking or swerve at the last moment – ideally, they have safely changed lane or slowed

[3] https://oaktrust.library.tamu.edu/items/12dbcb06-d466-4e44-9d21-b2f9eb4406e0

much earlier. Historical data will be compared (when available) of incidents in similar work zones without the system to those with the system. In simulation studies conducted as part of development, various near-miss scenarios were modeled to optimize the system's configuration, ensuring it would be effective in preventing those situations. The target is to approach zero actual collisions: "Vision Zero" for TMA strikes. While completely eliminating crashes may be ambitious, the system should at least drastically reduce their likelihood and severity. If a collision does occur, one would evaluate whether the driver reacted (slowed) at all – a scenario where the system gave an alert but the driver still hit at full speed might indicate need for even earlier or louder warnings. So, beyond counting incidents, the severity of outcomes will also be a metric (for example, impact speed of any collisions that do occur; lower impact speeds mean the alert had some positive effect even if the collision was not fully avoided). The metric of near misses can be tracked via the system's data: every time an alert is triggered and no collision occurs, that can be considered a successfully averted incident. Over time, the team would want to see high numbers of averted incidents correlating with improved safety and possibly reduced insurance or incident reports in those work zones.

- **False Alarm Rate (Aim for Zero False Alarms)**: An extremely important performance aspect is how often the system triggers an alarm when no real threat is present – i.e., false alarms. A false alarm could be not only a nuisance but also a safety risk (it could confuse drivers who are actually not in danger and erode trust in the system). The goal is to have essentially zero false alarms, meaning the system should almost never alert for benign situations. A false alarm is defined as an alert (horn/lights) in a scenario where no vehicle was actually on a collision course or the approaching vehicle was already responding appropriately. To achieve this, the detection and logic are tuned very conservatively. The performance metric here will be quantified as the false alarm rate (false alerts per hour of operation, or per 100 vehicles passing, etc.). During development, the system's AI and sensor logic will be optimized to filter out cases like vehicles that briefly appear but change lanes away, or cars that are slowing down normally behind the TMA – those should *not* trigger the alarm. The team will test the system in various traffic scenarios to ensure that, for instance, a vehicle passing in an adjacent lane does not cause an alert (since it is not a threat). The requirement might be something like *false alarm rate < 1%* of alerts, or even zero in a controlled test environment. Each false alarm incident (if any) will be logged and analyzed to adjust the system. The design includes multiple validation steps (like requiring continuous threat observation over a threshold) specifically to weed out false triggers. Our performance target is zero false alarms in normal operation, meaning the system should only activate when an actual errant vehicle is present. In practical terms, achieving literally zero might be challenging, so the team set a remarkably high reliability standard (e.g., no more than one false activation per hundreds of genuine ones, or ideally none observed in a lengthy trial). Hitting this metric is crucial for user confidence; thus, it will be monitored in all pilot deployments. If the false alarm rate is higher than acceptable, it indicates the need for further refinement in the software (either adjusting sensitivity or improving the AI model). The expectation is that through careful calibration and the use of multiple sensors, the system will be able to distinguish true dangers from normal traffic flow with near-perfect accuracy.

Other performance metrics will also be tracked, such as detection accuracy (the percentage of target vehicles that the system successfully detects – this should be very close to 100% for oncoming vehicles in the intended range) and system uptime/reliability (how often the system is operational and not down due to faults – aiming for >99% uptime during working hours). Additionally, driver behavior changes can be a metric: for instance, measuring if more drivers move over earlier when the system is used, indicating better compliance with Move Over laws. While not explicitly listed, these factors tie into the overall success of the system. Ultimately, a combination of these metrics – quicker driver reactions, fewer close calls, virtually no false alarms – will demonstrate that the Audible Alert System is making work zones safer and performing as required.

A.5 Regulatory Compliance

The Audible Alert System will be designed and implemented in full compliance with all relevant federal and state regulations governing work zone safety, vehicle-mounted alert devices, and automated systems on road vehicles. Meeting these regulations is critical not only for legal operation but also to ensure the system adheres to proven safety standards. Below, are outlined the key regulatory and standards considerations and how the system addresses them:

- **Federal Work Zone Safety Regulations**: The system supports and complies with the **Federal Highway Administration (FHWA)** rules on work zone safety and mobility (e.g., the FHWA Work Zone Safety and Mobility Final Rule in 23 CFR 630 Subpart J). This rule requires transportation agencies to adopt measures to improve work zone safety, and the automated alert technology developed by this project is aligned with that directive as an innovative safety enhancement[4]. Additionally, OSHA regulations for construction (29 CFR Part 1926, Subpart G – Signs, Signals, and Barricades) set forth requirements for traffic control in work zones, incorporating the Manual on Uniform Traffic Control Devices (MUTCD) as a guiding standard. This system is an augmentation to the standard signs and devices recommended by MUTCD, providing an extra layer of warning. It does not replace human flaggers or required signage but adds an OSHA-compliant audible signal to warn of impending danger to workers and drivers. Because the system automates what could be considered an emergency signal, it is ensured to fit within OSHA's allowances for automated systems that protect workers (similar in spirit to work zone intrusion alarms which OSHA supports for worker safety). There are currently no federal laws prohibiting or specifically governing the use of automated auditory warning systems on TMA trucks, so the system is implemented in accordance with general safety principles and the spirit of federal guidelines encouraging technology to save lives.

[4] https://westernhighwaystrafficsafety.com/state-specific-tma-regulations-a-comparative-analysis-2

- **Manual on Uniform Traffic Control Devices (MUTCD) Compliance**: The MUTCD is the national standard for all traffic control devices on public roads, including work zone signage and signals. While the MUTCD (latest edition) does not explicitly require TMAs or prescribe automated alert systems (TMAs are usually mentioned as optional safety devices)[5]. The Audible Alert System's visual components will conform to MUTCD specifications for visibility and operation. For example, if the system ties into the flashing arrow panel on the TMA, that arrow board must meet MUTCD Chapter 6F criteria (size of elements, illumination, flash rate, and permitted symbols). Any additional warning lights activated by the system will use colors allowed by MUTCD for warning beacons in work zones (amber or white, not red or blue which are reserved for emergency/police). They will flash at a rate compliant with MUTCD guidance to ensure they attract attention without causing excessive distraction]. Also, MUTCD requires that any traffic control device not confuse road users – so the system's alerts will be used in a manner that supplements the standard setup (cones, signs, arrow board) rather than conflicting with it. For instance, the horn will sound only in an emergency scenario, and the lights will augment but not replace the arrow board's function. All placements of equipment will respect MUTCD safety clearances (the system hardware will be on the TMA vehicle which is already a part of the traffic control plan). Essentially, the system operates within the MUTCD framework, adding a dynamic warning when needed. If any new sign or message is used (e.g., if it had an electronic message "Danger – Slow Down" sign triggered by the system), it would follow MUTCD standards for temporary changeable message signs. At this time, the focus is on horn and lights, which are already recognized warning methods. The research team will coordinate with traffic engineers to ensure the system's operation is MUTCD-compliant in each deployment. Also, MUTCD requires that any traffic control device not confuse road users – so the system's alerts will be used in a manner that supplements the standard setup (cones, signs, arrow board) rather than conflicting with it. For instance, the horn will sound only in an emergency scenario, and the lights will augment but not replace the arrow board's function. All placements of equipment will respect MUTCD safety clearances (the system hardware will be on the TMA vehicle which is already a part of the traffic control plan). Essentially, the system operates within the MUTCD framework, adding a dynamic warning when needed. If any new sign or message is used (e.g., if it had an electronic message "Danger – Slow Down" sign triggered by the system), it would follow MUTCD standards for temporary changeable message signs. At this time, the focus is on horn and lights, which are already recognized warning methods. The research team will coordinate with traffic engineers to ensure the system's operation is MUTCD-compliant in each deployment.

- **Vehicle Equipment Standards (FMVSS and EPA Noise)**: The TMA truck and attached devices must continue to meet Federal Motor Vehicle Safety Standards (FMVSS) and other vehicle regulations. The truck-mounted attenuator itself must meet crash performance criteria (discussed under MASH below). Regarding the audible alert device (horn/siren): Vehicles are generally required by FMVSS to have a horn, and there are noise

[5] https://onlinepubs.trb.org/Onlinepubs/trr/1991/1304/1304-035.pdf

regulations for heavy trucks. The system's horn will conform to the EPA noise emission standards for heavy trucks (40 CFR Part 205) which set limits on noise at certain distances[6]. Typically, stationary emergency signals are allowed some leeway for short-term use, but it will be ensured that the horn is not excessively loud beyond what is needed (for example, it will likely comply with SAE J994 or similar standards for alarm loudness used in construction equipment). Many states also have laws about sirens – usually only emergency vehicles (police, fire, ambulance) may use certain siren sounds. The system's audible alert will use an acceptable sound (likely a loud air horn or pulsating alarm) that is permitted for highway safety vehicles. For visual alerts, any added lights will meet SAE specifications (e.g., SAE J845 for strobe warning lights, SAE J595 for flashing warning lamps) and applicable state laws (which typically allow amber lights on construction and maintenance vehicles). The team will avoid colors or flash patterns reserved for true emergency responders. The system will also not interfere with required vehicle lighting (for example, if the truck's hazard lights are on, the system will not negate them but may coordinate additional lighting). Additionally, FMCSA (Federal Motor Carrier Safety Administration) rules consider an attenuator truck being hit as a reportable accident[7]; while this does not directly affect our system's design, it underscores the importance of reliability – false alarms or malfunction should not cause any unsafe truck behavior. It will be ensured that any physical modifications (like mounting hardware, wiring) do not violate DOT vehicle codes (e.g., brake lights and other mandatory lights remain visible and operational, vehicle width/length is not dangerously increased except as allowed by the attenuator itself, etc.). The system's weight is minimal compared to the truck and attenuator, but proper weight distribution and secure mounting as per FMVSS cargo securement rules, if relevant, will be ensured. Lastly, if the system uses wireless transmitters (cellular, Wi-Fi, V2X), those devices will be FCC certified for their frequency bands to ensure communications regulations are met.

- **AASHTO MASH Crashworthiness (TMA requirements)**: All Truck-Mounted Attenuators used should comply with the Manual for Assessing Safety Hardware (MASH) guidelines, which is the current standard for crash testing roadside safety features. MoDOT, for example, mandates that new TMAs purchased after 2023 must be MASH 2016 Test Level 3 compliant[8] (able to safely absorb impacts from vehicles up to highway speeds). This system will be installed on MASH-compliant attenuators and will not compromise their crash performance. This means any attachment to the attenuator is designed such that it does not create hazardous debris or alter the attenuator's energy absorption in a crash. The team will coordinate with attenuator manufacturers if needed to use approved mounting points. If the system's components are mounted on the truck bed (not on the attenuator structure), it will be ensured that they are shielded or placed in a way that they will not be directly impacted. Essentially, the presence of the alert system must not

[6] https://nepis.epa.gov/Exe/ZyPDF.cgi/9100NQJQ.PDF?Dockey=9100NQJQ.PDF
[7] https://www.federalregister.gov/documents/2022/07/15/2022-14330/federal-motor-vehicle-safety-standards-rear-impact-guards-rear-impact-protection
[8] https://epg.modot.org/index.php/Category:612_Impact_Attenuators

negate the attenuator's function as the "last line of defense." Compliance with MASH also means that if the attenuator associated with the system gets hit, the attenuator performs its job of protecting the crew, and the system's failure mode is safe (it may be destroyed, but it should not cause extra harm). It should also be noted that MUTCD and many state DOTs require or recommend TMAs for certain operations even though MUTCD doesn't mandate them outright[9]. By adhering to MASH, it is ensured that the base safety device (the TMA) is up to standard, and by adding the system, any standard requirement is augmented rather than replaced. After any crash, per regulations, the TMA must be inspected and likely replaced or repaired, and this project's system will be inspected too. Any state inspection protocols for TMAs will be followed; for instance, states like Texas have regular inspections for TMA maintenance [10], and the project system hardware can be included in such checklists (verifying camera alignment, etc.).

- **State and Local Regulations for Work Zones**: Each state may have specific regulations or typical applications regarding the use of TMAs and any additional warning systems. This project's product is intended to be flexible to comply with state-specific rules. For example, some states like California have very stringent rules: California DOT (Caltrans) requires that TMAs used on state highways meet the latest MASH criteria and that TMA operators undergo specialized training[10]. This system would be incorporated into that training – i.e., operators in CA would be trained on the use of the Audible Alert System as part of their TMA operation training. Texas emphasizes visibility and maintenance – the system's lights would enhance visibility and the research team would ensure it does not violate any Texas rule (TxDOT allows warning devices as long as they do not distract from traffic control devices)[10]. Florida requires TMAs on certain high-volume projects and also has incident reporting mandates[10]. This system can assist with incident reporting by providing data on near misses and alerts, aligning with Florida's safety tracking objectives. New York demands annual certification of TMAs[10] and this system would be included in that inspection to certify it is correctly working each year. Missouri (MoDOT), which is spearheading this initiative, has updated its policy to explicitly allow and encourage the use of Emergency Alert Lights and Audible Alert Systems on TMAs, as long as they are used according to typical traffic control applications[11]. This policy framework in Missouri provides a model for other states – the research team can show that the system was developed in line with MoDOT's standards and then adapt it to any additional requirements another state might have. For instance, if a state restricts the use of sirens, the team will ensure the sound used is permitted. If a state requires a permit for any new type of device on a roadway, the team or the implementing contractor would obtain such approval. Any state highway patrol guidelines for warning devices will be adhered to, to ensure they are not mistaken for enforcement signals. Additionally, Work Zone intrusions

[9] https://onlinepubs.trb.org/Onlinepubs/trr/1991/1304/1304-035.pdf
[10] https://westernhighwaystrafficsafety.com/state-specific-tma-regulations-a-comparative-analysis-2/
[11] https://epg.modot.org/index.php/Category:612_Impact_Attenuators

and alarms are an area of active interest, and some states have pilot programs for worker alarms. This system can complement those, and the team will ensure coordination (for example, if a state uses personal alarms for workers, the system's activation could potentially tie in to also alert workers, though that is beyond the current scope, it is a consideration to not interfere). In summary, the team will conduct a regulatory review for each deployment locale, checking that the system's operation (horn sound type, light color, usage conditions) meets that state's DOT and OSHA requirements. The product documentation will include guidance on state-specific settings (for example, "In State X, use setting Y for horn pattern to comply with law ABC"). This way, the system can be universally deployed yet locally compliant.

- **Standards for Automated Systems and V2X**: While the Audible Alert System is not driving the vehicle, it is an automated safety system, and thus general standards like ISO 26262 (Functional Safety for Road Vehicles) and ISO 21448 (Safety of the Intended Functionality) provide guidance on ensuring that the system's automation does not introduce hazards. The team will follow a safety lifecycle in the design – performing hazard analyses (for example, what if the system false-alarms, what if it fails to alarm, what if it malfunctions and continuously sounds, etc.) and mitigate those. This is in line with emerging autonomous vehicle guidelines, even though the system is limited to warnings. If the team implements any wireless vehicle-to-vehicle alerts (V2X), it will use the standards set by USDOT for connected vehicle communications. That means if broadcasting a message, it would use the SAE J2735 format and be consistent with the CV2X deployment guidelines. The research team will ensure the DSRC/C-V2X device is FCC certified for the 5.9 GHz ITS band and operates under the FCC's rules. The system will only broadcast relevant safety messages and will respect any required message prioritization in the V2X network. In terms of data, any collection of video that might capture license plates will be handled per privacy laws (if applicable, e.g., California has license plate reader regulations. However, since this is short loop recording and for safety use, it is generally exempt, but data will still be treated carefully). Finally, the system complies with electrical safety and EMC regulations: it will be built to meet SAE or IEC standards for electromagnetic compatibility so it doesn't interfere with vehicle electronics or roadside communication devices.

- **Emergency Signaling and Lighting Rules**: The use of horns and flashing lights on public roads is typically regulated under state vehicle codes. Construction and maintenance vehicles are usually granted permission to use amber flashing lights when working, and some states allow use of siren-like devices for work zone emergencies (or at least do not prohibit audible warnings on vehicles used to warn traffic). It will be ensured that the horn's use is limited to emergency situations to be considered a legitimate warning device. For example, continuous or arbitrary use of a siren on a non-emergency vehicle could violate laws, but the system only sounds when a collision is imminent, essentially acting as an emergency alarm for life safety. This is analogous to an intrusion alarm that sounds when a person or vehicle breaches a work zone – such devices have been trialed and are not prohibited as long as they serve a safety purpose. The team will work with authorities if any clarification is needed, but generally by designing the sound to be clearly a warning (and not, say, a police siren imitation), it stays within allowed use. The lighting will be compliant too; no red/blue colors (to avoid looking like law enforcement), and mounting heights and angles will follow guidelines so as not to blind drivers but to be conspicuous. If the state has specific standards (e.g., California Title 13 for amber lights on service vehicles), hardware that is certified to those standards will be used.

In summary, regulatory compliance for the Audible Alert System includes making sure the base TMA and truck meet crash and safety standards (MASH, FMVSS), the warning devices meet traffic device standards (MUTCD, SAE, state codes), and the operation aligns with both federal guidance and state-specific rules for work zone safety. These requirements have been identified from federal law and various state DOT policies, and the system is engineered to either meet or exceed all of them. This ensures that when the system is deployed, agencies can be confident they are not introducing any legal complications; the system is operating squarely within the existing safety framework as an enhancement. In fact, by preventing crashes, it helps agencies comply with the spirit of laws aimed at protecting roadway workers and motorists alike. All documentation for the product will clearly list these compliances, and if required, the team will seek any necessary approvals or certifications (for instance, if a state wants to pilot it, the team will cooperate in getting any experimental use authorization, etc., although generally no special permission should be needed beyond standard equipment approval). The development team will continue to monitor changes in regulations (for example, if USDOT or a state issues new rules on work zone technology) to update the system accordingly so it remains in full compliance going forward.

A.6 Integration and Future Development

The design of the Audible Alert System takes into account not just current requirements, but also future integration, scalability, and enhancements. This section outlines how the system will integrate with standard TMA equipment and how it will evolve over time to become more effective, standardized, and compact. Key areas of focus include:

- **Standardization of Interfaces and Radar Components**: To facilitate widespread adoption, the system will use standardized interfaces for both its connection to the TMA truck and for any optional sensors like radar. On the vehicle side, a universal wiring harness and communication protocol will be developed that can interface with different TMA truck makes/models and attenuator setups. This could mean using a common connector for power and signals that many TMA trucks can support, and a standard CAN message set or simple trigger line for the horn and lights. By having a plug-and-play interface, retrofitting the system onto existing TMA fleets (or transferring it between trucks) becomes much easier. For example, if the truck has an existing TMA controller (for an arrow board, etc.), our system would have defined integration points with it. We are also advocating for an industry standard in this domain – perhaps via AASHTO or ATSSA – so that in the future, attenuators come “alert-ready” with a port the system can connect to.

Along the same lines, the radar integration is being standardized. Currently, radar is optional, but the team foresees that as the technology proves its worth, a radar unit could become a standard part of the system for additional reliability. The team will pick an automotive-grade radar sensor that is commonly available and ensure the software can interface through a well-documented API or protocol (for instance, using CAN bus with an agreed message format for detected object info). By doing so, if down the line a state DOT wants to use a different radar brand, as long as it adheres to the standard interface, it could be swapped in. Likewise, if the DOT wants to omit radar for cost reasons, the standard interface would be simply left unused without affecting the rest of the system. This modular approach (camera module, radar module, etc., all talking through standard interfaces to the core computer) will be documented in a System Requirement/Specification document and shared for industry feedback. The team believes this could set a foundation for future smart TMAs that various vendors can build to, fostering interoperability. Additionally, manual override integration is part of standardization: the team will ensure that regardless of truck, there is a way for the vehicle's operator or other safety systems to override or interface with this system. For instance, if the truck has a master alarm kill switch or if a connected vehicle network wants to trigger the alarm remotely (in some advanced scenario), having a standard command interface would allow that. Overall, standardization will reduce customization needed per vehicle and lead to easier maintenance and upgrades.

- **System Miniaturization**: As technology advances, one of the team's goals is to shrink the size and weight of the system components without sacrificing performance. The initial prototype uses a relatively bulky edge computing platform (Jetson) and discrete sensors, which occupy space in the cab and on the vehicle. Future development will focus on integrating these into a smaller form factor. This could involve designing a custom embedded board that incorporates the necessary GPU/CPU but in a more compact package or utilizing next-generation AI chips that are much smaller and more power-efficient. The team anticipates being able to consolidate multiple functions (compute, communication, storage) onto one board. The camera sensor might be made smaller or even integrated with the processing unit in a single enclosure. Radar sensors are also getting smaller with on-chip signal processing – those could be integrated behind a low-profile radome. Ultimately, the team envisions that the entire system (except perhaps the display and the external horn) could be contained in a single box that is easy to mount on the truck. For example, a rugged box that you bolt near the rear of the flatbed containing the camera, radar, processor, and cellular modem, with just a cable running to the cab for power and the in-cab display. Reducing size and wiring complexity will simplify installation and make the system more robust (fewer parts to fail). A smaller system is also beneficial for crash safety, because there is less mass that could become a projectile. On the power consumption side, miniaturization often goes hand in hand with efficiency – using less power means it is easier on the vehicle's alternator and could even allow running the system on battery for a while with the engine off (useful in short-term scenarios). The system's development roadmap includes exploring more efficient AI models (so a smaller computer can be used) and possibly using hardware acceleration (such as vision ASICs).

The team will also look at packaging; perhaps the camera and radar can share a housing or be mounted on the same bar to reduce the need for separate mounts. By the time of full deployment, the team aims to have a sleeker unit than the initial prototype, making it practically invisible to the TMA operator (in terms of intrusiveness) and seamlessly integrated into the truck.

- **Enhanced Detection and Alert Accuracy**: Future development will continuously improve the system's ability to detect threats accurately and early. This involves several enhancements: (1) **Algorithm Refinement** – using larger and more diverse datasets (including data from pilot deployments) to retrain the AI models so they can recognize vehicles and predict collisions even more reliably. Edge cases like motorcycles or very fast-changing scenarios will be targeted for improvement. (2) **Sensor Fusion** – if not already implemented, combining camera and radar data in a more sophisticated way. For example, a fusion algorithm can validate a camera detection with a radar return to reduce false positives or use radar's speed measurement to better calculate TTC. Multi-sensor fusion is known to greatly enhance detection robustness, especially in adverse conditions (rain, glare, nighttime), and research supports that it can handle situations one sensor alone might miss[12]. (3) **Extended Range and Field of View** – exploring higher resolution cameras or additional cameras (perhaps a stereo camera setup) to cover more area and see farther. If the system can detect a threat one to two seconds earlier by having better range, that directly translates to more warning time. The research team will also investigate infrared/thermal cameras for night use as a future add-on, since a warm vehicle can be picked up in thermal imagery even if headlamps are small at a distance. (4) **Adaptive Alert Logic** – making the alert triggering smarter by considering context. For instance, using machine learning to adapt the threshold based on how drivers are responding; if on a particular highway, drivers tend to brake later, the system might learn to trigger slightly earlier. Vehicle classification may be incorporated – recognizing if the oncoming vehicle is a large truck (which needs more stopping distance) and thus giving an earlier warning than for a small car. All these improvements aim at increasing the precision of the system: triggering on the right events at the right time, with virtually no misses or false alarms. Over the air updates and modular software design mean the team can deploy these enhancements to units in the field as they are developed. The team will also keep an eye on the development of connected vehicle data – for example, if direct vehicle telemetry from approaching cars via V2X (like their own reported speed) can be shared, that could enhance the system's knowledge beyond what sensors see. In the long run, better detection accuracy could mean predicting driver behavior (such as noticing erratic approach and that that indicates distraction) and tailoring the alert accordingly (maybe a more urgent pattern). All such enhancements will be tested thoroughly in

12 https://ml4ad.github.io/files/papers/Radar%20and%20Camera%20Early%20Fusion%20for%20Vehicle%20Detection%20in%20Advanced%20Driver%20Assistance%20Systems.pdf

simulation and closed-course trials (some of which were outlined, e.g., using driving simulators and human factors studies to see what alert schemes work best). The system's software architecture will be maintained in a way that allows for these new algorithms to be integrated without a complete redesign (using containerized AI models, for example).

- **Integration with Autonomous and Connected Systems**: Looking to the future, work zone safety might involve autonomous TMA trucks (driverless shadow vehicles) and more connected infrastructure. The Audible Alert System is being built with this evolution in mind. For autonomous TMAs (which some DOTs are piloting as "leader-follower" systems or remote-operated vehicles), the alert system would be even more critical because there's no human driver in the TMA to possibly notice an oncoming car. The team plans to ensure that the system can function autonomously in such a scenario – meaning it can not only issue warnings, but possibly communicate with the lead vehicle or a remote operator. For example, if a driverless TMA is about to be hit, the system could send an immediate alert to the operator of the convoy. In even more advanced integration, the system could tie into the autonomous vehicle's controls. MoDOT's guidelines already suggest that TMA operators (when present) are allowed to take preventive action like rolling ahead to mitigate an impact[13]. In a driverless setup, the team could program the TMA to automatically inch forward if a collision is imminent and if it's safe to do so, thus reducing impact force or avoiding the hit (this would require careful logic and likely regulatory permission for the vehicle to move autonomously in an emergency maneuver). The team is not implementing that in the first version, but the system's architecture can output a signal that could be used for such purpose in the future (e.g., an emergency brake light activation or a command that could tie into an autonomous controller). In terms of connected vehicle integration, as more cars on the road get V2V capabilities, this system could broadcast real-time hazard alerts that a connected car's on-board system can warn the driver about (displaying "Crash Ahead – Work Zone" on their dash, for instance). The system will keep alignment with USDOT's Connected Vehicle program so that any such messaging is done in the standard way (BSM or Road Hazard Message). Another integration point is with traffic management centers. The data from the system could feed into statewide traffic systems to give an immediate picture of work zone status. For example, if the cloud backend is linked, a traffic center could see an alert and maybe set dynamic message signs upstream ("Slow Down – Work Crew Ahead") in response to a pattern of alarms. While such integration is at the system-of-systems level beyond this device, the team will ensure the data formats and APIs used make this feasible (using JSON outputs or following DOT data specs for work zone events). Essentially, the Audible Alert System is built not just as a standalone gadget but as a component that can plug into the future ecosystem of smart work zones, autonomous maintenance vehicles, and connected cars. The team will seek opportunities to pilot these advanced integrations as the technology matures.

[13] https://epg.modot.org/index.php/Category:612_Impact_Attenuators

- **Continuous Improvement, Testing, and Mini-Goals**: The team treats the deployment of this system not as an end point but as part of an ongoing improvement cycle. Data collected (with the owner agency's permission) will be analyzed to see how effective the alerts are: Did drivers respond? Were there any false alarms or misses? Did any collisions still occur and why? Using this information, will allow for refinement of both hardware and software. For example, if it is found that a certain horn pattern is not very effective at getting attention, a different sound may be used in the next version. If a particular component has a high failure rate in the field (say, a camera gets too dirty), a self-cleaning housing or better enclosure may be included in future models. Additionally, it is anticipated that collaboration with regulatory bodies would occur to possibly develop standards or best practices. As this is a relatively new application, part of future development is working with FHWA and state DOTs on guidelines so that eventually the use of such alert systems can be codified (much like arrow boards or rumble strips are now standard practice). The team will also look at cost reduction – making the system affordable so that it can be deployed on many TMA trucks. This might involve using COTS (commercial off-the-shelf) components where possible and simplifying the design without compromising performance. The vision is that in a few years, every TMA in high-speed operations could be equipped with a refined version of this system, leading to widespread improvement in work zone safety. Future enhancements will be documented and fed back into the product roadmap. For instance, a planned "Generation 2" might include dual-camera setups for 3D vision, or integration with personal wearable devices for workers (to alert them too). While these are beyond the immediate requirements, the system is architected with enough flexibility (expansion ports, software modularity) to accommodate such features down the line.

In conclusion, integration and future development efforts will ensure that the Audible Alert System not only meets today's needs but also adapts to tomorrow's technological and regulatory landscape. By standardizing components, it will be easier to scale up; by miniaturizing, practicality improves; by enhancing detection, progress is made towards flawless performance; and by planning for autonomous/connected integration, the system remains relevant as the industry evolves. All these forward-looking steps are geared toward a singular mission: making work zones as safe as possible through intelligent, reliable alerts, now and into the future.

Appendix B: Software Requirements Specification (SRS) for the Audible Alert System

B.1 Introduction

B.1.1 Purpose

The purpose of this document is to define the Software Requirements Specification (SRS) for an Automated Audible Alert System designed for Truck-Mounted Attenuator (TMA) work zones. This safety system will automatically detect and warn drivers of vehicles that are on a collision course with a TMA in real time. By providing an early audible warning (such as an automated horn blast) to distracted or speeding drivers, the system aims to give them enough time and distance to react and avoid a rear-end collision with the TMA. The automated alert system operates without direct human intervention during detection and alerting, thereby reducing reliance on a work zone crew member to notice and signal an impending crash. Overall, the Audible Alert System's purpose is to enhance work zone safety by prompting immediate driver corrective action when a collision threat is detected, ultimately reducing TMA crash incidents and associated injuries.

B.1.2 Scope

This SRS covers the scope of features and capabilities for the Audible Alert System in TMA work zones. The system's primary scope includes:

- **Real-time Vehicle Detection and Tracking:** The system will detect oncoming vehicles approaching the rear of a TMA using sensor inputs (e.g. camera, and optionally radar/LiDAR) and track their positions and trajectories relative to the work zone. It will classify detected objects as vehicles and distinguish relevant attributes (such as vehicle type or size) as needed for threat assessment.
- **Speed and Trajectory Estimation:** For each approaching vehicle, the system will estimate its speed, acceleration, and predict its trajectory path. Using these, it will continuously compute the time-to-collision (TTC) with the TMA if the current trajectory continues. This predictive capability is central to determining collision risk in advance.
- **Collision Threat Assessment & Alert Triggering:** The system will autonomously determine if an approaching vehicle poses a collision threat based on defined alert criteria (e.g. TTC below a threshold, vehicle accelerating toward the TMA instead of slowing, or deviating into the closed lane). If a potential collision is detected, the system will trigger audible alarms in real time to warn the driver. The alert can include an on-board horn or siren and may also activate existing TMA flashing lights for a combined audio-visual warning.
- **Support for Multiple Sensor Configurations:** The solution is designed to work in different sensor setups. It can function with a camera-only configuration (using computer vision to estimate distance and speed), or a camera + radar/LiDAR configuration for enhanced accuracy and redundancy in detecting vehicle speed and range. The system's sensor

fusion approach allows flexibility: for example, radar can directly measure vehicle speed and distance, complementing camera-based detection. This modular design means agencies can deploy the alert system on TMAs with just vision or with additional sensors, depending on availability and budget.

- **Data Logging and Connectivity:** The scope also includes logging of events and system data for post-analysis. The system will record information such as detected vehicle counts, speeds, distance, time of alert trigger, etc., which can be uploaded to a cloud server or traffic management system for later review by safety engineers. Additionally, the system will expose interfaces or APIs to integrate with external traffic management platforms – for example, to send real-time alerts to a traffic operations center or to update connected work zone warning systems. (Detailed integration requirements are covered later in this document.)

Items *outside* the scope of this SRS include the detailed implementation of machine learning algorithms (the SRS focuses on requirements, not design), and any modifications to the TMA's physical attenuator hardware itself. The Audible Alert System augments existing TMAs but does not change their primary crash cushion function. It also assumes that standard TMA visual warning devices (e.g. arrow boards, signage) remain in use as per normal operation; this system adds an extra safety layer rather than replacing any existing safety device.

B.1.3 Definitions, Acronyms, and Abbreviations

- **TMA (Truck-Mounted Attenuator):** A crash cushion device mounted on the back of a truck used in work zones. It absorbs impact energy to protect roadside workers if a vehicle collides with the truck. In this document, *TMA* also refers to the safety vehicle carrying this attenuator.
- **Work Zone:** A roadway section under construction or maintenance, typically delineated by cones, signs, and protected by TMAs for mobile operations.
- **Audible Alert:** A loud sound (such as a horn or siren) used to warn drivers. In this system, the audible alert is automatically triggered to get an errant driver's attention and prompt braking/steering to avoid collision.
- **AI/ML (Artificial Intelligence/Machine Learning):** Techniques in computer science where algorithms learn patterns from data. The vehicle detection in this system uses ML-based computer vision – a trained model identifies vehicles in camera images in real time.
- **IoT (Internet of Things):** A network of physical devices (sensors, cameras, etc.) with connectivity allowing them to send/receive data. The Audible Alert System is an IoT device in that it can upload data to cloud services and be monitored remotely.
- **Time-to-Collision (TTC):** The estimated time remaining before a moving vehicle would collide with an object (here, the TMA) if it continues at its current speed and path. For example, a car 50 meters away traveling directly toward the TMA at 25 m/s has a TTC of 2 seconds. The system uses TTC as a primary metric for threat assessment.

- **NVIDIA Jetson Orin/Nano:** Embedded computing platforms by NVIDIA that include GPU acceleration for AI applications. The Jetson Orin (more powerful) and Jetson Nano (lower cost) are the hardware targets for this system's on-board processing. They provide the computational power to run neural networks for object detection in real time at the network edge (on the TMA vehicle).
- **LiDAR:** Light Detection and Ranging, a sensor technology that uses laser pulses to measure distance to objects by the time it takes for reflections to return. It produces a 3D "point cloud" of the environment and can be used to detect vehicles and measure their range very accurately.
- **Radar:** Radio Detection and Ranging, a sensor that emits radio waves and measures reflections to detect object positions and speeds. In this context, radar can be used to directly measure an approaching vehicle's speed and distance, supplementing the camera's data.
- **MUTCD:** The **Manual on Uniform Traffic Control Devices**, a U.S. federal regulation (administered by the FHWA) that defines standards for road signs, signals, markings, and other control devices in streets and highways. Part 6 of the MUTCD covers Temporary Traffic Control (work zones), and any warning system used in work zones (lights, signals, etc.) should comply with these standards for visibility, color, usage, etc.
- **FHWA:** Federal Highway Administration, the U.S. agency overseeing road safety regulations and guidelines. The FHWA issues rules and guidelines related to work zone safety (such as the requirement for positive protection measures and intrusion alarms in certain work zones). In this SRS, *FHWA guidelines* refers to applicable rules the system must follow, including the Work Zone Safety and Mobility Rule (23 CFR 630 Subpart K) and any relevant FHWA recommendations for work zone intrusion alert technologies.
- **ISO 26262:** An international standard for automotive functional safety titled *"Road Vehicles – Functional Safety."* ISO 26262 outlines a framework and requirements to ensure safety-critical electrical/electronic systems in vehicles perform reliably and safely, including risk assessment (ASIL levels), fault mitigation, and fail-safe designs. This standard is applicable to the system since it is an electronic safety device in a road vehicle context.
- **ASIL:** Automotive Safety Integrity Level, defined in ISO 26262, categorizing the level of risk reduction required (A through D, with D being the most stringent) for an automotive function to be acceptably safe. (The specific ASIL for this alert system would be determined by hazard analysis; not specified here, but the design must meet the corresponding requirements.)
- **Uptime:** The percentage of time the system is operational and available. "100% uptime" means no downtime — the system is always running during its intended operation period. For a safety system like this, high availability is critical.

B.1.4 References

The following standards and documents are referenced or are relevant to the Audible Alert System requirements:

- **ISO 26262:2018 – Road Vehicles – Functional Safety.** International Organization for Standardization. (Guidelines for ensuring functional safety of automotive electronic systems).
- Manual on Uniform Traffic Control Devices (MUTCD), 2009 Edition, Federal Highway Administration. (U.S. standard for traffic control devices, including work zone signage and warning devices).
- FHWA 23 CFR 630 Subpart K – Work Zone Safety and Mobility (Final Rule), 2008. Federal Highway Administration regulation requiring transportation agencies to implement positive protection and intrusion countermeasures in work zones.
- FHWA Work Zone Intrusion Alert Technologies – Assessment and Guidance, 2017. *(Listed as an informative reference)* A report providing evaluation of various work zone intrusion alert systems and recommendations.
- Project AutoTMA Research Proposal, 2022. University of Missouri and MoDOT – *"Automated TMA Warning System"* (background and objectives for an AI-based TMA alert system).

Note: The above references provide context and guidelines; the system implementation must adhere to the normative standards (ISO 26262, MUTCD, FHWA rules) and draw on best practices and findings from research.

B.1.5 Overview of Document

The remainder of this document outlines the overall product description and detailed requirements for the Audible Alert System. **Section 2 (Overall Description)** provides background on how the product fits into the larger context of TMA operations, its general functions, user characteristics, design constraints, and assumptions. **Section 3 (Specific Requirements)** then delineates the precise functional requirements of the system (what it must do), the user interface requirements (how it interacts with TMA operators and remote systems), performance requirements (accuracy, speed, reliability targets), hardware/software integration requirements, and regulatory compliance requirements. Each requirement in Section 3 is intended to be clear, verifiable, and traceable to the objectives and standards introduced in this section. Together, these sections form a comprehensive specification that will guide the development, testing, and validation of the Audible Alert System.

B.2. Overall Description

B.2.1 Product Perspective

The Audible Alert System is a safety subsystem integrated into a Truck-Mounted Attenuator vehicle. In the context of a TMA work zone setup, this system adds a proactive collision warning capability to the existing passive safety features. Traditionally, TMAs provide *“positive protection”* by physically shielding workers (they absorb impact energy if struck). The Audible Alert System complements this by attempting to prevent the collision in the first place: it identifies an oncoming vehicle that may hit the TMA and warns the driver in advance so they can slow or re-align their vehicle. This system fits within the TMA truck’s overall setup without altering the TMA’s primary function; it uses sensors (cameras and possibly radar/LiDAR units) mounted on the TMA truck (typically on or near the attenuator or vehicle rear) and an on-board computing unit (NVIDIA Jetson) housed inside the truck’s cabin or enclosure. It also interfaces with output devices – mainly a high-decibel horn or siren installed on the TMA, and optionally the light bar or arrow board on the truck – to issue alerts.

Integration with Existing Infrastructure: The design assumes that the TMA truck is already equipped with standard work zone signage and lighting (e.g., flashing arrow board, warning beacons) as required by MUTCD. The Audible Alert System will integrate with these such that, for example, an alert event could also trigger the TMA’s light bar to flash aggressively in tandem with the horn. The system is also intended to integrate with standard TMA controls and power. For instance, it will use the truck’s 12V/24V power system and should have a standardized interface so it can connect to the TMA’s horn circuitry or an add-on siren. The aim is to minimize custom modifications to the TMA; instead the alert system should be as plug-and-play as possible, allowing retrofitting into existing attenuator trucks. This may involve a common connector or module that ties into the truck’s electronics for horn control, and mounting brackets for cameras/lights that fit common attenuator hardware.

From a system perspective, the Audible Alert System is an embedded, real-time system operating on the edge (the TMA vehicle itself). However, it also has IoT connectivity for back-end integration. It can send data or notifications to a central server or traffic management center over cellular or wireless network, functioning as part of a broader “smart work zone” infrastructure. For example, multiple TMAs outfitted with this system could all report near-miss incidents to a central dashboard for agency oversight. In summary, the product exists as a component within the TMA truck environment and the larger highway safety ecosystem, interfacing both with the vehicle’s hardware and external systems.

B.2.2 Product Functions

At a high level, the Audible Alert System provides the following key functions and features:

- **Vehicle Detection and Classification:** Continuously monitor the approach to the TMA (typically the lane directly behind the work zone) and detect vehicles in that area. The system uses machine-learning-based computer vision to recognize oncoming vehicles in camera video feeds. It can distinguish vehicles from other objects and possibly classify the type of vehicle (e.g., car, truck) if needed for risk assessment. Multiple vehicles can be detected and tracked simultaneously.

- **Distance and Speed Estimation:** For each detected vehicle, the system determines its distance from the TMA and computes its speed and acceleration. If additional sensors are used, radar or LiDAR data will contribute to more accurate range and speed measurements. In camera-only setups, the system utilizes perspective geometry or stereo vision (if dual cameras) to estimate distance, and frame-to-frame tracking to estimate speed. These calculations are continuously updated as vehicles move.

- **Time-to-Collision Calculation:** Using the distance and speed information, the system calculates the Time-to-Collision (TTC) for an approaching vehicle – essentially predicting how soon (in seconds) the vehicle would reach the TMA if it doesn't slow or change course. This calculation updates in real time for each tracked vehicle and is a core part of deciding when an alert is necessary.

- **Trajectory and Lane Monitoring:** The system performs lane detection and tracking to understand the vehicle's trajectory relative to the TMA's lane. It can detect if a vehicle is in the closed work zone lane or drifting out of its intended lane toward the work area. By segmenting lanes and drivable areas in the camera's view, the system knows whether the approaching vehicle is aligned with hitting the TMA or is safely in an open lane. This function helps filter threats (e.g., a vehicle passing in an adjacent lane might be tracked but not cause an alarm unless it swerves toward the TMA).

- **Collision Risk Assessment:** The system's logic combines speed, acceleration, TTC, and lane position data to assess the risk level of each approaching vehicle. It applies predefined criteria (calibration parameters) to decide if a vehicle's behavior warrants an alert. For example, if a vehicle is closing distance too fast (short TTC) and not decelerating, or if it has entered the buffer space behind the TMA at high speed, it will be classified as a collision threat. There may be multiple levels of warnings (e.g., a "warning" state and a more urgent "danger" state) internally, but in this system they all result in a single type of audible alarm for the driver when a threshold is crossed.

- **Automated Audible Alert Activation:** When a collision threat is detected, the system automatically activates an audible warning device. This is typically a high-volume horn or siren mounted on the TMA. The system controls the horn via a relay or interface, sounding the alarm immediately and without human intervention once conditions are met. The alarm is intended to startle or alert the driver of the oncoming vehicle so they realize they must slow down or move over. The system will continue the alarm for the duration of the threat (for example, it may sound for as long as the vehicle remains dangerously close and is still moving toward the TMA). Once the vehicle either slows sufficiently, stops, or changes lanes away from the TMA, the system will turn off the alarm automatically. (Specific trigger conditions and alarm behaviors are detailed in Section 3.1.) Additionally, the system can be configured to flash existing warning lights concurrently with the audible alarm to maximize visibility.

- **Data Logging:** The system logs relevant data from each event and general operation. This includes timestamps of alert triggers, the measured parameters of the vehicle at the time (speed, distance, TTC), and potentially video footage or snapshots around the event. It also logs system status data (e.g., uptime, any errors, sensor statuses). These logs are stored locally and can be uploaded periodically or on-demand to a central repository for analysis. This function is crucial for **post-incident analysis**, performance tuning, and reporting to stakeholders. Road safety engineers can review logs to understand how many near misses occurred, how the system performed (e.g., any false alarms or misses), and gather statistics to improve work zone safety strategies.

- **System Health Monitoring:** The Audible Alert System monitors its own health and the status of its components (camera video feed, radar connectivity if present, processor status, etc.). If it detects a fault (for instance, a camera failure or an internal error), it can notify the operator (via the user interface) and take safe action. This may include disabling itself and/or triggering a maintenance alarm if critical (so that the crew knows the system is not functional). This function ensures that the system fails in a safe manner – it will never silently go offline without the crew realizing, thus avoiding a false sense of security.

- **Remote Communication and Alerts:** The system can communicate with external systems through network interfaces. Functions include sending real-time alert notifications to a cloud server or traffic management center when an alarm is triggered, and receiving remote commands (for example, from a central control to reset or change settings). A typical use of this function is a cloud dashboard or mobile app that shows all active TMAs and alerts; when this system triggers an alarm, it could push a notification like "TMA #3 – Collision Alarm Activated on I-70 at 2:35 PM" to supervisors. Another use is integration with connected vehicle systems – e.g., broadcasting a message that can be picked up by vehicles or V2X infrastructure. While such V2X integration is forward-looking, the system's design allows external connectivity so it can be part of future connected work zone schemes.

In summary, the Audible Alert System provides end-to-end functionality from sensing to actuation: *sense* (recognize approaching vehicles), *think* (analyze risk), and *act* (warn the driver and record the event). All these functions operate under real-time constraints and with safety and reliability considerations as described below.

B.2.3 User Characteristics

The users of the Audible Alert System include several groups, each with different needs and technical backgrounds:

- **TMA Operators / Work Zone Crew:** These are the people in the field responsible for the work zone and who will be directly interacting with the system on a day-to-day basis.

Typically, a TMA operator is the truck driver or a crew member in the TMA vehicle. Their characteristics: they are likely road construction professionals, not computer experts, so the system's user interface needs to be remarkably simple and intuitive. They will use the in-cab interface to check system status (ensure it is armed and functioning at the start of a job), and possibly to manually activate or disable alarms in special situations. They need to trust that the system will alert them (or directly alert the errant driver) reliably. Training for these users will cover understanding what the system is doing (e.g., what it means when it alarms, how to respond if anything goes wrong, how to do basic troubleshooting or sensor cleaning). Since work zone crews operate in high-risk, high-noise environments, the system's design should accommodate rugged use and not distract the crew from their primary tasks. For instance, the in-cab display should be glanceable and possibly use audible tones or simple signals for status, so that the operator does not have to navigate complex menus while driving or setting up the zone.

- **Road Safety Engineers/Analysts:** This group includes engineers or analysts (for example, at the Department of Transportation or research units) who will review the system's data output to evaluate work zone safety. They typically have an engineering background and are interested in metrics like the frequency of alerts, time-to-collision statistics, and false alarm/near-miss analysis. They may use a back-office software or cloud platform to retrieve logs from the system. Their interaction with the system is not direct in the field, but via the data it produces. They might also be involved in updating the system's algorithms (deploying new ML model updates) as they analyze performance. Their needs include comprehensive data and possibly the ability to adjust system parameters (like tweak the TTC threshold) in future deployments. They will also ensure the system meets safety performance requirements (e.g., verifying the 95% detection accuracy in practice) and will be looking at the system from a continuous improvement perspective.

- **Supervisors and Traffic Management Center Personnel:** In some deployments, a work zone or TMA might be monitored remotely by a supervisor or by staff in a Traffic Management Center (TMC). These users would use the remote access capabilities – e.g., a web dashboard showing live status of multiple TMAs across the region. Their technical level can vary; they may be familiar with traffic operations software. They will use the system to get real-time alerts (perhaps an audible alert on their console or a pop-up when a TMA alarm goes off) so they can coordinate emergency response if needed. For example, if an alarm triggers and then a collision still occurs, the TMC can immediately dispatch help. These users need **reliable notifications** and possibly a summary view rather than detailed technical data. They may also remotely check that systems are online at the start of shifts.

- **Regulatory and Compliance Officials:** This includes safety inspectors or DOT officials responsible for ensuring the work zone safety systems comply with regulations (like checking that the audio alarm conforms to legal noise limits or that the system does not inadvertently cause any traffic control violations). They might not interact with the system's UI much, but they will review documentation (including this SRS, test results, etc.) and may observe the system in action during pilots. They typically have a civil engineering or safety background and will focus on whether the system's presence improves safety without introducing new hazards. For example, they will be concerned with false alarms or any possibility that an alarm could startle a driver in a way that causes unintended consequences. They require that the system meets standards (MUTCD, etc.) and will use the logged evidence to verify compliance (like confirming that every time the alarm went off, there was indeed a vehicle that met the criteria – to ensure the system is not crying wolf).

- **Maintenance Technicians/IT Support:** Although not explicitly mentioned, it is worth noting that those responsible for maintaining the system (updating software, repairing/replacing sensors, ensuring connectivity) will also interact with it. They will have a technical background in electronics or IT. They might use diagnostic interfaces to check sensor feeds, update firmware, or replace components. The system should provide them with diagnostic info (like error codes) to facilitate troubleshooting. This user group needs the system to be modular and maintainable (quick swap of a broken camera, clear error logs for why something failed, etc.).

User Environment: The primary users (TMA operators) will be using the system outdoors, in a vehicle cab, often under stressful conditions (e.g., traffic passing by, loud equipment noise). The UI must be usable in bright sunlight or night, with possibly gloved hands, and withstand vibrations of the truck. The remote users and engineers will mostly interact via office environments or mobile devices. Security levels vary: field users are trusted operators allowed to control the system; remote viewers might be read-only; engineers might have administrative access. The system should accommodate these roles with appropriate access controls (e.g., preventing an untrained person from inadvertently disabling the system).

In summary, the system's design must balance the needs of field operators for simplicity and reliability, with the needs of analysts and administrators for data and control. It should present the right information to the right user group without overwhelming them, and remain robust against human error (for example, protect against an operator accidentally turning off the system, while still allowing an emergency override when truly needed).

B.2.4 Constraints

The development and operation of the Audible Alert System are subject to several constraints:

- **Hardware Platform Constraints:** The system is constrained to run on the NVIDIA Jetson family (specifically the Jetson Orin or Jetson Nano platforms) as the edge computing device. This imposes limits on processing power, memory, and available interfaces. The Jetson Nano, being a lower-end device, has relatively limited CPU/GPU capabilities and memory, which means the machine learning models and software must be optimized for efficiency (e.g., using lower precision calculations or optimizing neural network architectures) to achieve real-time performance. The Jetson Orin provides more compute, but even it is an embedded device with power and thermal limits (unlike a desktop GPU).

Therefore, the software must be designed within these hardware limits – for example, heavy image processing should utilize the GPU via CUDA, and the ML models may need to use accelerators or be quantized to run faster. The choice of this hardware also means any libraries or frameworks used must be compatible with ARM architecture and Linux for Tegra.

- **Real-Time Processing Constraints:** The system must operate in real-time, analyzing video frames and sensor data continuously with minimal latency. This real-time requirement (detailed in performance requirements as ~50 ms response time) means that all algorithms for detection, tracking, and decision-making have strict time budgets per cycle. There is a constraint on computational complexity of the ML models – for instance, an algorithm that is too slow to run at ~20 frames per second on the Jetson hardware would not meet the requirement. As a result, complex deep learning models might need to be pruned or simplified. Also, running multiple sensors (camera + radar/LiDAR) means sensor fusion algorithms must be efficient. If the system falls behind (e.g., processing takes too long and frames queue up), it could miss timely alerts, which is unacceptable. Thus, meeting real-time constraints is critical and will likely require using asynchronous processing, parallel threads, and hardware acceleration.

- **Environmental and Operating Constraints:** Being deployed on a work zone truck, the system hardware (cameras, computing unit, etc.) will face harsh conditions. Cameras might be exposed to weather (rain, dust) and varying light (night, glare from sun). The computing unit will face vibration, heat inside the truck cabin during summer, and cold in winter. All components must be industrial-grade or ruggedized to some extent. This is a constraint that influences the choice of camera (e.g., need high dynamic range for night/day transitions), enclosure design (for the Jetson), and possibly requires the system to perform self-calibration (like adjusting camera exposure) to handle environmental changes. Additionally, connectivity may be constrained – remote features depend on cellular signals which might be weak in some rural areas. So the system must not *solely* rely on constant connectivity; it should perform its safety function standalone and cache data if needed, only uploading when network is available.

- **Existing Vehicle Constraints:** The system must fit into the existing TMA vehicle without excessive rework. This includes power constraints (it should not draw more power than the vehicle can provide), physical space constraints for mounting cameras and the Jetson unit in the cab, and interfacing with the truck's electrical system safely. It likely has to run off the vehicle's battery/alternator system, so power usage is a concern especially when the truck engine is off (to avoid draining battery). The hardware also cannot interfere with the TMA's crashworthiness – e.g., the camera mount must not create a hazard in a collision, and wiring must be secure so it does not get severed or entangled with other equipment.

- **Regulatory and Safety Constraints:** The system's behavior is constrained by safety regulations. For example, the audible alarm must not exceed certain decibel levels that could harm hearing if a worker is close by, as per occupational safety guidelines (this is both a requirement and a constraint in design – e.g., the horn type is constrained by what is legally allowed for use on roads). The system also must not distract or confuse drivers not involved in the alert – for instance, if two lanes are open and a car in lane two triggers the alarm, a driver in lane one might also hear it; the alert method must be chosen to minimize any negative effect (this often means using a directional siren or ensuring the context makes it obvious who it's for). Another safety constraint is fail-safe operation: if the system fails, it should do so in a way that doesn't cause a hazard (for instance, it should not randomly trigger the horn when there is no danger due to an internal fault – better to fall silent and indicate an error to the operator).

- **Development Time and Update Constraints:** If this system is part of a research or pilot project (as indicated by references), there may be timeline constraints for delivery (e.g., needing a prototype by a certain date) which can affect the scope of features included initially. Additionally, the machine learning model may require periodic updates (new training with more data). A constraint here is ensuring that the system can be updated (software/firmware updates) during maintenance windows and that such updates are tested (cannot introduce regression in detection quality). Compatibility between different versions (like Jetson Nano might run a lighter model than Jetson Orin) should be managed, meaning possibly maintaining multiple model variants – a maintenance overhead.

In summary, the main constraints are technical (hardware and real-time limits), environmental (rugged conditions), and regulatory (safety standards). All development and design decisions for the Audible Alert System must be made in recognition of these constraints to ensure the final product is practical, reliable, and compliant in the field.

B.2.5 Assumptions and Dependencies

The following assumptions and dependencies are identified for the Audible Alert System:

- **Availability of Properly Equipped TMA Vehicles:** It is assumed that the system will be deployed on TMA trucks that have the necessary infrastructure to support it. This includes adequate mounting positions for cameras (with an unobstructed rear view of traffic) and any other sensors, a stable power source, and an accessible interface to the vehicle's horn or alert mechanisms. For example, it is assumed the TMA has an electronic horn that can be triggered or that an auxiliary siren can be installed. If a particular TMA model does not allow external control of its horn, that would be a dependency on modifying that vehicle or using a separate audible device.

- **Sensor Quality and Calibration:** It is assumed that the sensors (camera, radar, LiDAR) used by the system are properly calibrated and provide reliable data. Camera calibration (for distance estimation) is a dependency – if the camera's field of view and mounting angle are known, the system can map pixels to real distances. It is assumed calibration will be done initially and checked periodically. Similarly, if radar/LiDAR are used, it is assumed they are installed such that their coverage overlaps with the camera's coverage (to detect the same vehicles) and time-synchronized for sensor fusion. The performance of the system is dependent on these sensors functioning correctly; any significant misalignment or hardware degradation (blurred camera lens, etc.) will affect detection accuracy. Regular maintenance (cleaning the camera lens, verifying sensor alignment) by the crew is assumed.

- **External Systems and API Dependency:** The integration with external traffic management systems assumes that those systems (like a DOT’s central server or a cloud IoT platform) exist and provide documented APIs or channels. It is assumed that network connectivity (cellular, Wi-Fi, or other) can be established from the TMA to these external systems. If connectivity is unavailable in certain areas, the system’s remote features will be limited – the assumption is that this does not impact the core safety function (which works locally). The dependency here is on telecommunications providers for data coverage, and on the external systems to receive/process the data (for example, an assumption might be that the DOT’s cloud can accept JSON messages of alerts via a REST API; the Audible Alert System will depend on that interface being available and secure).

- **Operator Training and Compliance:** It is assumed that TMA operators and work zone personnel will be trained in using the system and will follow proper procedures. For instance, it’s assumed that at the start of each work zone operation, the crew will ensure the system is powered on and engaged (the system might not automatically start if the truck isn’t configured that way). It’s also assumed they won’t intentionally disable or ignore the system except under appropriate circumstances. The effectiveness of the system partly depends on operators trusting it and not overriding it without cause. If the operator must take a specific action to enable the system (like arm it when the work zone is set up), it is assumed this becomes part of their standard checklist.

- **Driver Reaction Assumption:** While not exactly a dependency the system can control, an underlying assumption is that drivers who are alerted by the audible alarm will respond appropriately (slow down, regain attention). The system is designed based on the premise that an audible alert can change driver behavior in time to prevent a collision. If for some reason drivers do not react (due to impairment or not hearing the alarm because of loud music, etc.), the system cannot physically prevent a collision – it’s not an active braking system, it’s a warning system. The success of the system thus assumes typical cases where an alert gives a distracted driver enough of a jolt to hit the brakes. This assumption will be validated through field testing and is backed by prior research indicating loud auditory warnings are effective in capturing driver attention.

- **Periodic Model Updates and Configuration:** It is assumed that the machine learning model used for vehicle detection will be updated periodically as more data is collected (to improve accuracy, reduce false alarms). A dependency is that the project team or vendor provides these updates in a timely manner and that the update process (either manual via maintenance or over-the-air if supported) is available. Additionally, it is assumed that threshold parameters (like the TTC threshold for alarm) might be adjusted after initial testing. The requirement specifications give initial values, but the system may need fine-tuning; this assumes collaboration with safety experts to set those final values. There's also a dependency on performing *validation tests* after any model update to ensure it still meets the requirements (e.g., >=95% detection accuracy).

- **Compliance Dependencies:** The system's deployment depends on regulatory approval or acceptance by relevant authorities (DOT, etc.). It's assumed that by adhering to standards (MUTCD, etc.) and demonstrating safety, the system will be permitted for use. However, if local policies require specific certification (for example, some states might need an approval for electronic devices on work vehicles), obtaining those is a dependency. It is assumed that cooperation with regulators is ongoing and positive.

- **Attenuator Activation Not Dependent:** It's important to note an assumption that the Audible Alert System operates independently of the attenuator deployment. Whether the TMA attenuator is up or down (some are raised during travel), the system's sensors and alerts can function. Only when the TMA is actually being used in a work zone (vehicle stopped or moving slowly as a buffer) will the system be active. It is assumed that the system is smart enough or configured to not issue alerts during normal driving of the TMA truck (to avoid alarming regular traffic when the TMA is just driving to a site). This may depend on an input (perhaps the operator sets "work zone mode" when at the site), or geofencing. For the requirements, it is assumed that such operational mode management will be handled to ensure the system only runs when appropriate.

In summary, the project's success is dependent on proper installation and maintenance of hardware, availability of network and integration endpoints, user training, and regulatory support. The assumptions listed above set the context under which the requirements in this SRS are valid. If any of these assumptions change, the requirements and design may need to be revisited accordingly.

B.3. Specific Requirements

This section details the specific requirements of the Audible Alert System. The requirements are organized into categories: **Functional Requirements** (the core behaviors and features of the system), **User Interface Requirements** (the look and interaction of the system for operators and remote users), **Performance Requirements** (quantitative criteria the system must meet, like speed and accuracy), **Hardware/Software Integration Requirements**, and **Regulatory & Compliance Requirements**. Each requirement is stated in clear terms. Wherever applicable, rationale or references are provided to standards or research that justify the requirement. The word "shall" indicates a mandatory requirement, while "should" indicates a desirable but not strictly required feature.

B.3.1 Functional Requirements

B.3.1.1 Vehicle Detection (Machine Learning):

The system shall automatically detect vehicles approaching the rear of the TMA using a machine-learning based vision model running on the on-board camera feed. It shall identify a vehicle's presence with high confidence and locate it (e.g., with a bounding box or coordinates in the frame). The detection algorithm should be robust to various lighting and weather conditions (day/night, rain) to the extent possible. The detection performance shall not significantly degrade for typical highway speeds of vehicles. The system's design shall allow for periodic updates of the detection model to incorporate new training data and improve accuracy over time. For example, the model might be retrained periodically with new dashcam footage data; the updated model can be deployed to the device to enhance detection of difficult scenarios (such as motorcycles or glare conditions). Model updates will be done in a controlled manner (ensuring backward compatibility with hardware). *Rationale:* A learning-based detection approach is chosen because it can generalize to different vehicle types and has shown high accuracy in identifying vehicles in real time. Keeping the model updateable ensures the system can adapt to evolving vehicle shapes and any failure modes discovered in the field.

B.3.1.2 Vehicle Speed and Trajectory Calculation:

The system shall estimate the speed and trajectory of each detected vehicle. This involves computing the vehicle's *current speed* and *acceleration* (positive acceleration indicating the vehicle is speeding up, negative indicating braking) relative to the TMA. It shall also determine the vehicle's current lane or path – i.e., whether the vehicle is directly behind the TMA or offset in another lane. If the vehicle is equipped with radar or LiDAR data, the system shall use that data for precise range and speed calculation (e.g., Doppler speed from radar). In a camera-only setup, the system shall infer speed by tracking the vehicle's change in position over time (frame-to-frame) and using perspective mapping (with an assumed calibrated distance scale). The **Time-to-Collision (TTC)** for each vehicle shall be computed continuously whenever a vehicle is detected and moving toward the TMA. The TTC calculation will use the current distance and relative speed: for example, TTC = distance/relative_speed (assuming the vehicle continues at the same speed). If a vehicle is slowing down (braking), the system should account for deceleration when estimating collision time – but for safety, a conservative approach (assuming no significant slowdown until detected) is acceptable. The system shall maintain these calculations in real-time for multiple vehicles, prioritizing the vehicle with the smallest TTC (highest threat).

B.3.1.3 Collision Threat Assessment (Alert Conditions):

The system shall determine when an approaching vehicle constitutes a collision threat that warrants an alarm. This decision will be based on one or more of the following alert conditions, which can be configured by safety engineers:

- **TTC Threshold Breach:** If a vehicle's Time-to-Collision falls below a critical threshold (for example, TTC < three seconds) and is still decreasing, the system shall consider this an imminent collision risk and trigger the alert. The default threshold (to be fine-tuned in testing) could be around 2.5–3 seconds for highways, but it may vary depending on road type and desired sensitivity. This condition ensures that if a vehicle is dangerously close and closing in fast, the alarm sounds to get the driver's attention.

- **High Speed/No Deceleration in Close Proximity:** If a vehicle is detected within a defined distance (e.g., 60 meters behind the TMA, which is roughly the "danger zone") and is travelling significantly above safe speed (for instance, more than the work zone speed limit or not slowing down), the system shall trigger an alert. In essence, a vehicle that blasts into the buffer zone at highway speed is a threat even if its TTC might be slightly above the threshold momentarily. This condition uses absolute speed and distance checks – for example, >70 mph at 50 m distance triggers alarm.
- **Acceleration Toward TMA:** If the system observes that a vehicle is *accelerating* toward the TMA when it should typically be decelerating (such as when other vehicles would be slowing for the work zone), this is a red flag. The system shall factor in acceleration: a vehicle with positive acceleration in the danger zone or with a shortening TTC trend triggers the alarm earlier. Even if TTC hasn't reached the absolute threshold yet, continued acceleration can prompt an earlier warning (since it indicates the driver is not reacting). For example, a vehicle 100 m away accelerating from 60 to 70 mph pointed at the TMA would qualify for an early alert.
- **Lane Deviation into Work Zone Path:** The system shall monitor the lane position of approaching vehicles using lane detection. If a vehicle that was in an adjacent open lane deviates or drifts into the closed lane or buffer space behind the TMA, it shall immediately be considered a threat and trigger the alarm. This covers scenarios where a driver might initially be in the correct lane but then starts moving into the protected area (perhaps due to distraction). The system's lane segmentation and tracking will identify such a deviation. The trigger might be when a significant portion of the vehicle crosses into the TMA's lane within a certain distance.

These conditions can work in combination. The system's logic shall trigger an alarm if any one of the configured conditions is met (logical OR), to ensure no potential threat goes unwarned. At the same time, the logic shall be refined to avoid trivial triggers – e.g., a vehicle passing safely in an adjacent lane should not trigger an alarm just because it's within 3 seconds of passing distance to the TMA if it's clearly in another lane. Therefore, the implementation will likely use a combination (e.g., TTC & same lane) for some cases. All the specific parameter values (TTC threshold, distance zones, speed thresholds) shall be configurable in the software, allowing calibration per work zone requirements or policy. Initial values will be chosen based on engineering judgment, simulation, and guidelines (for instance, ensuring the alarm triggers with enough time for a driver to react, typically two to three seconds ahead). The system should also implement hysteresis to some degree to avoid oscillating alarms (e.g., if TTC hovers around three seconds, the alarm shouldn't rapidly switch on/off). Once an alarm condition is met, the alarm will stay on until the situation is clearly resolved (see B.3.1.5).

B.3.1.4 Alarm Activation (Audible Alert Output):

When a collision threat is identified as per the above conditions, the system shall automatically activate an audible alarm to warn the at-risk driver. The alarm shall be loud and distinct enough to get the driver's attention amidst traffic noise. Specifically, the system will activate a horn or siren device mounted on the TMA. The activation shall occur with minimal delay – effectively immediately when the trigger condition is detected (within the 50 ms processing time – see performance requirements – plus whatever negligible relay activation time). This means as soon as the internal logic flags a danger, the horn output is turned on in real time. The alarm should continue for the duration of the threat: the system shall keep the horn on (or in a pulsing pattern if that is more effective/legally required) until the vehicle either slows down sufficiently or changes course away from the collision path. In practice, the system might implement this as: once triggered, sound the horn for a minimum duration (say one second), and then keep it on until the vehicle's TTC rises above the safe threshold again (e.g., driver braked and now TTC > five seconds, or the vehicle has passed by). The system shall then automatically silence the alarm. If multiple vehicles trigger alarms in succession (e.g., two vehicles one after another), the system shall handle that seamlessly by extending the alarm or re-triggering as needed, without requiring manual reset.

The audible alert device shall meet any pertinent requirements (e.g., use a specific pattern or volume as recommended by work zone safety studies). It's expected to be an electronic air horn or siren that can output ~120 dB sound directed rearward. The system's output to this device will likely be a simple electrical signal. The requirement is that the system must reliably drive this output whenever needed. Redundancy: if one horn fails, and if a backup is installed, the system should be able to drive the backup (or at least alert the operator that the horn failed – see self-diagnostics). Additionally, the system should simultaneously activate a visual alarm (like strobing the TMA's lights) in sync with the audible alarm to provide a multi-modal warning. (This visual component is highly encouraged by safety guidelines, but since this SRS is focused on the audible system, it is listed as a "should". It may be mandatory per some agency policy to have lights with the horn, so it can be refined accordingly.) The audible alarm output is considered safety-critical; thus the requirement is that this output must function whenever commanded, with no missed activations. It will be tested thoroughly (for example, the horn will be honked in routine system tests to ensure the relay and device work).

Finally, once an alarm event is over (vehicle gone or slowed), the system shall reset itself for the next potential threat without needing intervention. There should be a brief cool-down to prevent continuous blaring in case of uncertainty, but essentially it should be ready to trigger again within fractions of a second if another trigger condition arises. The system shall also log that the alarm was activated (see logging requirements). *Rationale:* An automated audible alarm can significantly improve reaction time of a distracted driver, as it removes human delay in activation. By maintaining the alarm until the threat is gone, it is ensured that the driver is continuously warned while danger persists, as recommended in alerting best practices.

B.3.1.5 Alarm Deactivation Criteria:

(This is a counterpart to activation and is important to avoid unnecessary continued alarms.) The system shall automatically deactivate the audible alarm when the collision threat has passed or been mitigated. Specific deactivation conditions include: the vehicle has come to a stop or slowed below a safe speed (for example, now moving at a crawl, indicating it stopped for the work zone), the vehicle has changed lanes away from the TMA and is no longer on a collision course, or the vehicle has already collided (in which case the impact might be obvious or the TMA's separate impact sensors, if any, might register it – but in any case post-collision there's no need to keep alarming). The system will use parameters like TTC increasing above a threshold (e.g., TTC > six seconds and increasing) and distance increasing (vehicle moving away) as signs to turn off the alarm. Also if the vehicle simply passes the TMA without incident (goes by), once it's in front of the TMA or well past, the alarm should cease. The requirement is that the alarm should not remain on excessively long to avoid distracting other drivers and to reset for the next threat. In practice, after an alarm triggers, the system can check every 100 ms if conditions to turn it off are met. Hysteresis or a short delay (e.g., require safe state for one second before turning off) should be used so that the alarm doesn't flicker on/off if the situation is borderline. This requirement ensures the alarm is only active during genuine danger windows and helps minimize noise pollution and driver confusion when the danger is over.

B.3.1.6 False Alarm Minimization:

The system shall minimize false alarms (i.e., avoid triggering the audible alert for non-dangerous scenarios). While it is difficult to completely eliminate false positives in any detection system, the logic should be tuned so that common non-threatening situations do not trigger the horn. For example, vehicles that are slowing appropriately behind the TMA should not trigger an alarm simply because they got somewhat close; the system should recognize the deceleration and longer TTC and refrain from alarming. Similarly, traffic in adjacent lanes that is going to pass the TMA with a reasonable clearance should not cause an alarm. The multi-factor threat assessment (speed + TTC + lane) is intended to reduce false positives. Another example: a vehicle already stopped behind the TMA (like queued traffic) is not a threat, so no alarm even if TTC mathematically could be low (due to zero relative speed, TTC is infinite, so that's fine). The requirement is qualitative: the design shall include strategies (like the two-zone warning/danger logic, confirmed threat triggers, etc.) to keep false alarm rate low. A target could be set that false alarm occurrences should be less than e.g. one in eight hours of operation or some acceptable frequency (to be determined in pilot). Each false alarm that does occur shall be logged (with data) so engineers can analyze and adjust parameters if needed. This requirement is in line with ensuring the system's reliability and acceptance by users—too many false alarms could cause operators to distrust or disable the system, or cause annoyance to drivers, which would defeat the purpose. Therefore, in all design choices, a balance of sensitivity vs specificity is required, leaning slightly towards avoiding misses (because missing a real threat is worse) but still carefully controlling false triggers. Field testing and calibration are expected to refine this.

B.3.1.7 Data Logging and Event Recording:

The system shall log data for each significant event and during continuous operation to support analysis and reporting. At minimum, the following information must be recorded:

- Every time an audible alert is triggered: timestamp (date/time), the values of key metrics at trigger (e.g., vehicle speed, distance, TTC, lane position), and an identifier for the triggering vehicle (it could be a track ID in the system or a brief video snippet).

- When the alert is cleared: timestamp and reason (e.g., vehicle slowed, vehicle passed, manual cancel by operator if that ever happened).
- Detection events: it should log when a new vehicle is detected and starts being tracked (with time, initial distance/speed) and when a vehicle tracking ends (vehicle passed or out of view). This can be more granular if needed for analysis of near misses that didn't trigger the alarm.
- System status changes: e.g., system startup/shutdown times, mode changes, sensor errors, or manual overrides. If the operator manually triggers or suppresses an alarm, that should be noted in the log (with a flag indicating manual intervention). Similarly, if the system experiences a fault or goes into a fail-safe mode, log the time and nature of the fault.

All logs should be timestamped with synchronization to a real-time clock (GPS or system clock). The logs will be stored in a local storage (like an SD card or SSD on the Jetson) in a structured format (for example, CSV or JSON lines, or a lightweight database). The system shall ensure logs are written in a way that a sudden power loss does not corrupt all data (e.g., flush writes frequently). If storage space is limited, it shall implement a rolling log (overwriting oldest data) but ensuring at least the last several days or weeks of data are kept. The data logging should also capture enough information to reconstruct the sequence of events for an incident. For instance, recording the time series of a particular vehicle's distance over the last few seconds before an alarm could help in investigating driver behavior. Ideally, the system should also save a short video clip or a sequence of images around each alarm event (e.g., five seconds before and after the alarm) as this visual record can be extremely useful for post-event analysis. However, video consumes a lot of storage, so this is a should requirement; if included, it must manage storage (maybe only keep if requested or for actual collision incidents).

The system's logging capability will support generating reports such as: number of alerts per day, average TTC of alerts, false alarm count, etc., which safety engineers will use. Additionally, the logs (especially alarm events) can be uploaded to a cloud server whenever connectivity is available – either in real time or batch – for centralized monitoring. This leads to the next requirement.

B.3.1.8 Cloud Connectivity and API Integration:

The system shall integrate with external systems via network APIs to enhance monitoring and data utilization. Specifically, it should provide the ability to:

- **Upload logged data to a cloud server or central database** at configurable intervals. For example, every alarm event could be immediately sent over a cellular connection to a backend server (as a JSON or XML message containing the event details). Less urgent data like periodic health status or summary stats can be sent every few minutes or hours.
- **Real-time Alert Notifications:** When an alarm triggers, the system shall be capable of sending an instant notification through an API. This could be a RESTful HTTP POST to a known URL or a MQTT message to an IoT broker, etc. The content would include the TMA

identifier, location (if GPS is available on the TMA, include coordinates or route info), and the nature of the alert. This allows traffic management centers or cloud applications to immediately know of a dangerous event. For instance, MoDOT's traffic center could receive an automated alert and display it on their incident console or send a message to highway patrol.

- **External Command Interface:** The system shall expose a secure API for a limited set of remote commands. At minimum, a command to query status (ping the system, get current mode, number of vehicles tracked) and a command to remote-activate or remote-disable the alert (this would be used carefully by authorized users, e.g., if a supervisor sees something and wants to trigger an alarm manually or turn it off). Another potential command is to update configuration (like adjusting a threshold or deploying a new ML model) – though model updates might be done via a maintenance process rather than ad-hoc API, depending on security. In any case, the architecture should allow receiving messages/commands from the cloud.

The API integration needs to comply with data format standards that the external systems expect. If integrating with a Traffic Management Center, it might use protocols like DATEX II or custom web services – the system will adhere to the interface they provide. A generic approach is to have a REST API with endpoints for posting events and retrieving status. The system is dependent on network connectivity for this function; if the network is down, it should queue messages and send when back online.

Security is paramount (covered later): all external communications shall be encrypted and authenticated. The system must ensure that only authorized systems can send it commands (e.g., using API keys or certificates).

Rationale: Integration with external systems leverages the Internet of Things aspect of the device – it becomes part of a broader smart work zone ecosystem. It allows remote monitoring (e.g., a manager could even get a smartphone alert if a TMA alarm goes off), and it ensures data collected is centralized for analysis without having to manually retrieve logs from each unit.

B.3.1.9 Manual Override Functionality:

Though the system is automated, it shall allow manual control overrides by the TMA operator for safety and flexibility. This includes:

- A **Manual Alarm Trigger:** The operator (or a worker) can manually activate the audible alarm via a physical button or the software UI in the cab. This is useful if the crew observes a dangerous situation that the system has not detected or if they want to warn a motorist for any reason (like a precaution if a driver is approaching too fast but maybe the algorithm has not triggered yet). When manual trigger is pressed, the system will sound the horn immediately, regardless of the algorithm's own decision. The manual activation should also be logged (marked as manual). The system should continue its automatic function in parallel (it might also detect the threat and that is fine). If the manual trigger is kept activated (say a button held down), it should keep the horn on; once released, if the system still sees a threat it might continue the horn due to its own logic. Essentially manual trigger forces an alarm on.

- A **Manual Alarm Disable/Silence:** Conversely, the operator shall have the ability to silence or cancel an ongoing alarm. This is mainly for cases of false alarm or if the alarm is no longer needed but maybe the system has not turned it off yet. For example, if the system were to malfunction and sound erroneously, the operator needs a way to shut it off (to prevent undue distraction to drivers). Another scenario: after a collision, if the horn is stuck on (due to damage or because the system still thinks it is in danger), the crew should be able to turn it off. This manual cancel should be an action that is deliberate (perhaps a covered switch or a two-step confirmation on UI) to avoid accidental deactivation. When an operator manually overrides an alarm off, the system shall record this and, if possible, indicate on the UI that it's in a manual override state. The system may either resume normal operation after a manual cancel or require the operator to re-arm it (depending on design choice, but to keep it simple for user, probably resume watching but perhaps with some lockout if needed).
- A **Mode Switch (On/Off):** The operator shall be able to turn the entire alert system on or off (for example, a power switch or a software toggle). This is for instances like driving to the job site (one would turn it off so it does not trigger on highway when not needed) and then turning on when in position. It's assumed in normal use, it will be kept on while working and off while traveling between sites. The off mode ensures no detection or alarms occur. The system should clearly indicate if it's off (so an operator does not forget to turn it on).

Manual overrides are crucial for safety – they provide a human-in-the-loop failsafe. However, their use is expected to be infrequent; the system is intended to work autonomously nearly all the time. To encourage trust, the interface for manual control will be simple and reliable. For instance, a big red button for horn, and maybe a guarded toggle for system on/off.

From a requirements standpoint: the system's software shall continuously check the state of manual input controls and immediately act on them with highest priority (e.g., if manual off is activated, it should cease alarm regardless of sensor readings). Also, if the system is manually deactivated, it should ideally stop processing to avoid confusing logic (or at least not trigger anything).

B.3.1.10 Self-Diagnostics and Fault Handling:

The system **shall monitor its critical components and alert in case of any malfunction**. This includes:

- **Sensor Health Monitoring:** The system will periodically check that the camera feed is coming through (not lost or excessively corrupted). For example, if the camera returns no frames or all-black frames (could indicate a blockage or failure), that is a fault. Similarly for radar/LiDAR: if they have not reported data in expected intervals, flag a fault.

- **Processor/System Health:** Monitor CPU temperature (Jetson) and available memory. If temperature exceeds safe limits, it might indicate an issue (like fan failure); the system should log a warning or gracefully reduce processing (maybe drop frame rate) if possible. Memory leaks or high usage should be caught by watchdogs. Also, a software watchdog timer shall run that resets the system if the main program hangs (to avoid the system just freezing silently).
- **Communication Links:** If the system uses the vehicle's CAN bus or other interface (for example, to read speed), loss of that link is noted. Also, network connectivity status can be monitored (though not critical to core function, it's good to log if the cloud link is down).
- **Horn/Lights Circuit Monitoring:** If possible, the system should detect whether the horn circuit actually activated when commanded (some horns might provide a feedback or at least measure current draw). If the system triggers the horn but senses no current draw, it could mean the horn is disconnected or failed. This might be an advanced feature; at minimum, if such feedback is available, use it. If not, periodic manual tests are assumed.
- **Failure Alerts:** If any critical fault is detected (camera failure, etc.), the system shall notify the operator promptly. This can be done via the in-cab UI (e.g., flashing an error message or LED) and optionally a different audible tone in the cab (not the external horn, but a cockpit buzzer) to get attention. The idea is to inform the crew that the system may not be operational so they can take necessary steps (like extra vigilance or fixing it). In certain fault cases, the system might automatically default to a safe mode. For example, if the camera is out and it cannot "see" anything, continuing normal operation might be pointless; it could either restart itself to try to fix or just go into a standby state and signal fault[14].Depending on design, a safe action might be to not trigger any alarm except perhaps a continuous tone to indicate failure. However, sounding the main horn for a system fault might confuse drivers, so a better approach is a distinct indicator for the crew (like an internal alarm or a special light). The reference suggests "raise an audible alert and notify remote operator" in case of fault[14] – in this system case, notifying the remote center could also be done (send an alert that this unit has a malfunction).
- **Fault Logs:** The system shall log all faults with timestamp and nature for maintenance review. If the fault is transient and the system recovers (say camera feed was momentarily lost), it should log that too.
- **Redundancy/Failsafe:** Where feasible, the system should have fallback modes. For instance, if radar fails but camera is working, it continues operation with camera only (perhaps with reduced accuracy but still functional). Or vice versa, if camera fails but radar is present, maybe it can still trigger an alarm on pure radar-based closing speed detection (though with less context). The requirements acknowledge that some partial operation is better than none, so the system shall be designed to degrade gracefully under some failures. However, certain failures (like total processing failure) will obviously stop the

[14] https://rosap.ntl.bts.gov/view/dot/73210/dot_73210_DS1.pdf

system, in which case at least the operator is alerted so they know they have lost that safety net.

In essence, this requirement ensures the Audible Alert System is *self-aware* of its health and does not silently fail. Given the safety-critical nature, any failure must be obvious to humans so that protection is not mistakenly assumed when there is none[15]. Also, by detecting issues early (e.g., camera obstruction by dirt), the crew can fix it (clean the camera) and restore full functionality, thereby maintaining the system's reliability.

B.3.2 User Interface Requirements

B.3.2.1 In-Cab Display Interface:

The system shall provide an in-cab user interface for the TMA operator. This UI will be the primary point of interaction for the crew. The interface shall be designed to be simple, glanceable, and informative without causing distraction. The requirements for this UI include:

- **Live Camera Feed View:** The UI should display the live rear-view camera feed (or a processed version of it) to the operator on a screen or tablet mounted in the cab. This allows the operator to see what the system "sees" behind them. The video feed may have overlays, such as bounding boxes around detected vehicles, distance readings, or color-coded indicators (green/yellow/red) to show how close a vehicle is. If possible, highlighting the vehicle that is currently the top threat (e.g., with a red box) can be useful. This visual feedback builds operator trust that the system is correctly tracking vehicles. The feed should refresh in real-time (at least e.g. 10-15 FPS on the UI, which is enough for monitoring).

- **Status Indicators:** The UI shall include clear status indicators for: System Armed/Active, any Faults, and Connectivity. For example, a green light icon when the system is functioning normally (ready to alert), which might turn red or blink if a fault is detected (like camera malfunction or radar offline). Also, an icon for whether the system is currently in automatic mode or if it's been manually overridden/off. Perhaps a text like "AUTO" vs "MANUAL" mode display. Connectivity to cloud (if relevant) could be shown with a small icon (but this is lower priority for the operator). Essentially, the operator at a glance should know "Is my collision alert system on and okay?".

- **Distance/Speed Display:** The UI should show the current distance and speed estimates of the closest approaching vehicle (or the most relevant vehicle). This can be numeric (e.g., "Car at 80 m, 70 mph") or represented graphically (like a bar that fills as distance closes). It might also show multiple vehicles' info in a minimal way (like icons for each with a number). However, clutter must be avoided, so perhaps focusing on the worst-case vehicle is best. If multiple are approaching, maybe the top two could be shown in a small

[15] https://rosap.ntl.bts.gov/view/dot/73210/dot_73210_DS1.pdf

list. The speed could be shown with a label “Speed: XX mph” and distance “XX m”. If available, time-to-collision “TTC: X.X s” might be displayed for the top threat as well, since that’s intuitive for understanding urgency (e.g., TTC 2.5s means very urgent).

- **Alarm Status:** There should be a prominent indicator when the system has triggered an alarm (so the operator knows the horn is sounding if they did not hear it for some reason, or just to confirm it is the system not them honking). For instance, a big red flashing “ALARM” message or the border of the screen turns red when alarm is active. This lets the operator know an event is happening. Possibly, the UI could also show why (such as “Danger: Vehicle approaching fast!”) but even just indicating active alarm is enough in the moment.

- **User Controls:** The UI shall incorporate controls for manual override functions (as per B.3.1.9). This could be physical buttons or software buttons on a touchscreen. Key controls: a **Manual Alarm Activate** button (perhaps labeled “Sound Horn” or a horn icon) which the operator can press to manually trigger the horn. Also a **Manual Alarm Silence** or system pause button to cancel an ongoing alarm or temporarily disable the system shall be included. If using a touchscreen, these should be large, easy to press buttons. If physical, they should be located conveniently (like on a control box). The UI should clearly reflect the state when manual override is engaged (e.g., show “MANUAL” mode if the operator turned system off or silenced an alarm).

- **Menu/Settings Access:** While not heavily used in the field, the UI might allow access to a settings menu (maybe requiring a password or confirmation to avoid accidental changes). In settings, an engineer or authorized person could adjust thresholds or check sensor calibration, or connect to Wi-Fi, etc. But for the crew’s daily use, this is less relevant, so it could be hidden behind a long-press or separate mode to avoid confusion.

- **Display Hardware and Ergonomics:** The display should be readable in sunlight (so a high-brightness screen likely needed) and dimmable at night (so it does not blind the driver). The text should be large enough to read at a quick glance (avoiding lengthy text). Color coding (green safe, red danger) should be used along with text, but not solely (to account for color blindness, use labels or different shapes too). The interface needs to update in real time with minimal lag from what the system is doing. If the system triggers an alarm and it shows on UI a second later, that is okay, but ideally sub-second so the operator sees essentially simultaneously.

- **No Driver Distraction:** It is worth noting the TMA operator might not be actively driving (if the TMA is stationary or slowly moving in a work zone), so they can look at the UI occasionally. However, the UI should not require constant monitoring. It is mainly there as a confidence display and manual control interface. The operator’s primary role in a work zone is usually driving the TMA or monitoring traffic visually; this system’s UI is secondary. Therefore, it must be **non-intrusive** – for example, no loud in-cab noises unless needed for a fault (so as not to startle the driver). The alarm itself is external; there might be a modest in-cab chime for faults.

B.3.2.2 Remote Monitoring Interface (Web/Mobile):

The system shall support a remote user interface accessible via web browser or mobile application for authorized users to monitor and control the system from off-site. This could be a part of a larger “cloud dashboard” or a dedicated app. The requirements for this interface are:

- **Live Status View:** Users should be able to see the current status of the TMA’s Audible Alert System remotely. This includes whether the system is online, currently active, and any current alerts. For example, a web dashboard could list multiple units: “TMA Truck #1 – Active – No alert – 2 vehicles detected (closest 5s TTC) – Battery OK – Last check 10s ago”. If an alarm triggers, it should visibly highlight that unit (“ALERT ACTIVE at 14:35:27 for TMA #1”). Essentially, remote users get a snapshot similar to what the in-cab UI shows but in a summary form.

- **Live Data/Video (if bandwidth allows):** Ideally, authorized users could also view the live camera feed remotely to verify situations. If the system streams video to the cloud (which might be heavy on data), the interface can show that. Alternatively, it might show just a snapshot or a simplified graphic of the situation (like distances). A mobile app might, for instance, pop up an alert with a still image of the approaching vehicle when an alarm triggers, so that the supervisor can see what is happening. This is a desirable feature but depends on connectivity. At minimum, textual/graphical status should show; live video is a plus if feasible.

- **Alert Notifications:** The remote system (cloud platform) shall send notifications to users who subscribe. For example, push notifications on a mobile app or SMS/email alerts. An example use case is: a project supervisor gets a phone alert “Collision alert triggered for TMA at [location]”. This keeps them informed, especially if multiple incidents are happening. The requirement is the system must interface with such notification services (likely as part of the integration API sending events out). The UI on the mobile app would then show details when tapped.

- **Control Commands:** The remote interface should allow certain controls, with proper security. For instance, a command to remotely enable/disable the system (if a decision is made to turn it off, maybe due to abnormal behavior or at day’s end to save power). It could also possibly allow for a manual trigger remotely, though this would rarely be used (imagine a scenario: an operator in a control room sees a vehicle not slowing and can trigger alarm, but realistically the local automation should have done it already). More practically, remote interface could allow toggling between modes or adjusting sensitivity (e.g., a supervisor could increase the sensitivity if they notice drivers are particularly not attentive on a given day). However, any remote control must be carefully managed to avoid conflicts with the local operator’s control. A likely approach is: remote interface primarily monitors, and any changes might require confirmation from on-site or have safeguards. For now, the requirement is that at least a remote silence command could be issued (if for example the horn is stuck and operator can't turn it off, someone remotely might try as backup), and a remote reset command to reboot the system if needed.

- **Multi-User Access and Roles:** The remote system will be used by different roles (engineers, supervisors, etc.), so it shall have authentication (username/password, etc.) and possibly role-based access. For example, a supervisor can view and receive alerts but not change settings, whereas an admin can. The SRS does not need to go deep into that, just note that secure login will protect the interface.

- **User Experience:** The web/mobile UI should be clean and focused on alerting. It might include a map view showing where all TMAs are and highlight one if alarmed (if GPS is integrated). It would also have the ability to select a unit to see its status history or live feed. For mobile UI, it should have responsive design or a native app with clear notification handling. The remote UI is essentially an extension of the system's monitoring capability to anywhere.

- **Performance:** The remote UI should update reasonably close to real-time for active alerts (within a few seconds of an event). For general monitoring, it can poll or update every, say, 30 seconds for routine data. The system's back end should handle multiple concurrent viewers if needed (though likely a handful of users, not thousands, since it's internal use).

B.3.2.3 Usability and Accessibility:

Both the in-cab and remote UIs shall be designed for usability and safety. In practice, this means: large, clear text; avoiding technical jargon on screens that operators see (use simple language like "Vehicle Approaching Fast!" vs. "TTC = 2.3s" unless the user is expected to know that). Use of symbols (a car icon, an exclamation mark for warning, etc.) to transcend language barriers if needed (work crews might have varying language skills). The UI should also consider accessibility – for example, colorblind-friendly color schemes (don't rely on red/green alone, include symbols or text). The mobile app should follow accessibility guidelines (for any visually impaired supervisors, though that's less likely needed, but still good practice).

B.3.2.4 Training and Documentation (UI):

The system shall come with a straightforward user manual or quick-reference card for the interface so that new operators can quickly learn what each indicator means and how to operate the controls. This is not a UI software requirement per se, but it is a deliverable – ensure the UI is simple enough that the documentation can be minimal. Ideally, the interface is almost self-explanatory (e.g., a horn icon for manual horn, a power symbol for on/off). In training sessions, the crew should be able to simulate some scenarios (maybe via a test mode that fakes an approaching car) so they see the UI in action and know what to expect.

B.3.2.5 Fail-Safe UI Behavior:

In case the system goes into a fail-safe mode or experiences a fault, the UI should clearly display that status (such as a big "SYSTEM FAULT – NOT ACTIVE" message) so the operator knows the system is not currently protecting them. This was touched on in status indicators. Additionally, if the system needs a reset or attention, the UI could prompt that (e.g., "Camera feed lost – please check camera"). This merges with self-diagnostics but with a user-facing component.

In summary, the UI requirements focus on giving the operator situational awareness and control without burden, and extending that awareness to remote stakeholders via web/mobile interfaces. The design will follow best practices from automotive HMI (Human-Machine Interface) and safety system interfaces, prioritizing clarity, minimalism, and responsiveness.

B.3.3 Performance Requirements

B.3.3.1 Detection Accuracy:

The vehicle detection component of the system shall achieve at least 95% accuracy in correctly identifying real collision-threat vehicles in the TMA's vicinity. In practical terms, this means the system should detect >95% of vehicles that approach the TMA within the defined alert zone and meet alert criteria, ensuring that virtually no truly dangerous vehicle goes unnoticed (very low false-negative rate). Accuracy here can be measured as recall of the detection system for relevant targets – for example, during testing, if 100 vehicles drove in the protected lane within, say, 120 m range, the system should detect 95 or more of them. The system should also maintain a high precision to minimize false detections of non-existent vehicles (see false alarm requirement). In the context of object detection, a mAP (mean average precision) of around 0.8 or higher for vehicle detection is desirable (as an internal metric, the referenced model achieved ~0.79 mAP, the team aims to meet or exceed that). Specifically, for vehicles on a collision course, detection should not fail. The system should be robust to different vehicle types (cars, trucks, motorcycles) and should not miss motorcycles or smaller vehicles (the model should be trained accordingly). The distance accuracy of detection and ranging should be such that the system knows the vehicle's distance with a small error margin (e.g., within ± five meters at 100 meter distance) because that affects TTC calculation. If radar/LiDAR is used, distance accuracy will be high (± one meter); if camera-only, the system should still estimate within maybe 10% error at range through calibration. The lane detection accuracy also factors in: it should correctly identify the lane of the vehicle in at least ~80-90% of cases (the MDPI paper reported ~83.8% accuracy for distance classification and 81.5% for lane segmentation, which serves as a benchmark). While 100% detection is ideal, it is set at 95% as a minimum acceptable level to account for rare edge cases (like extreme weather obscuring view). This high accuracy is crucial as missing a vehicle could mean a missed alarm and a potential crash.

The system shall be tested in various conditions to verify this accuracy: day/night, different road geometries (straight vs curved, since camera detection on curves can be tricky), and with multiple vehicles. The performance should hold across these. If needed, the model may run at different sensitivities in different modes (e.g., could have a slightly lower threshold at night if detection is harder, to ensure recall). The requirement of 95%+ ensures the system is reliable enough for real-world deployment, aligning with industry expectations for safety systems (for comparison, many

ADAS systems aim for even higher, but this is a specialized scenario with a controlled environment behind a TMA).

B.3.3.2 Alert Trigger Precision (False Positive Rate):

The system shall have a false alarm rate below five percent of alert events. This means that no more than one in 20 alarms should be a “false” alarm (triggering when there was actually no dangerous vehicle or it was not needed). In practice, over many hours of operation, the alarm should only sound when there is a genuine reason. This performance metric complements the detection accuracy by ensuring high precision in the decision logic. It’s important because frequent false alarms could desensitize drivers and annoy workers. To achieve this, the algorithm uses multiple criteria (TTC, speed, lane) and has been tuned to avoid triggering on vehicles that are slowing or not aiming at the TMA. During testing, scenarios like vehicles decelerating normally behind the TMA should not cause an alarm. To quantify, for example, if 100 vehicles pass the TMA (most slow down properly), perhaps the alarm should trigger for the 10 that truly were problematic. If it triggers for more than that, logic would be adjusted. The < five percent false alarm rate is a target; actual acceptable rate might depend on agency tolerance, but it gives a baseline. Additionally, any alarm that is not clearly justified by the logged data should be investigated and counted as a false positive for improvement purposes. The system should achieve this precision while still maintaining the sensitivity (it should not skip real threats just to avoid false ones – that is why a balance is needed). This requirement will be validated in pilot projects by logging each alarm and checking camera footage to confirm if a threat was real. The design already calls for false alarm minimization strategies to meet this performance.

B.3.3.3 System Response Time (Latency):

The system shall respond to a detected threat and activate the audible alarm within 50 milliseconds (0.05 seconds) from the moment the alert conditions are met. This latency includes processing time from camera frame capture (or sensor input) through the detection and decision algorithm to activating the horn output. Essentially, the system’s internal processing pipeline must be fast enough that there is no perceptible delay between a vehicle meeting the criteria and the horn sounding. Fifty ms is an ambitious real-time requirement, but this is roughly equivalent to 20 frames per second processing speed (frame time = 50 ms). The system’s software (especially on Jetson Nano) should be optimized (e.g., using neural network accelerators) to achieve at least this frame rate for analysis. If multiple frames or sensor cycles are needed to confirm something, the decision should still be made quickly. The reason for 50 ms is to ensure that the alert is effectively instantaneous from the perspective of a human. Human reaction times to hazards are on the order of 1.5 to two seconds for braking, and even just noticing an event takes 200-300 ms. A 50 ms system reaction is negligible in comparison, ensuring the system doesn’t add any significant delay to the warning. In practical terms, suppose a car suddenly swerves toward the TMA – the system might detect the lane departure and in 50 ms have the horn blaring, giving the driver as much warning time as possible.

If 50 ms cannot be consistently met on the Jetson Nano due to resource limits, the system shall in no case exceed 100 ms latency (this is an upper bound). Preliminary tests with a similar vision system on Jetson showed ~83 ms per frame processing, which is about 12 fps, so optimizing to 50 ms (~20 fps) on Jetson Orin is feasible. The requirement stands that 50 ms is the target for typical operation on the recommended hardware (Jetson Orin). On a Nano, performance might be slightly lower, but the requirement is still to strive for minimal delay (the system could degrade frame resolution or use a simplified model on Nano to meet timing). The team will verify response time in testing by measuring time stamps in logs from detection to alarm command. Also, the system architecture might pipeline tasks (detection, tracking, decision) to effectively reduce perceived latency. The network communication for remote alerts is not included in this 50ms; that can be slower. This is specifically for the on-board reaction to trigger the local horn.

B.3.3.4 System Throughput (Frame/Sensor Rate):

The system's design should allow it to handle at least 20 frames per second from the camera (or equivalent sensor update rate) in order to achieve the above latency and to track fast-moving vehicles smoothly. If radar/LiDAR are used, they often update at, 10-20 Hz; the system should accommodate that in sync with camera frames. This effectively means the system can process data fast enough for highway speeds (at 70 mph (~31 m/s), a vehicle travels ~1.5 m in 50 ms, which is fine granularity to catch). The system should also handle multiple targets: e.g., if two vehicles are in view, it still processes without slowdown or dropping targets. It should scale to at least five vehicles without issue (it is rare to have more than a few close vehicles in a work zone scenario). This throughput requirement is mostly covered by the latency requirement but is stated here to ensure multi-target tracking and continuous operation is considered.

B.3.3.5 Reliability and Uptime:

The Audible Alert System shall be operational with 100% uptime during active work zone operations. This means whenever the TMA is deployed to protect a work zone, the system is expected to be running and available at all times, with no unscheduled outages. In practical terms, if a TMA is on duty for, say, eight hours, the Audible Alert System should not crash or become unresponsive during that period. The target is essentially zero crashes or hangs in the field. To support this, the system will have been tested for long-duration stability and will include watchdog timers to auto-recover from any software lockups. It is understood that 100% is a target – realistically, if a fault occurs, the system might need a reboot, but the design aim is to minimize that to nearly never. Additionally, the system should boot up quickly when powered on (ideally within a minute or two) so that even if it is powered down between jobs, it does not cause much downtime at startup. If the system does experience a failure, it should fail safe (alert operator and stop functioning rather than give false info), but the performance requirement is focusing on maximizing availability.

High **durability** is also required: The system should function in a wide temperature range (for example -20°C to 50°C ambient) and not degrade in performance due to heat (ensuring proper thermal management of Jetson). It should handle vibration and shocks from the truck motion without rebooting or losing connections. Essentially, it must be built as an automotive-grade system. Uptime also means the system can run for long hours day after day with minimal maintenance. For instance, the OS and software should not have memory leaks that cause it to crash after 24 hours, etc. The use of a real-time OS or a stable Linux setup is implied.

In quantitative terms, one could say the system should have a mean time between failures (MTBF) corresponding to thousands of hours so that daily use for months does not see a failure. If integrated into an overall maintenance schedule, maybe the device could be rebooted once a week during checks just as a precaution, but it should not spontaneously crash in between.

B.3.3.6 Horn Audible Range and Volume:

The audible alert (horn/siren) should meet performance criteria such that it is audible to the target driver with enough margin. While this is more of a hardware spec, it is critical to the performance of the system's intended effect. The horn shall produce sound at a level of around ~120 dB at one meter, which typically ensures it can be heard inside a vehicle cabin a fair distance away (for example, ~70-80 dB inside the car at 30-50 m, depending on attenuation). It should be audible over ambient traffic noise. The effective range should be at least 100 meters in open air for the driver to hear it (of course, it gets louder as they approach). Also, the sound should be distinct (using a pattern like two-tone wail or pulse) to differentiate from normal car horns or background noise. If there are specific OSHA limits or local ordinances, the volume can't exceed those for worker safety (e.g., workers with hearing protection can withstand 120 dB in short bursts, but one has to be careful if they are right next to the horn). Possibly directional speakers can focus sound towards traffic and away from workers – but that is an additional design. The requirement is to ensure the alert is effective: in testing, a typical driver with windows up should notice the horn at least 2–3 seconds before impact, which correlates to being loud enough at that distance.

B.3.3.7 System Capacity:

(Optional to mention) The system should be able to handle at least one critical scenario at a time. If multiple threat vehicles approach simultaneously (rare but possible if two lanes both have fast vehicles), the system should ideally alert for both. This could mean either it just stays on because one triggered it (which covers the other too), or if they approach at identical times, one alarm covers both anyway. So capacity in terms of multi-threat should not be a limiting factor.

B.3.3.8 Maintenance and Support:

The system's design should allow a technician to run a full diagnostic in less than 30 minutes and replace any failed component (camera, compute unit) within an hour, minimizing downtime between deployments. This ensures that if it does go down, it can be fixed quickly.

In summary, the performance requirements ensure the system is highly accurate and fast (safety-critical reaction time), exceptionally reliable (no downtime), and effective in real-world conditions (loud enough, wide detection range) to accomplish its safety mission. These performance targets align with the expectation that an automated safety system outperforms human capabilities (faster response, continuous vigilance) and adheres to safety standards for critical systems.

B.3.4 Hardware and Software Integration

B.3.4.1 Embedded Platform (NVIDIA Jetson) Integration:

The software shall be optimized for the NVIDIA Jetson Orin and Jetson Nano platforms as the deployment hardware. This means using appropriate libraries (like NVIDIA's TensorRT or CUDA acceleration) to run the machine learning inference efficiently on the GPU. The requirement is that the entire system software stack fits within the resources of the Jetson (CPU, GPU, RAM, storage) without exhausting them. For instance, on Jetson Nano (which might have 4 GB RAM), the loaded model and program should operate within that memory footprint. On Jetson Orin (with more power), it can use more advanced models but should still be efficient to keep processing fast. The software shall also handle the differences in these platforms – maybe the Orin version loads a higher complexity model for better accuracy, whereas the Nano uses a lighter model, but from an external perspective, both meet the requirements (just possibly one has more headroom). The integration will also consider the operating system (likely Linux for Tegra). The system shall start on boot of the Jetson and run as a service, interfacing with any required OS-level APIs (e.g., camera drivers).

- **Drivers and Interfaces:** The software must properly interface with the camera module (via CSI interface or USB depending on camera), and with any radar/LiDAR through their drivers (could be serial, CAN, Ethernet depending on device). It shall also interface with output devices: possibly using GPIO pins or CAN messages to trigger the horn or lights. For example, a Jetson might send a signal to a relay module to sound the horn; the software needs to control that GPIO. If the TMA's horn is controlled via CAN bus, then the software must send the correct CAN frame to honk it. This implies understanding and using the TMA's interface protocol. Since integration is key, there might be the need to implement or use a library for that communication. The requirement is the software and hardware work seamlessly together, with proper timings (if radar provides data at 20Hz and camera at 30Hz, the software fuses these smoothly).

- **Power Management:** The integration must ensure that the Jetson and sensors can be powered by the TMA's electrical system. The requirement may be that the system runs off 12V DC from the truck with appropriate converters for Jetson (which typically runs 5V/19V depending on dev kit). It should handle voltage fluctuations. From software perspective, it should be tolerant to abrupt power loss (thus using journaling file systems to not corrupt logs). Also, when the TMA's ignition is off, the system should either shut down safely or have a separate battery if needed. However it is likely tied to the vehicle power, so the requirement is it can cold boot quickly when power is applied.

- **Physical Integration:** The Jetson Orin (or Nano) computing unit will likely be mounted in the cab or a weatherproof box on the truck. The requirement is the form factor and mounting of this hardware should accommodate the space available (e.g., behind the seat or in an electrical cabinet on the truck). The device should be secured against vibration and enclosed to avoid dust ingress. If a cooling solution is needed (fan or heatsink), that must be considered so it doesn't overheat in a hot truck cab. All wiring from sensors to the Jetson and from Jetson to horn/lights should be done with automotive-grade connectors to avoid loose connections. This requirement ensures that the hardware is installed in a way that is durable and doesn't interfere with other vehicle functions.

- **Environmental Protection:** The cameras and any external sensors must be properly housed (waterproof enclosures, maybe heated to prevent icing in winter). While integration is partly mechanical, it's within scope to specify that the hardware integration will use IP67 rated camera enclosures, and shock-absorbing mounts, etc., to ensure longevity.

B.3.4.2 Sensor Modularity:

The system **shall support a modular sensor configuration**, meaning it can operate with different combinations of sensors, such as:

- **Camera-Only Mode:** The system uses one (or multiple) cameras as the sole input for detecting vehicles and estimating distance (using vision techniques). In this mode, it likely relies on trained depth estimation or known perspective geometry. The requirements (detection, etc.) still must be met in this configuration, though distance accuracy might be a bit lower, the system must compensate accordingly (maybe slightly more conservative thresholds).

- **Camera + Radar Mode:** The system uses a camera plus a radar unit. The radar provides direct measurements of vehicle range and speed for objects in its beam. The software shall fuse radar data with camera detection – e.g., by associating radar targets with visual detections (perhaps by matching angle and range)[16].The integration means the system can take advantage of radar's precise speed to confirm the camera's computed speed and use radar range to refine TTC calculations. If the camera fails, at least the radar could still trigger an alert if a target is coming in fast (though identification might be less certain). The system should be tested with a certain radar model(s) and allow calibration of the radar alignment with the camera.

- **Camera + LiDAR Mode:** The system uses a camera plus a LiDAR sensor. LiDAR can provide a point cloud of the area behind the TMA. The software will likely use LiDAR to get very accurate positions of approaching vehicles and could even detect vehicles by point cloud clustering independent of camera. More realistically, the camera does primary detection and LiDAR verifies range[17] . The integration requires time-syncing LiDAR data with video frames. LiDAR can also help at night or with obscured vision. The system shall be capable

[16] https://rosap.ntl.bts.gov/view/dot/73210/dot_73210_DS1.pdf

[17] https://rosap.ntl.bts.gov/view/dot/73210/dot_73210_DS1.pdf

of integrating such data without major code changes – ideally via a sensor abstraction layer.

- **Multiple Cameras:** The architecture should allow multiple cameras if, say, a wider coverage is needed (like one looking straight back, one angled). While not initially required, supporting it means video pipelines can be extended. This is less of a priority than the other configurations.

The requirement is that the system design is scalable and flexible: agencies might start with camera-only (lower cost) and later add radar for better performance; the software should accommodate that addition easily (maybe by enabling a radar module in configuration). Conversely, if a sensor fails or is removed, the system should gracefully continue with the remaining ones. This modularity also helps future-proof the system as new sensors (perhaps thermal cameras for night) could be incorporated.

B.3.4.3 Communication Interfaces:

The system will integrate with the TMA's existing communication infrastructure. If the TMA trucks have their own telematics (GPS, 4G modem), the system might piggyback on them for cloud connectivity. Otherwise, the system will include its own communication module (like a cellular modem or connected tablet's internet). Either way, integration means ensuring data can be transmitted out. The requirement is to have at least one reliable communication channel to send data to the cloud. If using the truck's radio, then working with that protocol is needed; if using a standalone, ensure the Jetson can interface (USB modem, etc.).

For local integration: some TMA trucks might broadcast their GPS location to a central system already. The Audible Alert System should integrate with that by either receiving location data from the truck's GPS or using its own GPS sensor. Integration wise, it might simply have a GPS module attached to the Jetson via UART/USB for coordinates (this helps with remote monitoring).

B.3.4.4 Data Formats and Protocols:

The internal integration between subsystems shall use common data formats. For example, if using ROS (Robot Operating System) middleware, topics for camera images, detection results, radar points, etc., can be standardized. If not using ROS, then a custom but still modular, integration will be used. The point of this is to allow ease of adding/removing modules. For external API, adhere to the JSON format agreed upon. For CAN bus integration to the horn, use the correct CAN ID and message format specified by the TMA manufacturer.

B.3.4.5 Testing and Debug Interfaces:

The integrated system shall have interfaces for debugging and testing. For instance, a console over SSH on the Jetson for developers, or a maintenance port. It should also allow connecting a laptop to fetch logs or update software. This requirement ensures the integrated system is not a black box that is hard to maintain. Possibly a USB port or Wi-Fi access point can be used during maintenance.

B.3.4.6 Physical Safety Integration:

The installation of this system on the TMA must not impede the function of the TMA or pose new risks. For instance, wiring should be routed so it does not get severed by the attenuator in a crash or entangle with workers. The camera must be mounted in a way such that if the TMA is hit, it does not become a dangerous projectile. Brackets should be secure and horns should be placed such that they are audible but not at ear level of workers if possible (higher up aiming back). These are mechanical integration details to ensure the integrated system is safe and reliable.

Overall, the integration requirements aim to produce a solution that is cohesive: hardware components and software working in harmony, the system can be easily installed on existing TMAs (modular and standardized interfaces), and the addition of this technology does not negatively impact the vehicle or workers. By optimizing for Jetson and supporting various sensors, the solution is ensured to be both high-performance and adaptable.

B.3.5 Regulatory and Compliance Requirements

B.3.5.1 Functional Safety Compliance (ISO 26262):

The development process and design of the Audible Alert System shall comply with ISO 26262 for automotive functional safety[18]. This means performing a hazard analysis and risk assessment for the system's functions (identifying potential malfunctions and their automotive safety integrity level, ASIL), and meeting the associated safety requirements. For example, a possible hazard is the system failing to alert when needed (leading to an undetected collision) – this would be analyzed and mitigations would be defined (such as requiring redundancy or self-test to ensure functionality). Compliance involves maintaining a safety lifecycle: documenting safety goals, technical safety requirements, design with freedom from interference (since it is an add-on, ensure it does not hamper other vehicle functions), and thorough verification and validation (including fault injection testing). If the determined ASIL is, for example ASIL B, then the system's hardware and software must be developed to meet ASIL B requirements (like single-point fault metric, development process rigor, etc.). Safety mechanisms such as watchdog timers, self-diagnostics (as required in B.3.1.10), and safe state definition (possibly the safe state is to fail silent but notify operator) are to be implemented in line with ISO 26262 best practices. All critical decisions (like when to alarm) happen in a deterministic, testable way, and if the AI component is involved, additional measures (like monitoring of the AI's output plausibility) might be needed to satisfy safety requirements (since ML is usually not 100% deterministic, a parallel simpler check may be used as a safety net, for instance a radar-based TTC check that will trigger the alarm even if vision might glitch). Documentation such as a functional safety concept and technical safety concept shall be produced. While full formal certification might not be sought given this is an add-on system, the design should follow the spirit of ISO 26262 to ensure no unreasonable risk

[18] https://www.dnv.us/services/functional-safety-for-road-vehicles-iso-26262-82719/

is introduced by the system[19] . Additionally, any hardware used (sensors, compute) should ideally be automotive grade or have safety ratings if available, or at least be proven in similar deployments.

B.3.5.2 Work Zone Regulations (MUTCD Compliance):

The Audible Alert System shall comply with the Manual on Uniform Traffic Control Devices (MUTCD) guidelines for work zones. The MUTCD (particularly Part 6, Temporary Traffic Control) sets standards for how warnings should be given in work zones. While MUTCD mostly covers signs and lights, any new warning method should not contradict its principles. For instance:

- The system's use of a horn should not violate any rules that prohibit certain sounds; currently, there is no specific MUTCD provision against audible warnings – in fact, some agencies use air horns as manual intrusion alarms – but it must be used as a supplement to, not a replacement for, required signs and arrow boards. So compliance means the TMA still has all required signage and lighting per MUTCD, and the audible alert is an additional device.

- If the system includes flashing lights, the color and flash rate should conform to MUTCD standards for warning lights (e.g., amber color is standard for work vehicles; flash frequency one to two Hz, etc.). It must be ensured that any integrated flashing does not confuse drivers (for example, the arrow board should continue to operate normally directing traffic; the audible alert should not make them think something else like an emergency vehicle is present). The design might include signage on the TMA indicating "Warning System in Use" if needed, but that is not mandated.

- The system should not create a distraction beyond the work zone. MUTCD emphasizes not to have misleading or extraneous devices on the road; the horn will only sound in emergencies, which is consistent with an intrusion alarm concept accepted in many work zone guides. If any guidance exists from FHWA or state DOTs about audible intrusion alarms, those should be followed (for example, placement of speakers or expected decibel levels).

Essentially, compliance with MUTCD means the presence of this system does not cause the overall work zone traffic control plan to fall out of spec. It augments the standard setup (signs, cones, arrow board) in a compliant way. Any modifications to standard practice (like adding an alarm) should be documented and likely approved by the agency's traffic control policy. FHWA's acceptance of positive protection measures including audible warnings as fulfilling the intent of safety enhancements, will be referenced.

B.3.5.3 FHWA and OSHA Guidelines:

[19] https://www.dnv.us/services/functional-safety-for-road-vehicles-iso-26262-82719/

The system shall adhere to FHWA guidelines and any OSHA (Occupational Safety & Health Administration) regulations regarding work zone safety devices. The FHWA Work Zone Safety and Mobility Rule (23 CFR 630 Subpart K) encourages innovative safety measures and requires agencies to consider and manage intrusion risks. The system is directly addressing so that, it is in spirit with FHWA's rule. The team should ensure documentation is provided for how this system meets the definition of a "positive protection or alert system" as may be described in FHWA resources. If FHWA or the Highway Safety Manual provides guidance on intrusion alarms (such as recommended distances for alarms, or training for workers), the implementation should follow those. For example, some Work Zone Intrusion Alert Technology assessments (like the one by Oregon DOT[20]) recommend that alarms have certain response times and reliability – the system's requirements align with those. The team will ensure any "minimum standards" that have been suggested for such systems are met (the Oregon report mentions needs such as ease-of-use, cybersecurity, reliability, redundancy[20] which are covered).

OSHA may care about worker hearing safety. If a 120 dB alarm is used, OSHA regulations (1910.95) require hearing protection plans for workers exposed to >85 dB over time. Though the alarm is intermittent, exposure should be mitigated (perhaps by directional sound or training workers to stand away from horn when possible). Compliance means the team acknowledges and plans to not cause any OSHA violations (maybe provide ear protection or ensure alarm bursts are short enough). The system should also not interfere with workers' ability to communicate or hear other alarms (for example, if workers use two-way radios, the system's noise shouldn't be constant. Since the horn only goes off during imminent danger, that should be fine).

B.3.5.4 Cybersecurity (ISO 21434 or Equivalent):

The system shall implement cybersecurity measures to protect against unauthorized access, consistent with emerging automotive cybersecurity standards (ISO 21434) and best practices[20]. While ISO 21434 (road vehicle cybersecurity) is not explicitly mentioned by the user, they did ask for encrypted communication, which falls under this. Concretely, the system will:

- **Encrypt all wireless communications** (e.g., use HTTPS/TLS for any API calls to cloud, use VPN or secure MQTT for IoT messages). This prevents eavesdropping or injection of false data.
- **Authenticate remote commands and access:** Require strong authentication for the web interface and any remote control commands to ensure only authorized personnel can influence the system. Possibly use two-factor authentication for critical actions.
- **Secure Boot and Software:** The Jetson system should be secured such that only authorized firmware/software runs. If possible, enable secure boot so that the device is not easily tampered with. Also, disable unused ports and services on the OS to reduce attack surface.

[20] https://rosap.ntl.bts.gov/view/dot/73210/dot_73210_DS1.pdf

- **Data Protection:** Logs that are uploaded or stored should be protected especially if they contain any sensitive info (like license plates visible in images—though that is more of a privacy concern; but if needed, blur license plates in shared data, etc.).
- **Resilience to Cyber Attacks:** The system should be tested against common vulnerabilities (penetration testing) to ensure that someone cannot, for example, hack into it and cause the horn to trigger falsely (which could cause chaos or be used maliciously) or disable it without notice. As it is connected, it is a potential target, so it must be hardened. The requirement might be that it passes a vulnerability scan and any critical issues are resolved.
- **Compliance with Agency IT policies:** If connecting to DOT networks, it may need to meet their IT security requirements (like specific encryption, firewalls, etc.). The team will follow up on any such guidelines.

In summary, the system will follow the *"secure by design"* principle: secure communication protocols (no plaintext sensitive communication) and safeguarding against unauthorized physical or remote access to the system's controls[21].

B.3.5.5 Electrical and EMC Compliance:

All electrical components of the system shall comply with automotive electrical standards and electromagnetic compatibility (EMC) regulations (e.g., FCC rules for electronic devices). The added hardware should not emit interference that could affect vehicle electronics or communications. For example, FCC Part 15 for unintentional radiators must be satisfied for the computing unit and sensors. If radar is used, it must operate in a permitted frequency band and power (most automotive radars do). Any wireless modem must be FCC certified. On the other side, the system must tolerate typical automotive transients (like load dump on the power line) as per ISO 7637 or similar standards. While these details may be more design-level the requirement are stated to ensure use of automotive-grade or certified components meet these norms.

B.3.5.6 Documentation and Certification:

The system shall be delivered with the necessary documentation to demonstrate compliance with the above standards and guidelines. This may include a safety case for ISO 26262 (or at least a hazard analysis document), test reports showing MUTCD compliance (may not be needed, but at least a letter stating it does not conflict), and results of any regulatory tests (e.g., FCC ID for any wireless hardware). If required by the state DOT, the system might undergo a field evaluation to certify it meets safety needs; the design should be robust to pass such evaluation.

B.3.5.7 Data Privacy:

[21] https://rosap.ntl.bts.gov/view/dot/73210/dot_73210_DS1.pdf

If the system collects video that could identify drivers (faces or plates), the system should comply with privacy laws/policies. Usually, DOTs have exemptions for safety cameras, but there is still a need to ensure the data is used internally and not publicly released without anonymization.

B.3.5.8 Environmental Compliance:

The hardware should be RoHS compliant (no hazardous substances) and meet IP ratings for waterproofing as needed. Also, disposal of electronics should follow regulations at end-of-life (though beyond the scope of this SRS).

By meeting these regulatory and compliance requirements, the Audible Alert System will be built and operated in accordance with industry standards for safety, reliability, and legality. This ensures not only the effectiveness of the system but also that it can be adopted by transportation agencies without regulatory hurdles, and it upholds public trust (secure and safe operation). Each of these compliance items will be verified through audits, tests, or certification processes during development and deployment.

Appendix C: Hardware Requirements Specification (SRS) for the Audible Alert System

This document outlines the hardware requirements for an Automated Audible Alert System designed for Truck-Mounted Attenuator (TMA) vehicles used in roadway work zones. The system's purpose is to detect oncoming vehicles that pose a collision risk to the TMA and automatically trigger loud audible warnings (and supplemental visual alarms) to get the driver's attention, giving them time to avoid a crash. The hardware solution must be rugged, self-contained, and compatible with a variety of TMA trucks, while meeting all relevant performance and safety standards. The following sections detail the technical specifications, compliance considerations, and recommendations for robust real-world performance of the system.

C.1. General Requirements

- **Adaptability to Various TMA Trucks:** The alert system should be modular and easily adaptable to different TMA truck models without major vehicle modifications. A standardized mounting mechanism and interface **must** allow the system to be installed on existing TMAs (truck backs or frames) with minimal custom fitting. All cabling and harnesses should be designed for plug-and-play integration. This modular approach ensures **robust compatibility and seamless interaction** between the alert system and a range of TMAs. It also facilitates transfer of the system between vehicles if needed (e.g., when a truck is replaced or taken out of service).

- **Seamless Power Integration:** The system will tie into the TMA's electrical system **without requiring any vehicle computer (CAN bus) integration**. It should have a simple electrical interface: drawing power from the vehicle's battery/alternator and tapping into existing alarm devices (e.g., truck horn or external warning lights) for actuation. When the TMA's ignition is on, the system uses vehicle power; when the vehicle is off, it should automatically switch to backup battery power (see Power Requirements). An ignition-sense line can be used to detect when the vehicle is on. The system's design must ensure no interference with the truck's normal operation – it operates independently of vehicle ECU signals. (Manual override inputs may be provided for safety, but no reliance on CAN data).

- **Self-Contained Operation:** All sensing, processing, and decision-making hardware will be self-contained within the system's enclosure. The unit should include its own processor and logic to detect vehicles and decide when to trigger alerts, **without** needing data from the truck's CAN bus or other external control networks. The only vehicle connections needed are for power and for triggering the alert devices (such as a relay to honk the horn or flash existing lights). This simplifies installation and avoids compatibility issues with different truck electronics. The system's self-sufficiency also means it continues to function even if the host truck's engine is off or if it is installed on older trucks lacking modern electronic control networks.

- **Minimal Impact on TMA Function:** The alert system must not impede the normal function or crashworthiness of the TMA. It should be mounted such that it does not alter the energy-absorbing mechanism of the attenuator or protrude in a way that could become a hazard. The weight and placement should respect the TMA manufacturer's guidelines. In essence, adding the alert hardware should not compromise the TMA's ability to **meet safety standards (e.g., MASH criteria)** as a crash cushion. All added components should be secure under high deceleration forces in the event the TMA is struck.

C.2. Camera System

- **Field of View (FoV):** Utilize a narrow FoV camera to detect vehicles at long distances behind the TMA. Instead of a wide-angle lens, a telephoto-style lens should be chosen to concentrate on the lane(s) following the work zone. A narrower horizontal FoV (for example, on the order of ~10–30 degrees) ensures that a vehicle at 150–200 meters appears large enough in the frame for reliable detection and tracking. By comparison, many long-range security cameras achieve very tight angles (even ~9° at max zoom) to recognize distant subjects[22] . The exact FoV should be selected to cover the approach path directly behind the TMA (and adjacent lanes if needed) without diluting focus with irrelevant periphery. Adjustable or interchangeable lenses (or a motorized zoom) are recommended so the FoV can be tuned per deployment (e.g. adjusting for different road configurations or desired range).

- **High-Resolution 4K Sensor:** The camera must have a high-resolution image sensor (on the order of 4K Ultra HD, ~8 megapixels). This resolution is needed to **capture clear details of approaching vehicles at long range**, improving the accuracy of the AI/machine vision in classifying and tracking those vehicles. A 4K sensor provides significantly more pixel detail on a distant target compared to 1080p, enabling the system to detect subtle changes (like brake lights or turn signals of the oncoming car, if needed). However, using a high megapixel sensor means each pixel is smaller, which can **reduce low-light sensitivity** if not properly addressed[22] . Therefore, the camera should be a quality automotive or industrial-grade unit with a large enough optical format (sensor size) and possibly HDR capability to handle varied lighting. The high resolution also supports digital zoom or cropping if the system needs to focus on a region of interest. The camera interface could be USB 3.0, GigE, or MIPI CSI depending on the processing unit, but it must reliably deliver full-resolution frames at a sufficient frame rate (e.g. 30 FPS) for the detection algorithms to operate in real-time.

- **Low-Light/Night Vision:** Night vision capability is **desirable** (though not strictly required) to allow vehicle detection in darkness or low-light conditions. If included, an infrared (IR) enhanced camera or an IR illuminator should be part of the system. An IR-capable camera (with IR-cut filter that can be removed at night) paired with IR LED floodlights would enable the system to "see" vehicles by their reflection of IR light even in total darkness.

[22] https://www.getscw.com/knowledge-base/long-range-security-camera

For example, some outdoor 4K security cameras with IR illumination can capture clear images of objects at **up to 300+ feet (≈100 m) at night**. The system can optionally use thermal imaging as an alternative for night detection, though that adds cost. At minimum, the camera should have good low-light performance ("Starlight" sensor technology or similar) so that approaching vehicle headlights or road lighting provide enough illumination. While IR night vision is not mandatory, planning for it ensures the system remains effective 24/7. If night vision is omitted initially, the design should allow retrofitting an IR illuminator or upgrading the camera later.

- **Image Processing and Analytics:** (Note: Though primarily a software consideration, it influences camera hardware) The camera feed will be analyzed by an AI/machine learning model to recognize and track vehicles. Thus, the camera should output a video stream with minimal compression (or lossless if possible) to preserve detail for the AI. A digital interface (Ethernet or direct to the processing board) is preferred over analog to maintain image fidelity. The camera should also support synchronization or timestamping if multiple sensors are fused (e.g., aligning radar data with video).

- **Environmental Ruggedness (Camera):** The camera unit itself should be housed in a rugged enclosure or be an automotive-rated camera module. It will likely be externally mounted (e.g., on the back of the attenuator or the truck), so it needs to withstand weather and debris. Ideally the camera meets at least IP67 and has an operating temperature range suitable for outdoor conditions (detailed in Environmental section). The lens must resist vibration-induced focus shift (use of industrial-grade autofocus or fixed-focus optics with locking). A lens heater/defroster is a bonus to prevent ice or fog in cold conditions. All cabling to the camera should be shielded and robust, possibly using automotive-grade connectors to prevent disconnections under vibration.

C.3. Radar and LiDAR System (Optional)

- **Long-Range Automotive Radar:** An automotive-grade radar sensor is required to detect and track vehicles at highway speeds, providing range and relative speed data complementing the camera. The radar should reliably detect vehicles at **a minimum of 150 meters**, with an ideal detection range around 200 m or more to maximize warning time. This corresponds to a **long-range radar (LRR)** classification; typically LRR units operate in the 77 GHz band and can cover ~80 m up to 200+ m for automotive applications[23]. The radar's field of view can be moderate (covering the lane and some spread, e.g. ~ ±10-20°) since the primary threat is directly behind the TMA. The selected radar module should provide distance and velocity (Doppler) information for multiple targets, updating at least 10-20 times per second for effective tracking. It must be an **automotive-certified radar** module – meeting automotive standards for reliability and electromagnetic compatibility – since it will be operating in a roadside environment with other vehicles present.

[23] https://www.nxp.com/company/about-nxp/smarter-world-blog/BL-RADAR-LIDAR-V2X-AUTONOMOUS-CARS

- **Radar Performance Requirements:** The radar should be able to detect both large and small vehicles (motorcycles, cars, trucks) approaching the TMA. It must handle high closing speeds (for instance, if the work truck is moving slowly and an incoming vehicle is at 70 mph, the relative speed could be >100 mph or 160 km/h). The range resolution and accuracy should be sufficient to feed into time-to-collision calculations (e.g., range accuracy on the order of < one meter, speed accuracy of a few km/h). The radar should also have a wide enough field or multiple beams to monitor at least one lane on either side of the TMA's lane, in case an errant vehicle is slightly off-path. If using a modern radar, angular resolution is good enough to separate vehicles in adjacent lanes. **Multi-target tracking** capability is important, as there may be several vehicles within its view – the system should identify which one is on a collision course. Radar data will be fused with camera data by the system's processor to improve detection robustness.

- **LiDAR (Optional for Enhanced Accuracy):** The design may incorporate a LiDAR sensor as an **optional component** to improve detection accuracy and redundancy. LiDAR can provide high-precision distance measurements and 3D shape information of objects. If used, the LiDAR should be an automotive-grade unit (with a robust housing and operating range for outdoor use). A forward-facing LiDAR with at least 120° horizontal FoV (to cover multiple lanes) and a range of ~200 m is desirable. Many automotive LiDAR's (905 nm wavelength types) can reach about **200 m in range under a narrow field-of-view configuration**[24] , and newer 1550 nm LiDAR's promise even longer range. A solid-state LiDAR is preferred for durability (no moving parts) even if it currently has narrower coverage – multiple solid-state LiDAR's or a scanning unit could be considered to widen the coverage. The LiDAR should output data at a sufficient rate (e.g., 10 Hz or more) and resolution to detect an oncoming vehicle as a distinct object by 150–200 m. **Eye safety** is a requirement: the LiDAR's laser emissions must be Class 1 eye-safe per IEC 60825, given it will operate in public areas[24] . If LiDAR is included, the system's sensor fusion should accommodate its inputs, but the overall system must also function acceptably without it (so that the radar-camera duo is the primary detection method, with LiDAR as a bonus).

- **Sensor Integration:** Both radar and LiDAR (if present) will be co-located with or near the camera to cover the same general area behind the TMA. Their data should be time-synchronized for sensor fusion; the hardware may include a synchronization module or rely on GPS time or internal clocks. The radar and LiDAR antennas/sensors must be mounted in a way that they have clear line-of-sight to the rear traffic (no blockage by the attenuator structure or signage). The enclosure or placement should minimize exposure to debris strikes or tampering. It's recommended to mount them high enough (e.g., on the TMA frame or truck bed) to "see" over any spray or dust from the road immediately behind the truck. Both sensors should have self-diagnostics (reporting if blocked or malfunctioning).

[24] https://www.nxp.com/company/about-nxp/smarter-world-blog/BL-RADAR-LIDAR-V2X-AUTONOMOUS-CARS

- **Compliance (Radar/LiDAR):** The radar must operate within the regulated frequency bands and power levels (e.g., 76–81 GHz is standard for automotive long-range radar, complying with FCC and ITU emissions limits). The LiDAR, if used, must meet laser safety regulations. Also, using these sensors in a roadside scenario should comply with any FCC rules regarding unlicensed millimeter-wave devices or require appropriate certification if not already certified as automotive components.

C.4. Power Requirements

- **Wide DC Input Range (6V to 56V):** The system's power supply must accommodate a **dynamic input voltage from 6 V up to 56 V DC**. This wide range ensures compatibility with various truck electrical systems and scenarios: from 12 V passenger-vehicle systems, 24 V commercial truck systems, up to potentially 48 V systems or any fluctuations (for example, load dump transient can temporarily raise voltage, and a deeply discharged battery can drop below 12 V). Designing for 6–56 V means the unit can be installed on essentially any vehicle or equipment without additional DC/DC converters. In practice, many in-vehicle electronics use wide-range inputs (e.g., 8–35 V in some designs[25]), and this system extends that envelope further for extra margin. The internal power supply should regulate this range down to the voltages needed by the electronics (5 V, 12 V, etc.) with high efficiency and minimal heat. It must also handle brief over-voltage spikes and voltage dips in accordance with ISO 7637 or SAE transient standards for vehicular power.

- **Power Consumption and Current Draw:** At maximum operation (all sensors active, processor under full load, communications transmitting, and alarms sounding), the system may draw **up to 8 A** from the 12 V supply (which is about 96 W, or equivalent power from other voltages). The hardware components (camera, radar, processor, cellular radio, etc.) should be chosen and designed with power efficiency in mind to stay within this power budget. Typical idle or monitoring consumption will likely be lower, but the design must support the peak 8 A safely. All wiring and connectors for power input should be rated for at least 8–10 A continuous to provide overhead. Additionally, the PCB traces and power regulators inside the device must handle this current without overheating. Thermal management (heat sinks, possibly fans or passive cooling fins) should be implemented to dissipate heat from power regulators and processors when running at full power.

- **Reverse Polarity Protection:** The power input stage must include protection against reverse polarity connection of the supply leads. Maintenance personnel could accidentally swap + and – when hooking to the truck battery; a robust input protection (such as a diode or MOSFET-based reverse polarity circuit or a full-wave bridge rectifier) is required to prevent damage. This protection should cover the entire 6–56 V range and the 8 A current. Using an **input rectifier or equivalent circuit** will allow the device to survive a reversed connection indefinitely, though it may not function until corrected. The

[25] https://www.neousys-tech.com/en/core-technologies/fanless-in-vehicle-pc

protection device should have minimal voltage drop (to not waste power or cause heating at 8 A). In addition, transient suppression (TVS diodes) should be placed on the input to clamp any voltage spikes from the vehicle (e.g., load dump can be ~60–100 V for milliseconds). These measures are standard practice for in-vehicle electronics to ensure reliability[26].

- **Automatic Power Source Switching:** The system will have two power sources: the vehicle's main power (when ignition is on) and a backup battery inside the device for when the vehicle is off. The hardware must **automatically switch to vehicle power when the TMA is turned on**, and conversely switch to the backup battery when the ignition is off. This can be achieved with a power path controller or relay that senses the ignition/accessory line. When vehicle power is present and above a certain threshold, it should be used to run the system and simultaneously charge the backup battery. When vehicle power is lost or drops (engine off), the controller should seamlessly transfer the load to the backup battery with no interruption to the electronics (to avoid system reboot or sensor reset). This "ignition power control" behavior is common in in-vehicle controllers[26] and ensures the system is always active and monitoring, even if the truck's engine is off (for example, when parked on the roadside with the work crew still present). The design should also gracefully shut down or sleep if the backup battery gets critically low, to avoid deep discharge.

- **Backup Battery System:** A dedicated backup battery (or supercapacitor bank) within the unit will supply power when the vehicle is off. The HRS should specify the required **capacity** of this battery – for instance, enough to run the system for X hours in standby/monitor mode. For a practical example, if it is assumed that roughly 50 W is consumed in monitoring mode, a 100 Wh battery could run the system for about 2 hours. The exact capacity should be chosen based on expected use cases (e.g., providing alerts when the truck is stationary waiting for the next job or during short breaks). The battery must be rechargeable and managed by a charger circuit (taking power from the vehicle when available). It should have safeguards: over-charge protection, over-discharge cutoff, short-circuit protection, and temperature monitoring. Ideally, it should be an easily replaceable module for maintenance. Using lithium iron phosphate (LiFePO4) chemistry is a good option for safety (wide temperature range, lower fire risk than Li-ion). The backup power also ensures that if a vehicle is struck and its electrical system fails, the alert system might still operate for a brief period (though in a crash scenario, its main role is already done).

- **Ignition Sense and Low-Power Modes:** The hardware should include an ignition sense input (from the truck's ignition circuit) to coordinate power states. When ignition is off, the system might go into a low-power monitoring mode to conserve the backup battery, waking up fully if the radar/camera detect something or at intervals. When ignition is on, the system should be full power. Additionally, there may be a need for an external **master**

[26] https://www.neousys-tech.com/en/core-technologies/fanless-in-vehicle-pc

power switch for maintenance or in case the system needs to be completely powered down by technicians – this could disconnect both vehicle and battery power for storage or repairs.

C.5. Environmental and Durability Requirements

- **Ingress Protection (Water/Dust):** The entire system (enclosure and any external connections) **must be rated at least IP67** or higher. An IP67 rating ensures total protection against dust ingress and the ability to withstand immersion in water up to one meter for 30 minutes. In practical terms, this means the system is safe from heavy rain, splashing water, mud, and dust/debris often present in work zones or kicked up by traffic. Rugged **waterproof connectors** should be used (e.g., M12 circular connectors for power, Ethernet, etc., with seals) to maintain the IP rating when cables are attached[27] . Gaskets and sealants on the enclosure are to be employed to prevent water ingress. The enclosure material should be corrosion-resistant (aluminum alloy or polycarbonate, etc.) and UV-resistant if exposed to sunlight. Meeting IP67 is critical as the device will be mounted externally on a work truck facing the elements; any failure of seals could lead to electronics damage.

- **Operating Temperature Range:** The hardware must operate reliably under extreme temperature conditions encountered in Missouri and similar locales. A typical required range is **-40°C to +70°C** (or at least -30°C to +60°C) to cover cold winter mornings and hot summer afternoons inside a truck or under direct sun. Industrial/automotive grade components rated for this range should be used. For example, many embedded automotive systems are designed for -40°C to +70°C operation[28] . The system should include thermal management like heat sinking and perhaps internal heating for extreme cold (to warm up batteries or electronics). It should also handle thermal cycling (repeated heating and cooling) without seal failure or condensation issues. If the enclosure is in sunlight, solar heating could raise internal temps even above ambient, so design for that scenario (consider a sunshade or reflective coating).

- **Shock and Vibration Resistance:** The system will be subjected to continuous vibration from the truck (engine vibrations, rough road surfaces) and shock from road impacts or possibly minor collisions. The hardware must comply with relevant **shock and vibration standards for mobile/vehicle equipment**. It is recommended to design and test according to **MIL-STD-810G** for shock and vibration durability[28] , as well as SAE J1455 or ISO 16750-3, which are automotive environment standards. All internal circuit boards should be securely mounted (or potted) to avoid fatigue failure. Use of shock-absorbing mounts for the enclosure itself is advisable if mounted on a rigid truck frame. Connectors should have locking mechanisms that resist loosening under vibration. As noted in industry best practices, embedded in-vehicle systems often go through extensive validation for

[27] https://www.getscw.com/knowledge-base/long-range-security-camera
[28] https://premioinc.com/blogs/blog/top-5-embedded-computing-design-requirement

shock/vibe because loose cables or components can lead to failure[29]. The design should ensure **no connectors or parts will shake loose** under prolonged use. For shock, the unit should withstand sudden deceleration or impacts (for instance, a drop of the tailgate or even the force of a crash into the TMA). MIL-STD-810G includes procedures for functional shock (up to tens of Gs). Ensuring compliance with these tests will guarantee the system remains operational after the kind of jolts and bumps expected in its service.

- **Physical Durability:** The enclosure and mounting brackets should be robust and made of durable materials (metal enclosure or high-strength polycarbonate, etc.). The system should be able to handle the occasional knocks from tools or debris. It should also be **vibration-isolated** from the truck as needed: for example, using rubber dampers in the mount to reduce high-frequency vibration transmission. All exposed cables must be abrasion-resistant and routed to avoid sharp edges. The design should prevent water pooling (e.g., use a drain hole or conformal coating on internal PCBs as a backup). In addition, **electromagnetic compatibility (EMC)** hardening is needed so that external RF noise or electromagnetic fields (from radios, power lines, etc.) do not upset the system. This means a well-grounded enclosure, shielding for sensitive electronics, and meeting standards like CISPR 25 for radiated and conducted emissions in vehicles.

- **Maintenance and Longevity:** Environmental durability also means the system should have a long service life with minimal maintenance. Components should have a high mean-time-between-failure (MTBF) even in harsh conditions. The design might include features like a Gore-Tex vent (to equalize pressure in the enclosure when temperatures change, preventing seal stress). All indicators or displays on the outside should also meet the same environmental rating (if any LED status lights are exposed, they should be potted or sealed). The unit should remain functional after years of exposure to sun, vibration, temperature swings, and electrical stress. Regular calibration or cleaning requirements should be minimal (perhaps occasional lens cleaning). Any maintenance port or removable cover must preserve sealing when closed.

C.6. Communication Interfaces

- **Ethernet Connectivity:** The system should provide a standard **Ethernet interface** (such as 100BASE-TX or Gigabit Ethernet) for wired communication. This allows direct connection to a laptop or network for configuring the system, retrieving data logs, or updating software. Ethernet could also be used to interface an external device like a separate display or a network of multiple sensors if needed. The port should support automotive Ethernet standards if applicable, or just standard TCP/IP networking. It must have a weatherproof connector if exposed or reside inside the cabin (connected via a sealed cable). Having Ethernet ensures a reliable high-bandwidth link for maintenance and that a connection can be made and used at district offices or by technicians to remotely monitor the system when the truck is parked (via a long cable or depot network).

[29] https://premioinc.com/blogs/blog/top-5-embedded-computing-design-requirement

- **Wi-Fi Wireless LAN:** Integrated **Wi-Fi (802.11)** capability is required for short-range wireless access. The system should act either as a Wi-Fi hotspot (access point) or client to an existing Wi-Fi network, or both. For example, work zone supervisors or technicians might use a tablet to wirelessly connect to the device when they approach it, to check status or download video clips of detected incidents. Wi-Fi connectivity (likely using 2.4 GHz and/or 5 GHz bands) must follow standard security (WPA2 or WPA3 encryption) to prevent unauthorized access. This interface enables convenient field access without needing physical cables. *Use case:* A worker in a support vehicle could get an alert on a tablet via Wi-Fi that the system has detected a threat, or a technician could update settings from a distance. The Wi-Fi module used should be industrial grade for reliability, and FCC certified. (Since Wi-Fi is an unlicensed band, ensure the module passes FCC Part 15 rules for emissions[30] .) Antennas for Wi-Fi (and other wireless) should be placed such that they have adequate range (likely a small external antenna on the box or on the truck roof).

- **Cellular 4G/5G Connectivity:** For long-range communication and remote monitoring, the system will include a cellular modem supporting **4G LTE** and preferably with a path to **5G** (either 5G-ready hardware or modular upgrade). This allows the device to transmit data in real time to a cloud server or central monitoring station. For instance, if a potential collision is detected, the system could send an alert (with GPS location, maybe a snapshot) via the cellular network to an operations center or send a text/email to designated personnel. The cellular interface also enables remote diagnostics and firmware updates when the truck is in the field. The hardware must have a SIM slot (or eSIM) and support relevant frequency bands for the region of operation (at least all major US carriers' bands for LTE). The design should consider using a **pre-certified cellular module** to simplify compliance (FCC and carrier certifications). It should also handle typical automotive power conditions (the module and its DC/DC converter coping with the 12/24V input variation). An external high-gain antenna or multiple antennas (for diversity/MIMO, and possibly GPS if included in module) will be mounted on the vehicle for reliable connectivity. The system should also implement watchdogs or ping mechanisms to reset the modem if connectivity is lost, ensuring robustness. **Data security** over cellular (VPN or encryption) should be considered since this might deal with safety-critical alerts. Data usage should be optimized to keep costs manageable (e.g., not streaming video constantly unless needed).

- **Future V2X Communication:** The hardware design should be **future-proof with support for V2X (Vehicle-to-Everything)** communications. While V2X is not required in the initial deployment, the system should be designed so that a V2X module (DSRC or C-V2X) can be integrated later with minimal effort. For example, providing a spare interface slot or USB/Serial connection that could host a **DSRC radio (IEEE 802.11p)** or **Cellular-V2X PC5** radio in the future. V2X would allow the TMA to broadcast a standardized warning message to approaching vehicles equipped with V2X receivers, extending the system's

[30] https://f2labs.com/technotes/2021/10/07/fcc-part-15-requirements-for-bluetooth-and-wi-fi-modules-devices/

reach beyond line-of-sight (vehicles could get an alert a mile in advance in their onboard systems[31]). The HRS should note compliance with any V2X standards: if DSRC, FCC rules in the 5.9 GHz band (which is partly reallocated, but remaining spectrum can be used for C-V2X); if C-V2X, 3GPP release 14+ specifications. Essentially, ensuring **modular expandability** for V2X will keep the system relevant as connected vehicle technology becomes common. This could be achieved by designing in an expansion port or ensuring the processing unit can handle V2X message protocol stacks.

- **Bluetooth Interface for Standby Controller:** A Bluetooth connectivity option should be included to interface with a *standby controller* – likely a handheld remote or a smartphone app used by the crew. This low-power link would be convenient for short-range, on-site control or status queries. For example, a crew member approaching the truck could use a Bluetooth-connected device to put the system in standby mode or acknowledge an alert. Bluetooth is also useful for configuration via a phone app. The implementation could use Bluetooth Low Energy (BLE) for simple data exchange and to conserve power. The standby controller might simply display status (e.g., "System Armed/Disarmed") and have a button to mute or test the alarm. The hardware should ensure secure pairing (to prevent anyone from connecting unauthorized). The range of Bluetooth (typically ~10m) is suitable for within the work zone. Including this interface provides convenience without needing network infrastructure. **Note:** Bluetooth and Wi-Fi typically use the 2.4 GHz band, so care must be taken in the design to avoid interference and meet FCC Part 15 requirements for both.

- **GPS/GNSS (Optional):** (Not explicitly listed, but possibly useful) The system could include a GPS/GNSS receiver for location and time synchronization. This would allow tagging alerts with exact location, and could help in synchronization (e.g., timestamping events in absolute time, or providing location to a V2X message). If included, the GPS antenna should have a clear sky view (maybe integrated with the cellular antenna). The hardware should protect this data and ensure it is only used for the system's function (and possibly not required by the user unless remote monitoring uses location).

- **Interface Summary:** In summary, the system will have **multiple communication interfaces**: a wired port (Ethernet), local wireless (Wi-Fi, Bluetooth), and wide-area wireless (cellular), plus potential V2X and GPS. These ensure the system can communicate on different levels – locally with workers and vehicles, and remotely with management systems. Many modern in-vehicle control units already support such rich I/O (e.g., ruggedized PCs often include ignition control, digital I/O, CAN, and sockets for 4G/Wi-Fi/GPS connectivity[32]). Likewise, this system's hardware will integrate these communication channels in a cohesive manner.

[31] https://www.nxp.com/company/about-nxp/smarter-world-blog/BL-RADAR-LIDAR-V2X-AUTONOMOUS-CARS
[32] https://www.neousys-tech.com/en/core-technologies/fanless-in-vehicle-pc

C.7. User Interface

- **In-Cabin Touchscreen Display:** The system shall include a **physical touchscreen interface** mounted in the TMA truck's cabin. This serves as the primary user interface for operators or supervisors inside the vehicle. A rugged tablet-like display (e.g., seven to ten inch diagonal) with touch input is suitable. It should be securely attached on or near the dashboard, within easy reach and view of the driver or passenger seat. The UI device should communicate with the main system (likely via Ethernet or Wi-Fi, or a direct display cable if the processing unit is nearby). Its enclosure or mounting should handle the same environmental conditions (especially vibration and temperature inside a vehicle – often up to 60°C when parked in sun). The display should be **sunlight-readable** (high brightness, anti-glare coating) and dimmable for night use. Touch input must be responsive even if the user is wearing light work gloves. Having a dedicated display ensures the crew can quickly check the system status and manually interact with it, rather than relying on external devices.

- **Real-Time Alerts Display:** The in-cabin UI should graphically and textually present real-time alerts detected by the system. For example, if a vehicle is approaching dangerously, the screen could flash an alert message like "**Warning: Vehicle Approaching Fast at 180m!**" along with a color-coded indicator (red for imminent collision risk, yellow for moderate). It may also show a simple visualization (perhaps a simplified rear-view showing the detected vehicle position). This helps the TMA driver be aware of threats (though typically the driver might not have much to do if they are already in the work zone, it is more for awareness and possibly to radio other workers). The UI should also indicate when the audible alarm has been activated (so the user knows the horn is sounding if they're in a noisy environment or wearing headphones). Essentially, any event that triggers the system should be clearly shown on the display in real-time.

- **System Status and Diagnostics:** The interface needs to provide at-a-glance status of all system components. This includes power status (running on vehicle power or battery, battery charge level), sensor status (camera OK, radar connected, etc.), and communications status (cellular signal, Wi-Fi connected, etc.). If any sensor or component fails or is offline, the UI should show a warning (e.g., "Radar fault" or "Camera disconnected"). There should also be indicators for the system mode (Active/Armed vs Standby). A health monitor section can show temperatures of key components, CPU load, or memory usage for advanced diagnostics (likely under a technical menu). The goal is to make it easy for an operator or technician to ensure the system is functioning correctly before starting a work operation. Self-test results (for example, on startup the system can test the horn and lights briefly and the UI confirms all good) would be displayed.

- **User Controls and Configuration:** The touchscreen will allow the user to configure certain settings and control the system. Key controls should include: system power on/off (or standby mode toggle), volume control for the audible alert, brightness for any integrated lights, and perhaps sensitivity settings (e.g., distance threshold for trigger if adjustable, though likely fixed by policy). A **manual trigger** button can be provided on the UI to allow the operator to activate the audible alert manually (for testing or if they visually spot a danger before the system does). Conversely, a **mute/acknowledge** button is crucial so that if an alert is triggered in a known false alarm scenario, the operator can silence it. Configuration screens might allow setting up the communications (Wi-Fi network credentials, cellular APN, etc.), time/date (if not automatic), and viewing logs of past alerts. All such interactions should be designed to be as simple as possible, given that the users may not be tech experts. Large, clear buttons and intuitive menu flow are important. The UI software should prevent any distracting complexity during operation – possibly locking out deep configuration when the vehicle is in motion, for safety.

- **Physical Interface Considerations:** In addition to the touchscreen, there could be a few **physical buttons or knobs** for critical functions (since using a touchscreen while driving can be difficult). For example, a physical emergency **kill switch** to disable or power-down the alert system instantly can be installed on the dashboard – in case the system malfunctions or in scenarios where the alarm is not desirable. There might also be an LED indicator light on the dash that mimics the system's status (green = active, red = fault, etc.) so the driver can see status without looking at the screen. The HRS should specify any required physical control beyond the touchscreen for safety or convenience. All these cabin components should be designed to automotive standards (robust against vibration, extreme temperatures inside a vehicle, and electrically noise-tolerant).

- **User Feedback and Logging:** The UI should provide feedback to the user for any actions taken. If the user presses "Test Horn", it should confirm "Horn sounded" or show an error if not. If configuration changes are made, confirmation messages should appear. Additionally, the system should log user interactions (like manual triggers, mutes, config changes) with timestamps, and these logs should be accessible (on the UI or via download) for maintenance or incident review.

- **Ergonomics and Safety:** The interface must be designed such that it does not distract the driver of the TMA. During normal operation, the system is mostly autonomous, so the UI might just sit idle showing a status. Only when an event occurs does it demand attention, and even then it should be a clear, concise alert. The screen should be positioned and have brightness controls to avoid glare at night. Touch targets should be big enough to hit while the vehicle might be moving or vibrating. The UI software should likely lock out configuration while driving to avoid someone trying to navigate menus on the road. Essentially follow automotive HMI best practices (similar to how infotainment or GPS units are designed to minimize driver distraction).

- **Remote UI (Future):** While the primary UI is inside the truck, the HRS can note the possibility of mirroring the interface on a mobile device (through the Wi-Fi or Bluetooth connection). This would allow someone outside the truck (but within Wi-Fi range) to see the same info. This could be useful if the work crew is not in the truck but wants to see approaching threats on a handheld device. If implemented, ensure secure access control for that feature.

C.8. Compliance and Regulatory Standards

- **Federal Work Zone Safety Regulations:** The system and its usage must comply with all applicable federal regulations regarding work zone safety and traffic control devices. In the U.S., the Federal Highway Administration (FHWA) has rules such as **23 CFR 630 Subpart K – Temporary Traffic Control Devices** that govern how warning devices are implemented in work zones. While this regulation primarily ensures devices like TMAs meet crashworthiness, any new warning system should align with the spirit of these rules by enhancing safety without introducing new hazards. The system's alerts (audible and visual) should complement the existing Manual on Uniform Traffic Control Devices (**MUTCD**) guidelines. For example, MUTCD specifies the types of warning signs and signals allowed – the automated audible alert should be an augmentation and not conflict with any required signage or procedures. If the system uses flashing lights to warn drivers, those lights may need to be colors and flash patterns permitted for work zones (e.g., amber lights are typically allowed on construction vehicles). It is important to review MUTCD sections on **work zone warning systems** to ensure compliance. Additionally, OSHA regulations for construction safety (which apply to highway work zones) should be observed – if the system produces sound, OSHA/NIOSH guidelines on permissible noise exposure for workers might come into play (the alarm should be loud enough for drivers but not permanently harmful to workers hearing in proximity).

- **State and Local Regulations:** State Departments of Transportation (DOTs) and local authorities may have specific rules or pilot programs for intrusion warning systems. For instance, since this project is Missouri-based (MoDOT), any Missouri state standards or experimental use approvals for such alert systems must be followed. Some states require special permits for using certain types of alarms on public roads. The team must ensure the audible alert (horn or siren) used by the system is legal for use – generally, non-emergency vehicles are not allowed to use sirens or extremely loud horns on public roads except in emergencies. Because this system essentially creates an "emergency warning" scenario, coordination with state regulations is needed so that, for example, the horn pattern or any new sound device is within legal limits for a work zone warning. If a new type of audible device is used (like a high-decibel siren distinct from the truck's horn), it might require a regulatory exemption or at least not violate noise ordinances. The HRS should also consider **compliance with state work zone intrusion alert guidelines** (if any exist; some DOTs have experimented with systems that alert workers of intrusions – our system alerts drivers, but any overlap should be looked at). Liaise with state traffic control committees for acceptance of the device on roadways, especially if it will be used on high-speed facilities.

- **FCC Regulations for Wireless Devices:** Given the system's multiple wireless interfaces (Wi-Fi, Bluetooth, Cellular, possibly radar and V2X transmitters), **FCC compliance is**

mandatory. All radio-frequency emitting components must either have their own FCC certification or the entire system must be tested as an RF device. Wi-Fi and Bluetooth operate under FCC Part 15 rules (unlicensed intentional radiators)[33] , so the system must conform to the emission limits and spectrum use requirements (likely by using pre-certified modules and antennas within allowed gain limits). The cellular modem must be FCC certified (typically covered under the module's certification) and also network-approved (PTCRB certified and carrier-specific approvals for Verizon/AT&T, etc.). If a DSRC or C-V2X module is added, that too falls under FCC regulations (5.9 GHz ITS band usage). The radar operating at 77 GHz is usually covered by FCC Part 95 or 15 (depending on specifics) for automotive radar – most automotive radars are already compliant, but integration should ensure the radar placement and any additional enclosure doesn't violate those rules (e.g., no unintended reflections causing out-of-band emissions). The LiDAR (if used) must meet FDA/IEC laser safety standards (Class 1 eye-safe as mentioned, which is mandated for any consumer-facing LiDAR). Overall, **the product as a whole should go through FCC equipment authorization** procedures (either Supplier's Declaration of Conformity if using all pre-certified transmitters, or Certification if needed) before it can be lawfully operated and marketed[33]. This ensures no harmful interference is caused and the device legally uses the RF spectrum. The HRS should recommend using certified communication modules to simplify this compliance process and allocate space on the product labeling for FCC ID numbers or compliance statements as required.

- **Automotive Electrical Standards:** The system should adhere to relevant automotive standards for electrical and electronic equipment. For instance, **SAE J1455** is a recommended practice for environmental conditions for heavy-duty vehicle electronics (covering power input range, transients, thermal, vibration, etc. which the team has aligned with). **ISO 16750** series also covers similar environmental tests for automotive electronic hardware. Meeting these standards will ensure the system can handle the electrical environment of a truck (like the load dump transient, cranking voltage drop, electromagnetic interference, etc.). Additionally, since the system interfaces with the vehicle's horn and possibly lights, it should follow **SAE J1939** or other standard interface if any digital communication were ever used. In this case, the interface is simple (just triggering outputs), but if in the future the system needs to send a message to the vehicle (for example, to an integrated dash alert), using J1939 CAN messages would be the way to do it. This ensures the design does not conflict with any vehicle network if connection is important (though currently it is independent). **EMC testing** per automotive standards (like CISPR 25 for radio frequency interference and ISO 7637 for power transients) should be conducted so that the system does not emit excessive electromagnetic noise that could interfere with the vehicle or other devices, and vice versa.

- **Functional Safety Standards:** As this is a safety device (though an advisory one), it is good practice to follow **ISO 26262 (Road Vehicles – Functional Safety)** principles in the design and development process. This standard ensures that any potential hazards caused by

[33] https://f2labs.com/technotes/2021/10/07/fcc-part-15-requirements-for-bluetooth-and-wi-fi-modules-devices/

malfunctions of the system are analyzed and mitigated. For example, a malfunction that triggers false alarms constantly could distract drivers or cause unnecessary stops, while a failure to alarm when needed is obviously dangerous. By following ISO 26262 guidelines, the team would assign an Automotive Safety Integrity Level (ASIL) to the system (likely ASIL B or C since it can lead to an accident if it fails, though it is not controlling the vehicle, only warning). Then design redundancies or self-checks accordingly. While formal ISO 26262 certification may not be required by the client, adhering to it (or at least the spirit of fail-safe design) will improve reliability. For instance, the system should have a **self-diagnostic that if a critical sensor fails, it either alerts the operator of the failure or enters a safe state** (maybe defaults to on if unsure or triggers a minimal alert). Any software controlling the alerts should be thoroughly tested to avoid unintended behaviors (like errant alarms). Documentation of safety analysis might be needed for liability reasons if the device is deployed widely.

- **Industry Standards for Warning Devices:** If the system includes visual warning lights or sirens beyond the stock truck horn, those devices should conform to standards for light intensity, color, and sound levels. For example, **SAE J595** and **SAE J845** cover lights for emergency and service vehicles (e.g., amber beacon standards), and could be referenced if a flashing light bar was added. Audible warning devices might refer to SAE J994 (machine backup alarms) or other standards for sound levels. The intent is to ensure the alert is effective but also not overly hazardous (e.g., not causing hearing damage to crew or being so loud as to startle drivers into panic). The system's horn usage should respect that truck horns have legal limits (usually around 110 dB at a certain distance). If a separate siren is used, ensure it is only activated in imminent danger scenarios to be justified. Any radio transmissions (like V2X) should use standardized message formats such as the SAE J2735 DSRC message set (for example, sending a "Work Zone Alert" message). This guarantees interoperability if other systems (like a connected car) try to interpret the signals.

- **Certifications and Testing:** Prior to field deployment, the system should undergo various certification tests. **Third-party environmental testing** (vibration, shock, temperature, ingress) can verify the IP67 and MIL-STD compliance. **EMC testing** in a lab will validate that the device meets FCC emission limits and is not susceptible to interference. If the device is to be sold commercially, an **FCC Declaration of Conformity/Certification** must be obtained (and if any part of the system is under another regulatory body, e.g., if it were to be used in Canada, IC certification; in Europe, CE marking with RED for the radio, etc., but focusing on the U.S. for now). The radar likely will need to comply with FCC rules for unlicensed 77 GHz devices (which are typically OK under Part 15). For automotive use, getting an **E-mark or DOT approval** for the system as an aftermarket automotive device might be necessary – especially if connecting to vehicle lighting or if considered an automotive accessory, certain safety standards need to be met. If the system is considered part of the vehicle when installed, it should not violate FMVSS (Federal Motor Vehicle Safety Standards). For example, FMVSS rules on horns (standard 114) might specify when horns can be used. Because this is a retrofit to a work truck, it is likely outside

FMVSS as an aftermarket add-on, but worth checking. **Work zone field testing** should be done in a controlled environment to validate that the alerts indeed prompt driver responses in time. The results may need to be reported to agencies to prove its efficacy and safety before broad deployment.

- **Documentation and Training:** Compliance also includes having proper documentation for users (manuals, safety warnings) and training material per OSHA or DOT requirements. Operators of the system should be trained in its use and made aware of any limitations (for instance, "This is an advisory system; always continue to follow normal work zone safety protocols. Do not rely solely on the automated alert."). Liability considerations mean the manufacturer should include disclaimers and instructions aligning with regulations.

- **Summary of Key Compliance Items:** In summary, the hardware must be built to **automotive-grade standards and work zone regulations**, including:

- *Work Zone Device Compliance:* Adhere to FHWA and MUTCD guidelines for warning systems in work zones.

- *Communications Compliance:* FCC certification for all wireless functions (Part 15 for Wi-Fi/Bluetooth, Part 22/24 for cellular, etc.) and future DSRC/C-V2X compliance if applicable. Use FCC-certified modules where possible to simplify this.

- *Environmental/Reliability:* Meet MIL-STD-810G (shock, vibration, etc.) and IP67, as well as SAE/ISO automotive environment standards to ensure durability.

- *Vehicle Integration:* Follow SAE J1939 conventions if interacting with vehicle networks (though current design avoids this) and ensure not to violate any FMVSS or state vehicle codes with the alarm behavior.

- *Safety Process:* Implement ISO 26262 functional safety guidelines to minimize the risk of malfunction leading to hazardous situations.

- *Industry Standards:* If applicable, use SAE standards for lights/sirens (so any added hardware is up to spec for road use).

By designing the Automated Audible Alert System to these hardware requirements and standards, the team aims to ensure **robust performance under real-world conditions**, regulatory acceptance, and, most importantly, a meaningful improvement in work zone safety. The system will be built and tested to reliably function in the harsh environment of roadside construction, providing early warnings to drivers and reducing the likelihood of catastrophic collisions with TMA trucks and crews. Following this HRS will guide the development towards a device that is effective, durable, and compliant with all necessary standards, paving the way for successful deployment and operation in live work zones.

Appendix D: Bill of Materials (BoM) for the Audible Alert System

D.1 High-Level Summary

- **Cameras:** High-resolution, wide-angle cameras with night vision for monitoring oncoming traffic. Typically, a rear-facing camera on the TMA provides a broad Field of View (FOV) to cover multiple lanes and includes infrared capability for low-light conditions.
- **Radar Sensor:** Automotive-grade radar unit (77 GHz FMCW) for detecting vehicle speed and distance. Provides long-range detection of oncoming vehicles in all weather, complementing camera vision.
- **Edge AI Processing Unit:** An on-board AI computer (e.g., NVIDIA Jetson family) for real-time image/radar processing and alert decision-making. This unit runs the detection algorithms at the network edge (on the TMA truck).
- **Power Supply Unit:** Rugged automotive power supply supporting wide input voltages (12–24 V DC from the truck) and including a rectifier for AC input if needed. Ensures stable power for all components, with surge protection and voltage regulation.
- **Connectivity Modules:** Wireless communication units for data and remote control. Includes cellular 4G/5G modem for cloud connectivity, Wi-Fi for local interface or updates, optional **V2X** (Vehicle-to-Everything) module for DSRC or C-V2X communications, and Bluetooth for a standby remote controller.
- **Environmental Protection:** Robust enclosures and components rated IP67 or better for water and dust ingress. All hardware is compliant with automotive shock and vibration standards (e.g., MIL-STD-810H) to withstand the harsh work-zone environment.
- **Display Unit:** In-cabin touchscreen display for the driver/operator. Provides a user interface to monitor system status and alerts. This is a physical monitor mounted in the truck cab, designed for readability in daylight and ease of use.
- **Other Peripherals:** All necessary auxiliary hardware, such as wiring harnesses, connectors, mounting brackets, and an enclosure for housing electronics. It also includes an audible **siren speaker** to output the alert sound and any interface electronics (amplifiers, etc.) needed to drive it.

D.2 Detailed Parts List

D.2.1 Cameras (Vision Sensors)

- **High-Resolution Camera:** A rear-facing digital camera (typically 1080p Full HD) to capture approaching vehicles. For example, a two megapixel (1920×1080) camera with a wide

120° horizontal FOV provides broad coverage of adjacent lanes[34] . This ensures the system can monitor traffic in the lane behind the TMA and neighboring lanes.

- **Infrared Night Vision:** The camera includes an IR-cut filter and built-in infrared LED illuminators or low-light capability to operate at night. Many automotive cameras have **0 lux** minimum illumination with IR on (meaning they can see in total darkness with IR)[47]. Automatic day/night sensors switch the camera to night mode and IR LEDs in low-light conditions[47] .
- **Rugged Automotive Design:** Housed in a weatherproof enclosure, typically **IP67/IP68-rated** for outdoor use[47]. The camera housing protects against dust, rain, and road debris. It's built to handle vibrations and temperature extremes of a work zone. For instance, a continental rear-view camera lists IP68 ingress protection and operation on 12 V or 24 V vehicle power[47] .
- **Mounting and Quantity:** Usually one camera is mounted high at the rear of the TMA (e.g., on the attenuator frame or light bar) to look at oncoming traffic. Additional cameras could be added for side or forward views if needed, but a single wide-angle rear camera is the primary vision sensor. The mounting bracket will be heavy-duty to maintain alignment despite truck vibrations.

D.2.2 Radar Sensor (Distance/Speed Detector)

- **77 GHz Automotive Radar:** A forward-looking millimeter-wave radar sensor mounted at the rear of the TMA, aimed at oncoming traffic. This radar uses FMCW (frequency-modulated continuous wave) technology to measure vehicle range and speed. It is **automotive grade**, operating in the 76–81 GHz band, which is standard for vehicular radar sensors.
- **Detection Range and FOV:** Typical range is on the order of 100–200 meters. For example, a compact 77 GHz radar can detect cars up to ~175 m (574 ft) away and cover about a 100° field of view[35] . This range allows the system to sense fast-approaching vehicles with several seconds of warning. The wide FOV (e.g. ±50°) covers up to 4–6 lanes of traffic[48] , ensuring vehicles in adjacent lanes are also tracked.
- **Accuracy and Output:** The radar provides real-time data on target vehicles, including their distance, relative speed (via Doppler), and angle. Automotive radars can track dozens of objects simultaneously (e.g. up to 256 objects in some traffic radar)[48] , which is more than sufficient for the relatively sparse scenario of a work zone approach. The radar's speed measurements are very accurate (typically ±0.1 m/s) and it can detect vehicles moving up to highway speeds (e.g. 200 km/h or more).
- **Automotive-Grade Specs:** The radar unit is built for vehicle use – rated for -40°C to +85°C operation, sealed electronics, and compliance with standards like **AEC-Q100** for automotive electronic reliability. It will have a durable housing (often IP67) and secure

[34] https://gaugesvdo.com/products/453068752-2910002613400-continental-120-fov-rear-view-ahd-camera-1080p/
[35] https://www.smartmicro.com/traffic-sensor

mounting. Many such radars are **OEM automotive sensors or specialized aftermarket units**; they must also meet FCC regulations for 77 GHz emissions.

- **Example Module:** One example is a Texas Instruments automotive mmWave radar evaluation module or a smartmicro traffic radar. These units illustrate the specs: ~77–79 GHz operation, long and medium range modes, and robust performance in rain or fog. They are designed to survive the shock and vibration on a vehicle. The radar is typically mounted near the camera (rear of truck) to cover the same region of interest.

D.2.3 Edge AI Processing Unit (On-board Computer)

- **High-Performance Processor:** The system uses an NVIDIA Jetson-based edge AI computer for real-time data processing. The Jetson line is well-suited for AI at the edge, with GPU acceleration for neural networks. For this application, an **NVIDIA Jetson Orin** or **Jetson Nano** module is specified:

- *Jetson Orin Nano:* A newer module that delivers up to **40 TOPS** (trillions of operations per second) of AI performance while consuming seven to 15 W[36]. It features an eight GB memory and a 6-core ARM CPU, offering a huge performance boost over earlier models. This would allow for running multiple deep learning models (vehicle detection, tracking, etc.) with low latency.

- *Jetson Nano:* An alternative lower-cost option, providing ~**472 GFLOPs** (0.5 TFLOPS) of AI compute and running at five to 10 W[37]. The Nano (four GB RAM) can handle basic object detection networks and was used in early prototypes but has far less headroom for advanced models compared to Orin.

- **Role in System:** The edge AI unit processes camera feeds (running computer vision algorithms to detect vehicles and predict potential collisions) and radar data (for speed/distance calculation). It fuses sensor data and decides when to trigger alarms. By doing this on-device, the system can respond in fractions of a second (the project improved response from three seconds down to ~0.25 s, as noted in testing).

- **Hardware Configuration:** The Jetson module will be mounted on a carrier board or come as a Developer Kit. For instance, the Jetson Orin Nano Developer Kit is a compact board including the module, I/O ports (USB, Ethernet, display, etc.), and uses a nine to twenty V DC input. These dev kits are used for prototyping; for deployment, a more compact custom carrier might be used, or a ruggedized COTS system. The processing unit will include necessary storage (eMMC or SSD for logging data and running the OS/software) and possibly an integrated GPU for display output to the cabin touchscreen.

- **Thermal and Ruggedization:** The Jetson is passively cooled with a heatsink (and optionally a fan). Since this is an in-vehicle deployment, the unit may need a fanless design with a

[36] https://www.seeedstudio.com/NVIDIA-JETSON-ORIN-NANO-8GB-Module-p-5552.html
[37] https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-nano/product-development/

robust heatsink to avoid dust ingress. The compute box should be mounted in a location with some airflow or in the climate-controlled cab to avoid overheating. Industrial Jetson-based systems often specify operating temperature ranges (e.g., -25°C to 70°C) and comply with vibration standards, which this design will mirror[38] .

- **Software:** The Jetson runs Linux (JetPack SDK) and the developed AI models (e.g., using NVIDIA's DeepStream or TensorRT for acceleration). This software stack can be updated remotely via the connectivity modules. The processing unit also interfaces with the truck's systems (for example, to get speed or to send signals to the alert devices).

D.2.4 Power Supply Unit (Vehicle and AC Power Interface)

- **Input Voltage Range:** The power supply is designed to handle the wide voltage variations of vehicle power. It accepts **~12 V to 24 V DC** input to cover both standard automotive (12V) and heavy truck (24V) electrical systems. In practice, this means an input range of roughly 9–36 V DC to accommodate alternator spikes and battery voltage swings[38] . For example, when the truck's engine is running, a 12 V system can rise to ~14 V, and a 24 V system can be ~28 V; the PSU tolerates these and transient surges.
- **Rectifier for AC Input:** The unit includes an AC/DC rectifier stage to allow powering the system from mains electricity when the truck is not running. This feature is useful during **bench testing or overnight use** (e.g., plugging into a 120 V AC outlet). The PSU can automatically switch to AC input and provide the necessary DC outputs. Essentially, it acts like an on-board charger/adapter. (If the design uses a separate battery backup, the rectifier could also charge that battery).
- **Outputs and Regulation:** The power supply provides regulated DC outputs to all components. Likely a primary 12 V output rail is used (since cameras, radar, Jetson, etc., either take 12 V directly or have secondary regulators). The Jetson dev kit, for instance, runs on 12 V input; the camera example runs on 12/24 V; many radar sensors accept 12 V. The PSU may also provide a five V rail or others if needed (for smaller sensors or logic). Total power budget for the system is on the order of tens of watts (Jetson ~15–30 W peak, camera < five W, radar ~5–10 W, display ~10 W, etc.), so a 100–150 W power supply is ample.
- **Protections:** The unit includes over-voltage, over-current, and reverse polarity protection to prevent damage[38] . It should also smooth out voltage transients and electrical noise (meeting ISO 7637-2 for automotive electrical transients, for example). A fuse or circuit breaker will be in line with the supply. The inclusion of ignition sensing is likely – meaning the PSU can turn the system on/off with the vehicle's ignition state (this was noted as *IGN control* in some rugged PSU specs[38]).
- **Form Factor:** Typically the form factor is a compact DC/DC converter module or an industrial power supply brick mounted inside an enclosure. Automotive-rated power supplies in the ~100 W range are available (for example, Mean Well or Vicor make DC/DC

[38] https://www.nexcom.com/Products/mobile-computing-solutions/ai-edge-telematics-solution/nvidia-solution/atc-3750-ip7-8m

converters with wide input range for vehicular use). These units are often potted or conformal coated for vibration resilience. The PSU will be secured to avoid loose connections under vibration. Cooling is usually passive via its casing (which may be finned).

D.2.5 Connectivity Modules (Communication Interfaces)

- **Cellular 4G/5G Modem:** A cellular module enables the TMA system to send data to the cloud and receive remote commands. For instance, a 4G LTE CAT-12 or CAT-20 modem or a 5G NR modem is integrated for high-bandwidth, low-latency communication. This allows real-time video streaming and alerts to a remote monitoring dashboard. An example is a Sierra Wireless **M.2 modem** (e.g., the EM7565 for LTE or the EM9190 for 5G). Such modules support GPS/GNSS as well. Costs are in the few hundred dollars range (e.g., ~$185 for a 4G module)[39] . The modem will use the truck's roof antenna (if available) or a dedicated high-gain antenna for cellular and GPS signals.

- **Wi-Fi Module:** A Wi-Fi interface (802.11ac/ax) is included for local connectivity. This can serve multiple purposes: connecting a laptop or phone to the system for maintenance, offloading data when in a depot with Wi-Fi, or as a hotspot for field updates. Often, the Jetson's dev kit or a mini-PCIe card provides dual Wi-Fi/Bluetooth capability. For instance, an Intel Wi-Fi 6 module could be used, supporting dual bands and Bluetooth. This module might be pre-integrated or added via an M.2 slot (Jetson Orin Nano dev kit supports Wi-Fi 6/BT5 with an add-on).

- **V2X Communication:** For futureproofing, the BOM includes a **V2X module** that can broadcast warnings to nearby vehicles equipped with Vehicle-to-Everything receivers. This could be a DSRC (802.11p) radio or a C-V2X unit operating at 5.9 GHz. While not mandatory for initial operation, including compatibility means the system could send a standardized alert message (such as a Work Zone warning or TMA presence alert) to approaching connected cars. Modules for V2X (from companies like Autotalks or Cohda Wireless) can be integrated via USB or Ethernet. They typically meet SAE J2945/ITS G5 standards. These are specialized and may add cost, so the design allows adding it as an **optional module**.

- **Bluetooth:** A Bluetooth interface is provided for short-range connectivity. This can pair with a **standby controller** or a handheld device. For example, if an operator in a support vehicle or a worker on-site has a Bluetooth remote, they could receive system status or manually trigger/acknowledge alarms. In practice, Bluetooth is often bundled with the Wi-Fi module (as many Wi-Fi cards have Bluetooth functionality). It offers a convenient wireless link for low bandwidth needs like a smartphone app or a diagnostic tool.

- **Ports and Antennas:** The system will have SIM card slots for the cellular modem and external antenna connectors (SMA or automotive Fakra connectors) for Cellular/GNSS

[39] https://m2msupport.net/m2msupport/product-tag/4g-lte-module-for-verizon/

and V2X antennas. Each wireless module is automotive-rated (temperature and vibration). The overall connectivity suite ensures the TMA's alert system is not an isolated unit – it can report to a cloud dashboard, be updated remotely, communicate with nearby vehicles, and interface with users wirelessly.

D.2.6 Environmental Protection and Ruggedization

- **Ingress Protection:** All components exposed to the elements are rated **IP67** or better. This means they are dust-tight and can withstand immersion in water up to one m for 30 minutes. For example, the camera is IP68[40] and radar sensors are typically in IP65+ sealed housings. The main electronics enclosure will also be IP67 to protect the computer and power units from rain, dust, and debris. Connectors used for external cables are waterproof (sealed circular connectors, cable glands, or automotive sealed connectors like Deutsch DT series).

- **Temperature Tolerance:** The system is designed for extreme temperatures as encountered on roadways. Components meet **industrial/automotive temperature ranges** (-40°C to +85°C for many electronics). The Jetson Orin Nano module itself is specified for -25°C to 80°C in some platforms[41] . The display and other parts selected are rated for hot summers, direct sun exposure, and freezing winters. If the main processing unit is mounted in the cab, it is somewhat temperature-controlled; still, proper cooling (heat sinking) is ensured.

- **Shock and Vibration:** Truck-mounted equipment must endure constant vibration (engine, road surface) and occasional shocks (e.g., if the attenuator is hit or during transit over bumps). Hardware is compliant with **MIL-STD-810H for vibration and shock**[41] or equivalent SAE automotive standards. This includes using PCB mounting that can absorb vibration, potting of sensitive components, and sturdy metal enclosures. Mounting brackets have lock washers or vibration isolators. The design avoids fragile moving parts – the system is essentially solid-state (fanless cooling for the computer, if possible).

- **Electrical and EMC Compliance:** All electronic modules are selected to meet automotive **EMC standards** (like E-mark certification for in-vehicle electronic devices)[41]. This ensures the system does not interfere with nor is it unduly affected by other vehicle electronics (radios, engine ECU, etc.). For example, the computing unit and power supply carry CE/FCC and E-mark certifications in similar automotive AI systems[41] . The radar and wireless transmitters comply with FCC regulations for their frequencies. Additionally, safety compliance for work zones (such as MUTCD lighting/sound guidelines, if any) are

[40] https://gaugesvdo.com/products/453068752-2910002613400-continental-120-fov-rear-view-ahd-camera-1080p/
[41] https://www.nexcom.com/index.html?aspxerrorpath=/Products/mobile-computing-solutions/ai-edge-telematics-solution/nvidia-solution/atc-3750-ip7-8m

considered – the audible alert volume and frequencies are chosen to be attention-grabbing but not harmful.

- **Maintenance and Durability:** The enclosure will have proper seals (O-rings, gaskets) and possibly a gore vent to equalize pressure and avoid condensation. Connectors are keyed and locking to prevent loosening. All cabling is loomed and secured along the truck to avoid wear. In summary, the BOM components are industrial grade to **withstand weather, dust, vibration, and shock** over the lifetime of the TMA truck.

D.2.7 Display Interface (In-Cabin Touchscreen)

- **Touchscreen Monitor:** A dedicated display in the truck cabin serves as the user interface. A typical choice is a **seven-inch rugged touchscreen**. For example, a seven inch LCD with **1280×800** resolution and high brightness (on the order of 1000 cd/m²) for sunlight readability can be used[42] . The screen should be easily visible even in direct sun since TMAs operate outdoors. It features a multi-point capacitive touch panel for operator input (e.g., to silence an alert or navigate menus).
- **Rugged and Automotive-Ready:** The monitor is built for vehicle use – often in a metal housing with at least IP65 front panel sealing[42] . This protects against occasional water splash or dust in the cab. It also should handle the truck's power environment (some vehicle monitors comply with ISO 7637-2 for handling voltage transients[42]). The example monitor is rated IP65 and even supports auto-dimming (ambient light sensor) to avoid blinding the driver at night[42] .
- **Mounting:** The display will be mounted in the cab near the driver's field of view, perhaps on a gooseneck or dashboard bracket. It needs a secure mount to withstand vibrations and to not become a projectile in an impact. Many off-the-shelf vehicle monitors come with adjustable mounts that can attach to a dash or windshield frame.
- **Interface to System:** The Jetson processing unit will output video to the display. Commonly this is via HDMI or DisplayPort from the Jetson to the monitor's input (the example monitor supports HDMI, VGA, USB-C, etc.[42]). Touch input is fed back to the Jetson via USB. The display may also have additional features like showing the camera feed (so the driver can see what the rear camera sees). In the system, the UI likely shows status (e.g., "Vehicle detected at 100m, alarm active") and allows some control. If needed, the display could also show a live video of approaching traffic to the TMA driver for situational awareness.
- **Power:** The monitor will run on 12 V DC (typical for automotive monitors). It can be powered from the same regulated supply feeding the other components. Current draw is modest (likely one to two A at 12 V for a ~7" high-brightness screen). Some displays accept a wide input (e.g., 9–36 V DC) which simplifies integration.
- **User-Friendliness:** The touchscreen replaces earlier keyboard/mouse interfaces, making it more practical for a driver to use. The UI is designed with large buttons and simple

[42] https://lilliputweb.com/lilliput-719/

interaction given the bumpy environment. The inclusion of a physical display ensures the system is **stand-alone** (not requiring a separate laptop) and always available to the operator.

D.2.8 Other Required Peripherals and Hardware

- **Audible Alert Siren:** Since this is an audible alert system, a high-power **speaker/siren** is mounted on the TMA (typically at the rear, facing approaching traffic). This device emits the loud warning sound to get drivers' attention. A common solution is a 100 W rated siren speaker (the type used in emergency vehicles) which can output around **120–130 dB** sound levels[43]. It usually covers a wide frequency range (around 400 Hz – 4 kHz) to produce warbling siren tones. The speaker unit should be at least IP66 rated for outdoor mounting[43] and constructed of metal or tough plastic to survive the environment. An amplifier or siren driver module will be included to drive this speaker from the Jetson (the Jetson can send a trigger or audio signal to a siren controller). The siren is secured to the TMA frame and angled toward traffic.

- **Cables and Wiring:** All necessary cables to connect components are included in the BOM. This encompasses power cables (sized for the current and with proper insulation), coaxial or twisted-pair cables for the camera and radar (e.g., an automotive coax for the analog camera feed or an Ethernet cable if using IP camera, and a shielded cable for radar data if needed), USB cables for the touchscreen and any peripherals, and RF antenna cables for the connectivity modules. The cables are specified with automotive-grade insulation and temperature ratings. They are typically protected with conduit or loom and cut to length for the truck installation. Spare cable length and strain relief is provided for moving parts (like if the attenuator is raised/lowered).

- **Connectors:** The BOM accounts for all connectors, including: waterproof **circular connectors** (like M12 or Amphenol AT series) for camera and radar connections, heavy-duty **power connectors** (perhaps Anderson plugs or Deutsch DT connectors) for the power input, and antenna connectors (Fakra or TNC/SMA with sealing boots). Using standardized connectors eases replacement and ensures reliable connections in a vibration-heavy environment. For example, the Continental camera uses a specific four-pin waterproof connector that mates with its cable kit[44], which would be included. Also, any PCB terminal blocks, USB/HDMI adapters, etc., are listed as needed.

- **Mounting Brackets and Hardware:** Custom-fit brackets to mount the camera and radar on the TMA are part of the BOM. These are typically metal (aluminum or steel) brackets that attach to the truck or attenuator frame using bolts. They are designed to position the sensors at the correct angle and height. Vibration damping pads or bushings may be used. The display in the cab will have a mounting bracket (either an off-the-shelf dash mount or a custom bracket). Additionally, inside the electronics enclosure, mounting plates or

[43] https://www.amazon.com/SoundAlert-Waterproof-Universally-Compatible-Emergency/dp/B08B3FJ7PP
[44] https://gaugesvdo.com/products/453068752-2910002613400-continental-120-fov-rear-view-ahd-camera-1080p

DIN-rail clips will secure the Jetson module, power supply, and other modules. All nuts, bolts, and fastening hardware (lock nuts, etc.) for installation are itemized to ensure everything needed for assembly is available.

- **Enclosure for Electronics:** A weatherproof **enclosure box** is used to house the edge processor, power supply, and connectivity modules (essentially all sensitive electronics, except those designed to be directly exposed like camera/radar). The enclosure is IP67 rated, made of durable plastic or aluminum, with sealing gaskets on the lid. Size is chosen to accommodate the Jetson and other boards with some space for cable routing (for example, a box roughly 300×200×150 mm could be used). It includes cable glands or bulkhead connectors on its walls to interface cables without compromising the seal. An aluminum enclosure has the benefit of EMI shielding and heat dissipation. The enclosure is mounted likely on the truck bed or inside a cabinet on the TMA. In later revisions, the team moved the electronics **inside the truck cab** to help with overheating issues – if so, the enclosure still provides protection and tidy integration, but being inside the cab means less direct weather exposure.

- **Miscellaneous:** Other peripherals include an **audio amplifier module** (to drive the siren from a low-level signal, if the siren isn't self-powered), a **GPS unit** (if precise positioning or time sync is needed – some 4G/5G modems have GNSS built-in as noted), **indicator lights or LEDs** on the enclosure (to show power/status), and possibly a **manual override switch**. A manual kill-switch could be installed to power down the system or silence the alarm if needed, for safety. If the system ties into the TMA's existing light board or arrow board, relays or interface circuits for those could also be included (though the question focus is on audible alert, not lights). Finally, any **development/programming connectors** (like a debug port, or an external USB for retrieving data) are considered in the design, though not separate BOM line items.

D.3 Supplier and Cost Estimates

(All prices are rough estimates per unit, in USD, and will vary with supplier and quantity. Major electronics components are assumed to be sourced from reputable distributors like Digi-Key, Mouser, Arrow, or directly from manufacturers. Automotive-specific items may come from specialized vendors.)

Table D.1: Supplier and Cost Estimates

Category	Component (Name/Model)	Specifications	Estimated Cost (USD)	Supplier / Availability Notes
Cameras	High-Resolution Camera (e.g., e-con Systems STURDeCAM25)	1080p Full HD; Narrow FOV for long-range detection; 4K sensor option; IR/night vision desirable;	~$300 each	e-con Systems; available via distributors such as Digi-Key; typical lead time moderate

		IP67-rated enclosure; automotive-grade, robust against vibration		
Cameras	Optional Secondary Camera	Same specifications as primary for additional angles/redundancy	Additional ~$300	Use matching module for consistency
Sensors (Radar/LiDAR)	77 GHz Automotive Radar (e.g., Continental ARS 408-21)	77 GHz FMCW radar; Detection range: 150–200+ m; Provides distance, relative speed, and angle; IP67-rated; Automotive-grade (–40°C to +85°C)	~$200 each	Continental or similar OEM suppliers; check third-party distributors; lead time 6–8 weeks for specialized units
Sensors (Radar/LiDAR)	Optional LiDAR Sensor (e.g., Velodyne VLP-16 "Puck")	16-channel LiDAR; 360° horizontal, 30° vertical FoV; Range up to ~200 m; High precision point cloud; IP67-rated; automotive-grade	~$4,000 each	Velodyne; available via distributors such as Mouser; optional for enhanced accuracy
Processing Unit	NVIDIA Jetson AGX Orin 32GB Developer Kit	12-core ARM v8 CPU, 2048-core NVIDIA Ampere GPU; up to 200–275 TOPS; 32GB LPDDR5; 64GB eMMC; multiple I/O ports (Ethernet, USB, MIPI CSI); Operating range: -25°C to 80°C	~$1,999 each	NVIDIA; available through Arrow, Seeed Studio, SparkFun; check current stock and lead times
Power Supply	Automotive DC/DC Converter (e.g., Mean Well RSD-150 or equivalent)	Input range: 6V–48V DC; Outputs regulated 12V (or 19V if needed); Supports up to 8A; Includes reverse polarity protection and transient	~$90 each	Available via Mouser, Digi-Key; industrial/automotive grade with UL/SAE certifications

		suppression; Designed for automotive power conditions		
Connectivity Modules	Cellular 4G/5G Modem (e.g., Sierra Wireless EM7565 or EM9190)	4G LTE Cat-12 (or 5G upgrade option); Supports GPS/GNSS; Rugged design; 4G: ~$150–$300 range; Includes external high-gain antenna options	~$600–$900 (LTE); ~$1,500+ (5G)	Sierra Wireless; available from industrial networking suppliers; check FCC certification and regional compatibility
Connectivity Modules	Wi-Fi & Bluetooth Module (e.g., Intel AX210 M.2)	Dual-band Wi-Fi 802.11ac/ax; Bluetooth 5.x; Supports up to 1.2 Gbps throughput; Industrial grade	~$20 each	Available via Amazon, Digi-Key; commodity item with short lead times
Connectivity Modules	Optional V2X Module	DSRC or C-V2X radio for future V2X integration; Designed for 5.9 GHz ITS band; Compliant with SAE J2735 and related standards	(Optional – allocate ~$300–$1,000 per unit if integrated)	V2X modules available from suppliers like Cohda Wireless or Autotalks; future expansion option
User Interface	In-Cab Touchscreen Monitor (7-inch rugged display)	7-inch touchscreen; 1024×600 resolution; Sunlight-readable (≥1000 nits); IP65-rated; Capacitive touch (glove-friendly); Mountable in truck cabin; Interfaces via HDMI/USB	~$300–$400 each	Suppliers such as Xenarc Technologies, Lilliput Direct; check automotive-grade models with appropriate mounting options
User Interface	Operator Controls (Physical Override Buttons/LED Indicators)	Simple push-button manual override; Status LEDs for system state (green/yellow/red); Robust, automotive grade; Integrated	~$50 (set)	Standard automotive switches/indicators from Mouser or Digi-Key; widely available

		with the touchscreen interface		
Mounting & Enclosures	Electronics Enclosure (Weatherproof, IP67-rated)	IP67 or higher enclosure; Material: Polycarbonate or Aluminum; Size: ~300×200×150 mm; Includes cable glands, sealing gaskets; Designed for automotive vibration and weather	~$130 each	Suppliers like Polycase, Bud Industries; off-the-shelf enclosures with custom modifications possible
Mounting & Enclosures	Sensor Mounting Hardware (Brackets and Isolators)	Adjustable metal brackets; Vibration dampening mounts; Suitable for camera and radar; Stainless steel or aluminum; Standard bolt patterns (1/4″ -20)	~$50-$100 per set	RAM Mounts or custom-fabricated brackets from industrial hardware suppliers (e.g., McMaster-Carr)
Alarm System	Audible Alert Siren (e.g., Speco Technologies SA4P)	100W siren speaker; Output: ≥110–120 dB at 1 m; Frequency range: ~400 Hz–4 kHz; IP66-rated for outdoor use; Designed for vehicular applications; Requires amplifier or relay control	~$25 each (siren only); Additional ~$100 for amplifier (if needed)	Emergency vehicle equipment suppliers; available via Amazon, Allied Electronics; ensure FCC compliance for sound output
Miscellaneous	Cables, Connectors, and Wiring	Automotive-grade shielded cables; Waterproof connectors (M12, Deutsch DT series); Wiring harnesses; Strain relief components; Total estimated cost	~$100 per system	Sourced from Digi-Key, Mouser, or McMaster-Carr; ensure all components meet automotive environmental ratings

		covers all necessary lengths and types for interconnections		

D.4 Laboratory or Experimental Setup

Below is a draft Bill of Materials (BOM) for the AutoTMA Audible Alert System for experimental or laboratory setup. This table lists the major components, along with their specifications, quantities, estimated unit costs, and relevant comments. (Note: The prices are approximations based on current market trends and may vary.)

Table D.2: Bill of Materials

Item No.	Component	Specification / Model Description	Qty	Estimated Unit Cost	Total Cost	Comments
1	High-Resolut-ion Camera	Industrial-grade, 1080p resolution; 30–60 FPS; narrow field-of-view optimized for long-range detection; robust, waterproof with stabilization	1	$250	$250	Primary sensor for detecting oncoming vehicles; mounted at an elevated position on the TMA
2	LiDAR Sensor	Livox HAP LiDAR (T1) with 120° horizontal FOV, 25° vertical FOV; range ~100–120 m; generates 3D point cloud data	1	$2,000	$2,000	Augments camera data for precise distance measurement; optional but recommended for enhanced reliability
3	Radar Sensor	77 GHz automotive-grade radar; detection range up to 150–200 m; provides Doppler-based speed measurement	1	$1,000	$1,000	Enhances speed and range estimation, especially in adverse weather conditions
4	Onboard Computer	NVIDIA Jetson Orin NX (or similar edge-AI computer) with GPU	1	$800	$800	Processes sensor data in real-time; ruggedized and

		acceleration, 8-core ARM CPU; optimized for deep neural network inference				installed in a climate-controll ed enclosure inside the cab
5	DC-DC Converter	Wide dynamic range converter, 6V–56V input, up to 8A power draw; includes input rectifier for reverse-polarity protection	4	$100	$100	Conditions vehicle power for stable operation of electronics
6	Backup Battery/UPS	Automotive-grade backup battery for uninterrupted operation (approximately 30 minutes of operation during power loss)	1	$150	$150	Ensures system remains powered during engine off or transient power interruptions
7	Communicati -on Module	Multi-mode communication device supporting 4G/5G, Wi-Fi, and Bluetooth; future-ready for V2X integration	1	$150	$150	Provides remote monitoring and data exchange; secures communication with cloud servers
8	Audible Alarm Device	High-decibel siren/horn capable of ~120 dB output; rugged and weather-proof; optimized for rapid activation	1	$200	$200	Primary audible alert; designed to be unmistakable in traffic conditions
9	Visual Warning Devices	Set of high-visibility LED strobe lights (amber) with adjustable flash rates; compliant with MUTCD standards	4	$50 each	$200	Supplement audible alerts with visual cues; can be mounted on the TMA for increased

						situational awareness
10	Mounting Hardware	Custom-fabricated, vibration-damped brackets and mounts for sensors and computing unit; includes shock absorbers, clamps, and protective enclosures	Lump Sum	$300	$300	Ensures stable sensor placement and protection from vibration and environmental factors
11	Wiring & Connectors	High-grade cables (USB, Ethernet, power) with protective conduit; rugged connectors and harnesses	Lump Sum	$200	$200	For secure, interference-free connections between sensors, computer, and alert devices
12	Enclosure for Electronics	Rugged, weather-proof enclosure (IP67 rated) with internal cooling (fan/heat sink) for the onboard computer and associated electronics		$150	$150	Protects computing hardware from dust, moisture, and temperature extremes; installed in the cab

Total Estimated Cost: $5,900

Notes:

- **Integration and Modularity:** The BOM is designed with a modular approach to allow easy replacement or upgrades. For example, if a new radar sensor becomes available, it can be integrated with the same communication interface.
- **Regulatory Compliance:** All components are selected to meet industrial and automotive standards, including environmental ruggedness (IP67), shock and vibration resistance, and compliance with work zone safety regulations (see Appendix C for full hardware requirements).
- **Scalability:** The design supports plug-and-play installation, ensuring that the system can be retrofitted to various TMA vehicles with minimal modifications, as specified in the Hardware Requirements Specification (Appendix C).

- **Future Enhancements:** While the primary focus is on the automated audible alert system, future iterations could integrate additional sensor modalities (e.g., thermal imaging) to further improve performance.

This draft Bill of Materials aligns with the detailed system design provided in the report and serves as a reference for procurement and cost estimation for the AutoTMA project.

Appendix E: Design Schematics of the Audible Alert System

E.1 High-Level Schematic of Design Prototypes (Revisions)

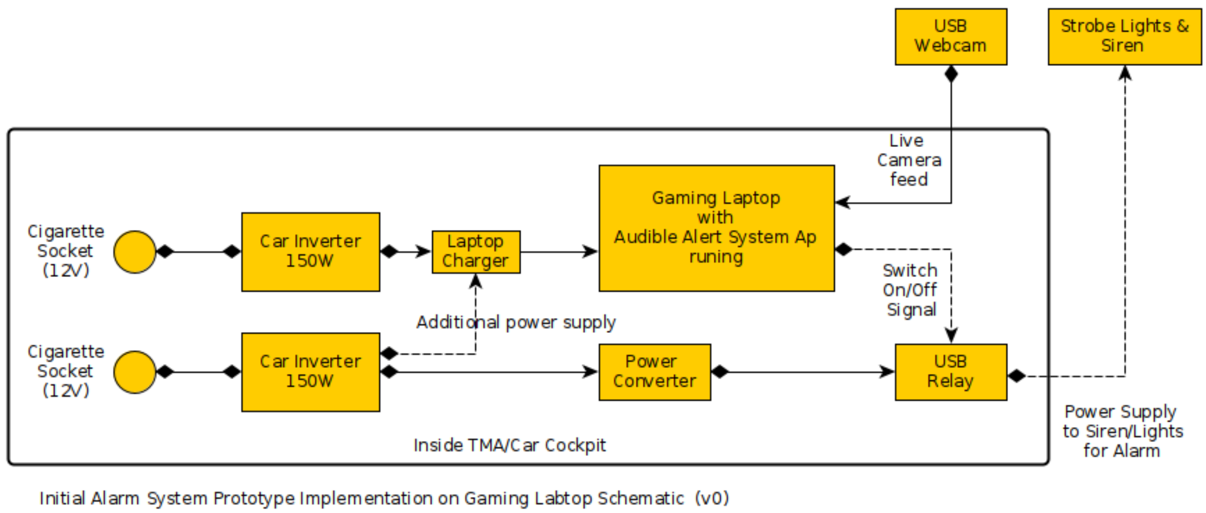

Figure E:1: Initial Demonstration Prototype Schematic

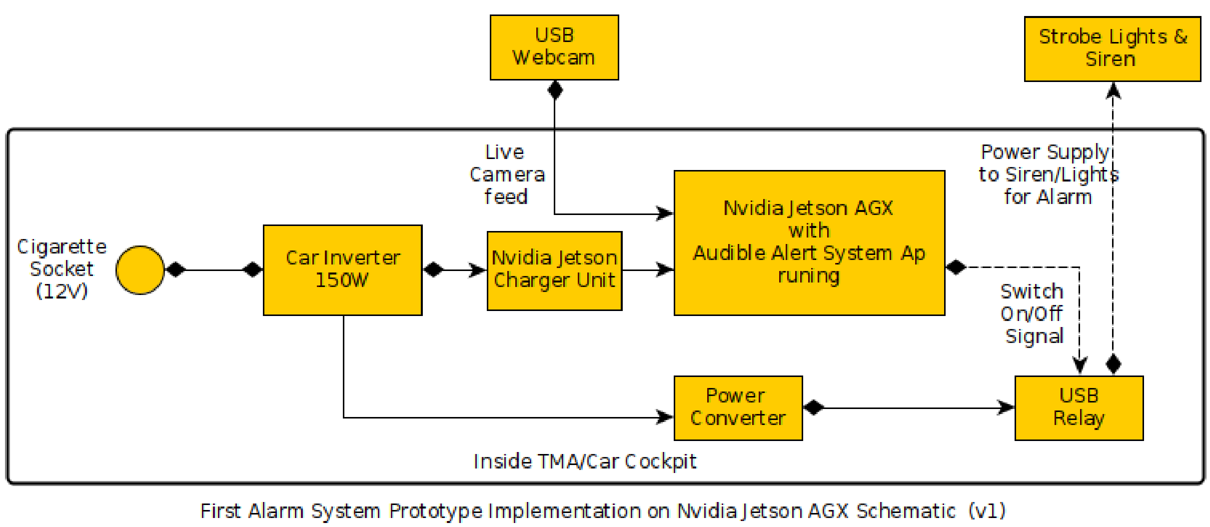

Figure E.2: First Alarm System Prototype Schematic

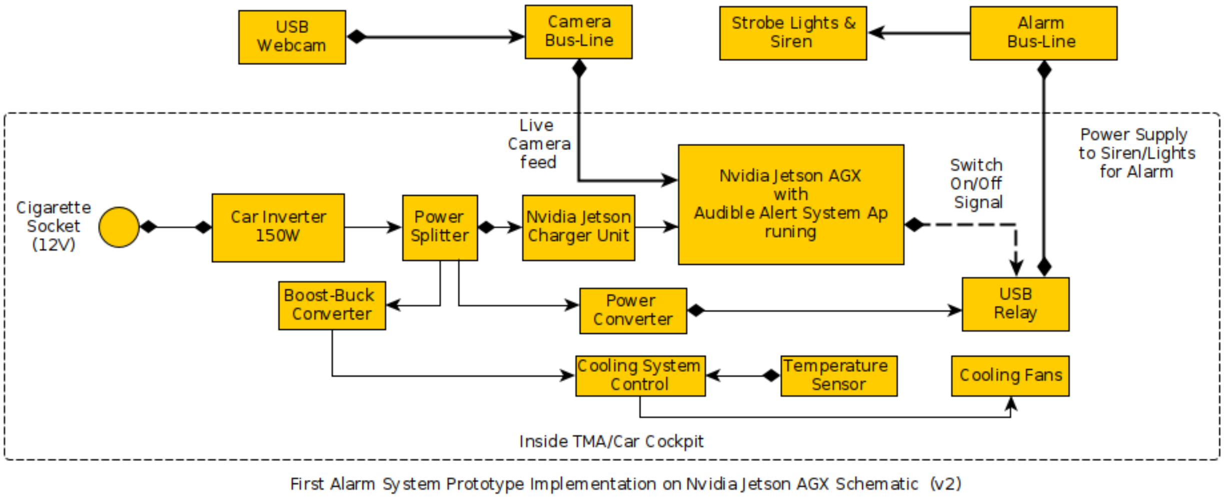

Figure E.3: First Alarm System Prototype Schematic (Revision 1)

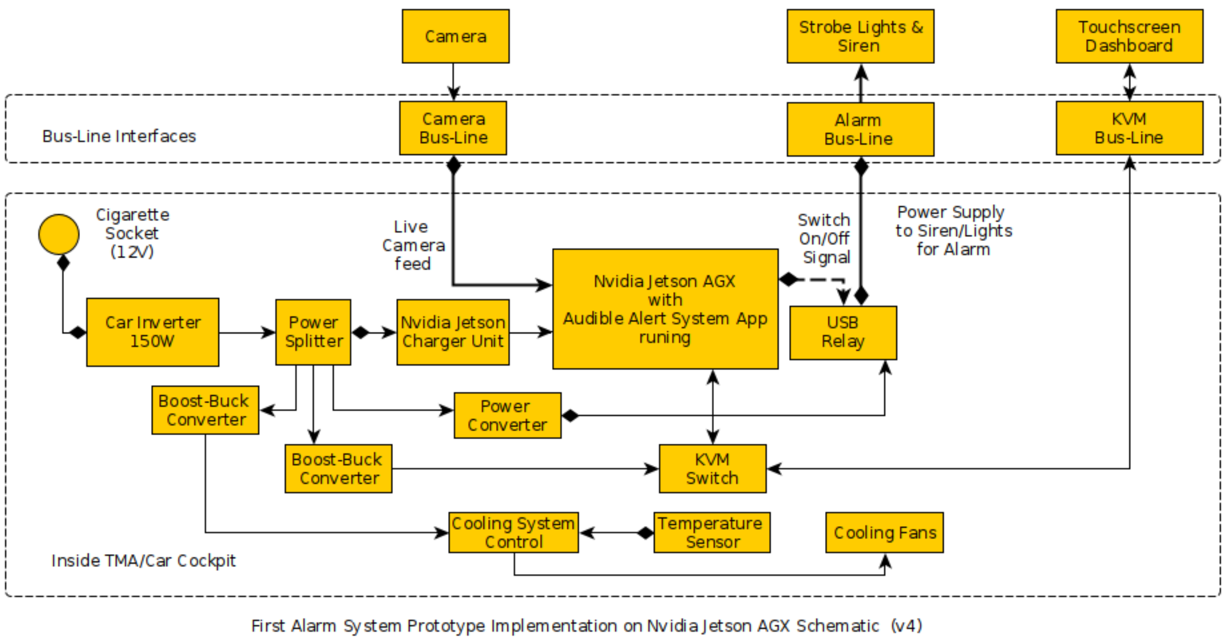

Figure E.4: First Alarm System Prototype Schematic (Revision 2)

E.2 High-Level Schematic of Final Prototype

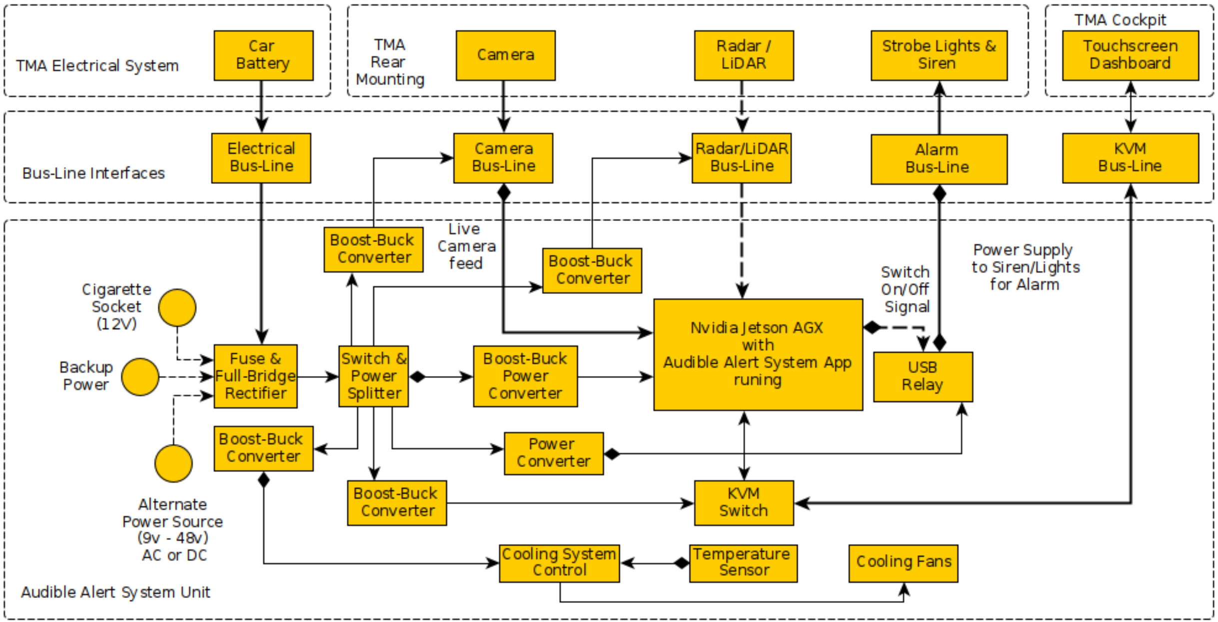

Figure E.5: Final Alarm System Prototype Schematic (Revision 3)

Appendices F: Light and Horn Simulation

Appendix F.1. Human Subject Consent Form

IRB# 2098240

HIGHWAY SAFETY STUDY

PARTICIPANT CONSENT FORM

You are being asked to take part in a research study about highway safety. We are asking you to take part in this study to obtain your feedback about driving a car simulator on a roadway. Please read this form carefully and ask any questions you may have before agreeing to take part in the study. Participants must be 18 years of age. The number of participants in the study is 50.

What the study is about: The purpose of this study is to learn about human behavior on roadways. What we will ask you to do: If you agree to be in this study, we will ask you to drive the car simulator on a highway. We will collect data from the simulator trip to help us evaluate how to best improve highway safety. Upon completion of the simulator trip, we will ask you to take a brief survey. The survey will ask you about your preferences while driving on a freeway. The entire study will take approximately 45 minutes. Risks and benefits: Even though the probability of experiencing simulator sickness is low, there is a potential for some participants to experience general discomfort, eye strain, dizziness, and/or nausea. The results of the study will benefit the state of Missouri by improving highway safety. Compensation: A $25 Amazon gift card will be offered. If the subject refuses to participate or drops out, there is no loss of benefits to the subject. Your answers will be confidential. In any type of report we make public, we will not include any information that will make it possible to identify you individually. Research records will be kept in a locked cabinet; only the researchers will have access to the records. Taking part is voluntary: Taking part in this study is completely voluntary. You may skip any survey questions that you do not want to answer. If you decide to take part in this study, you are free to withdraw at any time without the loss of compensation. If you have questions: The researcher conducting this study is Dr. Carlos Sun. Please ask any questions you have now. If you have questions later, you may contact Dr. Sun at csun@missouri.edu or 573-884-6330. If you want to talk privately about your rights or any issues related to your participation in this study, you can contact University of Missouri Research Participant Advocacy by calling 888-280-5002 (a free call), or emailing muresearchrpa@missouri.edu. If you have any questions or concerns regarding your rights as a participant in this study, you may contact the Institutional Review Board (IRB) at 573-882-3181. You will be given a copy of this form to keep for your records. The information we collect from you for this study will not be used or shared with other investigators for future research studies.

Statement of Consent: Please verbally acknowledge that you have read the above information and have received answers to any questions. Please acknowledge that you voluntarily consent to take part in the study.

Signature: ______________________________ Date: ______________________________

Appendix F.2. Gift Card Receipt Log

Serial Number	
Amount of Card	$25
Name	
Mailing Address	
Date	

Appendix F.3. Post-Simulator Survey

Participant #: ___ Date ________________________

Automated TMA Warning System

Thank you for sharing your opinions to help us improve safety and efficiency at work zones. Proper communication of work zone information is critical for the safe movement of traffic through work zones. Please share your perspective on how to make work zones better.

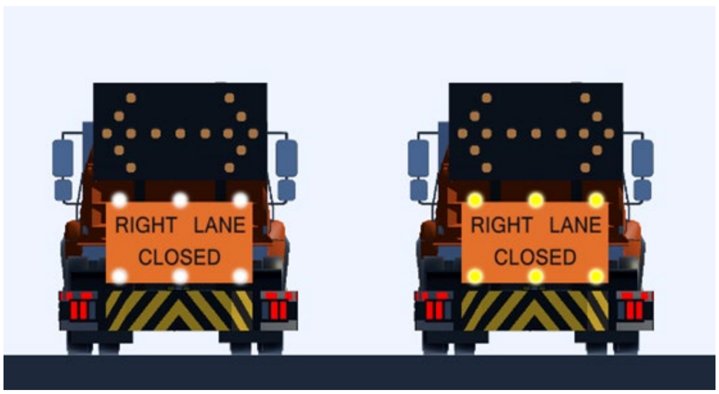

Figure 1a Figure 1b

1. Which work zone warning color scheme do you prefer?

   [ ] Figure 1a (white lights)

   [ ] Figure 1b (yellow lights)

2. Please rate all designs from a scale of 1 (worst) to 10 (best) with respect to following:

		
Clarity		
Visibility		

Safety		
Efficiency		
Comments		

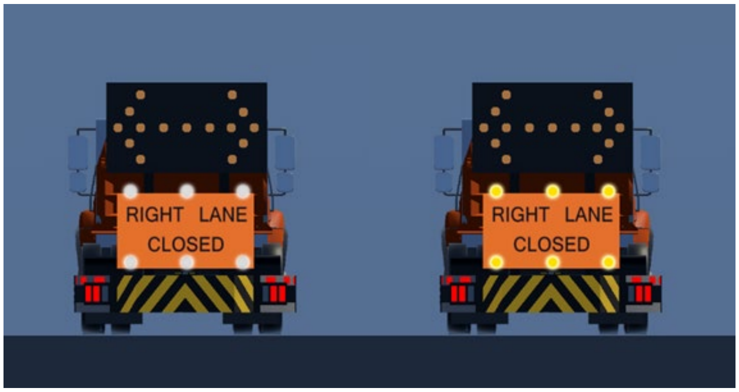

Figure 2a Figure 2b 3.

3. Which work zone warning color scheme do you prefer at night time?

   [ ] Figure 2a (white lights)

   [ ] Figure 2b (yellow lights)

4. Please rate all designs from a scale of 1 (worst) to 10 (best) with respect to following:

		
Clarity		
Visibility		
Safety		
Efficiency		
Comments		

Please answer questions about your simulator experience.

5. I felt the airhorn made me more alert to the TMA and work zones.

   [ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree
6. The sound from the airhorn was **<u>not</u>** too loud or disturbing.

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

7. I felt like I was actually there on the highway.

   [ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

8. I felt like I could drive around freely.

   [ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

9. Did any issues arise during your simulator experience?

   [ ] Yes [ ] No If yes, please explain the issue(s) that you experienced: ____
   ____
   ____

Please answer the demographic questions below.

10. Age range
[ ] 16-25 [ ] 26-40 [ ] 41-55 [ ] 56-70 [ ] 71-95
11. Gender
[ ] Male [ ] Female
12. My Residency
[ ] Urban [ ] Rural
13. My Regular Vehicle Type
[ ] Passenger Car [ ] Vehicle towing trailer [ ] Delivery/Moving Truck [ ] Tractor trailer truck [ ] Bus
14. Please enter any additional comments you may have regarding this study.

Please contact Mr. Carlos Sun (csun@missouri.edu) for additional comments, concerns or information on this survey. Thank you for completing this survey! We greatly appreciate your time!

Simulator Sickness Questionnaire

Instructions: Circle how much each symptom below is affecting you right now.

1.	General discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Headache	None	Slight	Moderate	Severe
4.	Eye strain	None	Slight	Moderate	Severe
5.	Difficult focusing	None	Slight	Moderate	Severe
6.	Salivation increasing	None	Slight	Moderate	Severe
7.	Sweating	None	Slight	Moderate	Severe
8.	Nausea	None	Slight	Moderate	Severe
9.	Difficulty concentrating	None	Slight	Moderate	Severe
10.	Fullness of the Head	None	Slight	Moderate	Severe
11.	Blurred vision	None	Slight	Moderate	Severe
12.	Dizziness with eyes open	None	Slight	Moderate	Severe
13.	Dizziness with eye closed	None	Slight	Moderate	Severe
14.	*Vertigo	None	Slight	Moderate	Severe
15.	**Stomach awareness	None	Slight	Moderate	Severe

16. Burping None Slight Moderate Severe

- *Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Appendix F.4 Institutional Review Board Approval Letter

Institutional Review Board
University of Missouri-Columbia
FWA Number: 00002876
IRB Registration Numbers: 00000731, 00009014

310 Jesse Hall
Columbia, MO 65211
573-882-3181
muresearchirb@missouri.edu

December 26, 2024

Principal Investigator: Yaw Okyere Adu-Gyamfi
Department: Civil/Environmental Engr

Your Annual Exempt Form to project entitled Automated TMA Warning System was reviewed and approved by the MU Institutional Review Board according to the terms and conditions described below:

IRB Project Number	2098240
IRB Review Number	444313
Funding Source	Missouri Department of Transportation
Initial Application Approval Date	January 02, 2024
Approval Date of this Review	December 26, 2024
IRB Expiration Date	January 02, 2026
Level of Review	Exempt
Project Status	Active - Exempt
Risk Level	Minimal Risk
HIPAA Category	No HIPAA

The principal investigator (PI) is responsible for all aspects and conduct of this study. The PI must comply with the following conditions of the approval:

1. No subjects may be involved in any study procedure prior to the IRB approval date or after the expiration date.
2. All study changes must be IRB approved prior to implementation utilizing the Exempt Amendment Form.
3. Major noncompliance must be reported to the MU IRB on the Event Report within 5 business days of the research team becoming aware of the deviation. Major noncompliance are deviations that caused harm or have the potential to cause harm to research subjects or others, and have or may have affected subject's rights, safety, and/or welfare. Please refer to the MU IRB Noncompliance policy for additional details.
4. The Annual Exempt Form must be submitted to the IRB for review and approval at least 30 days prior to the project expiration date to keep the study active or to close it.
5. Maintain all research records for a period of seven years from the project completion date.

If you are offering subject payments and would like more information about research participant payments, please view the MU Business Policy and Procedure Manual.

Please view the MU HRPP/IRB policies describing IRB exempt and other requirements.